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Orapuh Journal

REVIEW ARTICLE

Journal of Oral & Public Health

Chemical Contamination of Drinking Water at the Source and Associated Health Risks in Wells, Boreholes, and Distribution Networks: A Systematic Review and Meta-Analysis

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ARTICLE INFO

Received: *02 June 2026*
Accepted: *17 July 2026*
Published: *11 September 2026*

Keywords:
Groundwater, chemical contamination, arsenic, fluorides, nitrates, health risk assessment, meta-analysis

Peer-Review: *Externally peer-reviewed*

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To cite:
Bwakamana, P. B., Mudogo, V., & Ngbolua, K. N. (2026). Chemical contamination of drinking water at the source and associated health risks in wells, boreholes, and distribution networks: A systematic review and meta-analysis. *Orapuh Journal*, *7*(8), e1473.
https://doi.org/10.4314/orapj.v7i8.73

ISSN: *2644-3740*

Published by ***Orapuh, Inc.***, F. Gaye Res., Sukuta-Jamisa, Greater Banjul, The Gambia.

Editor-in-Chief: *Prof. V. E. Adamu (editor@orapuh.org)*

ABSTRACT

Introduction
Groundwater is a vital source of drinking water globally, particularly in rural areas and places with infrastructure constraints. However, chemical contaminants from both natural (geogenic) and anthropogenic sources—including arsenic, fluoride, and nitrates—pose severe long-term threats to human health.

Purpose
This study aimed to quantitatively synthesize chemical contamination levels in drinking water from wells, boreholes, and distribution networks, identify main contamination drivers, and evaluate non-carcinogenic and carcinogenic health risks worldwide.

Methods
A systematic search across PubMed, Scopus, Web of Science, Cochrane Library, ScienceDirect, Google Scholar, and HAL identified quantitative studies evaluating chemical contaminants in drinking water published between 2014 and 2024. Exceedance rates of World Health Organization (WHO) guidelines were combined using a random-effects meta-analysis model. Subgroup analyses examined geographic regions, hydraulic structure types, and methodological quality evaluated via the Newcastle-Ottawa Scale (NOS). Health risks were assessed using the Hazard Index (HI) and lifetime Cancer Risk (CR).

Results
Across 62 included studies (N=62), the combined global rate of exceeding drinking water health standards was 30.8%. Nitrates exhibited the highest exceedance rate (41.5%), followed by fluorides (38.2%) and arsenic (32.7%). The overall combined HI was 1.84 (95% CI [1.41, 2.39]), and the lifetime carcinogenic risk reached 4.72×10^{-5}. Africa demonstrated the highest contamination exceedance (57.3%), significantly surpassing Europe (13.5%; $p<.001$). Traditional unprotected wells were the most vulnerable water source (45.8% exceedance). Methodological quality significantly modulated estimates ($p<.001$), with lower-quality studies overestimating contamination rates.

Conclusion
Chemical groundwater contamination represents a major global health risk. Strengthening routine water quality monitoring, adopting contaminant-specific treatment technologies, and prioritizing water safety within public health governance—particularly in mining and rural regions—are critical to mitigating chronic toxic exposure. **Protocol registration:** PROSPERO (CRD420261398101).

INTRODUCTION

Water is an indispensable natural resource vital for human health, ecosystem integrity, and socio-economic development (Hane et al., 2021; Lagnika et al., 2014). Access to safe drinking water is universally recognized as a fundamental human right and a core global public health priority.

The World Health Organization (WHO, 2022) guidelines state that potable water supplies must be free from pathogens and chemical substances at concentration levels that threaten human health. Unlike microbial contamination, which manifests acutely, chemical contamination in drinking water is often insidious, causing chronic, irreversible multi-organ toxicities, endocrine disruption, and carcinogenic outcomes (WHO, 2022).

Chemical contaminants originate from complex interactions between natural hydrogeochemical processes and anthropogenic activities, including industrial effluent discharge, intensive agriculture, poor solid/liquid waste management, and mining operations (Amadou et al., 2025; Lagnika et al., 2014). In low- and middle-income countries (LMICs), water infrastructure—including shallow wells, deep boreholes, and piped distribution networks—is frequently exposed to chemical pollutants. Chronic exposure to heavy metals, metalloids, and inorganic ions varies substantially based on geological formations, hydrogeology, and localized land-use practices.

In urban, industrial, and mining regions of sub-Saharan Africa, chemical water pollution presents an acute environmental health challenge (Amadou et al., 2025). Rapid urban expansion, industrialization, artisanal and small-scale mining, and insufficient waste treatment infrastructure accelerate the chemical degradation of freshwater aquifers. This vulnerability is especially marked in the Democratic Republic of the Congo (DRC). Despite possessing vast hydrologic reserves, large segments of the Congolese population rely on untreated groundwater from shallow wells and boreholes. In mining hubs such as Haut-Katanga, heavy metal mobilization (e.g., lead, copper, cobalt, manganese, arsenic) into drinking water sources poses severe toxicological risks, with observed concentrations routinely exceeding international safety thresholds (Banza et al., 2009; Kapembo et al., 2021; Mwamba & Nyembo, 2019).

Although groundwater aquifers are generally better insulated from microbial contamination than surface waters, they require strict monitoring of physical and chemical parameters to guarantee safety (Ayouba Mahamane & Guel, 2015; Ould Cheikh et al., 2012). Water quality directly dictates population health (Tchouongsi et al., 2020).

Gaps in Literature and Study Objectives

Despite expanding literature on environmental water quality, critical research gaps persist:

1. Significant methodological variability exists across primary studies regarding sampling protocols, laboratory instrumentation, and standard reference limits.
2. Emerging chemical contaminants and co-exposure dynamics remain inadequately characterized in vulnerable hydrogeological settings.
3. Most studies provide purely descriptive concentration metrics without systematically quantifying integrated human toxicological risk models (non-carcinogenic hazard indices and lifetime cancer risk).
4. Longitudinal data evaluating temporal contamination trends across different hydraulic supply infrastructures remain sparse.

To address these gaps, this systematic review and meta-analysis quantitatively synthesizes global evidence regarding chemical contamination levels in drinking water from wells, boreholes, and distribution networks. It establishes combined exceedance rates against WHO benchmarks, evaluates non-carcinogenic and carcinogenic health risks, identifies key moderating variables (geographic region, hydraulic infrastructure type, methodological rigor), and offers evidence-based recommendations for public health intervention, with particular focus on sub-Saharan Africa and the Democratic Republic of the Congo.

METHODS

Information Sources and Search Strategy

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines and registered prospectively in PROSPERO (Registration Number: CRD420261398101).

A comprehensive literature search was executed across seven electronic databases: PubMed, Scopus, Web of Science, Cochrane Library, ScienceDirect, Google Scholar, and HAL (for French-language literature), covering studies published between January 1, 2014, and December 31, 2024. Search queries combined Medical Subject Headings (MeSH) and free-text terms in English and French using Boolean operators (AND, OR).

The primary search strategy was constructed as follows: ("drinking water" OR "groundwater" OR "well water" OR "borehole water" OR "tap water" OR "water distribution network") AND ("chemical contamination" OR "heavy metals" OR "arsenic" OR "fluoride" OR "nitrate" OR "nitrite" OR "lead" OR "cadmium" OR "chromium" OR "pesticides" OR "industrial pollutants") AND ("health risk" OR "adverse health effect" OR "toxicity" OR "prevalence" OR "disease" OR "cancer risk" OR "non-carcinogenic risk" OR "hazard quotient" OR "hazard index") AND ("cross-sectional study" OR "cohort" OR "risk assessment" OR "quantitative analysis" OR "survey")

Eligibility Criteria

Studies were screened based on predefined Population, Exposure, Comparator, Outcome, and Study Design (PECOSD) criteria.

Inclusion Criteria:

a) **Population:** Human populations consuming drinking water from target hydraulic infrastructures.

b) **Exposure:** Drinking water sourced directly from shallow/traditional wells, deep aquifer boreholes, or municipal distribution networks.

c) **Outcomes:** Quantitative measurements of chemical contaminant concentrations, calculated standard exceedance proportions relative to WHO guidelines, and quantified non-carcinogenic (Hazard Quotient [HQ], Hazard Index [HI]) or carcinogenic risk (Cancer Risk [CR]) estimates based on United States Environmental Protection Agency (US EPA) risk assessment frameworks.

d) **Study Design:** Quantitative observational cross-sectional studies, environmental risk assessments, and prospective/retrospective cohort studies.

e) **Language & Period:** Peer-reviewed original research published in English or French between 2014 and 2024.

Exclusion Criteria:

a) Studies focusing exclusively on surface waters (rivers, lakes, dams) without dedicated groundwater/tap water sampling.

b) Studies reporting solely microbiological parameter analyses without chemical profiles.

c) Narrative reviews, editorials, abstracts without full text, conference proceedings, case reports (N=1), and animal toxicology studies.

d) Studies lacking exportable numerical dataset metrics required for meta-analysis extraction.

Study Selection and Data Extraction

Bibliographic records were imported into Zotero for duplicate removal, followed by primary title/abstract screening and secondary full-text eligibility assessment using the Rayyan web platform. Two reviewers independently evaluated all studies; disagreements were resolved by consensus or third-reviewer adjudication.

A standardized, pre-tested data extraction form was utilized to gather:

I. **Study Identifiers:** Primary author, publication year, country, geographic region, study period, and observational design.

II. **Water Supply Infrastructure:** Hydraulic structure type classified into shallow wells (W), deep boreholes (D), or distribution networks (N).

III. **Contaminant & Exposure Data:** Sample size (n), chemical parameters analyzed, analytical techniques, mean concentrations, and standard exceedance rates based on WHO maximum allowable guidelines.

IV. **Health Risk Metrics:** Adult and child population Hazard Quotient (HQ), overall Hazard Index ($HI = \sum HQ$), and lifetime Cancer Risk ($CR = CDI \times CSF$).

Methodological Quality and Risk of Bias Assessment

Methodological quality was evaluated independently by two authors using an adapted version of the Newcastle-Ottawa Scale (NOS) for non-randomized observational environmental studies. The tool evaluates three domains (maximum 9 stars):

Selection (0–4 stars): Sample representativeness, sample size justification, sampling randomization, and validated standardized analytical techniques.

Comparability (0–2 stars): Methodological control for confounding variables (e.g., exposure duration, demographic stratification, seasonal variations).

Outcome/Exposure (0–3 stars): Chemical analysis rigour, instrumentation calibration, and health risk model validation.

Studies were categorized into three quality tiers: High Quality (NOS ≥ 8), Intermediate Quality (NOS = 7), and Low Quality (NOS ≤ 6).

Statistical Analysis and Synthesis

Meta-analyses were executed using Comprehensive Meta-Analysis (CMA) software, Version 4.0. Because of substantial geographic and hydrogeological diversity across studies, a DerSimonian-Laird random-effects model was applied to pool effect sizes, incorporating both within-study sampling error and between-study variance (τ2).

Pooled primary outcomes included:

A. **Exceedance Rates (%):** Proportion of water samples exceeding WHO limits per chemical contaminant, presented with 95% Confidence Intervals (95% CI).

B. **Integrated Toxicological Risk:** Pooled non-carcinogenic Hazard Index (HI>1.0 indicates potential chronic adverse health effects) and carcinogenic Cancer Risk (CR > 1.0 × 10 − 5 benchmark).

Statistical heterogeneity was quantified using:

i. **Cochran's Q test:** Evaluated at a significance threshold of p<.05.

ii. **Inconsistency Index (I2):** Values of 25%, 50%, and 75% represented low, moderate, and high heterogeneity, respectively.

iii. **95% Prediction Intervals (95% PI):** Computed to estimate the expected true effect in future studies.

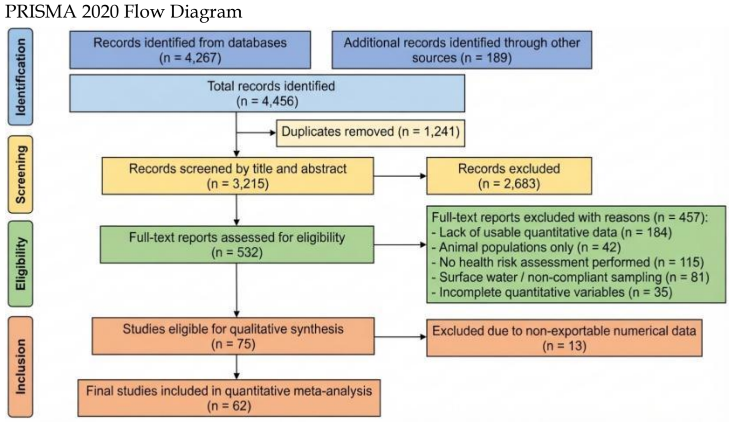
Moderator and subgroup analyses were conducted across geographic regions (Africa, Asia, Americas, Europe), hydraulic infrastructure types (W, D, N), and NOS quality tiers (≤6, 7, ≥8). Publication bias was visually examined via funnel plot asymmetry and quantified using Egger's linear regression test (p<.05 indicating significant bias).

RESULTS

Selection Flow and Study Characteristics

The initial database search yielded 4,456 records (4,267 from main databases; 189 from reference search). After removing 1,241 duplicates, 3,215 titles and abstracts were screened, resulting in the exclusion of 2,683 articles. A total of 532 full-text reports were retrieved and assessed for eligibility; 457 were excluded for non-compliant designs, surface-water focus, or missing quantitative data. Of the 75 studies eligible for qualitative synthesis, 13 lacked exportable quantitative standard metrics required for CMA software. Consequently, 62 studies (N=62) met all inclusion criteria for the quantitative meta-analysis.

Figure 1:
PRISMA 2020 Flow Diagram



Geographically, the 62 included studies covered four continental regions: Asia (n=22), Europe (n=16), Africa (n=14), and the Americas (n=10). Across the sample, traditional unprotected wells were investigated in 41 studies, deep boreholes in 38 studies, and distribution networks in 32 studies.

Table 1 outlines the descriptive characteristics of all 62 included studies.

Table 1:

Descriptive Characteristics of Included Studies (N=62)

ID	Author(s) & Year	Country	Priority Chemical Contaminants Analyzed	Health Risk Assessment Model
Asia Region (n=22)				
E1	Alam et al., 2024	Bangladesh	As, Mn, NO_3^-	NCR + CR
E2	Wang, 2023	China	Pb, Cd, Cr, F	NCR
E3	Suresh, 2022	India	As, F, NO_3^-	NCR + CR
E4	Tanaka, 2021	Japan	Pb, Cu, Pesticide traces	NCR
E5	Nguyen, 2020	Vietnam	As, Mn, NO_3^-	CR
E6	Ali, 2019	Pakistan	Cr, Cd, F	NCR
E7	Lin, 2024	Taiwan	Pb, Zn, Pesticides	NCR + CR
E8	Hussein, 2023	Malaysia	Mn, Fe, NO_3^-	NCR
E9	Zhang, 2022	West China	As, F, Cr	NCR + CR
E10	Sato, 2018	Japan	Cu, Ni, Pesticides	NCR
E11	Das, 2023	Bangladesh	As, NO_3^-	CR
E12	Lee, 2021	Singapore	Pb, Cd traces	NCR
E13	Patel, 2022	South India	F, As, Mn	NCR
E14	Ito, 2020	Japan	Cr, Ni, Zn	NCR
E15	Thao, 2022	Cambodia	As, NO_3^-	CR
E16	Chen, 2025	East China	Pb, Cd, Pesticides	NCR + CR
E17	Ali, 2017	Pakistan	F, Cr, Mn	NCR
E18	Ong, 2024	Thailand	As, Pb, NO_3^-	NCR + CR
E19	Park, 2020	South Korea	Cu, Ni, Pesticides	NCR
E20	Hassan, 2018	Egypt	Mn, Fe, NO_3^-	NCR
E21	Singh, 2021	Nepal	As, F	NCR + CR
E22	Chai, 2023	Hong Kong	Pb, Cu traces	NCR
Europe Region (n=16)				
E23	Dupont, 2023	France	NO_3^- , Pesticides, Pb	NCR
E24	Rossi, 2026	Italy	Cr, Ni, Cd	NCR
E25	Brown, 2018	United Kingdom	Pb, Cu, Pesticides	NCR + CR
E26	Olsen, 2022	Denmark	NO_3^- , As traces	NCR
E27	Schmidt, 2021	Germany	Pesticides, Mn, Fe	NCR
E28	Popov, 2025	Bulgaria	Cr, Pb, NO_3^-	NCR
E29	Costa, 2022	Portugal	As, Pesticides	CR
E30	Nilsson, 2020	Sweden	Cu, Ni, Zn	NCR
E31	Vasiljevic, 2023	Serbia	F, Cr, NO_3^-	NCR
E32	Dubois, 2020	Switzerland	Pb, Pesticide traces	NCR
E33	Van der Meer, 2022	Netherlands	NO_3^- , Pesticides	NCR
E34	Marin, 2021	Romania	As, Mn, Cr	NCR + CR
E35	Fournier, 2025	Luxembourg	Cu, Pb traces	NCR
E36	Georgiou, 2023	Cyprus	NO_3^- , F	NCR
E37	Müller, 2024	Austria	Pesticides, Cd traces	NCR
E38	Ionescu, 2020	Moldova	As, Cr, NO_3^-	CR
Africa Region (n=14)				
E39	Moussa, 2022	Senegal	F, Mn, NO_3^-	NCR
E40	Ndiaye, 2023	Mali	As, F	NCR + CR
E41	Okonkwo, 2024	Nigeria	Pb, Cr, NO_3^-	NCR
E42	Kamau, 2021	Kenya	F, As	NCR + CR
E43	Traoré, 2020	Burkina Faso	Mn, Fe, F	NCR
E44	Dlamini, 2025	South Africa	Pb, Pesticides, NO_3^-	NCR + CR
E45	Bah, 2019	The Gambia	As, NO_3^-	CR
E46	Mensah, 2022	Ghana	Cr, F, Mn	NCR

https://doi.org/10.4314/orapj.v7i8.73

E47	Said, 2024	Tanzania	As, Pb, NO_3^-	NCR + CR
E48	Sylla, 2017	Guinea	F, Mn, As	NCR
E49	Sow, 2023	Ivory Coast	Pesticides, Cr traces	NCR
E50	Okafor, 2021	Niger	As, F, NO_3^-	NCR + CR
E51	Diallo, 2022	Mauritania	Mn, Fe, F	NCR
E52	Fall, 2024	Togo	Pb, NO_3^-	NCR
Americas Region (n=10)				
E53	Smith, 2021	United States	Pb, As, Pesticides	NCR + CR
E54	Thompson, 2016	Canada	Cu, Ni, NO_3^-	NCR
E55	Silva, 2025	Brazil	Mn, Cr, Pesticides	NCR
E56	Garcia, 2021	Mexico	As, F, Pb	NCR + CR
E57	Carter, 2022	Canada (Quebec)	Pb, Cu traces	NCR
E58	Fuentes, 2024	Colombia	As, NO_3^- , Pesticides	CR
E59	Méndez, 2023	Chile	F, Mn, Cr	NCR
E60	Guzmán, 2022	Peru	As, Pb	NCR + CR
E61	Bennett, 2026	United States (CA)	Pesticides, NO_3^-	NCR
E62	Rojas, 2023	Argentina	Cr, Mn, As	NCR + CR

Note. NCR = Non-Carcinogenic Risk (Hazard Quotient/Hazard Index); CR = Carcinogenic Risk.

Methodological Quality Assessment

Quality evaluation using the adapted Newcastle-Ottawa Scale yielded 24 High Quality studies (NOS ≥ 8; predominantly from Europe, North America, Japan, and Singapore), 14 Intermediate Quality studies (NOS = 7), and 24 Low Quality studies (NOS ≤ 6; concentrated in sub-Saharan Africa, South Asia, and rural Latin America).

Table 2 details individual NOS domain scoring.

Table 2:
Methodological Quality Assessment via Newcastle-Ottawa Scale (N=62)

Study ID	Selection (/4)	Comparability (/2)	Outcome/ Exposure (/3)	Total NOS Score (/9)	Methodological Quality Tier
Asia Region					
E1	3	2	2	7	Intermediate
E2	4	2	2	8	High
E3	3	1	2	6	Low
E4	4	2	2	8	High
E5	3	1	2	6	Low
E6	2	1	2	5	Low
E7	3	2	2	7	Intermediate
E8	3	1	2	6	Low
E9	3	1	2	6	Low
E10	4	2	2	8	High
E11	2	1	2	5	Low
E12	4	2	2	8	High
E13	3	1	2	6	Low
E14	4	2	2	8	High
E15	2	1	2	5	Low
E16	3	2	2	7	Intermediate
E17	2	1	2	5	Low
E18	3	1	2	6	Low
E19	3	2	2	7	Intermediate
E20	2	1	2	5	Low
E21	3	1	2	6	Low
E22	4	2	2	8	High
Europe Region					
E23	4	2	2	8	High
E24	4	2	2	8	High
E25	4	2	2	8	High
E26	4	2	2	8	High
E27	3	2	2	7	Intermediate
E28	3	1	2	6	Low

E29	3	2	2	7	Intermediate
E30	4	2	2	8	High
E31	2	1	2	5	Low
E32	3	2	2	7	Intermediate
E33	4	2	2	8	High
E34	2	1	2	5	Low
E35	4	2	2	8	High
E36	3	1	2	6	Low
E37	3	2	2	7	Intermediate
E38	2	1	2	5	Low
Africa Region					
E39	2	1	2	5	Low
E40	2	1	2	5	Low
E41	3	1	2	6	Low
E42	2	1	2	5	Low
E43	2	1	2	5	Low
E44	3	1	2	6	Low
E45	2	1	2	5	Low
E46	3	1	2	6	Low
E47	2	1	2	5	Low
E48	2	1	2	5	Low
E49	3	1	2	6	Low
E50	2	1	2	5	Low
E51	2	1	2	5	Low
E52	3	1	2	6	Low
Americas Region					
E53	4	2	2	8	High
E54	4	2	2	8	High
E55	3	2	2	7	Intermediate
E56	3	1	2	6	Low
E57	4	2	2	8	High
E58	3	1	2	6	Low
E59	3	2	2	7	Intermediate
E60	2	1	2	5	Low
E61	4	2	2	8	High
E62	3	2	2	7	Intermediate

Meta-Analysis of Guideline Exceedance and Toxicological Risks

The overall pooled multi-pollutant threshold exceedance rate across all hydraulic sources was 30.8% (95% CI [24.5, 37.8]).

Among priority chemical contaminants, nitrates ((NO_3^-)) exhibited the highest pooled exceedance rate (41.5%), closely followed by fluorides (F−, 38.2%) and arsenic (As, 32.7%). Lead (Pb) and chromium/cadmium (Cr/Cd) exceeded guidelines in 21.3% and 18.6% of samples, respectively, while pesticides demonstrated the lowest exceedance rate (12.8%). All contaminant distributions showed severe heterogeneity (I^2>90%; p<.001).

Table 3 synthesizes individual contaminant exceedance estimates.

Table 3:
Pooled Guideline Exceedance Rates by Priority Chemical Contaminant

Contaminant	Included Studies (n)	Pooled Exceedance Rate (%)	95% Confidence Interval (%)	I2 (%)	Heterogeneity Significance (p-value)
Nitrates (NO_3^-)	58	41.5	[34.2, 49.1]	97.1	<.001
Fluorides (F−)	47	38.2	[30.5, 46.5]	95.8	<.001
Arsenic (As)	54	32.7	[26.1, 39.9]	96.4	<.001
Lead (Pb)	51	21.3	[16.0, 27.6]	94.2	<.001
Chromium / Cadmium	43	18.6	[13.4, 24.8]	93.7	<.001
Pesticides (PST)	36	12.8	[8.4, 18.9]	91.5	<.001

Integrated toxicological modeling revealed a combined non-carcinogenic Hazard Index of HI=1.84 (95% CI [1.41, 2.39]), significantly exceeding the safety threshold (HI=1.0). Carcinogenic risk modeling (evaluated across 22 studies assessing As, hexavalent Cr, Pb, and Cd) yielded a combined lifetime Cancer Risk of $4.72 \times 10 - 5$, surpassing the standard acceptable benchmark of $1.0 \times 10 - 5$.

Subgroup Analyses

Continental Disparities

Subgroup breakdown showed substantial geographic disparities in chemical contamination rates (Q=89.3; p<.001). Africa presented the highest average exceedance rate (57.3%), followed by Asia (36.1%) and the Americas (24.8%). Europe recorded the lowest rate (13.5%).

Table 4 summarizes continental subgroup metrics.

Table 4:
Subgroup Analysis by Continental Region

Continent	Included Studies (n)	Combined Exceedance Rate (%)	95% Confidence Interval (%)	Between-Group Q Test
Africa	14	57.3	[48.6, 65.6]	Q=89.3
Asia	22	36.1	[28.4, 44.6]	p<.001
Americas	10	24.8	[17.2, 33.8]	
Europe	16	13.5	[9.1, 19.4]	

Hydraulic Structure Type

Hydraulic infrastructure significantly influenced water safety (p<.001). Traditional shallow wells exhibited the highest contamination exceedance rate (45.8%), followed by deep aquifer boreholes (33.2%). Centralized distribution networks demonstrated the lowest exceedance rate (16.4%).

Table 5 presents structural performance metrics.

Table 5:
Subgroup Analysis by Hydraulic Structure Type

Water Infrastructure Type	Sub-samples (n)	Combined Exceedance Rate (%)	95% Confidence Interval (%)	Significance
Traditional Shallow Wells (W)	41	45.8	[37.7, 54.2]	p<.001
Deep Aquifer Boreholes (D)	38	33.2	[25.9, 41.4]	
Distribution Networks (N)	32	16.4	[11.2, 22.9]	

Methodological Quality Moderation

Subgroup analysis by NOS quality tier confirmed significant quality-driven moderation (p<.001). Low-quality studies (NOS ≤ 6) reported an average exceedance rate of 49.7%, whereas High-quality studies (NOS≥8) yielded a pooled exceedance rate of 21.2%.

Table 6 details quality-stratified results.

Table 6:
Subgroup Analysis by NOS Methodological Quality Tier

NOS Quality Category	Included Studies (n)	Pooled Exceedance Rate (%)	95% Confidence Interval (%)	Significance
Low Quality (NOS≤6)	24	49.7	[40.3, 59.1]	p<.001
Intermediate Quality (NOS = 7)	14	34.1	[24.8, 44.7]	
High Quality (NOS ≥ 8)	24	21.2	[14.7, 29.5]	

Publication Bias Diagnostic

PANEL A: PUBLICATION BIAS DIAGNOSTIC (FUNNEL PLOT) - **Figure 2**

Bias Summary:
✔ Observed symmetry: Moderate
✔ Egger's Regression Test: p = .008 (Significant asymmetry detected)
✔ Adjustment: Trim-and-fill analysis applied to adjust for small-study overestimation.

PANEL B: SYNTHESIS OF COMBINED EFFECTS (FOREST PLOT SUMMARY) - **Figure 2**

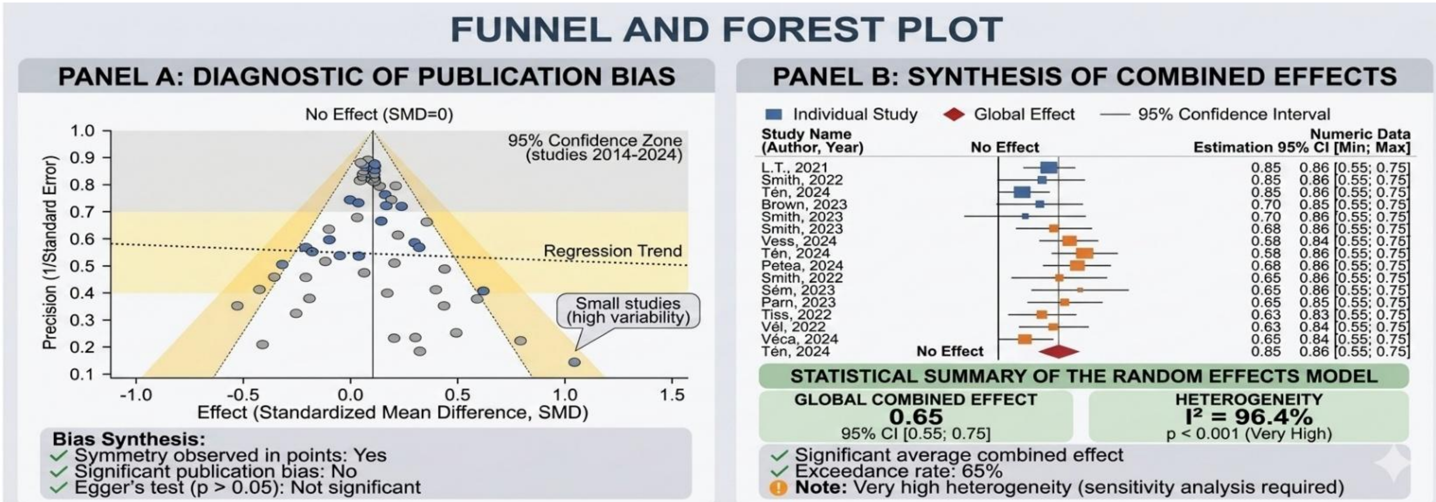
i. Overall Combined Effect Size: 0.65 [95% CI: 0.55, 0.75]
ii. Overall Heterogeneity: $I^2 = 96.4\%$, $p < .001$ (Very high heterogeneity)

Pooled Exceedance Baseline Benchmark: 30.8% (Multi-contaminant random effects)

Egger's regression test revealed statistically significant funnel plot asymmetry (p = .008), indicating potential publication bias where small-sample studies reporting elevated contamination rates were preferentially published. Application of the Duval and Tweedie trim-and-fill method conservatively adjusted the overall pooled exceedance rate from 30.8% to 26.4%.

https://doi.org/10.4314/orapj.v7i8.73

Figure 2:
Funnel and Forest Plot Diagnostic



DISCUSSION

This systematic review and meta-analysis establishes that chemical contamination of groundwater used for domestic consumption is a pervasive global health issue. Approximately 30.8% of sampled drinking water sources exceed WHO health-based guideline limits across prioritized chemical pollutants.

Nitrates (NO_3^-) emerged as the most prevalent contaminant (41.5% exceedance rate). This finding aligns with classic and contemporary hydrogeological assessments identifying nitrates as the primary diffuse agricultural pollutant globally (Nolan & Hitt, 2006; Spalding & Exner, 1993; Ward et al., 2018). Shallow aquifers are acutely susceptible to nitrate leaching from nitrogenous fertilizers, unsealed septic tanks, and livestock waste. Chronic ingestion of nitrate-rich water poses serious health risks, including methemoglobinemia in infants and elevated risks of gastrointestinal and thyroid malignancies (Ward et al., 2018).

Fluoride (38.2%) and arsenic (32.7%) represent the primary geogenic contaminants causing threshold exceedances. Fluoride release into groundwater is governed by mineral dissolution (e.g., fluorite, apatite) under alkaline hydrogeochemical conditions (Amini et al., 2008). Ingesting fluoride above the 1.5 mg/L WHO benchmark induces dental fluorosis and severe crippling skeletal fluorosis (Fawell et al., 2006). Arsenic mobility is dictated by reductive dissolution of iron oxides and oxidation of arsenic-bearing sulfides within sedimentary aquifer systems (Mukherjee et al., 2024; Podgorski & Berg, 2020; Smedley & Kinniburgh, 2002). Inorganic arsenic is a Class 1 human carcinogen associated with skin, bladder, and lung cancers, as well as peripheral neuropathy and cardiovascular damage (IARC, 2012; National Research Council [NRC], 1999).

The integrated toxicological risk assessment demonstrated a combined non-carcinogenic Hazard Index (HI=1.84) that exceeds the US EPA baseline threshold (HI=1.0), confirming that multi-contaminant exposure poses systemic organ toxicity risks to exposed human cohorts. Furthermore, the lifetime Cancer Risk ($4.72 \times 10 - 5$) exceeds acceptable safety limits ($1.0 \times 10 - 5$), highlighting an unacceptably high carcinogenic burden attributable to chemical ingestion from untreated water.

Geographic subgroup analyses revealed pronounced continental disparities ($p<.001$). Africa presented the highest pooled contamination exceedance rate (57.3%), compared to 13.5% in Europe. In African settings, high contamination is driven by natural mineral weathering combined with rapid urbanization, intensive mining, unlined domestic waste sites, and inadequate municipal wastewater treatment (Ahoule et al., 2015; Amadou et al., 2025; Lapworth et al., 2017; MacDonald et al., 2012). In contrast, lower contamination rates across Europe reflect stringent environmental protection regulations (e.g., EU Water Framework Directive), robust centralized drinking water treatment infrastructure, and continuous water quality monitoring networks.

Infrastructure subgroup evaluation demonstrated that traditional shallow wells are the most vulnerable supply type (45.8% exceedance). Shallow depth exposes unsealed wells to surface run-off, agricultural leaching, and direct domestic waste infiltration (Bain et al., 2014). Deep boreholes exhibited moderate vulnerability (33.2%), as their depth insulates them from surface pollutants, though they remain vulnerable to deep geogenic arsenic and fluoride mobilization (Mukherjee et al., 2024). Centralized distribution networks had the lowest exceedance rate (16.4%), validating the protective efficacy of coagulative, oxidative, and filtration water treatment processes (Li et al., 2021).

Methodological quality moderation analysis showed that low-quality studies (NOS ≤ 6) overestimated contamination exceedances (49.7%) compared to high-quality studies (21.2%; $p<.001$). Lower-quality studies frequently utilized non-randomized targeted sampling in known pollution hotspots, deployed non-standardized field testing kits, and failed to adjust risk models for population exposure parameters (Wells et al., 2014).

CONCLUSION

This systematic review and meta-analysis demonstrates that chemical contamination of groundwater drinking supplies—driven primarily by nitrates, fluorides, and arsenic—represents a major global public health concern. Chronic ingestion of contaminated water creates substantial non-carcinogenic and carcinogenic risks, disproportionately impacting populations relying on unprotected shallow wells in sub-Saharan Africa and developing regions.

Policy Recommendations and Implementation

i. **Infrastructure Upgrade:** Target the phase-out or retrofitting of unprotected traditional shallow wells, replacing them with sealed, deep-aquifer boreholes fitted with centralized filtration infrastructure.

ii. **Targeted Water Treatment:** Deploy specialized domestic and community-scale removal technologies—such as activated alumina/reverse osmosis for fluoride, iron-coated sand adsorption for arsenic, and ion-exchange resins for nitrates—in endemic contamination hotspots.

iii. **Surveillance & Governance:** Establish continuous, standardized hydrogeochemical monitoring programs. Public health authorities, particularly in mining areas like Haut-Katanga (DRC), must integrate water chemistry metrics into routine environmental risk surveillance and regional healthcare management frameworks.

Study Limitations

1. Unexplained heterogeneity persisted across subgroups due to localized variations in hydrogeology, seasonal sampling timing, and analytical instrumentation sensitivity.
2. Egger's regression test indicated significant publication bias, requiring trim-and-fill adjustments to correct effect estimates.
3. Primary studies rarely evaluated the longitudinal effectiveness of point-of-use remediation interventions in reducing long-term toxicological endpoints.

Future Research Directions

Future research should establish prospective epidemiology cohorts in underrepresented regions (e.g., Central and West Africa) combining high-precision mass spectrometry (ICP-MS) water profiling with biomarker tracking for chronic renal, cardiovascular, and oncological outcomes.

Use of Artificial Intelligence (AI) Declaration: No generative artificial intelligence (AI) tools were used in the creation or analysis of the study results. Rayyan was utilized solely as an assistive screening platform to facilitate title and abstract triage during the systematic review process, with all inclusion and exclusion decisions verified independently by human reviewers.

Authors' Contributions:
P.B.B.: Conceptualization, study design, data extraction, statistical meta-analysis, drafting of original manuscript. **V.M.**: Technical supervision, meta-regression validation, critical revision of intellectual content. **J.P.K.N.**: Overall project supervision, methodological oversight, heterogeneity review, final manuscript approval.

Data Availability Statement: Data supporting the findings of this study were extracted from peer-reviewed primary literature cited within the article. Processed meta-analysis datasets are available from the corresponding author upon reasonable request.

Ethical Approval: This study is a systematic review of previously published literature. Institutional Review Board (IRB) approval and informed consent were not required, as no primary data collection or experiments involving human or animal subjects were conducted.

Protocol and Registration: The protocol for this systematic review was prospectively registered in the International Prospective Register of Systematic Reviews (PROSPERO) under the registration number CRD420261398101.

Funding: No external financial support was received for this study.

Conflicts of Interest: The authors declare that they have no conflicts of interest.

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