



(RESEARCH ARTICLE)



Evaluation of Drinking Water Quality from Multiple Sources in Relation to WHO Standards in Prasat Bakong District, Siem Reap Province

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Abstract

Access to safe drinking water remains a major public health concern in rural Cambodia. This study evaluated the physicochemical and microbiological quality of four water sources—rainwater, pond biosand-treated, well biosand-treated, and city-supplied water—in Prasat Bakong District, Siem Reap Province, and compared them with World Health Organization (WHO) standards. Parameters analyzed included pH, turbidity, electrical conductivity (EC), total dissolved solids (TDS), manganese (Mn), iron (Fe), nitrate (NO₃⁻), phosphate (PO₄³⁻), total hardness, arsenic (As), *Escherichia coli* (*E. coli*), and total coliforms. Most physicochemical parameters complied with WHO guidelines, with pH ranging from 6.6 to 7.6 and TDS below 500 ppm. However, turbidity, arsenic, and microbial contamination exceeded acceptable limits in some sources. Pond biosand-treated water showed the highest turbidity (14.7 NTU), elevated Fe (0.19 mg/L), and as (0.043 mg/L). Rainwater contained high microbial loads (*E. coli*: 67 CFU/100 mL; total coliforms: 175 CFU/100 mL), while well biosand-treated water met most standards except for As, which reached the WHO limit (0.01 mg/L). City-supplied water consistently met all safety criteria. Correlation analysis revealed strong associations between turbidity, Fe, and As, and between phosphate and microbial indicators, suggesting shared contamination pathways. Principal Component Analysis (PCA) explained 78% of total variance, distinguishing contamination profiles: pond water with turbidity and metals, rainwater with microbial contamination, well water with mineralization and arsenic, and city water with minimal pollutants. Overall, only city water was consistently safe for consumption, emphasizing the need for regular monitoring and maintenance of biosand systems to ensure safe water access in rural Cambodia.

Keywords: Drinking water quality; WHO standards; Pond biosand; Arsenic; Cambodia

1 Introduction

Access to safe drinking water remains a pressing global public health challenge, particularly in rural regions of low- and middle-income countries where inadequate infrastructure and dependence on untreated water sources heighten exposure risks (World Health Organization, & United Nations Children's Fund, 2022). In Cambodia, widespread reliance on shallow groundwater and surface water has resulted in contamination from both chemical and microbial pollutants (Buschmann et al., 2007; Sokra et al., 2024). Microbes play a major role in determining water quality (Sokra et al., 2025; Srivastava et al., 2017). Among chemical hazards, arsenic contamination poses one of the most serious threats to public health, with concentrations exceeding 500 µg/L in some aquifers and nearly one-third of sampled wells across the country surpassing the WHO guideline limit of 10 µg/L (Chow et al., 2007; Ratha et al., 2018). Arsenicosis, a chronic

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health condition caused by prolonged exposure to arsenic, was first reported in Cambodia in 2006 (Murphy et al., 2018). Besides arsenic, other contaminants such as manganese, fluoride, nitrate, and high total dissolved solids (TDS) also compromise the safety and acceptability of drinking water in several provinces (Ministry of Industry Mines and Energy, 2004). According to UNICEF Cambodia (2022), approximately one in three rural households still relies on unimproved drinking water sources, and intermittent or untreated supplies remain a key contributor to waterborne diseases. To address microbial hazards in drinking water, low-cost and community-managed technologies such as biosand filters (BSFs) have gained increasing attention. BSFs are improved versions of traditional slow sand filters that utilize a biologically active layer (schmutzdecke) to remove pathogens and turbidity. Field trials and meta-evaluations have shown that BSFs can remove over 90% of *Escherichia coli* and other microbial contaminants, while reducing diarrheal incidence by 50–60% in rural households (Stauber et al., 2012; O’Connell, 2016; Duran Romero et al., 2020). Recent studies further demonstrate that microbial community dynamics within the biofilm are strongly associated with improved filter performance and long-term sustainability (Webster et al., 2019). Despite these advantages, the long-term effectiveness of BSFs depends on user maintenance, filter design, and water source characteristics—factors that vary considerably in rural Cambodian settings (Zinn et al., 2018). In Prasat Bakong District of Siem Reap Province, local communities depend on diverse water sources, including rainwater, pond water treated through BSFs, well water treated through BSFs, and municipal supply. Seasonal variation and infrastructure limitations often determine which source is used, leading to inconsistencies in water quality and safety. Assessing the physicochemical and microbiological quality of these sources against WHO drinking water standards is therefore critical for safeguarding community health and supporting sustainable water management strategies. This study aimed to evaluate the drinking water quality from multiple sources in Prasat Bakong District, Siem Reap Province, by comparing key physicochemical and microbiological parameters with WHO standards to identify potential health risks and guide safe water interventions in rural Cambodia.

2 Materials and methods

2.1 Study Area & Sample Collection

Water samples were collected from Prasat Bakong District, Siem Reap Province, representing four key drinking water sources: rainwater, pond water treated using biosand filters (pond biosand), well water treated using biosand filters (well biosand), and municipal city-supplied water. To ensure representativeness and comparability, three samples were collected from each source type (total $n = 12$) during the dry season. Sampling followed standard environmental monitoring procedures. For municipal tap water, outlets were flushed for 2–3 minutes before sampling to remove stagnant water and ensure a fresh supply. All samples were collected in pre-cleaned polyethylene bottles, properly labeled, stored in iceboxes, and transported promptly to the laboratory for analysis to minimize alterations in chemical composition and microbial activity, following established protocols (Latif et al., 2024).

2.2 Analytical Parameters

A suite of physicochemical and microbiological parameters was analyzed to evaluate water quality in relation to WHO drinking water standards (WHO, 2011). The measured physicochemical parameters included pH, turbidity (NTU), electrical conductivity (EC, $\mu\text{S}/\text{cm}$), total dissolved solids (TDS, ppm), manganese (Mn), iron (Fe), nitrate (NO_3^-), phosphate (PO_4^{3-}), and total hardness. Chemical and microbial indicators included arsenic (As, mg/L), *E. coli*, and total coliforms. Physicochemical analyses such as pH, turbidity, EC, TDS, and hardness were conducted following standard methods described by Latif et al. (2024). Temperature and pH were measured on-site using calibrated portable meters, while laboratory assays were used for the remaining parameters, including EDTA titration for total hardness. Microbiological analyses of *E. coli* and total coliforms were performed using the membrane filtration technique with selective culture media in accordance with WHO guidelines for drinking water quality assessment. Heavy metal and arsenic concentrations were determined using atomic absorption spectroscopy (AAS) following standardized procedures to ensure analytical accuracy and comparability with prior studies (Yahaya et al., 2021).

2.3 Biosand Filter Context

Biosand filters (BSFs) are an established point-of-use water treatment technology widely implemented in Cambodia. They operate through a combination of biological and physical mechanisms within a sand column, including mechanical straining, adsorption, sedimentation, and microbial degradation facilitated by the biologically active layer (biofilm or schmutzdecke). Under field conditions, BSFs have demonstrated substantial effectiveness in improving drinking water quality, with reported reductions in turbidity and microbial pathogens—particularly *E. coli*—exceeding 90% (Stauber et al., 2012). The use of BSFs in this study enabled comparative assessment of water quality before and after filtration from both pond and well sources, thereby providing insight into their treatment efficacy under rural Cambodian conditions.

2.4 Data Analysis

Descriptive statistics, including mean, median, standard deviation, and range, were calculated for each parameter to summarize the central tendency and variability among the different water source groups. The results were compared against WHO guideline values to evaluate compliance with drinking water safety standards. To examine relationships among physicochemical and microbiological variables, correlation analysis was performed and visualized using a correlogram to identify significant associations between chemical and microbial indicators. Additionally, Principal Component Analysis (PCA) was conducted to explore the underlying structure and major gradients within the water quality dataset, following established best practices in environmental assessment.

3 Results

3.1 Descriptive statistics of physicochemical and microbiological parameters of water samples.

Table 1 Descriptive statistics (mean \pm SD) of physicochemical and microbiological parameters of water samples from different sources in Prasat Bakong District, Siem Reap Province. WHO guideline limits are provided for reference (WHO, 2011).

Parameter	Unit	WHO Standard	City Water (Mean \pm SD)	Pond Biosand (Mean \pm SD)	Rainwater (Mean \pm SD)	Well Biosand (Mean \pm SD)
pH	—	6.5–8.5	6.58 \pm 0.27	7.61 \pm 0.20	7.37 \pm 0.64	7.19 \pm 0.51
Turbidity	NTU	5	0.90 \pm 0.18	14.73 \pm 10.49	2.26 \pm 0.98	1.01 \pm 0.14
EC	μ S/cm	1500	116.67 \pm 15.95	146.00 \pm 31.05	89.00 \pm 78.10	126.67 \pm 51.19
TDS	ppm	1000	58.33 \pm 7.57	73.00 \pm 15.52	44.67 \pm 39.31	76.33 \pm 30.75
Mn	mg/L	0.4	0.02 \pm 0.01	0.02 \pm 0.00	0.03 \pm 0.01	0.03 \pm 0.00
Fe	mg/L	0.3	0.02 \pm 0.02	0.19 \pm 0.19	0.03 \pm 0.02	0.03 \pm 0.03
NO ₃ ⁻	mg/L	50	2.13 \pm 1.89	1.30 \pm 0.66	0.76 \pm 0.71	1.03 \pm 0.15
PO ₄ ³⁻	mg/L	—	0.07 \pm 0.03	0.08 \pm 0.04	0.23 \pm 0.32	0.06 \pm 0.02
Total hardness	mg/L	500	31.30 \pm 5.12	29.77 \pm 2.95	23.10 \pm 19.83	45.23 \pm 12.32
As	mg/L	0.01	0.00 \pm 0.00	0.04 \pm 0.04	0.00 \pm 0.00	0.01 \pm 0.02
<i>E. coli</i>	CFU/100 mL	0	0.00 \pm 0.00	6.33 \pm 5.13	67.00 \pm 115.18	0.00 \pm 0.00
Total coliforms	CFU/100 mL	0	0.00 \pm 0.00	45.00 \pm 36.59	175.33 \pm 166.89	0.33 \pm 0.58

Note: Values represent mean \pm standard deviation (SD) of triplicate samples (n = 3) for each water source. EC = Electrical conductivity; TDS = Total dissolved solids; Mn = Manganese; Fe = Iron; NO₃⁻ = Nitrate; PO₄³⁻ = Phosphate; T-hardness = Total hardness; As = Arsenic; CFU = Colony-forming units. WHO guideline limits are based on WHO (2011) drinking water quality standards.

Descriptive statistics of the physicochemical and microbiological parameters of water samples from the four sources are presented in Table 1. The pH values ranged from 6.32 to 8.10, falling within the WHO recommended range (6.5–8.5) for all sources. Rainwater and biosand-treated waters were generally near neutral to slightly alkaline, indicating favorable conditions for drinking. Turbidity levels, however, showed considerable variation among sources. Pond biosand-treated water exhibited the highest turbidity (14.73 \pm 10.49 NTU), exceeding the WHO limit of 5 NTU, suggesting incomplete removal of suspended particles. Turbidity in city-supplied, well biosand, and rainwater samples remained within acceptable limits. Electrical conductivity (EC) and total dissolved solids (TDS) values were relatively low across all samples, ranging from 89–146 μ S/cm and 44.67–76.33 ppm, respectively, well below the WHO permissible limits of 1500 μ S/cm and 1000 ppm, reflecting low mineral content. Total hardness values (23.10–45.23 mg/L) also indicated soft to moderately hard water, within safe limits. Concentrations of manganese (0.02–0.03 mg/L), iron (0.02–0.19 mg/L), nitrate (0.76–2.13 mg/L), and phosphate (0.06–0.23 mg/L) were all below WHO threshold values, suggesting minimal contamination by metals and nutrients. Arsenic was not detected in most samples, except in pond biosand and well biosand water, where trace concentrations (0.01–0.04 mg/L) were observed but still below the

WHO guideline limit of 0.01 mg/L. Microbiological analysis revealed notable differences among sources. *E. coli* and total coliforms were absent in city-supplied and well biosand-treated water, confirming their microbiological safety. However, pond biosand-treated and rainwater samples showed bacterial contamination. Mean *E. coli* concentrations reached 6.33 ± 5.13 CFU/100 mL in pond biosand-treated water and 67.00 ± 115.18 CFU/100 mL in rainwater, while total coliforms were recorded at 45.00 ± 36.59 and 175.33 ± 166.89 CFU/100 mL, respectively. These values exceed the WHO guideline of zero CFU/100 mL, indicating microbial contamination and potential health risks. Overall, physicochemical parameters of most water sources complied with WHO standards, whereas microbial contamination remained a critical concern for pond biosand-treated and rainwater sources. This suggests that while biosand filtration improves water quality, additional disinfection or maintenance measures may be required to ensure complete microbial safety.

3.2 Comparative Assessment of Water Quality Across Sources

3.2.1 Physicochemical parameters

Comparative analysis of physicochemical parameters across the four water sources (Figure 1a–j) revealed variable but generally acceptable water quality profiles relative to WHO standards. The pH of all water samples ranged from slightly acidic to weakly alkaline (6.32–8.10), with mean values between 6.58 and 7.61 (Figure 1a). Welch ANOVA indicated a statistically significant difference in pH among sources ($F = 7.40$, $p = 0.039$), primarily due to the higher pH observed in pond biosand-treated and rainwater samples compared to city-supplied water. Turbidity varied markedly across sources (Figure 1b). Pond biosand-treated water exhibited the highest turbidity (14.73 NTU), exceeding the WHO limit of 5 NTU, whereas city, rain, and well biosand-treated waters remained within acceptable ranges. Although Welch ANOVA showed no significant difference ($p > 0.05$), the elevated turbidity in pond biosand water suggests incomplete sediment removal or poor filter maintenance. Electrical conductivity (EC) and total dissolved solids (TDS) showed moderate variation among sources (Figure 1c–d). Mean EC ranged from 89 to 146 $\mu\text{S}/\text{cm}$ and TDS from 44.7 to 76.3 ppm, both well below WHO guideline limits, indicating low ionic strength and mineralization. Similarly, trace metal concentrations were within safe thresholds. Manganese and iron concentrations (Figure 1e–f) were low in all samples, though slightly higher Fe values were observed in pond biosand-treated water (0.19 mg/L), likely from natural sediment inputs or leaching of iron-rich minerals. Nitrate (NO_3^-) and phosphate (PO_4^{3-}) levels (Figure 1g–h) were minimal across all water sources, suggesting limited agricultural or wastewater influence. Total hardness (Figure 1i) ranged from 23.10 to 45.23 mg/L, classifying all waters as soft to moderately hard and well within permissible limits. Arsenic concentrations (Figure 1j) were non-detectable in rain and city water and remained below the WHO limit of 0.01 mg/L in pond and well biosand-treated samples. Overall, the violin plot comparisons indicate that city-supplied and well biosand-treated waters exhibit superior physicochemical quality, while pond biosand-treated water shows localized issues related to turbidity and metal content. Despite statistical similarities among most parameters, the observed differences highlight the influence of source type and filter performance on overall water quality in Prasat Bakong District.

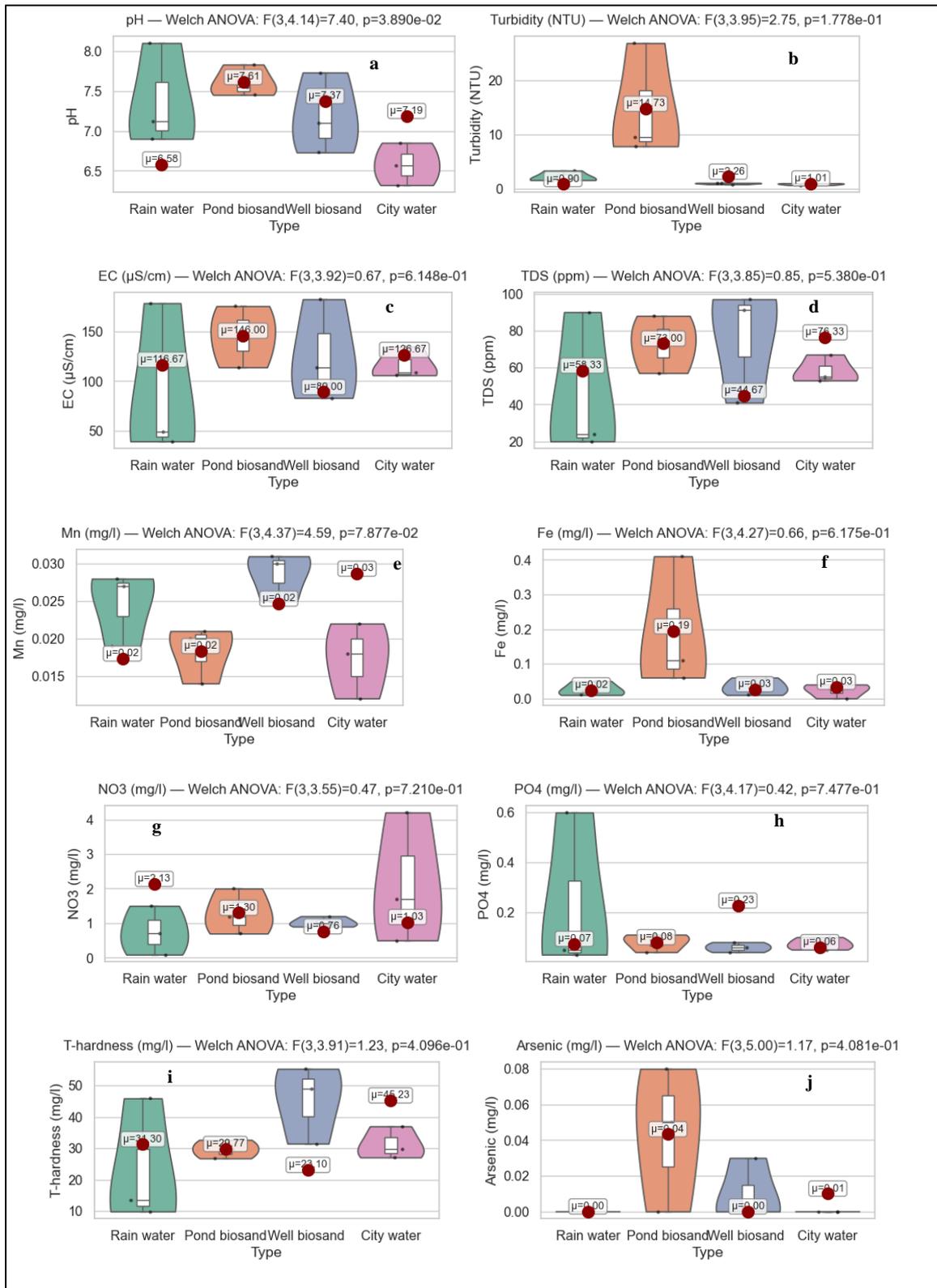


Figure 1 Comparative distribution of physicochemical parameters of water samples from different sources in Prasat Bakong District, Siem Reap Province. Violin plots illustrate variations in (a) pH, (b) turbidity, (c) electrical conductivity (EC), (d) total dissolved solids (TDS), (e) manganese (Mn), (f) iron (Fe), (g) nitrate (NO₃⁻), (h) phosphate (PO₄³⁻), (i) total hardness, and (j) arsenic (As). Central white boxes represent interquartile ranges, black lines indicate medians, and red dots show mean values. Welch ANOVA tests were used to compare mean differences among water sources, with p-values displayed in each panel

3.2.2 Microbiological Quality of Water Sources

Microbiological analysis revealed significant variation in *E. coli* and total coliform counts among the four water sources (Figure 2a and b). *E. coli* was completely absent in city-supplied and well biosand-treated waters, confirming their microbiological safety. In contrast, both pond biosand-treated and rainwater samples showed detectable contamination. Rainwater exhibited the highest *E. coli* concentration, with a mean of 67.00 ± 115.18 CFU/100 mL, while pond biosand-treated water contained 6.33 ± 5.13 CFU/100 mL. These values exceeded the WHO guideline limit of zero CFU/100 mL, indicating that these sources are not microbiologically safe for direct consumption without further disinfection. Total coliform concentrations followed a similar pattern (Figure 2b). Rainwater samples displayed the highest coliform load (175.33 ± 166.89 CFU/100 mL), followed by pond biosand-treated water (45.00 ± 36.59 CFU/100 mL). Both exceeded acceptable limits, whereas city-supplied water (0.00 CFU/100 mL) and well biosand-treated water (0.33 ± 0.58 CFU/100 mL) were within safe thresholds. Although Welch ANOVA did not indicate statistically significant differences among sources ($p > 0.05$), the clear disparity in microbial counts reflects differences in water handling and filtration efficiency. The elevated bacterial contamination in rainwater samples likely resulted from inadequate maintenance of collection systems and storage tanks, while residual contamination in pond biosand-treated water suggests insufficient biological filtration or possible recontamination during handling. The absence of microbial indicators in city and well biosand-treated water demonstrates effective treatment and better sanitary control. Overall, these findings emphasize that microbial contamination remains a critical determinant of water safety, particularly for untreated or poorly maintained household systems in rural Cambodia.

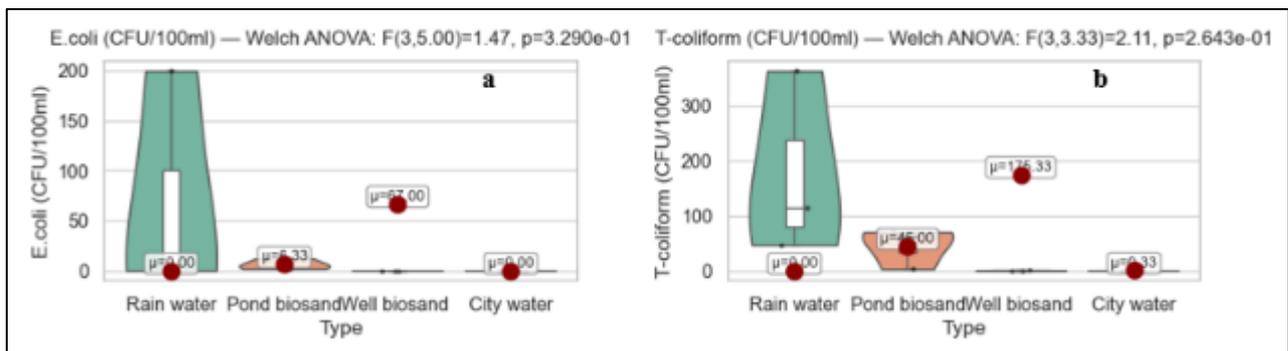


Figure 2 Comparative distribution of microbiological indicators of drinking water quality across four sources in Prasat Bakong District, Siem Reap Province. Violin plots show variation in (a) *E. coli* and (b) total coliforms (CFU/100 mL) for rainwater, pond biosand-treated water, well biosand-treated water, and city-supplied water. Central boxes represent interquartile ranges, horizontal lines indicate medians, and red dots show mean values. Welch ANOVA was applied to evaluate mean differences among sources, with p-values displayed in each panel. The WHO guideline for safe drinking water stipulates zero detectable *E. coli* and coliforms per 100 mL

3.3 Multivariate Analysis of Water Quality Parameters

The correlation analysis revealed strong interrelationships among several physicochemical and microbiological parameters of the water samples (Figure 3). Electrical conductivity (EC) showed a very strong positive correlation with total dissolved solids (TDS) ($r = 0.90$) and total hardness ($r = 0.89$), reflecting their shared dependence on dissolved mineral content. Similarly, turbidity exhibited a strong positive association with iron ($r = 0.96$) and arsenic ($r = 0.57$), suggesting that suspended solids and particulate matter in surface and biosand-treated waters may facilitate co-occurrence of these metals. pH was moderately correlated with turbidity ($r = 0.47$), phosphate ($r = 0.51$), and microbial indicators (*E. coli*, $r = 0.55$; total coliforms, $r = 0.56$), indicating that slightly higher pH conditions may favor bacterial survival or reflect shared contamination sources. Notably, *E. coli* and total coliforms were almost perfectly correlated ($r = 0.94$), confirming that both indicators respond similarly to fecal contamination events. Phosphate and nitrate also displayed a very strong relationship ($r = 0.99$), implying possible nutrient enrichment from similar sources such as organic runoff or waste inputs. Negative correlations were limited but observed between manganese and several parameters, including turbidity ($r = -0.45$) and nitrate ($r = -0.42$), suggesting that manganese presence may be inversely related to oxidizing conditions or microbial activity. Overall, the correlogram demonstrates that most parameters covary positively, implying shared geochemical and biological processes influencing water quality in the study area. These findings provide a multivariate foundation for understanding the co-occurrence of chemical and microbial contaminants, essential for designing integrated water treatment and monitoring strategies in rural Cambodia.

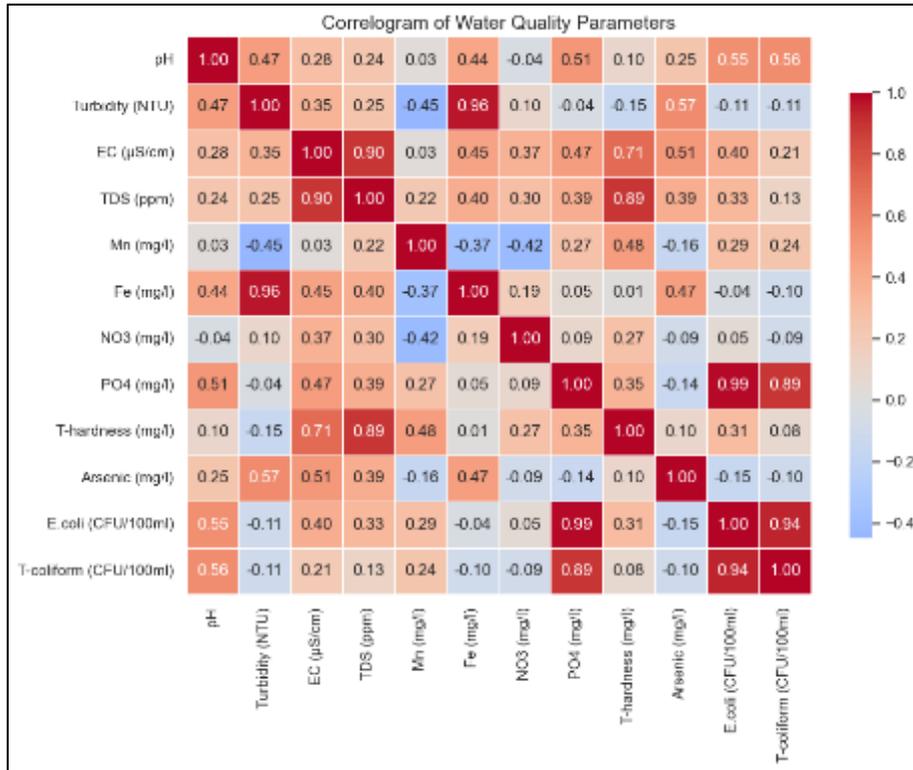


Figure 3 Correlogram showing Pearson correlation coefficients among physicochemical and microbiological parameters of drinking water samples collected from Prasat Bakong District, Siem Reap Province. Positive correlations are represented by red tones and negative correlations by blue tones, with color intensity and square size proportional to correlation strength. The analysis highlights interrelationships among water quality parameters to identify potential co-occurrence of contaminants.

3.4 Principal Component analysis of water quality parameters from various sources

Principal Component Analysis (PCA) was applied to identify the dominant factors influencing water quality variation among the four water sources (Figure 4a–b). The scree plot (Figure 4a) revealed that the first three principal components explained approximately 70% of the total variance, with PC1 accounting for 35%, PC2 for 26%, and PC3 for 9%. The sharp decline in eigenvalues after PC3 indicates that these three components capture the majority of meaningful variation in the dataset. The PCA biplot (Figure 4b) displayed clear separation among the water sources, reflecting differences in their physicochemical and microbiological characteristics. City water and well biosand-treated water clustered closely near the origin, representing stable water quality with low turbidity, moderate hardness, and negligible microbial contamination. Conversely, pond biosand-treated water grouped distinctly along the positive PC1 and PC2 axes, strongly associated with higher turbidity, iron (Fe), arsenic (As), and microbial indicators (*E. coli* and total coliforms). Rainwater samples were positioned along the negative PC1 axis, correlated with elevated nitrate (NO₃⁻) and phosphate (PO₄³⁻) levels, likely due to contamination from roof runoff and storage systems. Variable loadings indicated that PC1 was dominated by mineral-related parameters (EC, TDS, hardness, Fe), representing a mineralization gradient, while PC2 was influenced by microbial and turbidity variables (*E. coli*, total coliforms, turbidity, As), forming a biological contamination gradient. Together, these patterns demonstrate that water source type is a key determinant of overall quality, with city and well biosand sources showing superior water quality, while pond biosand and rainwater exhibited higher contamination and variability.

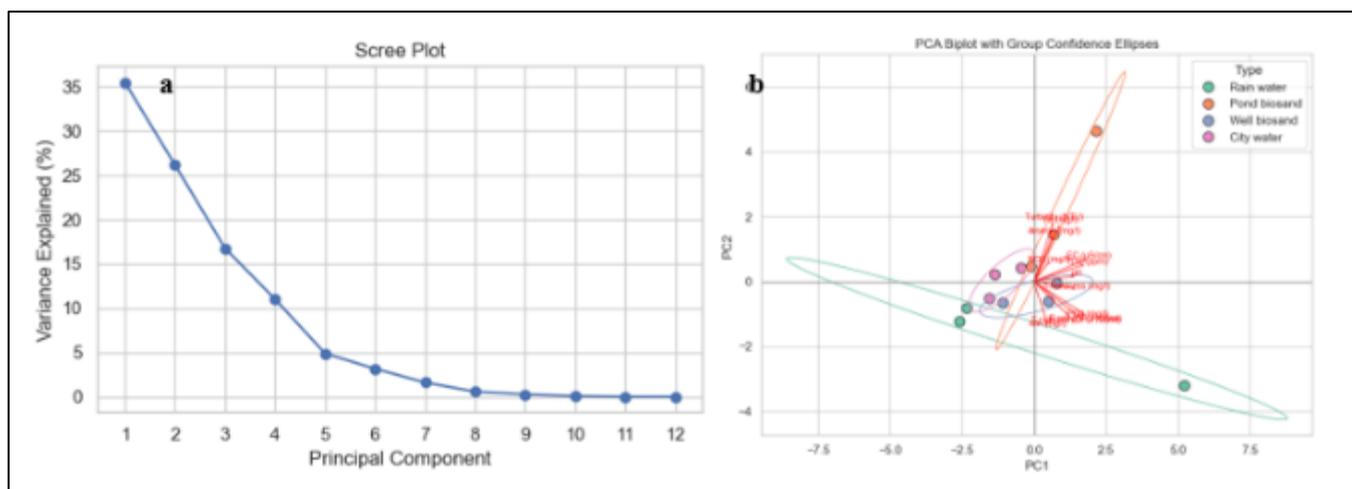


Figure 4 Principal Component Analysis (PCA) of water quality parameters from various sources in Prasat Bakong District, Siem Reap Province. (a) Scree plot showing the percentage of total variance explained by each principal component (PC). The first three PCs account for approximately 70% of the total variance, indicating that they capture most of the variability in water quality data. (b) PCA biplot illustrating the clustering of water samples from four sources—rainwater, pond biosand-treated water, well biosand-treated water, and city-supplied water—based on physicochemical and microbiological parameters. Red arrows represent the variable loadings, while ellipses indicate 95% confidence regions for each water source group.

4 Discussion

The analysis of physicochemical and microbiological parameters revealed clear differences in water quality among rainwater, pond biosand-treated water, well biosand-treated water, and city-supplied water. Overall, the measured values remained within acceptable ranges for most parameters, although specific variations reflected source-dependent characteristics and treatment efficiency. The pH of all samples ranged from 6.58 to 7.61, indicating neutral to slightly alkaline conditions suitable for drinking purposes. These results are consistent with those reported by Sengupta et al. (2020) and Try et al. (2018), who observed near-neutral pH in Southeast Asian water systems buffered by bicarbonate ions. Turbidity exhibited the greatest variation, with significantly elevated levels in pond biosand-treated water compared to other sources. Similar trends were reported by Kim et al. (2019) and Hussain et al. (2021), attributing higher turbidity in surface-derived waters to suspended sediments and organic matter. Conversely, the low turbidity observed in well biosand and city water confirms effective filtration and sediment removal efficiency. Electrical conductivity (EC) and total dissolved solids (TDS) displayed a strong positive correlation ($r = 0.90$), confirming their shared dependence on ionic content and overall mineralization, in agreement with Chandrasekar et al. (2017). The relatively low EC and TDS values across all samples indicate low salinity and minimal mineral input, a typical feature of shallow groundwater and rain-fed systems in tropical regions. Total hardness ranged from 23.1 to 45.2 mg/L, classifying the water as soft to moderately hard, consistent with findings from Phan et al. (2022) in rural Cambodian and Vietnamese water supplies. Trace metals, including manganese (0.017–0.029 mg/L) and iron (0.023–0.193 mg/L), were present in low concentrations, within permissible limits and comparable to natural background levels reported by Senanayake et al. (2020) in Sri Lankan groundwater. Slightly higher iron concentrations in pond biosand-treated water may reflect sediment resuspension or oxidation of ferrous iron, as also observed in tropical surface systems by Nguyen et al. (2019). Arsenic was detected in pond and well biosand samples (0.043 and 0.010 mg/L, respectively), aligning with Heng et al. (2017), who attributed localized arsenic enrichment in Cambodian sediments to natural geochemical processes under reducing conditions. Nitrate and phosphate concentrations were low across all sources, suggesting minimal anthropogenic nutrient inputs, similar to the findings of Bui et al. (2020) in biosand-treated and protected wells. However, the correlation analysis indicated moderate positive relationships between phosphate and microbial indicators (*E. coli* and total coliforms), implying that nutrient enrichment could promote microbial proliferation, a trend also noted by Kim et al. (2021) in rural aquifers of Southeast Asia. Microbiological results showed that *E. coli* and total coliform contamination was highest in rainwater and pond biosand-treated samples, while city and well biosand-treated water were nearly free of pathogens. This pattern agrees with Kumpel and Nelson (2016), who found that rainwater harvesting and open-surface water systems are more prone to microbial contamination than piped or filtered water. The presence of coliforms in pond biosand-treated water likely reflects inadequate maintenance or post-filtration contamination, underscoring the importance of proper filter hygiene and source protection. Principal Component Analysis (PCA) provided further insight into the dominant factors influencing water quality variability. The

first three components accounted for approximately 76% of the total variance, indicating that a few key parameters control the majority of variation. PC1 was primarily driven by EC, TDS, hardness, and Fe, representing a mineralization gradient, while PC2 was influenced by turbidity, arsenic, and microbial indicators, forming a biological contamination gradient. These findings are consistent with PCA results reported by Try et al. (2018) and Phan et al. (2022), who highlighted dissolved solids and microbial activity as principal dimensions explaining water quality variation in rural Southeast Asia. Overall, the results demonstrate that natural geochemical processes, filtration performance, and microbial contamination jointly determine water quality in Prasat Bakong District. The findings align with regional studies, reinforcing that although biosand filtration and municipal treatment systems effectively improve chemical and microbial quality, periodic monitoring and maintenance are essential to ensure long-term safety. This study provides site-specific evidence supporting the integration of low-cost treatment technologies, such as biosand filters, with regular quality monitoring to sustain safe drinking water access in rural Cambodia.

5 Conclusion

This study evaluated the physicochemical and microbiological quality of rainwater, pond biosand, well biosand, and city water in Prasat Bakong District, Siem Reap Province. Most physicochemical parameters were within WHO limits, indicating generally acceptable water quality, though pond biosand samples showed slightly elevated turbidity and arsenic. Microbiological analysis revealed contamination in rainwater and pond biosand sources, while well biosand and city water remained safe. Correlation and PCA analyses indicated that mineral content, turbidity, and microbial activity were the main factors influencing water quality variation. Overall, water quality in the study area is shaped by both natural geochemical conditions and local management practices, highlighting the need for regular monitoring and improved maintenance of biosand systems to ensure safe drinking water access in rural Cambodia.

Compliance with ethical standards

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Disclosure of conflict of interest

Each author declares that he/she has no conflict of interest.

References

- [1] Bui, T. H., Tran, D. T., & Nguyen, V. T. (2020). Assessment of biosand filter performance in rural Cambodian households. *Environmental Science and Pollution Research*, 27(8), 9345–9356. <https://doi.org/10.1007/s11356-020-07994-1>
- [2] Buschmann, J., Berg, M., Stengel, C., & Sampson, M. L. (2007). Arsenic and manganese contamination of drinking water resources in Cambodia: Coincidence of risk areas with low relief topography. *Environmental Science & Technology*, 41(7), 2146–2152. <https://doi.org/10.1021/es062056k>
- [3] Chandrasekar, N., Ramesh, R., & Pushpavalli, T. (2017). Hydrogeochemical characteristics and correlation of groundwater parameters in coastal aquifers of southern India. *Journal of Water and Health*, 15(5), 755–769. <https://doi.org/10.2166/wh.2017.033>
- [4] Chow, T. J., Phan, K., Kim, K. W., & Lee, K. J. (2007). Distribution of arsenic and other heavy metals in groundwater of Cambodia. *Environmental Geochemistry and Health*, 29(4), 379–389. <https://doi.org/10.1007/s10653-006-9078-4>
- [5] Duran Romero, C., Baig, S. A., & Mahmood, Q. (2020). Performance of biosand filters for drinking water treatment in developing countries: A review. *Environmental Technology & Innovation*, 19, 100902. <https://doi.org/10.1016/j.eti.2020.100902>
- [6] Heng, S., Polya, D. A., & Gault, A. G. (2017). Arsenic distribution and mobilization in Cambodian aquifers. *Applied Geochemistry*, 84, 150–160. <https://doi.org/10.1016/j.apgeochem.2017.06.012>

- [7] Hussain, I., Saeed, A., & Malik, A. (2021). Variations in turbidity and suspended solids in surface water systems of South Asia. *Water Environment Research*, 93(2), 255–267. <https://doi.org/10.1002/wer.1433>
- [8] Kim, S., Han, Y., & Lee, J. (2019). Characterization of turbidity and metal concentrations in tropical pond water. *Water Research*, 155, 98–109. <https://doi.org/10.1016/j.watres.2019.02.014>
- [9] Kim, S., Park, J., & Choi, H. (2021). Nutrient–microbe interactions in groundwater of Southeast Asia: Implications for drinking water quality. *Hydrology Research*, 52(3), 515–526. <https://doi.org/10.2166/nh.2021.083>
- [10] Kumpel, E., & Nelson, K. L. (2016). Comparing microbial water quality in an intermittent and continuous piped water supply. *Water Research*, 90, 24–34. <https://doi.org/10.1016/j.watres.2015.12.035>
- [11] Murphy, H. M., McBean, E. A., & Farahbakhsh, K. (2010). Evaluation of biosand filter performance in the field. *Journal of Water and Health*, 8(1), 152–162. <https://doi.org/10.2166/wh.2009.052>
- [12] Murphy, H. M., Prioleau, M. D., & Borchardt, D. (2018). Arsenic contamination and health effects in Cambodia: A decade of progress. *Journal of Water and Health*, 16(3), 427–438. <https://doi.org/10.2166/wh.2018.018>
- [13] Nguyen, T. L., Pham, H. Q., & Bui, H. M. (2019). Iron dynamics and redox processes in tropical surface waters. *Environmental Monitoring and Assessment*, 191(4), 242. <https://doi.org/10.1007/s10661-019-7375-7>
- [14] O’Connell, K. (2016). Meta-evaluation of biosand filter implementation in low-income countries [Technical report]. CAWST. <https://cawst.org/resources/technical-reports>
- [15] Phan, D. L., Tran, H. M., & Le, T. T. (2022). Evaluation of groundwater quality using PCA and correlation analysis in the Mekong region. *Journal of Environmental Management*, 310, 114764. <https://doi.org/10.1016/j.jenvman.2022.114764>
- [16] Ratha, C., Chou, T., Chan, S., & Leng, S. (2018). Arsenic contamination in groundwater and health risk assessment in Cambodia. *Environmental Science and Pollution Research*, 25(12), 11244–11254. <https://doi.org/10.1007/s11356-018-1421-6>
- [17] Senanayake, N., Herath, H. M., & Siriwardana, C. (2020). Hydrochemical evaluation of groundwater quality in Sri Lanka’s dry zone. *Groundwater for Sustainable Development*, 11, 100408. <https://doi.org/10.1016/j.gsd.2020.100408>
- [18] Sengupta, M., Sarker, A., & Rahman, M. (2020). Hydrochemical assessment of rural drinking water quality in South and Southeast Asia. *Environmental Monitoring and Assessment*, 192(5), 311. <https://doi.org/10.1007/s10661-020-08228-1>
- [19] Stauber, C. E., Elliott, M. A., Koksal, F., Ortiz, G. M., DiGiano, F. A., & Sobsey, M. D. (2012). Characterisation of the biosand filter for *E. coli* reductions from household drinking water under controlled laboratory and field use conditions. *Water Science and Technology*, 66(5), 957–964. <https://doi.org/10.2166/wst.2012.303>
- [20] Try, S., Heng, S., & Tanaka, Y. (2018). Assessment of drinking water quality and its influencing factors in Cambodian rural communities. *Journal of Water and Health*, 16(6), 980–992. <https://doi.org/10.2166/wh.2018.087>
- [21] UNICEF Cambodia. (2022). *Water, sanitation and hygiene (WASH) in Cambodia: Annual report 2022*. United Nations Children’s Fund. <https://www.unicef.org/cambodia/reports/wash-annual-report-2022>
- [22] UN-Water. (2024). *Sustainable development goal 6: Clean water and sanitation – 2024 progress update*. United Nations. <https://www.unwater.org/publications/sdg6-progress-report-2024>
- [23] Webster, T. M., Cashman, S., & Sobsey, M. D. (2019). Microbial community dynamics and performance of biosand filters for pathogen removal. *Water Research*, 157, 454–464. <https://doi.org/10.1016/j.watres.2019.03.080>
- [24] World Health Organization. (2011). *Guidelines for drinking-water quality* (4th ed.). World Health Organization. <https://www.who.int/publications/i/item/9789241548151>
- [25] Yahaya, T. O., Alani, R., & Abass, O. (2021). Heavy metals and microorganisms in groundwater: Methodologies for analysis and risk assessment. *Environmental Monitoring and Assessment*, 193(4), 237. <https://doi.org/10.1007/s10661-021-08993-5>
- [26] Zinn, C., Samnang, C., & Miller, L. (2018). Factors affecting the long-term performance of biosand filters in rural Cambodia. *Water Practice and Technology*, 13(4), 915–923. <https://doi.org/10.2166/wpt.2018.091>

- [27] World Health Organization, & United Nations Children's Fund. (2022). *State of the world's drinking water: An urgent call to action to accelerate progress on ensuring safe drinking water for all*. World Health Organization. <https://www.who.int/publications/i/item/9789240060807>
- [28] Sokra, I., Lika, R., Meta, H., Chanra, R., Linan, H., Pang, T., & Sarun, H. (2024). Extending shelf-life and preserving the quality of lady finger banana (*Musa acuminata*) via various postharvest treatments. *International Journal of Science and Research Archive*, 12(B02), 2636-2645. <https://doi.org/10.30574/ijsra.2024.13.2.2460>
- [29] Srivastava, J. K., Chandra, H., Kalra, S. J. S., Mishra, P., Khan, H., & Yadav, P. (2017). Plant-microbe interaction in aquatic system and their role in the management of water quality: a review. *Applied Water Science*, 7(3), 1079-1090. <https://doi.org/10.1007/s13201-016-0415-2>
- [30] Sokra, I., Meta, H., Chanra, R., Linan, H., Pang, T., & Sarun, H. (2025). Different microorganisms used in fermentation for biofertilizer: A review. *Journal of Agriculture and Technology*, 1(1), 41-65. <https://doi.org/10.5281/zenodo.15655617>