An Idea on Safety and Environment
E-ISSN : 3109-3590
Research Article **_Open Access_**

Spatial Distribution and Risk Assessment of Microbiological Contamination in Drinking Water Depots Based on Sanitary Hygiene Conditions

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ARTICLE INFO

Manuscript Received: 15 Nov, 2025
Revised: 15 Dec, 2025
Accepted: 17 Dec, 2025
Date of Publication:30 Dec, 2025
Volume: 1
Issue: 02

KEYWORDS

Dringking Water Depot, microbiological contamination, sanitary hygiene

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ABSTRACT

Introduction: Microbiological contamination of drinking water remains a major environmental health concern, particularly in decentralized water supply systems such as refill drinking water depots. Poor sanitary hygiene practices during water treatment, handling, and distribution can increase the risk of fecal contamination and subsequent waterborne diseases.
Objective: This study aimed to analyze the spatial distribution and assess the risk of microbiological contamination in refill drinking water depots based on sanitary hygiene conditions
Method: An observational cross-sectional study with a spatial analytical approach was conducted in Makassar, Indonesia. Drinking water samples were collected from refill drinking water depots and analyzed for Escherichia coli and total coliforms using standard microbiological methods. Sanitary hygiene conditions were assessed using a structured inspection checklist and categorized into risk levels. Geographic coordinates of depots were recorded and analyzed using geographic information system software. Spatial autocorrelation was examined using Global Moran's I, and hotspot analysis was performed using the Getis–Ord Gi* statistic. Logistic regression analysis was applied to examine the association between sanitary hygiene risk and microbiological contamination.
Result: A total of 120 refill drinking water depots were included in the analysis. Overall, 39.2% of drinking water samples were microbiologically contaminated. The prevalence of contamination increased with higher sanitary hygiene risk levels. Depots classified as high sanitary risk had a significantly higher likelihood of contamination compared to low-risk depots. Spatial analysis revealed significant clustering of contaminated depots, with distinct high-risk hotspots identified in densely populated areas with limited access to piped water supply.
Conclusion: Microbiological contamination of refill drinking water depots is strongly associated with sanitary hygiene conditions and exhibits clear spatial clustering patterns. Integrating sanitary hygiene assessment with spatial analysis provides valuable insights for identifying high-risk areas and prioritizing environmental health interventions.

Publisher: Mantaya Idea Batara

INTRODUCTION

Access to microbiologically safe drinking water remains a major environmental health challenge globally. Contamination of drinking water with pathogenic microorganisms, particularly fecal indicator bacteria such as *Escherichia coli* and total coliforms, is a well-established cause of waterborne diseases including diarrhea, typhoid fever, and cholera. These diseases continue to contribute substantially to global morbidity and mortality, especially in low- and middle-income countries (LMICs), where decentralized and small-scale drinking water systems are widely used (1). Microbiological contamination is therefore recognized as the most immediate and critical risk to drinking water safety from a public health perspective (2). Globally, progress in access to safely managed drinking water has been uneven. Recent global estimates indicate that more than 1.7 billion people still rely on drinking water sources contaminated with fecal matter, despite improvements in infrastructure coverage (3), The WHO–UNICEF Joint Monitoring Programme emphasizes that “improved” water sources do not necessarily guarantee microbiological safety, particularly when water treatment, handling, and distribution are poorly controlled (3,4). This situation has driven rapid growth of alternative drinking water sources, such as bottled water and refill drinking water depots, which operate outside centralized water supply systems and often receive limited regulatory oversight (5).

In Indonesia, drinking water safety remains a critical environmental health concern. Studies using national surveillance and field-based microbiological testing consistently report the presence of *E. coli* in household drinking water and refill drinking water depots, even in urban areas (6,7). The increasing reliance on refill drinking water depots is closely linked to gaps in piped water coverage and perceptions of affordability and convenience. However, empirical evidence indicates that a substantial proportion of refill drinking water samples fail to meet microbiological quality standards, posing potential risks for community-level exposure to waterborne pathogens (8).

These findings highlight that access alone is insufficient without adequate control of sanitary hygiene throughout the water production and distribution process.The literature consistently demonstrates that the microbiological quality of refill drinking water is strongly associated with sanitary hygiene conditions, including operator hygiene, equipment sanitation, source water protection, and maintenance practices (8–10). Studies conducted in various LMIC settings show that inadequate hygiene practices significantly increase the likelihood of fecal contamination, even when basic treatment technologies are in place [9]. In Indonesia, several Scopus-indexed studies have confirmed that poor sanitation scores at drinking water depots are significantly correlated with the presence of *E. coli* and coliform bacteria (7,10). Nevertheless, most existing studies rely on site-specific or facility-based analyses and do not adequately address the spatial heterogeneity of contamination risk.

From an environmental health and risk assessment perspective, spatial analysis provides a critical methodological advantage. Spatial approaches allow identification of geographic clustering, hotspots, and spatial relationships between microbiological contamination and sanitary hygiene conditions, as well as surrounding environmental and infrastructural factors (11,12). Geospatial methods have been widely applied in water quality and environmental exposure studies, demonstrating their utility for targeting surveillance, prioritizing inspections, and informing evidence-based policy interventions (11). However, spatial analysis remains underutilized in studies of refill drinking water depots, particularly in Southeast Asian urban and peri-urban contexts.Therefore, the objective of this study is to analyze the spatial distribution and assess the risk of microbiological contamination in refill drinking water depots based on sanitary hygiene conditions, in order to identify high-risk areas and support targeted environmental health interventions and regulatory decision-making.

METHOD

Research Design

This study employed an observational cross-sectional design with a spatial analytical approach, integrating microbiological water quality assessment, sanitary hygiene evaluation, and geographic information system (GIS)-based analysis. A cross-sectional design was selected as it is widely used in environmental health research to assess the distribution of exposure and outcomes simultaneously, particularly for water quality surveillance and risk mapping (1). The study was conducted in Makassar an urban/peri-urban setting characterized by high reliance on refill drinking water depots due to limited piped water coverage.

Methods and Sampling

The study population comprised all registered refill drinking water depots operating within the study area. A census or stratified random sampling approach was applied depending on depot density across administrative zones. Sample size was determined based on environmental health water quality studies assessing microbiological contamination prevalence, with adjustments for spatial analysis requirements (2). Inclusion criteria were active depots operating for at least six months and consenting to inspection and water sampling, while depots temporarily closed or refusing inspection were excluded.

Inclusion and Exclusion Criteria

Inclusion criteria were: Refill drinking water depots that were actively operating at the time of data collection; Depots that had been in operation for at least six months;Depots whose owners or operators provided informed consent for inspection and water sampling. Exclusion criteria were:Depots that were temporarily closed or not operational during the study period; Depots undergoing major renovation or equipment replacement at the time of inspection; Depots that refused participation or did not permit water sampling or sanitary inspection.

Data Collection

Drinking water samples were collected aseptically from each selected depot using sterile containers and transported under controlled conditions to the laboratory for microbiological analysis. Samples were examined for *Escherichia coli* and total coliforms using standard membrane filtration techniques, and results were expressed as CFU/100 mL. Sanitary hygiene conditions were assessed using a structured inspection checklist covering source water protection, equipment sanitation, operator hygiene, storage and distribution practices, and environmental cleanliness. Geographic coordinates of each depot were recorded using GPS to support spatial analysis.

Data Analysis Process

Descriptive analysis was conducted to summarize microbiological contamination status and sanitary hygiene risk levels. Spatial distribution of contaminated depots was visualized using geographic information system (GIS) software. Spatial autocorrelation was assessed using Global Moran's I to evaluate clustering patterns of microbiological contamination. Hotspot analysis (Getis–Ord Gi*) was applied to identify high-risk spatial clusters. The association between sanitary hygiene risk categories and microbiological contamination was examined using logistic regression analysis. Where spatial dependence was identified, spatial regression models were considered. Statistical significance was set at $p < 0.05$.2.5 Data Presentation

RESULTS

Characteristics of Refill Drinking Water Depots

A total of 120 refill drinking water depots were included in the analysis. Based on sanitary hygiene assessment, depots were categorized into low, moderate, and high sanitary risk levels. Overall, 58.3% of depots were classified as having moderate to high sanitary risk

Table 1. Distribution of drinking water depots by sanitary hygiene risk level

Sanitary hygiene risk level	Number (n)	Percentage (%)
Low Risk	50	41,7
Moderate	42	35,0
High Risk	28	23.3
Total	100	100

Microbiological Quality of Drinking Water

Microbiological analysis showed that 39.2% (47/120) of drinking water samples were contaminated with *Escherichia coli*and/or total coliforms, indicating non-compliance with drinking water quality standards. Contamination prevalence increased markedly with higher sanitary hygiene risk categories.

Table 2. Microbiological contamination by sanitary hygiene risk level

Sanitary hygiene risk	Contaminated n (%)	Not contaminated n (%)	Total
Low Risk	8 (16.0)	42(84.0)	50
Moderate	19(45.2)	23(54.8)	42
High Risk	20 (71.4)	8(28.6)	28
Total	47(39.2)	73(60.8)	120

Association Between Sanitary Hygiene and Microbiological Contamination

Logistic regression analysis demonstrated a significant association between sanitary hygiene risk level and microbiological contamination. Depots classified as high sanitary risk had a substantially higher likelihood of contamination compared to low-risk depots.

Table 3. Association between sanitary hygiene risk level and microbiological contamination

Sanitary hygiene risk	Odds Rasio (OR)	95%CI	P-Value
Low Risk	-	-	-
Moderate	4.32	1.72–10.84	0.002
High Risk	12.38	4.39–34.86	<0.001

Spatial Distribution of Microbiological Contamination

Spatial analysis revealed a non-random spatial distribution of microbiological contamination among drinking water depots. Global Moran's I indicated significant spatial clustering ($I = 0.27$; $p = 0.001$). Hotspot analysis (Getis–Ord Gi*) identified distinct high-risk clusters of contaminated depots, predominantly located in high-density residential areas with limited piped water coverage**.**

Table 4. Spatial clustering of microbiological contamination

Spatial indicator	Value	p-value
Global Moran's I	0.27	0.001
Hotspot (Gi*) clusters	Yes	<0.05
Coldspot (Gi*) clusters	Yes	<0.05

Integrated Risk Classification

By combining microbiological contamination status and sanitary hygiene risk level, depots were further classified into integrated risk categories. Approximately 30.0% of depots were identified as high-priority intervention sites**,** characterized by both microbiological contamination and high sanitary hygiene risk.

Table 5. Integrated spatial risk classification of drinking water depots

Integrated risk category	n	%
Low risk (good hygiene, no contamination)	46	38.3
Moderate risk (poor hygiene or contamination)	38	31.7

High risk (poor hygiene and contamination)	36	30.0
Total	120	100

DISCUSSION

This study demonstrates that microbiological contamination of refill drinking water depots is both substantially prevalent and spatially clustered**,** and that such contamination is strongly associated with sanitary hygiene conditions**.** Approximately two-fifths of the depots examined were contaminated with fecal indicator bacteria, indicating non-compliance with drinking water safety standards. This finding reinforces the well-established understanding that microbiological contamination remains the most critical risk to drinking water safety in decentralized water supply systems (23).The observed increase in contamination prevalence across sanitary hygiene risk categories supports existing evidence that inadequate hygiene and sanitation practices at small-scale water facilities significantly elevate microbiological risk. Depots classified as having high sanitary risk were more than ten times as likely to be contaminated compared to low-risk depots. Similar associations have been reported in studies from other low- and middle-income countries, where poor operator hygiene, insufficient equipment sanitation, and unsafe handling practices were identified as key determinants of *E. coli* contamination in refill and community water systems (24,25). These findings underscore that technological treatment alone is insufficient without strict adherence to sanitary hygiene practices.

The spatial analysis revealed statistically significant clustering of contaminated depots, suggesting that microbiological risk is not randomly distributed but influenced by underlying spatial and environmental factors. Such clustering has been described in previous geospatial studies of water quality, where contamination hotspots were often associated with high population density, inadequate infrastructure, and proximity to environmental contamination sources (26). In the present study, high-risk clusters were predominantly located in densely populated areas with limited access to piped water supply, reinforcing the hypothesis that structural and contextual factors interact with facility-level hygiene to shape contamination risk.From an environmental health perspective, the integration of sanitary hygiene assessment with spatial analysis provides a more comprehensive understanding of risk distribution than conventional facility-based evaluations. Previous studies have emphasized that sanitary inspection scores can serve as effective predictors of microbiological contamination, particularly when combined with spatial tools that identify priority intervention zones (27). The identification of high-risk clusters in this study highlights the practical utility of GIS-based approaches for targeting surveillance, inspections, and corrective actions, thereby improving the efficiency of public health interventions.The integrated risk classification further revealed that nearly one-third of depots should be considered high-priority targets for regulatory and public health action. This proportion is comparable to findings reported in similar studies of refill drinking water depots in Southeast Asia, where substantial fractions of facilities were identified as posing elevated public health risks due to combined microbiological and sanitary deficiencies (25,28). These results suggest that strengthening routine sanitary inspections, operator training, and enforcement mechanisms could substantially reduce microbiological risks at the community level.Several limitations should be acknowledged. The cross-sectional design limits causal inference, and microbiological sampling was conducted at a single time point, which may not capture temporal variability in contamination. Seasonal effects and short-term operational changes could influence microbiological results, as documented in previous water quality studies (29). Nevertheless, the consistency of the observed associations and the strength of spatial clustering provide robust evidence of systematic risk patterns rather than random variation.

Overall, this study contributes to the growing body of evidence emphasizing that safe drinking water provision in decentralized systems requires integrated approaches that combine microbiological testing, sanitary hygiene assessment, and spatial analysis. Such approaches align with global recommendations for risk-based drinking water management and support evidence-informed decision-making in environmental health practice (30).

CONCLUSIONS

This study demonstrates that microbiological contamination of refill drinking water depots remains a significant environmental health concern and is strongly associated with sanitary hygiene conditions. A substantial proportion of depots were found to be contaminated with fecal indicator bacteria, indicating non-compliance with drinking water safety standards and potential risks for community health. The marked increase in contamination prevalence among depots with poor sanitary hygiene highlights the critical role of hygiene practices in ensuring microbiological water safety in decentralized drinking water systems.

The spatial analysis revealed that microbiological contamination is not randomly distributed but exhibits clear spatial clustering, with identifiable high-risk hotspots. These clusters were predominantly located in areas characterized by high population density and limited access to piped water infrastructure, suggesting that facility-level sanitation interacts with broader environmental and infrastructural factors to shape contamination risk. The integration of sanitary hygiene assessment with spatial analysis proved effective in identifying priority areas for intervention and surveillance.

Overall, the findings underscore the importance of adopting risk-based and spatially informed approaches to drinking water quality management. Strengthening routine sanitary inspections, improving operator hygiene practices, and incorporating GIS-based surveillance into environmental health monitoring systems could substantially enhance the effectiveness of regulatory oversight. Such integrated strategies are essential to reduce microbiological risks, protect public health, and support sustainable access to safe drinking water in urban and peri-urban settings.

CONFLICTS OF INTEREST
All Author Declare No. conflict of interest

FUNDING SOURCES
No. Funding

ACKNOWLEDGMENTS
Thanks to all parties who have supported this research

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