

Contextual Determinants of Escherichia coli Contamination in Point-of-Use Household Drinking Water in Indonesia: Distinct Urban and Rural Risk Profile

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Research Article

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Abstract

Access to safe drinking water is essential for achieving SDG 6. However, microbiological contamination remains widespread in Indonesia, with persistent urban–rural disparities. This study aimed to identify the context-specific determinants of *Escherichia coli* contamination in household point-of-use (PoU) drinking water across urban and rural Indonesia. We analyzed nationally representative 2023 Sistem Informasi Pengawasan Kualitas Air Minum (SIPEKAM) data, which covered 61,695 households. *E. coli* contamination was measured by membrane filtration. Survey-weighted stratified logistic regression was used to identify predictors of sociodemographic, infrastructure, and hygiene variables. The results showed that *Escherichia coli* contamination was detected in 25.4% of households, with a higher prevalence in rural areas (26.9%) than in urban areas (23.2%). The risk factors varied significantly across settings. A lower educational level was a dominant predictor in urban areas (e.g., No formal education versus higher: AOR = 2.93), whereas informal employment (AOR = 1.14) was a unique risk factor in rural households. Deficiencies in the WASH infrastructure, including unimproved water sources (Urban AOR = 1.41; Rural AOR = 1.42) and the absence of handwashing facilities (Urban AOR = 1.44; Rural AOR = 1.28), were consistent predictors. A key and paradoxical finding emerged regarding waste management: the absence of waste containers was a significant risk factor in urban settings (AOR = 2.43) but appeared protective in rural settings (AOR = 0.54). In conclusion, distinct, context-specific pathways drive household water contamination in Indonesia. Moving beyond uniform infrastructure solutions to include targeted educational campaigns in urban areas, coupled with water safety and tailored waste management interventions in rural communities, is crucial for achieving equitable and safe access to water and accelerating progress toward SDG 6.

Introduction

Access to microbiologically safe drinking water is fundamental for reducing the incidence of waterborne diseases and achieving SDG 6. However, microbial contamination remains a significant challenge, particularly in low- and middle-income countries where inadequate infrastructure compromises water safety. *E. coli*, a key indicator of fecal contamination (World Health Organization, 2017), is commonly used to detect the presence of enteric pathogens, such as *Salmonella* and *Shigella*, which are major drivers of diarrheal diseases and the leading causes of morbidity and mortality among children under five years of age (Cantrell et al., 2023; Dessale et al., 2023; Gomes et al., 2024; Heijnen et al., 2024). The growing prevalence of antimicrobial resistance (AMR), with resistance genes increasingly detected in both water and stool samples, further exacerbates this burden and underscores the urgency of an integrated, cross-sectoral, and one-health approach. (Suge et al., 2023).

In Indonesia, ensuring a safe water supply and sanitation remains a challenge. Approximately 33 million people lack access to improved drinking water, and nearly 100 million lack access to improved sanitation, placing the country among the highest in the world for open defecation (Cameron et al., 2021). Urban-rural inequalities further exacerbate this issue; urban centers, such as Jakarta, face severe pollution and groundwater contamination, whereas rural areas struggle with inadequate infrastructure

and inadequate protection of water sources (Genter et al., 2022; Luo et al., 2019). National data indicate widespread *E. coli* contamination in 66% of groundwater sources and up to 82% of unprotected dug wells, disproportionately affecting low-income households and increasing the risk of diarrheal disease and stunting among children (Genter et al., 2022; Zikrina et al., 2024). Despite increased access to improved sources, reliance on packaged water and self-supply reflects persistent safety concerns, as these sources are often sporadically contaminated (Cameron et al., 2021).

In contrast to previous region-specific studies (Genter et al., 2022; Indrastuti et al., 2021; Putri et al., 2025). This analysis provides a comprehensive national assessment of household *E. coli* contamination stratified by urban and rural residence using survey-weighted regression. National-level analyses examining the predictors of *E. coli* contamination across rural and urban settings in Indonesia are limited. Such evidence is crucial for identifying key risk factors, prioritizing interventions, and informing strategies aligned with Indonesia's commitment to the Sustainable Development Goals.

Material and Method

Study design and data source

This study employed a cross-sectional design using secondary data from the 2023 Sistem Informasi Pengawasan Kualitas Air Minum (SIPEKAM), an Indonesian national surveillance system for household drinking water quality. SIPEKAM routinely assesses the microbiological and physicochemical quality of water in urban and rural households. Surveillance was implemented across all provinces except West Papua, where data were unavailable due to non-response, thereby limiting the national representativeness. Water samples were collected by trained sanitarians at primary health centers (Puskesmas) using standardized national procedures. The dataset was obtained through formal requests to the Center for Data and Information (Pusdatin) of the Indonesian Ministry of Health. It contained only de-identified aggregated records at the household and facility levels with no individual-level identifiers.

Sample

The study sample comprised 61,695 Indonesian households (24,909 urban and 36,786 rural). A multistage sampling design was employed to ensure representativeness at the district and municipal levels while maintaining operational feasibility. Primary health centers (PHCs), selected based on operational readiness, specifically, the availability of trained sanitarians and standard water-sampling equipment, served as the primary sampling units (PSUs). From each participating PHC, 15 households were randomly selected. This approach ensured coverage across all targeted administrative levels. To correct for this imbalance and ensure nationally and provincially representative estimates, survey weights were applied. The weighting procedure accounted for three key probabilities: (1) the probability of selecting a PHC within a district, (2) the probability of selecting a household within a PHC, and (3)

household response rates. Final weights were normalized so that their sum equaled the total analyzed sample size (N = 61,695). All descriptive and analytical statistics were calculated using weighted data.

Variables

The primary outcome was *E. coli* contamination in household drinking water at the point of use, measured using membrane filtration (MF), and classified as detected (≥ 1 CFU/100 mL) or not detected (0 CFU/100 mL) according to the World Health Organization (WHO) (World Health Organization, 2022) and Indonesian Ministry of Health standards (Kementerian Kesehatan Republik Indonesia, 2023). The independent variables were grouped into three domains. Household head (HH) characteristics included age (< 35, 35–49, 50–59, and ≥ 60 years), educational level (non-formal, primary, secondary, and higher), and occupation (formal, informal, and unemployed). WASH indicators were defined according to the WHO/UNICEF Joint Monitoring Program criteria (WHO & UNICEF, 2021), including the type of drinking water source (improved vs. unimproved), sanitation facilities (improved vs. unimproved), presence of handwashing stations (available vs. not), and household water treatment practices (any treatment vs. none, where 'any treatment' included boiling, filtration, chlorination, or the use of commercially sourced water). Waste management practices included the type of organic waste container (closed vs. open) and the method of domestic wastewater disposal (septic tank/closed storage vs. direct discharge).

Data analysis

Descriptive statistics were used to summarize household characteristics and WASH coverage. Differences between urban and rural areas were assessed using a chi-squared test ($p < 0.05$, considered significant). Bivariate associations were examined using simple logistic regression to calculate CORs with 95% confidence intervals (CIs). Variables with $p < 0.25$ in the bivariate analysis were included as potential confounders in the initial multivariate model, following model-building strategies commonly used in epidemiological studies (Hosmer & Lemeshow, 2000) to minimise the risk of omitting potential confounders.

A separate backward stepwise logistic regression was employed in the multivariate analysis to identify factors independently associated with *E. coli* contamination in urban and rural households. All analyses incorporated sampling weights to account for the complex survey design and were conducted using Stata v.16. The backward elimination procedure iteratively removed the least significant variable—defined as the variable with the largest p -value—at each step using a removal threshold of $\alpha = 0.05$. This process continued until all remaining variables were statistically significant ($p < 0.05$) or were considered important confounders (defined as causing a $> 10\%$ change in the ORs of other predictors upon their removal). Model adequacy was evaluated using the F-adjusted goodness-of-fit test and a link test to assess overall fit and functional specification, respectively.

Ethics approval

This study used fully de-identified secondary data from the 2023 SIPEKAM national surveillance system, obtained with formal authorisation from the Centre for Data and Information (Pusdatin) of the Ministry of Health of the Republic of Indonesia. The dataset contained no personal identifiers. The dataset contained no personal identifiers and was analyzed in accordance with applicable Indonesian regulations on health research governance and data protection, including Law No. Twenty-seven of 2022 on Personal Data Protection.

Results

Respondent characteristics

This study included 61,695 households, comprising 24,909 urban and 36,786 rural households. Rural households were generally more socioeconomically disadvantaged than their urban counterparts. While overall access to basic water, sanitation, and hygiene (WASH) services was high, *Escherichia coli* contamination at the point of use was slightly more frequent in rural settings (26.90% vs. 23.22%), indicating modest but meaningful disparities in water safety. These households tended to have younger heads but lower educational attainment, with nearly half having completed only primary education. Employment structures further highlight economic inequality, with informal work predominating in rural areas and formal employment being more common among urban households. Differences in infrastructure were also evident: urban households reported better access to improved drinking water, sanitation, handwashing facilities, and safer waste management systems. Collectively, these findings highlight the intersection of socio-economic and infrastructural disparities that may exacerbate the risk of *E. coli* contamination in rural areas.

Table 1
Household Characteristics in Urban and Rural

Variable	Urban (N = 24,909) n (%)	Rural (N = 36,786) n (%)	Chi ² (p-value)
E. coli contamination			
Not detected	16,546 (76.78)	25,714 (73.10)	< 0.001
Detected	5,244 (23.22)	9,732 (26.90)	
Age group of the household head			
< 35 years	2,766 (11.46)	4,680 (13.73)	< 0.001
35–49 years	9,696 (39.08)	15,094 (41.11)	
50–59 years	6,964 (27.95)	9,697 (26.02)	
60 + years	5,483 (21.52)	7,315 (19.14)	
Education level of household head			
No formal education	365 (1.31)	803 (2.06)	< 0.001
Primary education	9,936 (38.75)	18,149 (47.24)	
Secondary education	10,372 (43.00)	13,011 (37.40)	
Higher education	4,222 (16.93)	4,813 (13.30)	
Occupation of household head			
Formal sector employee	5,718 (24.52)	6,100 (19.52)	< 0.001
Informal sector employee	17,461 (68.26)	29,035 (75.74)	
Unemployed	1,710 (7.22)	1,649 (4.74)	
Drinking water facilities			
Improved	2,4331 (98.24)	35,279 (97.15)	< 0.001
Unimproved	578 (1.76)	1,507 (2.85)	
Sanitation facilities			
Improved	20,963 (85.37)	29,786 (81.75)	< 0.001
Unimproved	3946 (14.63)	7,000 (18.25)	
Household water treatment practices			
Notes: The data are survey-weighted. n (%): Number and percentage of households, <i>P-values</i> from the chi-square test.			

Variable	Urban (N = 24,909) n (%)	Rural (N = 36,786) n (%)	Chi ² (p-value)
E. coli contamination			
Yes	22,650 (91.20)	34,054 (92.25)	< 0.001
No	2,259 (8.80)	2,732 (7.75)	
Handwashing facility			
Available	23,869 (96.90)	34,907 (95.91)	< 0.001
Not available	935 (3.10)	1,740 (4.09)	
Organic waste containers in households			
Available - closed container	1,0651 (44.63)	12,966 (38.12)	< 0.001
Available - opened container	13,663 (53.12)	23,544 (60.75)	
Not available	595 (2.25)	276 (1.13)	
Household wastewater storage			
Closed container/septic tank	10,572 (44.94)	12,163 (38.43)	< 0.001
Opened container in the yard.	4,743 (17.41)	8,359 (20.87)	
Container outside the yard	1,819 (7.07)	2,839 (7.67)	
No container/ Direct disposal to ground	7,775 (30.58)	13,425 (33.04)	
Notes: The data are survey-weighted. n (%): Number and percentage of households, <i>P-values</i> from the chi-square test.			

The choropleth map (Fig. 1) illustrates the spatial distribution of *E. coli* contamination across Indonesian provinces, revealing marked geographic variation in prevalence. The highest prevalence (30.16%–40.25%) was observed in parts of Sulawesi, Kalimantan, and selected provinces in Sumatra (e.g., Aceh and West Sumatra), as well as in the eastern regions of Maluku and Papua. Conversely, most provinces in Sumatra, East and West Kalimantan, Bali, and West Nusa Tenggara exhibited the lowest levels (9.04%–21.73%). Highly populated provinces, such as West Java, Central Java, East Java, North Sumatra, and South Sulawesi, fell within an intermediate range (21.73%–30.16%). Visually, contamination appears higher in eastern Indonesia compared to the more urbanized regions of Java and western Sumatra, although this descriptive observation warrants formal spatial analysis to confirm statistical significance.

Darker shading indicates higher contamination levels, revealing an east–west gradient with a greater burden in the eastern regions.

Bivariate analysis

Bivariate analysis identified distinct risk patterns of *E. coli* contamination in urban and rural settings (Table 2). In urban areas, younger household heads (aged < 35 years) and lower levels of education were significant risk factors; households with no formal education had 3.19 times the odds of contamination (COR = 3.19, 95% CI: 2.33–4.36). WASH infrastructure deficiencies consistently predicted contamination in both settings, notably unimproved water sources (urban COR = 1.94, 95% CI: 1.44–2.62; rural COR = 1.66, 95% CI: 1.31–2.11) and unimproved sanitation (urban COR = 1.33, 95% CI: 1.10–1.61; rural COR = 1.44, 95% CI: 1.21–1.71).

Rural areas showed unique vulnerability among older household heads (≥ 60 years) (COR = 1.13, 95% CI: 1.03–1.23) and informal workers (COR = 1.42, 95% CI: 1.28–1.57). Notably, the absence of waste containers showed opposing effects—significantly increasing risk in urban areas (COR = 2.90, 95% CI: 2.00–4.19) while appearing protective in rural settings (COR = 0.57, 95% CI: 0.35–0.91), warranting further investigation in multivariate models.

Table 2
Crude ORs for E. coli contamination (in PoU) predictors in urban and rural households

Characteristics	Urban (N = 24,909)		Rural (N = 36,786)	
	% (95% CI)	COR (95% CI)	% (95% CI)	COR (95% CI)
The age group of the household head				
< 35 years	25.26 (22.73–27.96)	1.21 (1.04–1.39)*	27.00 (25.01–29.09)	1.05 (0.94–1.18)
35–49 years	23.57 (22.00–25.22)	1.1 (1.00–1.21)	26.66 (25.22–28.16)	1.03 (0.96–1.11)
50–59 years	21.89 (20.27–23.61)	<i>ref</i>	26.05 (24.54–27.62)	<i>ref</i>
60 + years	23.27 (21.49–25.15)	1.08 (0.97–1.21)	28.46 (26.62–30.38)	1.13 (1.03–1.23)**
Educational level of the household head				
No formal education	38.62 (31.81–45.91)	3.19 (2.33–4.36)***	29.89 (22.45–38.57)	1.76 (1.18–2.61)**
Primary education	28.30 (26.44–30.22)	2 (1.74–2.29)***	30.01 (28.43–31.64)	1.77 (1.57–1.99)***
Secondary education	21.05 (19.54–22.64)	1.35 (1.19–1.54)***	25.28 (23.80–26.83)	1.39 (1.24–1.56)***
Higher education	16.49 (14.80–18.33)	<i>ref</i>	19.54 (17.86–21.33)	<i>ref</i>
Occupation of the household head				
Formal sector employee	19.87 (18.16–21.71)	<i>ref</i>	21.56 (19.84–23.37)	<i>ref</i>
Informal sector employee	24.85 (23.37–26.39)	1.33 (1.20–1.49)***	28.06 (26.72–29.45)	1.42 (1.28–1.57)***
Unemployed	20.27 (17.65–23.16)	1.02 (0.86–1.23)	28.74 (25.49–32.22)	1.47 (1.22–1.76)***
Drinking water facilities				
Notes: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$. COR: crude odds ratio, CI = confidence interval, <i>ref</i> = reference, Estimates are based on survey-weighted logistic regression (svy: logistic), adjusted for complex design.				

Characteristics	Urban (N = 24,909)		Rural (N = 36,786)	
	% (95% CI)	COR (95% CI)	% (95% CI)	COR (95% CI)
The age group of the household head				
Improved	22.98 (21.67–24.35)	<i>ref</i>	26.57 (25.33–27.84)	<i>ref</i>
Unimproved	36.69 (29.99–43.94)	1.94 (1.44–2.62) ^{***}	37.57 (32.23–43.23)	1.66 (1.31–2.11) ^{***}
Sanitation facilities				
Improved	22.65 (21.27–24.10)	<i>ref</i>	26.49 (25.22–27.79)	<i>ref</i>
Unimproved	26.62 (23.60–29.88)	1.33 (1.10–1.61) ^{**}	28.69 (25.58–32.02)	1.44 (1.21–1.71) ^{***}
Household water treatment practices				
Yes	22.75 (21.43–24.14)	<i>ref</i>	26.30 (25.07–27.56)	<i>ref</i>
No	28.22 (24.55–32.22)	1.24 (1.04–1.47) [*]	33.90 (30.00–38.04)	1.12 (0.95–1.32)
Handwashing facility				
Available	22.88 (21.55–24.26)	<i>ref</i>	26.55 (25.30–27.83)	<i>ref</i>
Not available	34.84 (28.43–41.86)	1.8 (1.33–2.45) ^{***}	34.98 (29.90–40.42)	1.49 (1.18–1.88) ^{**}
Organic waste container in a household				
Available - closed container	18.92 (17.36–20.58)	<i>ref</i>	22.47 (20.72–24.32)	<i>ref</i>
Available—opened container	26.40 (24.65–28.23)	1.54 (1.36–1.74) ^{***}	29.82 (28.35–31.33)	1.47 (1.31–1.64) ^{***}
Not available	40.33 (31.94–49.34)	2.9 (2.00–4.19) ^{***}	14.09 (9.31–20.75)	0.57 (0.35–0.91) [*]
Notes: ^{***} $p < 0.001$; ^{**} $p < 0.01$; [*] $p < 0.05$. COR: crude odds ratio, CI = confidence interval, <i>ref</i> = reference, Estimates are based on survey-weighted logistic regression (svy: logistic), adjusted for complex design.				

Characteristics	Urban (N = 24,909)		Rural (N = 36,786)	
	% (95% CI)	COR (95% CI)	% (95% CI)	COR (95% CI)
The age group of the household head				
Domestic wastewater storage				
Closed container/septic tank	21.20 (19.48–23.03)	<i>ref</i>	24.33 (22.58–26.18)	<i>ref</i>
Open the container in the yard.	27.45 (24.68–30.40)	1.41 (1.19–1.66)***	28.90 (26.73–31.16)	1.26 (1.1–1.45)**
Container outside the yard	26.78 (22.66–31.34)	1.36 (1.07–1.73)*	28.06 (24.70–31.67)	1.21 (1.01–1.46)*
No container or direct disposal to the ground	23.22 (21.02–25.58)	1.12 (0.96–1.32)	28.22 (26.33–30.20)	1.22 (1.07–1.39)**
Notes: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$. COR: crude odds ratio, CI = confidence interval, <i>ref</i> = reference, Estimates are based on survey-weighted logistic regression (svy: logistic), adjusted for complex design.				

Multivariate analysis

The final multivariate logistic regression models revealed distinct contextual patterns in determinants of *E. coli* contamination between urban and rural households (Table 3). In urban settings, younger household heads (< 35 years; aOR = 1.21, 95% CI: 1.04–1.40) had significantly higher odds of contamination; in contrast, age was not retained in the final rural model after variable selection. Educational inequalities were pronounced in both settings, with the steepest gradient observed in urban areas. Households without formal education had nearly threefold the odds of contamination (AOR = 2.93, 95% CI: 2.12–4.05) compared with households with higher education (Table 3).

Table 3
Adjusted odds ratios for E. coli contamination (in PoU) predictors in urban and rural households

Characteristics	Urban (N = 24,909) AOR (95% CI)	Rural (N = 36,786) AOR (95% CI)
Age group of the household head		
< 35 years	1.21 (1.04–1.4)*	-
35–49 years	1.1 (1.00–1.21)	-
50–59 years	<i>ref</i>	-
60 + years	0.99 (0.88–1.10)	-
Educational level of the household head		
No formal education	2.93 (2.12–4.05)***	1.39 (0.95–2.02)
Primary education	1.8 (1.55–2.10)***	1.48 (1.30–1.69)***
Secondary education	1.28 (1.11–1.46)***	1.26 (1.11–1.42)***
Higher education	<i>ref</i>	<i>ref</i>
Occupation of the household head		
Formal sector employee	<i>ref</i>	<i>ref</i>
Informal sector employee	1.01 (0.90–1.14)	1.14 (1.02–1.28)*
Unemployed	0.79 (0.65–0.96)*	1.15 (0.95–1.39)
Drinking water facilities		
Improved	<i>ref</i>	<i>ref</i>
Unimproved	1.41 (1.05–1.91)*	1.42 (1.13–1.79)**
Household water treatment practices		
Yes	<i>ref</i>	<i>ref</i>
No	1.22 (1.01–1.48)*	1.41 (1.18–1.68)***
Handwashing facility		
Available	<i>ref</i>	<i>ref</i>
Not available	1.44 (1.06–1.96)*	1.28 (1.01–1.62)*
Organic waste container in		

Characteristics	Urban (N = 24,909) AOR (95% CI)	Rural (N = 36,786) AOR (95% CI)
Age group of the household head a household		
Available - Closed container	<i>ref</i>	<i>ref</i>
Available - opened container	1.36 (1.20–1.54)***	1.36 (1.20–1.53)***
Not available	2.43 (1.66–3.56)***	0.54 (0.33–0.89)*

Post-estimation analysis for the final model:

Urban model: $N = 21,703$; F-adjusted GoF = 0.718 ($p = 0.693$); linktest _hat = 0.804 ($p = 0.003$); _hatsq = -0.090 ($p = 0.447$). Rural model: $N = 35,304$; F-adjusted GoF = 0.377 ($p = 0.933$); linktest _hat = 1.011 ($p = 0.013$); _hatsq = 0.006 ($p = 0.976$).

Notes:*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$, AOR: adjusted odds ratio; CI = confidence interval.

Estimates are based on survey-weighted logistic regression (svy: logistic), adjusted for complex design.

Contextual socio-economic vulnerabilities were further evident in occupational patterns. Informal employment significantly predicted contamination only in rural households (AOR = 1.14, 95% CI: 1.02–1.28), while unemployment was uniquely protective in urban settings (AOR = 0.79, 95% CI: 0.65–0.96). This contrast suggests that informal workers in rural areas may face compounding environmental exposures that are not captured by conventional WASH indicators.

WASH infrastructure deficiencies consistently predicted contamination across both models. Unimproved water sources increased the odds by 41–42% in both settings, whereas the lack of water treatment had stronger effects in rural households (AOR = 1.41 vs 1.22 in urban households). The absence of handwashing facilities increased odds by 44% in urban and 28% in rural areas, reinforcing hygiene as a cross-cutting determinant.

Table 4
Determinants of household E. coli contamination: Average marginal effects (AME) from final urban and rural models

Determinants	Urban Final Model AME (95% CI)	Rural Final Model AME (95% CI)
Age group (ref: 50–59 years)*		
< 35 years	0.03 (0.01–0.06)*	-
35–49 years	0.02 (0.00–0.03)	-
60 + years	-0.00 (-0.02–0.02)	-
Education (ref: Higher education)		
No formal education	0.21 (0.13–0.28)***	0.06 (-0.01–0.13)
Primary education	0.10 (0.08–0.12)***	0.07 (0.05–0.10)***
Secondary education	0.04 (0.02–0.06)***	0.04 (0.02–0.06)***
Occupation (ref: Formal sector)		
Formal sector employee		
Informal sector employee	0.00 (-0.02–0.02)	0.03 (0.00–0.05)*
Unemployed	-0.04 (-0.07–-0.01)*	0.03 (-0.01–0.06)
Drinking water facilities (ref: improved)		
Unimproved	0.07 (0.00–0.13)*	0.07 (0.02–0.12)**
Household water treatment practices (ref: yes)		
No	0.04 (0.00–0.07)*	0.07 (0.03–0.11)***
Hand washing facility (ref: Available)		
Not available	0.07 (0.01–0.13)*	0.05 (0.00–0.10)
Organic waste container in a household (ref: Close container)		
Available – open waste container	0.05 (0.03–0.07)***	0.06 (0.04–0.08)***
Not available	0.18 (0.09–0.26)***	-0.09 (-0.15–-0.03)**
Notes: ***p < 0.001, **p < 0.01, *p < 0.05		

Waste management emerged as the most context-dependent factor. Open containers increased risk uniformly (AOR = 1.36 in both settings), whereas absent containers showed opposing effects: substantially increasing urban risk (AOR = 2.43) and reducing rural contamination (AOR = 0.54). This striking divergence suggests fundamentally different contamination pathways related to waste disposal practices and environmental conditions.

Average Marginal Effects (AME) analysis quantified the population-level impacts (Table 4). In urban areas, educational deprivation had the greatest effect (+ 21 percentage points), followed by the presence of missing waste containers (+ 18 percentage points). Rural contamination was primarily driven by water-related factors, including a lack of treatment (+ 7 pp) and the use of unimproved sources (+ 7 pp). The protective effect of the absence of waste containers in rural settings (−9 pp) illustrates the importance of context-specific intervention strategies.

Discussion

This nationally representative study of 61,695 Indonesian households reveals distinct and context-specific pathways of microbial contamination between urban and rural settings. Most notably, the absence of waste containers protected against contamination was associated with a reduced risk in rural areas (AOR = 0.54; 95% CI: 0.33–0.89), whereas it was associated with a substantially increased risk in urban settings (AOR = 2.43; 95% CI: 1.66–3.56). This divergence may reflect differences in spatial organization and waste disposal practices: rural households are more likely to dispose of waste farther from water sources, whereas urban households face constraints related to higher population density, limited space, and greater proximity between waste and water. This divergence challenges the adequacy of conventional WASH indicators, which often classify infrastructure as "improved" without capturing context-specific practices, such as waste-disposal behaviors and spatial proximity to contamination sources. Beyond this key finding, our analysis confirms that *Escherichia coli* contamination remains highly prevalent (23.2% in urban areas; 26.9% in rural areas) and is shaped by a complex interplay of sociodemographic, infrastructural, and behavioral determinants that operate differently across contexts. Notably, education emerged as a dominant protective factor in urban areas (AOR = 2.93 for no formal education), while informal employment represented a distinct vulnerability in rural settings (AOR = 1.14).

Sociodemographic factors (household head characteristics)

Education emerged as the strongest predictor of *E. coli* contamination, with particularly pronounced effects in urban areas. Households without formal education had nearly three times the odds of contamination compared with those with higher education (urban AOR = 2.93; 95% CI: 2.12–4.05), corresponding to a 21 percentage-point increase in the probability of contamination (AME = + 0.21, $p < 0.001$). This gradient likely operates through multiple pathways, including health literacy, which facilitates safer water handling practices; economic capacity to invest in improved WASH infrastructure; and social capital, which enables households to navigate complex urban service environments. This finding is

consistent with evidence from multiple low- and middle-income country settings, including Peru, Indonesia, and Ethiopia, where higher educational attainment has been associated with improved hygiene behaviors and reduced risk of microbiological contamination (Genter et al., 2022; Hernández-Vásquez et al., 2023). Beyond knowledge, education also influences economic capacity, enabling households to invest in safer WASH infrastructure (Zikrina et al., 2024). Taken together, these findings suggest that education functions not only as a protective factor but also as a structural determinant that shapes both behavioral practices and access to safe WASH services. In urban Indonesia, these results suggest that educational and behavior change interventions may yield greater marginal benefits than infrastructure investments alone, particularly in settings where basic services are already in place but safe practices remain suboptimal.

Beyond education, the age of the household head revealed context-specific patterns, underscoring the importance of life course dynamics and environmental context. In urban areas, younger household heads (< 35 years) had significantly higher odds of contamination (AOR = 1.21; 95% CI: 1.04–1.40), potentially reflecting limited experience in managing household water safety and lower adherence to recommended hygiene practices (Oswald et al., 2007). Conversely, older household heads (≥ 60 years) in rural areas exhibited an elevated risk in bivariate analysis (COR = 1.13), although this effect was attenuated after adjusting for other factors, suggesting that socio-economic or infrastructural characteristics may mediate age-related vulnerability in rural settings. This pattern aligns with studies documenting that older adults in rural communities often rely on traditional, less safe practices and face declining physical capacity to maintain or access improved water sources, particularly in environments where unprotected wells and poor sanitation are common (Lee & Murphy, 2020; Montealegre et al., 2018). Collectively, these findings highlight the need for age-sensitive interventions that account for both behavioral capacity and environmental constraints, with younger urban households benefiting from targeted hygiene promotion and older rural populations requiring structural and social support to sustain safe water practices.

Occupational status further differentiates risk profiles, with informal employment emerging as a context-specific vulnerability in rural areas. Household heads engaged in the informal sector in rural areas had 14% higher odds of contamination than formal workers (AOR = 1.14; 95% CI: 1.02–1.28), corresponding to a 3 percentage-point increase in the probability of contamination (AME = + 0.03, $p < 0.05$). This association likely reflects underlying economic insecurity and constrained access to improved WASH services among informal workers, who may lack the financial resources and institutional support to invest in safe water sources, household treatment technologies, or adequate sanitation. Similar associations between precarious employment and water insecurity have been reported in Bangladesh, Ethiopia, and across Africa (Carson et al., 2011; Geere & Cortobius, 2017). Notably, this pattern was not observed in urban areas, suggesting that rural informal workers experience compounded environmental and infrastructural exposures that are not fully captured by conventional WASH indicators. These findings have important implications for social protection and rural development policies, highlighting the need to integrate WASH considerations into programs targeting informal workers in resource-constrained settings.

Drinking water facility and sanitation

Although access to improved water sources has expanded substantially in Indonesia, infrastructure alone does not guarantee microbiological safety at the point of use. Households relying on unimproved water sources faced significantly higher odds of *E. coli* contamination in both urban (AOR = 1.41; 95% CI: 1.05–1.91) and rural areas (AOR = 1.42; 95% CI: 1.13–1.79), corresponding to a 7 percentage-point increase in contamination probability (AME = + 0.07). Importantly, even households with improved water sources experienced substantial levels of contamination (23.0% in urban areas; 26.6% in rural areas), indicating that source-level improvements alone are insufficient to ensure microbiological safety. Similar patterns have been documented across diverse low- and middle-income country settings, including Mozambique, Nepal, and Tunisia (Adamu et al., 2022; Aragaw et al., 2023; Fitouri et al., 2024), where post-supply contamination during transport, storage, and handling has been identified as a major determinant of drinking water quality.

Compounding these risks, inadequate sanitation independently contributed to contamination in both settings (urban AOR = 1.44; rural AOR = 1.28), with corresponding population-level effects of + 7 and + 5 percentage points, respectively. This association likely operates through multiple environmental transmission pathways, including fecal contamination of soil and groundwater, particularly in settings with shallow wells, as well as the transfer of pathogens into households via contaminated surfaces, footwear, and hands, ultimately leading to recontamination of stored drinking water. These findings align with evidence from Sudan, Malawi, and Ethiopia (Asmally et al., 2025; Girmay et al., 2023; Hinton et al., 2024), yet the persistence of contamination despite high sanitation coverage (85% urban; 82% rural improved) suggests that infrastructure quality and behavioral adherence are as critical as access. Achieving SDG 6, therefore, requires integrated, systems-level approaches that simultaneously address source protection, water service reliability, safe storage, sanitation quality, and sustained hygiene practices, particularly in rural areas where overlapping vulnerabilities amplify exposure risks.

Hygiene and household practices

Hygiene-related household practices independently predicted contamination beyond sociodemographic and infrastructural factors, highlighting the critical role of behavior in shaping microbiological water quality at the point of use. The absence of handwashing facilities significantly increased risk in both urban (AOR = 1.44; 95% CI: 1.06–1.96) and rural households (AOR = 1.28; 95% CI: 1.01–1.62), reinforcing evidence that hands act as key vectors for enteric pathogen transmission and that the presence of designated handwashing facilities promotes consistent handwashing with soap (Cantrell et al., 2023; Tamene et al., 2023; WHO & UNICEF, 2021). However, waste management practices exhibited the most pronounced context-dependent effects, underscoring the importance of local environmental and spatial conditions. While open containers elevated risk uniformly (AOR = 1.36 in both settings), the absence of containers was paradoxically protective in rural areas (AOR = 0.54; 95% CI: 0.33–0.89) but strongly hazardous in urban settings (AOR = 2.43; 95% CI: 1.66–3.56). This divergence likely reflects fundamental differences in disposal practices and spatial configurations between rural and urban environments. Rural

households may dispose of waste away from water sources, whereas in dense urban environments, cross-contamination can be exacerbated when containers are absent (Ebdon & da Silva, 2019; Pickering et al., 2019). These findings underscore that improving hygiene requires not only the provision of infrastructure but also context-sensitive behavior change strategies tailored to local practices and environmental constraints: urban areas need improved containerized waste collection, whereas rural communities may benefit more from promoting safe disposal away from households and water sources.

The Paradox of Waste Container Absence

The absence of waste containers paradoxically appeared protective in rural areas (AOR = 0.54) but posed a significant hazard in urban settings (AOR = 2.43), highlighting fundamentally different exposure pathways. Rural households often dispose of waste communally or in gardens, physically distancing fecal sources from water and food zones (Esteban Cantillo & Quesada, 2022; Mogane & Momba, 2025), while adaptive practices such as boiling water and community-based initiatives (e.g., Waste Sadaqah) may further mitigate exposure risks (Genter et al., 2022; Yandri et al., 2023). In contrast, dense urban environments experience cross-contamination when containers are absent, as uncollected waste attracts vectors (Ginn et al., 2021; Putri et al., 2025). These findings challenge standardized “improved/unimproved” classifications, which may obscure important contextual differences in waste management practices and associated exposure pathways (Degefa et al., 2025; Tahulela et al., 2025).

Environmental hygiene and wastewater management

Environmental conditions further shape contamination risks beyond household-level factors, highlighting the importance of broader ecological and infrastructural contexts. Our findings show that open wastewater storage in household yards significantly increased the odds of *E. coli* contamination in both urban (AOR = 1.41) and rural settings (AOR = 1.26), consistent with evidence linking inadequate sanitation and wastewater management to groundwater contamination (Bindra et al., 2021; Genter et al., 2022). Moreover, stored household water frequently exhibits higher microbial loads than source water, underscoring the critical importance of safe storage conditions and hygienic handling practices (Lavanya & Ravichandran, 2013; Oswald et al., 2007). At a systems level, evidence from Ghana and Vellore demonstrates that improved sanitation coverage and fecal sludge management can reduce environmental contamination and infectious disease prevalence (D. Berendes et al., 2017; D. M. Berendes et al., 2018), reinforcing the need for integrated approaches that simultaneously disrupt multiple fecal–oral transmission pathways across environmental, infrastructural, and behavioral domains.

Implications for Indonesia's WASH strategy

These findings have direct implications for refining Indonesia's WASH strategy, particularly in addressing context-specific determinants of contamination. In urban contexts, policies should prioritize health education and community engagement strategies, particularly targeting younger household heads through digital platforms and community-based networks, while strengthening neighborhood-level waste management systems to reduce risks associated with inadequate waste containment. In rural areas,

interventions should prioritize point-of-use water safety through improved source protection, promotion of household water treatment, and targeted outreach to vulnerable groups such as informal-sector workers and older adults using context-appropriate communication strategies. Critically, rural programs should promote safe final-disposal practices (e.g., composting sites away from wells) rather than merely providing containers, given the paradoxical protective effect of the absence of containers (AOR = 0.54). At the national level, monitoring frameworks such as SIPEKAM should incorporate more granular, context-sensitive indicators—including distances between water sources and sanitation facilities, well-construction quality, service continuity, and household treatment practices—beyond conventional improved/unimproved classifications. Adopting a One Health approach is also essential for addressing human–animal–environment interactions, particularly in rural areas where proximity to livestock may introduce additional zoonotic contamination pathways.

Limitations and strengths

This study has several limitations. First, the cross-sectional design precludes causal inference, and the observed associations should be interpreted as indicative rather than causal. Second, single-visit water sampling may not capture temporal and seasonal variability in microbial contamination. Third, behavioral variables were self-reported and therefore subject to recall and social desirability biases. Finally, the absence of detailed spatial indicators, such as distances between water sources and sanitation facilities, limited more granular analysis of contamination pathways. Despite these limitations, this study has several important strengths. It utilizes a large, nationally representative sample with survey-weighted analysis, enhancing the generalizability of findings. The urban–rural stratified approach enables identification of context-specific determinants, while the use of average marginal effects (AME) provides interpretable estimates of population-level impact. Collectively, these features strengthen the policy relevance and external validity of the findings for informing Indonesia's progress toward SDG 6 strategies.

Conclusion

E. coli contamination in Indonesia reflects distinct and context-specific urban–rural transmission pathways shaped by environmental, infrastructural, and behavioral factors. Achieving microbiologically safe drinking water, therefore, requires moving beyond infrastructure provision to address key determinants, including educational disparities, context-specific waste management practices, and household-level water treatment and safe storage. Future research should investigate the causal mechanisms underlying these associations, particularly the observed waste container paradox, using longitudinal and mixed-methods designs that integrate environmental, behavioral, and microbiological data within a One Health framework. From a policy perspective, these findings highlight the need for geographically tailored interventions and strengthened monitoring systems, such as SIPEKAM, enhanced with context-sensitive indicators to more accurately capture exposure pathways and accelerate progress toward SDG 6.

Declarations

Author Contributions

Asep Hermawan is the sole author of this manuscript. He contributed to the conception and design of the study, data acquisition and analysis, interpretation of results, drafting and critical revision of the manuscript, and final approval of the version to be published.

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Competing Interests

The authors declare no competing interests.

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Data Availability

The data used in this study were obtained through a formal request from the Center for Data and Information (Pusdatin), Ministry of Health, Indonesia, at <https://layanandata.kemkes.go.id/>

Ethics approval

Secondary de-identified data from the 2023 SIPEKAM system were used with formal authorization from Pusdatin, Indonesian Ministry of Health. The dataset contained no personal identifiers. Analysis complied with Indonesian Law No. 27/2022 on Personal Data Protection

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Figures

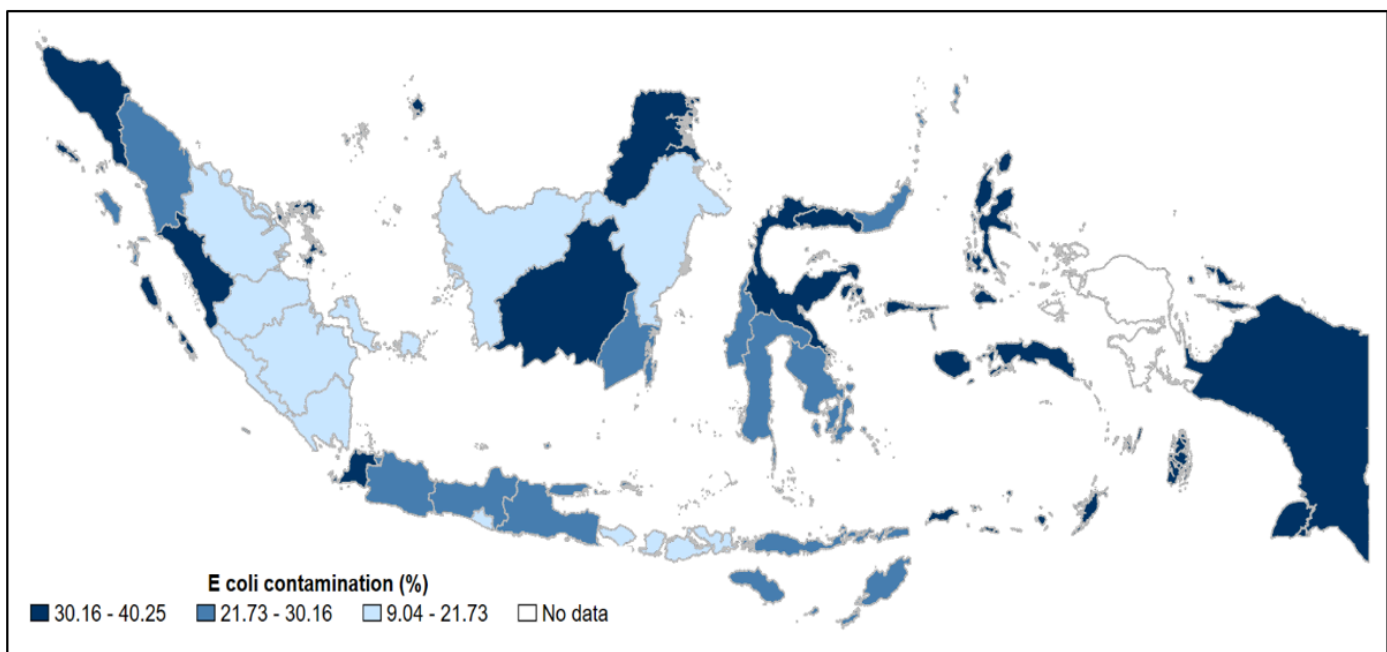


Figure 1

Spatial distribution of *Escherichia coli* contamination in household drinking water at the PoU across Indonesian provinces, 2023.

Supplementary Files

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