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ORIGINAL RESEARCH ARTICLE

A retrospective assessment of rural drinking water quality and influencing factors in Weifang City, China

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Abstract

Access to safe drinking water remains a critical, yet unmet, public health priority in rural China. Weifang City, a major agricultural region, exemplifies this challenge, but evidence to guide targeted, context-specific interventions is lacking. We conducted a mixed-methods explanatory study in Weifang City from August 2024 to May 2025. A repeated cross-sectional survey of all 724 rural water supply projects was performed, involving 1,452 water samples collected quarterly from factory outlets and end-user taps. Water quality compliance was assessed against China's national standard (GB 5749-2022). The overall water quality compliance rate was 81.47%. However, an estimated 560,300 rural residents (10.82% of the population served) were exposed to non-compliant water. Microbial contamination was the predominant failure mode (68.77% of non-compliant samples), followed by nitrate pollution (29.00%). Multivariable analysis identified the use of shallow well water as the factor most strongly associated with non-compliance (adjusted odds ratio [AOR] = 31.02; 95% confidence interval [CI]: 14.95–64.36), followed by absence of water treatment (AOR = 16.46; 95% CI: 6.55–41.36). Decentralized systems exhibited the highest failure rates, a risk fully mediated by poor source quality and lack of treatment. Centralized systems showed significant water quality deterioration between treatment plants and taps (93.40% vs. 79.44%), indicating pervasive secondary contamination. Rural drinking water safety in Weifang is compromised through two distinct, modifiable pathways: source and treatment deficiencies in decentralized systems, and secondary contamination in centralized distribution networks. This evidence provides a novel, mixed-methods, risk-based roadmap for transitioning from infrastructure coverage to equitable, sustainable, safe water access.

Keywords: Drinking water safety; Rural health; Water quality; Risk factors; China; Mixed-methods

1. Introduction

Access to safe drinking water is a fundamental human right and a critical determinant of public health and socio-economic development.[1] Globally, contaminated water remains a primary vehicle for transmitting waterborne diseases such as cholera, dysentery, and typhoid, imposing a substantial health burden, particularly in resource-limited settings. Although China has achieved near-universal access to improved water sources, significant

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disparities in drinking water safety persist between urban and rural areas.[2,3] Studies in other regions of China have similarly documented this urban–rural divide, including recent analyses from peri-urban areas in northern China.[4,5] Rural regions often face systemic challenges, including ageing infrastructure, limited financing, and fragmented monitoring systems, which undermine the sustainability of water safety improvements.

The Huang-Huai region, including Shandong Province, is an economically vital and densely populated area where rural water security challenges are pronounced. Weifang City, a major prefecture within this region, exemplifies these ongoing concerns. Despite local initiatives to enhance rural drinking water safety, operational constraints—such as geographical barriers, funding shortages, and institutional gaps—often result in inadequate surveillance coverage and delayed responses to contamination events.[6] Consequently, persistent issues like source water pollution, deteriorating pipe networks, and insufficient treatment continue to threaten community health and impede sustainable local development.

Existing literature consistently highlights the systemic nature of rural drinking water insecurity in China. National studies report suboptimal compliance with water quality standards, with microbial contamination—especially total coliforms—being a prevalent issue strongly associated with decentralized and untreated water sources.[7-9] This challenge is particularly pronounced in rural areas of developing countries,[10,11] where groundwater nitrate pollution has become a growing concern worldwide.[12,13] Studies in the North China Plain have similarly documented groundwater quality challenges in rural areas.[14] Research specific to Weifang further indicates that local water quality is shaped by a complex interaction of natural, economic, and social determinants.[6] Broader analyses identify recurring structural barriers, including regulatory supervision deficits, outdated infrastructure, and pollution from diffuse sources such as scattered domestic sewage.[3,15,16] Recent reviews of rural drinking water quality testing have further highlighted these systemic challenges.[17] Theoretical frameworks such as the socio-ecological model appropriately conceptualize drinking water safety as an outcome shaped by interconnected environmental, social, and infrastructural factors.[2]

Internationally, a range of analytical frameworks has been developed to assess drinking water quality and identify contamination sources. The water quality index method, which aggregates multiple physicochemical parameters into a single score, has been widely adopted for integrated water quality assessment.[18] For source apportionment, multivariate statistical techniques—including principal component analysis, factor analysis, and cluster analysis—have been applied to distinguish between natural and anthropogenic pollution sources.[19] Geospatial modeling approaches, such as geographic information system-based risk mapping and spatial interpolation, enable the visualization of contamination hotspots and vulnerability assessment at regional scales. For health risk evaluation, the hazard quotient and carcinogenic risk assessment models recommended by the United States Environmental Protection Agency provide standardized frameworks for quantifying human health risks from chemical contaminants in drinking water.[20] More recently, machine learning algorithms—including random forest, support vector machines, gradient boosting, and artificial neural networks—have emerged as powerful tools for predicting water quality compliance and identifying key drivers, often outperforming traditional statistical methods in handling non-linear relationships and complex interactions among water quality parameters.[21,22] However, the application of these advanced methods has been largely concentrated in high-income or urban settings, with limited adoption in rural, resource-constrained contexts such as rural China.[23-25] Recent studies have demonstrated the potential of machine learning approaches for water quality prediction,[26,27] yet their application in rural water systems remains sparse.

A critical translational gap remains between this generalized understanding and the context-specific, actionable evidence needed for effective local policymaking in Weifang. While prior studies have described common problem categories and influencing factors, there is a distinct lack of localized, quantitative evidence that measures the relative contribution of these factors within Weifang and, crucially, translates such diagnostics into prioritized, feasible intervention strategies.[11,12] This gap limits the precision of local decision-making and constrains the effective allocation of resources.

To address this gap, this study aims to:

(i) Assess the current status of rural drinking water quality in Weifang City;
(ii) Identify and analyze the key factors influencing drinking water quality in rural areas of Weifang;
(iii) Explore and propose strategies to improve rural drinking water quality in the region.

This study advances existing knowledge in three specific ways. First, while previous studies in Weifang have described general water quality problems, none have quantitatively estimated the population-level exposure burden (560,300 residents) or identified the distinct risk pathways for centralized versus decentralized systems using multivariable adjustment. Second, this study integrates quantitative risk-factor analysis with qualitative stakeholder perspectives—a mixed-methods approach rarely applied in rural water quality research in China—revealing not only what fails but also why and for whom. Third, by demonstrating that the elevated risk of decentralized systems is fully mediated by source quality and treatment status (rather than system scale), this study provides a targeted, evidence-based intervention framework that shifts policy focus from infrastructure coverage to modifiable risk factors. These contributions move beyond descriptive assessment toward actionable, context-specific guidance for rural water safety governance.

By pursuing these objectives, this study seeks to generate robust, localized targeted interventions, strengthen strategic planning, and support effective governance, thereby contributing to the protection of public health and the promotion of sustainable rural development in Weifang.

2. Methods

2.1. Study design and setting

We conducted a mixed-methods explanatory sequential study in Weifang City, Shandong Province, China, from August 2024 (Q3) to May 2025 (Q2). The quantitative component comprised a repeated cross-sectional survey with quarterly water quality sampling. The qualitative component involved focus group discussions (FGDs) held after the quantitative data analysis to contextualize and elucidate the statistical findings. The study encompassed all 13 county-level administrative divisions and targeted all operational, government-led rural drinking water safety projects. In China, "rural drinking water safety projects" (hereafter referred to as "water safety projects") is an official term denoting government-funded or -supervised infrastructure constructed specifically for drinking water treatment and supply in rural areas. These projects vary widely in scale, treatment capacity, and management model. The primary objective of this study is to assess whether these projects, as implemented, actually deliver drinking water that meets national safety standards (GB 5749-2022) and to identify project- and system-level factors associated with non-compliance. Therefore, the water safety project serves as the main unit of analysis throughout this investigation.

2.2. Study area description

Weifang City (35°41'–37°26' N, 118°10'–120°01' E) is located in the central-northern part of Shandong Province, covering an area of approximately 15,859 km^2. The terrain gradually slopes downward from south to north, encompassing mountainous, hilly, and plain areas. According to the chorography of Weifang, the city consists of three major geomorphological zones: the southern low mountain and hilly area (approximately 6,676 km^2, 42.1% of the total area), the central alluvial and diluvial plain (6,551 km^2, 41.3%), and the northern coastal lowland (approximately 2,632 km^2, 16.6%). The central plain was formed by sediment deposition from major rivers, including the Weihe, Mihe, Bailanghe, and Jiaolaihe Rivers. These plains are characterized by thick soil layers, shallow groundwater tables, and high fertility, making them the primary agricultural and population concentration zones (Figure 1). The southern region is underlain by carbonate and clastic rocks with relatively low groundwater abundance, while the northern plain consists of Quaternary alluvial deposits where groundwater is more abundant but vulnerable to surface contamination.

Hydrogeologically, the northern part of Weifang has experienced a significant decline in groundwater level due to long-term over-extraction, forming a large groundwater depression cone (funnel area). This depression cone not only increases the risk of land subsidence and seawater intrusion but also accelerates the downward transport of surface contaminants into the shallow aquifer system. Consequently, shallow wells in these areas are particularly susceptible to nitrate and microbial contamination from agricultural and domestic sources. This hydrogeological setting provides critical context for interpreting the extremely high risk associated with shallow well water sources identified in our quantitative analysis (adjusted odds ratio [AOR] = 31.02; 95% confidence interval [CI]: 14.95–64.36).

Agriculture is the dominant land use in Weifang, with extensive cultivation of wheat, corn, and vegetables. The city has actively promoted soil-testing-based fertilization and water-saving irrigation technologies in recent years. According to available data, total chemical fertilizer application in the region has decreased compared to previous years, while the comprehensive utilization rate of crop straw exceeds 96%. Despite these reductions, the historical overuse of nitrogen (N) fertilizers has led to legacy nitrate accumulation in soils and shallow groundwater. These agricultural practices, particularly the intensive application of nitrogenous fertilizers, are the primary drivers of elevated nitrate concentrations in rural drinking water sources, as observed in this study (nitrate exceeding the standard in 29.00% of non-compliant samples, with concentrations up to 38.3 mg/L).[28-30]

Industrial activities in Weifang are concentrated in the eastern and northern zones, including chemical manufacturing, metal processing (particularly aluminum processing in Linqu County), textile production, and machinery manufacturing. While heavy metal contamination was not a predominant issue in the current study (detection rates were low for most toxic metals), the presence of these industrial activities underscores the need for ongoing monitoring of emerging chemical contaminants.

These geological, agricultural, and industrial characteristics provide essential context for interpreting the contamination patterns observed in this study. The high vulnerability of shallow groundwater documented in the hydrogeological setting directly explains the elevated risk associated with shallow wells (AOR = 31.02). The intensive agricultural activities, along with historical fertilizer overuse, account for the prevalence of nitrate contamination (29.00% of non-compliant samples). Together, this contextual information supports the development of targeted, source-specific interventions to improve rural drinking water safety in Weifang.

2.3. Study population and sampling

The sampling frame included all 724 documented rural drinking water safety projects in Weifang. To ensure representativeness, a two-stage stratified random sampling strategy was employed:

(i) First stage (stratification): Projects were stratified by administrative district (13 strata) and project type. Project types include: (i) urban network extension, (ii) large-scale centralized water supply, (iii) joint-village (small centralized) supply, and (iv) single-village (decentralized) supply.
(ii) Second stage (point selection): From each stratum, a predefined number of factory outlet sampling (FOS) points (water collected post-treatment) and terminal water sampling (TWS) points (water from end-user taps) were randomly selected each quarter. This yielded 363 sampling points per quarterly round (53 factory outlets and 310 household taps), aggregating to 1,452 water samples for the entire study period. This sample size provided the basis for all subsequent water quality analyses presented in Section 3.

Importantly, the sampling locations were not fixed across quarters. Instead, each quarterly round employed a new independent random selection of FOS and TWS points from each stratum, stratified by project type and administrative district. This repeated cross-sectional design ensured that the quarterly samples were representative of the entire project population at each time point, rather than tracking a fixed cohort of projects. The total of 1,452 samples (363 points × 4 quarters) thus represents a cumulative characterization of water quality across all 724 projects over the study period, with each project having a selection probability proportional to its population served.

To verify representativeness, we compared the distribution of project types in the full sampling frame (n = 724 projects) with that in the aggregated quarterly samples (n = 1,452 samples). The proportions were consistent across all four project types, with deviations less than 3% for each category (urban extension: 2.6% in frame vs. 2.7% in sample; large-scale: 6.9% vs. 7.1%; joint-village: 2.6% vs. 2.5%; single-village: 87.9% vs. 87.7%), indicating that the quarterly sampling strategy adequately represented the full project population.

The sampling strategy and rationale for point allocation are summarized in Table 1. A detailed geographical

Figure 1. Location of Weifang City in Shandong Province, China. The map shows the geographical position of Weifang City within Shandong Province (inset: China) and the administrative boundaries of its 13 county-level divisions. The base layer is derived from Esri World Imagery.

distribution of sampling points is provided in Table S1.

2.4. Water sampling and infrastructure survey

Water collection, preservation, and transportation strictly adhered to China's national standard methods (GB/T 5750-2022). At each FOS and TWS point, field personnel recorded Global Position System coordinates, ambient temperature, and humidity. For microbial analysis, samples were collected aseptically using sterile containers after disinfecting the tap with 75% ethanol. Concurrently, a structured questionnaire was administered to project managers via face-to-face interview and direct observation. This instrument captured data on:

- Project characteristics: Type, design capacity, population served.
- Water source and treatment: Primary source (e.g., reservoir, deep well), presence and type of treatment processes (coagulation, filtration, disinfection), and specific disinfectants used (e.g., chlorine dioxide [ClO_2], sodium hypochlorite).
- Infrastructure: Age and material of distribution pipelines, general sanitary condition within 30 m of the source.

These data constituted the exposure variables analyzed in relation to water quality outcomes.

2.5. Quality assurance and control

Rigorous quality assurance/quality control protocols were implemented, including the collection of field duplicate samples from > 10% of sampling points, preparation of field and transport blanks, and routine analysis of certified reference materials (CRMs) and matrix spike samples with each analytical batch to ensure accuracy and precision.

2.6. Focus group discussions

One FGD was conducted with eight purposively selected participants from areas where water quality testing had indicated non-compliance with national standards. Participants represented four stakeholder groups: rural residents ($n = 3$), village committee members ($n = 2$), water utility operators ($n = 2$), and local public health officials ($n = 1$). The selection criteria were: (i) residence or work in a village with documented water quality non-compliance based on quantitative sampling results from the first two quarters of the study period (Q3 and Q4 2024), (ii) ability to provide informed perspectives on daily water use, operational challenges, or health concerns, and (iii) willingness to participate and provide written informed consent.

A semi-structured discussion guide was used to explore: (i) daily water use experiences and perceptions of water quality, (ii) observed changes in water quality over time, (iii) health concerns attributed to drinking water, (iv) coping strategies and household adaptations, (v) perceived causes of water quality problems, and (vi) suggestions for system improvement. The session lasted approximately 90 minutes, was audio-recorded, transcribed verbatim, and anonymized.

Thematic saturation was assessed during analysis using the method of thematic recurrence. After transcribing and coding the discussion, no new themes emerged after the sixth participant, indicating that the key domains of

Table 1. Quarterly sampling point allocation by project type

Project type	Factory outlet sampling (FOS)	Terminal water sampling (TWS)	Total points per quarter	Allocation rationale
Urban extension	14	65	79	≥1 FOS per district; proportional to population
Large-scale centralized	28	120	148	Proportional to population and source diversity
Joint-village	11	20	31	~1 TWS per 1,000 residents
Single-village	0	105	105	Stratified random sample of villages (no central treatment)
Total	53	310	363	—

Notes: Sampling points were randomly reselected each quarter; points were not fixed across rounds.

concern were captured within this sample. However, given the exploratory nature of this qualitative component—designed to contextualize and enrich the quantitative findings rather than to serve as a stand-alone qualitative study—we acknowledged that a single FGD cannot achieve full theoretical saturation. The findings are therefore presented as complementary contextual insights, not as exhaustive qualitative evidence.

2.7. Laboratory analysis

All water samples were analyzed at an accredited laboratory (e.g., Weifang Municipal Center for Disease Control and Prevention). Analysis followed the Standard Examination Methods for Drinking Water (GB/T 5750-2022). Parameters tested were selected based on the Sanitary Standards for Drinking Water (GB 5749-2022) and included:

- Microbiological indicators: Total coliforms, *Escherichia coli*, heterotrophic plate count.
- Chemical and toxicological indicators: Nitrate (as N), fluoride, arsenic (As), lead (Pb), mercury (Hg), cadmium (Cd), hexavalent chromium, trihalomethanes, haloacetic acids, chlorite, chlorate.
- Physical indicators and disinfectant residuals: Turbidity, pH, free chlorine, and ClO_2.

This comprehensive analytical profile generated the dataset for descriptive statistics and compliance determination.

Analytical procedures followed the specific method codes within GB/T 5750-2022 series. Total coliforms and *E. coli* were analyzed using the enzyme–substrate method (Quanti-Tray/2000, IDEXX, USA). Nitrate, fluoride, chloride, and sulfate were determined using ion chromatography (Dionex ICS-6000, Thermo Fisher, USA). Heavy metals (As, Cd, Pb, Hg) were measured using inductively coupled plasma-mass spectrometry (ICP-MS 7900, Agilent, USA). Free chlorine and ClO_2 residuals were measured on-site using a portable colorimeter (DR900, HACH, USA). Turbidity was measured using a portable turbidimeter (2100Q, HACH, USA), and pH was measured using a calibrated pH meter (SX751, Sanxin, China). For all chemical analyses, calibration curves were prepared with $R^2 \geq 0.999$. Detection limits for each parameter are provided in Table S2. Values below the detection limit were replaced with half of the detection limit for statistical analysis. Quality control included analysis of CRMs from the National Institute of Metrology, China, and matrix spike recoveries ranging from 90% to 110%. Field duplicates (10% of samples) and field blanks were analyzed to assess precision and contamination.

2.8. Study variables

The primary outcome of this study (water quality compliance) is a binary variable. A sample was classified as "non-compliant" if the measured concentration of any parameter exceeded its respective maximum allowable limit (MAL) as per GB 5749-2022.

The independent variables categorized in this study for analysis included:

(i) Project type: urban extension, large-scale, joint-village, single-village.
(ii) Water source: reservoir, deep well, shallow well, spring.
(iii) Treatment status: fully treated (included disinfection), no treatment.
(iv) Disinfectant used: high-purity ClO_2, compound ClO_2, sodium hypochlorite, none.
(v) Sampling point: factory outlet, end-user tap.

2.9. Quantitative statistical analysis

Data were analyzed using Statistical Package for Social Sciences (SPSS 26.0, IBM, United States). Descriptive statistics (means, medians, interquartile ranges) summarized the concentrations of water quality indicators. Univariate analyses assessed the association between each exposure variable and water quality compliance using Pearson's χ^2 test (or Fisher's exact test for small cell counts). All exposure variables showing significant associations in univariate analysis ($p < 0.001$) were eligible for inclusion in the multiple models. A multiple logistic regression model was constructed using forward stepwise selection (entry criterion: $p < 0.05$; removal criterion: $p \geq 0.05$) to identify independent predictors of non-compliance, adjusting for sampling quarter as a potential temporal confounder. Results are presented as AORs with 95% CIs. Model fit was evaluated using the Hosmer–Lemeshow goodness-of-fit test.

Variable selection for the multivariable model was based on three criteria: (i) statistical significance in univariate analysis ($p < 0.001$), (ii) clinical and epidemiological relevance based on prior literature on rural drinking water quality, and (iii) absence of strong multicollinearity with other candidate variables. Multicollinearity among independent variables was assessed using the variance inflation factor (VIF); variables with VIF > 5 were considered collinear and were not entered simultaneously. The highest VIF observed among retained variables was 4.396 (for project type and treatment status), indicating no significant collinearity. Model performance was evaluated using multiple metrics. The Hosmer–Lemeshow goodness-of-fit test yielded $\chi^2 = 11.793$ ($p = 0.161$), indicating adequate model calibration. The area under the receiver operating characteristic curve was 0.840 (95% CI: 0.813–0.866), indicating good discriminative ability. The Nagelkerke pseudo-R^2 was 0.367.

2.10. Qualitative data analysis

Transcripts from FGD were analyzed using inductive thematic analysis following the framework by Braun and Clarke.[31] Two researchers independently performed open coding, grouped codes into potential themes, reviewed and refined themes, and defined the final thematic framework. Consensus was reached through discussion. The resulting themes are presented to provide contextual depth to the quantitative results.

2.11. Ethical considerations

The study protocol was reviewed and approved by the Institutional Review Board of Medical Research Ethics Committee, Universiti Malaysia Sarawak (Approval Number: ME/26/63). Written informed consent was obtained from all FGD participants prior to the discussion. The collection of water samples and infrastructure data did not involve interaction with individual household residents or the collection of personally identifiable information, thereby minimizing risk and ensuring participant anonymity.

3. Results

3.1. Study population and project characteristics

A total of 724 rural drinking water safety projects in Weifang City were included in this study. These projects served 5.18 million residents across 7,436 villages, representing 56.59% of the city's total rural population. The distribution of project types and their service coverage was highly heterogeneous. While single-village supply projects constituted the vast majority in number (636 projects, 87.85%), they served the smallest population (366,500 people, 7.08%). In contrast, large-scale water supply projects, though few in number (50 projects, 6.91%), served the largest population segment (3.45 million people, 66.69%), making them the predominant model for rural water supply in the region. Urban extension projects and joint-village supply projects each accounted for 19 projects (2.62%), serving 1.32 million (25.40%) and 43,000 people (0.83%), respectively. The detailed distribution is presented in Table 2.

3.2. Water source, treatment process, and disinfection status

Deep well water was the most common source (585 projects, 80.80%). However, projects drawing from reservoirs, though fewer (35 projects, 4.83%), served the largest absolute population (3.32 million, 64.02%), highlighting their critical role in large-scale centralized supply.

A stark disparity existed between centralized and decentralized systems. Full treatment (including coagulation, sedimentation, filtration, and disinfection) was nearly universal in urban extension and large-scale projects. In contrast, its application was severely limited in decentralized systems. Critically, 73.68% of joint-village and 98.11% of single-village projects operated without any disinfection equipment. Consequently, 88.12% of all surveyed projects (638/724) used no disinfectant. The comprehensive profile is shown in Table 3.

3.3. Overall water quality compliance and seasonal trend

A total of 1,452 water samples were collected and analyzed quarterly. The overall compliance rate with the Sanitary Standards for Drinking Water (GB 5749-2022) was 81.47% (1,183/1,452). A statistically significant improving trend in compliance was observed over time (χ^2 = 14.578, p = 0.002). The compliance rate increased from 75.48% (274/363) in the third quarter of 2024 (August) to 85.67% (311/363) in the second quarter of 2025 (May) (Figure 2A). The comprehensive profile is shown in Table 4.

3.4. Characteristics of water quality indicators

The concentrations of all 38 tested indicators for the 1,452 samples are summarized in Table 5. Twelve indicators (31.58%) were detected above their respective regulatory limits in at least one sample. Key observations include:

- Microbial indicators: The median total bacterial count was 15 colony-forming units (CFUs)/mL (interquartile range [IQR]: 0–76), with a maximum of 5,100 CFU/mL. Total coliforms and *E. coli* were predominantly not detected (median: 0 most probable number/100 mL).
- Nitrate: Concentrations ranged up to 38.3 mg/L (median: 4.7 mg/L), exceeding the standard limit for centralized supply (10 mg/L) in some samples.
- Disinfection byproducts and residuals: Trihalomethane levels were low (median: 0.02 μg/L). However, median residual levels for free chlorine (0.10 mg/L) and ClO_2 (0.05 mg/L) were often exceed the recommended minimum residual concentrations.

For brevity, Table 5 presents only the core indicators. The complete table with all 38 indicators is provided in Table S2.

Table 2. Distribution of rural drinking water safety projects and service coverage in Weifang City

Project type	Number of projects, *n* (%)	Villages covered, *n* (%)	Population served (10,000), *n* (%)
Urban extension	19 (2.62)	1767 (23.76)	131.55 (25.40)
Large-scale centralized	50 (6.91)	4,980 (66.97)	345.45 (66.69)
Joint-village	19 (2.62)	53 (0.71)	4.30 (0.83)
Single-village	636 (87.85)	636 (8.55)	36.65 (7.08)
Total	724 (100.00)	7,436 (100.00)	517.95 (100.00)

Note: Percentages may not sum to 100% due to rounding.

Table 3. Characteristics of Water Supply Projects by Type

Category	Urban extension (*n* = 19)	Large-scale (*n* = 50)	Joint-village (*n* = 19)	Single-village (*n* = 636)	Total *n* (%)
Water source					
Reservoir	12	23	0	0	35 (4.83)
Deep well	7	24	17	537	585 (80.80)
Shallow well	0	3	2	50	55 (7.60)
Spring	0	0	0	49	49 (6.77)
Treatment status					
Fully treated	19	50	5	12	86 (11.88)
No treatment	0	0	14	624	638 (88.12)
Disinfectant used					
Sodium hypochlorite	1	3	0	0	4 (0.55)
Compound ClO_2	11	31	0	3	45 (6.22)
High-purity ClO_2	7	16	5	9	37 (5.11)
None	0	0	14	624	638 (88.12)

Note: Values are presented as *n* (%), where *n* represents the number of projects.
Abbreviation: ClO_2: Chlorine dioxide.

Table 4. Sampling quarter between investigated factors and water quality compliance (*n* = 1,452 samples)

Factor	Category	Samples tested (*n*)	Compliant samples, *n* (%)	χ^2	*p*-value
Sampling quarter	Q3-24 (August, summer)	363	274 (75.48)	14.578	0.002
	Q4-24 (November, autumn)	363	293 (80.72)		
	Q1-25 (February, winter)	363	305 (84.02)		
	Q2-25 (May, spring)	363	311 (85.67)		

Notes: Q3-24: Third quarter of 2024 (August, summer); Q4-24: Fourth quarter of 2024 (November, autumn); Q1-25: First quarter of 2025 (February, winter); Q2-25: Second quarter of 2025 (May, spring); *p*-values were calculated using Pearson's χ^2 test.

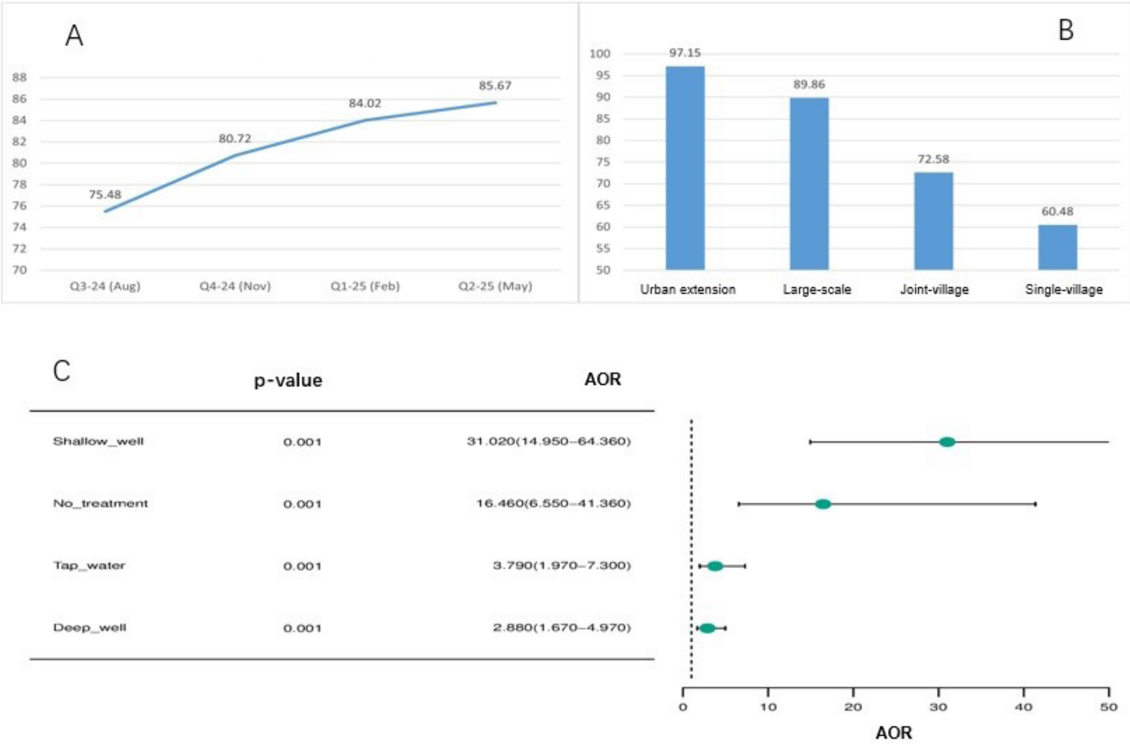

Figure 2. Key analytical results. (A) Quarterly water quality compliance trend from Q3-2024 to Q2-2025. (B) Compliance rates by project type. (C) Forest plot of adjusted odds ratios (AORs) for factors independently associated with non-compliance. Error bars represent 95% confidence intervals.
Abbreviation: HR: Hazard ratio.

Table 5. Summary of key water quality indicators (*n* = 1452)

Indicator	Detection range	Median (P25, P75)	Standard limit
Microbial indicators			
Total bacterial count (CFU/mL)	0–5,100	15 (0, 76)	≤100 (C); ≤500 (D)
Total coliforms (MPN/100 mL)	0–540	0 (0, 0)	0
E. coli (MPN/100 mL)	0–23	0 (0, 0)	0
Chemical indicators			
Nitrate (as nitrogen, mg/L)	0–38.30	4.7 (2.5, 8.5)	≤10 (C); ≤20 (D)
Turbidity (NTU)	0–3.72	0.1 (0.00, 0.23)	≤1 (D); ≤3 (C)
Free chlorine (mg/L)*	0–0.83	0.10 (0.04, 0.13)	≥0.05–0.3 (C); not routinely applicable (D)
Chlorine dioxide (mg/L)*	0–0.67	0.05 (0.02, 0.08)	≥0.02–0.1; not routinely applicable (D)

Notes: C: Centralized supply; D: Decentralized supply; Residual disinfectant standards are lower limits (≥).
Abbreviations: CFU: Colony-forming unit; MPN: Most probable number; NTU: Nephelometric turbidity unit.

3.5. Univariate analysis of factors associated with water quality

All investigated factors showed statistically significant associations with water quality compliance (Pearson's χ^2 test, $p < 0.001$ for all). Compliance was highest for urban extension projects (97.15%) and lowest for single-village projects (60.48%) (Figure 2B). Reservoir-sourced water showed the highest compliance (95.70%), while shallow well water had the lowest (35.87%). The absence of treatment or disinfection was strongly associated with failure. A significant decline in compliance was observed between factory outlets (93.40%) and end-user taps (79.44%). The complete results of the univariate analysis are presented in Table 6.

3.6. Analysis of non-compliant water samples

Analysis of the 269 non-compliant samples (18.53% of total) revealed that microbial contamination was the predominant issue: total bacterial count (68.77% of non-compliant samples), total coliforms (37.92%), and *E. coli* (26.39%) were the most frequent causes of failure. Nitrate was the primary inorganic contaminant (29.00%). Other notable causes included insufficient disinfectant residuals, elevated total hardness, ammonia, turbidity, and manganese. The characteristics of these non-compliant samples are detailed in Table 7.

The normal range in Table 7 is determined in accordance with the Standards for Drinking Water Quality (GB 5749-

Table 6. Univariate associations between investigated factors and water quality compliance (*n* = 1,452 samples)

Factor	Category	Samples tested, *n*	Compliant samples, *n* (%)	χ^2	*p*-value
Project type	Urban extension	316	307 (97.15)	208.256	<0.001
	Large-scale	592	532 (89.86)		
	Joint-village	124	90 (72.58)		
	Single-village	420	254 (60.48)		
Water source	Reservoir	628	601 (95.70)	246.801	<0.001
	Deep well	676	518 (76.63)		
	Shallow well	92	33 (35.87)		
	Spring	56	31 (55.36)		
Treatment status	Fully treated	991	904 (91.22)	234.785	<0.001
	No treatment	461	270 (58.57)		
Disinfectant used	High-purity ClO_2	488	458 (93.85)	275.807	<0.001
	Compound ClO_2	440	399 (90.68)		
	Sodium hypochlorite	63	56 (88.89)		
	None	461	270 (58.57)		
Sample type	Factory outlet	212	198 (93.40)	23.378	<0.001
	Tap water	1240	985 (79.44)		
Sampling quarter	Q3-24 (Aug)	363	274 (75.48)	14.578	0.002
	Q4-24 (Nov)	363	293 (80.72)		
	Q1-25 (Feb)	363	305 (84.02)		
	Q2-25 (May)	363	311 (85.67)		

Notes: χ^2 values were calculated from Pearson's χ^2 test; *p*-values < 0.001 indicate statistical significance.
Abbreviation: ClO_2: Chlorine dioxide.

Table 7. Exceedance of indicators in unsafe water samples (unsafe water samples *n* = 269)

Exceeded indicator	Exceedance frequency, *n* (%)	Normal range	Exceedance range	Median (P25, P75)
Total plate count (CFU/mL)	185 (68.77)	≤100 CFU/mL	113–5,100	599 (346,749)
Total coliforms (MPN/100 mL)	102 (37.92)	Not detectable	4–540	24 (15, 43)
Nitrate (as nitrogen, mg/L)	78 (29.00)	≤10 mg/L	10.1–38.3	22.6 (16.0, 26.7)
Escherichia coli (MPN/100 mL)	71 (26.39)	Not detectable	1.1–23.0	3.6 (2.2, 5.9)
Chlorine dioxide (mg/L)	51 (18.96)	0.1–0.8 mg/L (treated water)	0.01–0.67	0.06 (0.03,0.13)
Free chlorine (mg/L)	30 (11.15)	Residual ≥ 0.05 mg/L and ≤2 mg/L (tap water)	0.01–0.31	0.12 (0.06,0.23)
Total hardness (as calcium carbonate, mg/L)	39 (14.50)	≤450 mg/L	458.3–628.6	477 (464, 496)
Ammonia (as nitrogen, mg/L)	24 (8.92)	≤0.5 mg/L	0.53–1.21	0.67 (0.59, 0.81)
Turbidity (NTU)	21 (7.81)	≤1 NTU	1.14–3.72	1.54 (1.29, 1.70)
Manganese (mg/L)	16 (5.95)	≤0.1 mg/L	0.11–0.18	0.15 (0.14, 0.16)

Notes: M(P25, P75) represents the median and the 25th and 75th percentiles, with the same units as the normal range column; The number of decimal places for each indicator is retained according to laboratory testing precision and the characteristics of the indicator.
Abbreviations: CFU: Colony-forming unit; MPN: Most probable number; NTU: Nephelometric turbidity unit.

2022). The exceedance range refers to the range of measured values from all monitoring sites (or samples) classified as non-compliant. Since the same site may be tested multiple times at different time points, the exceedance range may include values that meet the standard. For disinfectant indicators, ClO_2 applies to treated water, and free chlorine applies to tap water. The normal range has both lower and upper limits. Exceedance includes values below the minimum requirement (insufficient disinfection) and values above the maximum limit. The exceedance data in Table 7 primarily represent values below the minimum requirement. Exceedance frequency, *n* (%), refers to the number and proportion of water samples in which a specific indicator exceeded the national standard, relative to the total number of unsafe water samples (*n* = 269). Since a single water sample may have multiple indicators exceeding the standards, the sum of exceedance frequencies across all indicators exceeds 269.

3.7. Population exposure to unsafe drinking water

By extrapolating the endpoint (tap water) compliance rates to the served populations, we estimated that approximately 560,300 rural residents (10.82% of the total population served) were exposed to drinking water that did not meet safety standards. Risk profiles varied drastically across project types. Single-village projects exhibited the highest exposure rate (45.81%), meaning nearly half of their users received non-compliant water. However, due to their large service base, large-scale projects contributed the largest absolute number of affected individuals (an estimated 337,200 people). Detailed estimations are shown in Table 8.

3.8. Multivariate logistic regression analysis

Multivariable logistic regression was performed to identify factors independently associated with non-compliance.

Table 8. Estimated population exposure to unsafe drinking water

Project type	Population at sampling points (10,000)	Unsafe population at sampling points (10,000)	Failure rate at points (%)	Total served population (10,000)	Estimated total unsafe population (10,000)
Urban extension	15.07	0.48	3.19	131.55	4.19
Large-scale	23.36	2.28	9.76	345.45	33.72
Joint-village	11.59	3.60	31.06	4.30	1.34
Single-village	33.51	15.35	45.81	36.65	16.79
Total	83.53	21.71	25.99	517.95	56.03

Notes: Population at sampling points: Population served by the sampled projects; Failure rate: Proportion of non-compliant tap water samples from the sampled projects; Unsafe population at sampling points: Population at sampling points × failure rate; Total served population: Total population served by all projects of each type; Estimated total unsafe population: Total served population × failure rate.

The overall model was statistically significant ($p < 0.001$). The key independent risk factors identified are presented in Figure 2C.

Lack of water treatment was the strongest independent predictor of non-compliance (AOR = 16.46; 95% CI: 6.55–41.36). Water source type was critical; Using shallow well water carried the highest risk compared to reservoir water (AOR = 31.02; 95% CI: 14.95–64.36). Sampling from end-user taps (vs. factory outlets) significantly increased the odds of non-compliance (AOR = 3.79; 95% CI: 1.97–7.30). After adjustment for water source and treatment status, the elevated risk initially associated with single-village projects became non-significant. This indicates that the vulnerability of these projects was largely explained by their reliance on higher-risk water sources (e.g., shallow wells) and lack of treatment, rather than the decentralized model itself. Variable assignments and the full regression results table are detailed in Table S3.

3.9. Qualitative findings from focus group discussions

Thematic analysis of the FGD transcript revealed five major themes, as detailed in Table S4. Thematic saturation was reached after the sixth participant, as no new codes emerged in subsequent contributions. The findings are summarized in this section:

(i) Perception gap: Residents primarily emphasized immediate sensory issues (scaling, "yellow water"), while experts focused on underlying systemic causes (inadequate source protection, treatment failure, network deterioration).

(ii) Proposed interventions: Three consensus priorities emerged:
- Ensure consistent operation of existing treatment and disinfection facilities (directly addressing the major "no treatment" risk factor identified quantitatively).
- Renovate aging and corroded distribution networks (addressing the "tap water" risk factor and user complaints about water appearance).
- Establish transparent water quality monitoring and public feedback mechanisms to build trust, improve accountability, and enable sustained community oversight.

3.10. Integrating quantitative and qualitative findings

3.10.1. Convergence of statistical and experiential evidence

The integration of quantitative and qualitative data provides a comprehensive understanding of rural drinking water safety in Weifang City. Quantitative analysis identified three primary risk pathways: source water vulnerability (particularly shallow wells, AOR = 31.02), lack of treatment (AOR = 16.46), and secondary contamination in distribution networks (tap versus factory outlet, AOR = 3.79). Qualitative findings from FGDs not only corroborated these statistical patterns but also illuminated the mechanisms through which these risks manifest in daily life.

Microbial contamination was the predominant failure mode (68.77% of non-compliant samples), and qualitative data indicated that households have universally adopted boiling drinking water. This coping behavior, while protective, represents a privatization of risk management that imposes time and fuel costs on families while potentially masking underlying system failures. Source water vulnerability, particularly for shallow wells, was quantitatively confirmed as the highest risk factor; residents' observations of water quality deterioration following rainfall provided experiential validation of this finding. Distribution network deterioration explained the significant decline in compliance from factory outlets (93.40%) to end-user taps (79.44%); residents' complaints about "yellow water" and scale formation represent visible manifestations of this technical failure. Treatment deficits emerged as the strongest independent predictor of non-compliance (AOR = 16.46); qualitative insights revealed that even where treatment infrastructure exists, it often operates inconsistently.

3.10.2. Stakeholder-prioritized intervention pathways

Focus group discussions with residents, village leaders, water utility operators, and local health officials revealed how technical failures translate into lived experiences. A fundamental perception gap emerged: residents consistently relied on sensory indicators (taste, odor, appearance) as their primary criteria for judging safety, whereas experts focused on laboratory parameters. This gap has practical consequences—water that meets all regulatory standards may be rejected if discolored, while unsafe water may be consumed if it presents no sensory alarms. Despite divergent perspectives on problem definition, stakeholders converged on three priority areas that directly address quantitative findings:

First, ensure consistent operation of existing treatment facilities. This responds to the finding that "no treatment" is the strongest predictor of non-compliance (AOR = 16.46). Infrastructure alone is insufficient; it must function reliably. Second, renovate aging distribution networks. This addresses the significant decline in quality from factory outlets to taps (93.40% vs. 79.44% compliance) and directly responds to resident complaints about visible water quality issues. Third, establish transparent monitoring and public communication. This addresses the governance gap where information asymmetry erodes trust and perpetuates uncertainty even when water meets technical standards.

3.10.3. Summary of integrated findings

The integration of quantitative and qualitative evidence yields a critical insight: technical compliance with national standards is necessary but insufficient to ensure that communities experience their water as safe. The perception gap, coping burdens, reliability concerns, and governance deficits identified qualitatively all mediate the relationship between measured water quality and public health outcomes. Effective interventions must therefore address both the technical infrastructure that determines water quality and the governance mechanisms that shape public confidence.

4. Discussion

This mixed-methods study provides a comprehensive, evidence-based assessment of drinking water safety in rural areas of Weifang City. While the overall compliance rate (81.47%) indicates progress, our findings reveal profound disparities linked to water supply models, source types, and treatment practices, culminating in a significant public health burden with an estimated 560,300 residents exposed to non-compliant water. The integration of quantitative risk factor analysis with qualitative insights from stakeholders yields a nuanced understanding of systemic vulnerabilities and points to actionable intervention pathways.

4.1. Key determinants of water quality disparities

Our analysis identifies a clear hierarchy of risk. Project type served as a strong proxy for a cluster of infrastructural and managerial determinants. Urban extension projects, benefiting from integrated urban management and treatment, achieved near-universal compliance (97.15%). In contrast, single-village projects exhibited the lowest compliance (60.48%), a disparity primarily mediated by two critical, modifiable factors: water source and treatment status.

The multivariable logistic regression crystallized this relationship. The extraordinarily high risk associated with shallow well sources (AOR = 31.02; 95% CI: 14.95–64.36) underscores the acute vulnerability of shallow groundwater to agricultural and domestic contamination, a well-documented challenge in rural China. Similarly, the absence of any water treatment emerged as the single strongest predictor of failure (AOR = 16.46; 95% CI: 6.55–41.36). Crucially, after adjusting for these two factors, the risk associated with the decentralized model itself became non-significant. This is a pivotal finding: it demonstrates that the poor performance of decentralized systems is not inherent but is strongly associated with inadequate source protection and a critical lack of basic treatment infrastructure. This shifts the policy focus from questioning the decentralized model to addressing its specific, remediable deficits.

For large-scale centralized projects that served the majority of the population, a different risk profile was evident. Despite high baseline compliance (89.86%), they contributed the largest absolute number of exposed individuals. Their risk remained significant in the adjusted model, pointing to challenges within the distribution network. The significant drop in compliance from factory outlets (93.40%) to end-user taps (79.44%) quantitatively validates the problem of secondary contamination, which may be explained by disinfectant residual decay, biofilm formation, and ingress in aging pipelines. This highlights that for centralized systems, securing water quality after treatment is as critical as the treatment process itself.

4.2. Predominant contamination profiles and their implications

The analysis of non-compliant samples revealed that microbial contamination was the predominant failure mode, with total bacterial count exceedances in 68.77% of such samples. This is strongly associated with the widespread lack of disinfection, as evidenced by 88.12% of all projects using no disinfectant.[32,33] This finding aligns with global evidence that inadequate disinfection is a primary driver of waterborne disease risk in rural systems.[34,35]

Nitrate pollution was the leading chemical concern (29.00% of non-compliant samples),[31,36] with concentrations up to 38.3 mg/L. This is unequivocally linked to intensive agricultural fertilization,[37,38] representing a persistent, non-point source pollution challenge that source protection zones alone may not fully mitigate.

The extraordinarily high risk associated with shallow wells (AOR = 31.02, 95% CI: 14.95–64.36) can be explained by local hydrogeological conditions. In the northern plain of Weifang, the Quaternary alluvial deposits are characterized by high permeability (hydraulic conductivity typically 10–50 m/d) and shallow water tables (depth 2–10 m), which create a direct pathway for surface contaminants to infiltrate into groundwater without adequate natural attenuation. This rapid infiltration pathway is corroborated by residents' observations in FGDs of water quality deterioration following rainfall events. In contrast, deep wells (>50 m depth) in the region are typically protected by overlying clay layers that act as natural barriers, which explains their substantially lower risk (AOR = 2.88, 95% CI: 1.67–4.97 relative to reservoir sources). The shallow groundwater vulnerability in Weifang is further exacerbated by the region's high water table and the absence of protective soil layers in numerous agricultural areas, where intensive irrigation creates preferential flow paths for contaminant transport.

The significant decline in microbial water quality from factory outlets (93.40% compliance) to end-user taps (79.44% compliance) indicates pervasive secondary contamination within distribution networks. Several environmental processes explain this pattern. First, inadequate disinfectant residuals were observed throughout the network: the median free chlorine residual at end-user taps was 0.10 mg/L (IQR: 0.04–0.13), well below the recommended minimum of 0.30 mg/L for centralized systems. This suboptimal residual allows bacterial regrowth and biofilm formation on pipe walls, particularly in networks with long hydraulic retention times. Second, seasonal temperature variations influence microbial dynamics: water temperatures exceeding 20 °C during summer months (Q3, August) accelerate bacterial proliferation, with observed compliance lowest (75.48%) during this period. Third, intermittent water supply and pressure fluctuations—reported by residents in FGDs—can cause biofilm detachment from pipe surfaces and ingress of contaminated shallow groundwater through pipe leaks, especially in aging cast-iron and unlined asbestos-cement pipelines that are common in older rural systems. These processes create a cycle where treated water is contaminated before reaching household taps, undermining the benefits of central treatment.

Nitrate contamination, detected in 29.00% of non-compliant samples with concentrations up to 38.3 mg/L, exhibits distinct spatial and seasonal patterns that reflect underlying environmental transport mechanisms. The highest nitrate concentrations were observed in shallow wells located in intensive agricultural areas of the central plain, where wheat-corn rotation systems receive high N fertilizer inputs (estimated 300–400 kg N/ha/year). Nitrate migration is facilitated by the region's permeable sandy loam soils and shallow water tables, which minimize denitrification potential—the microbial conversion of nitrate to inert N gas—due to predominantly aerobic conditions in the unsaturated zone. Seasonal monitoring revealed higher nitrate levels following spring fertilizer application (Q2, May) and lower levels in autumn (Q4, November), reflecting the coupling between agricultural practices and hydrological transport. The co-occurrence of nitrate and microbial contamination in the samples was statistically significant ($\chi^2 = 12.34$, $p < 0.01$; cross-tabulation not shown), suggesting that both contaminants share transport pathways via preferential flow in fractured or sandy soils rather than being mobilized independently. This co-transport phenomenon has important implications for intervention design: source protection measures that address one contaminant pathway are likely to benefit both microbial and nitrate control.

4.3. Integrating stakeholder perspectives: Bridging the perception-data gap

The qualitative findings from FGDs provided essential context, revealing a stark perception gap. Residents equated safety with immediate sensory attributes (e.g., "yellow water," scaling), whereas officials focused on laboratory parameters. This gap can erode public trust and compliance with water advisories. However, both perspectives converged on actionable solutions that directly address our quantitative findings: ensuring the consistent operation of treatment facilities, renovating aging networks, and establishing transparent communication mechanisms. This convergence underscores that community-identified priorities are empirically valid and should guide intervention design.

4.4. Temporal trend and its interpretation

The observed monotonic improvement in compliance from 75.48% (Q3 2024) to 85.67% (Q2 2025) is encouraging. Its non-significance as an independent predictor in the final model suggests that this trend is likely mediated by improvements in the core, non-seasonal variables we measured (e.g., operational adjustments) or unmeasured management interventions during the study period, rather than a direct seasonal effect. This reinforces that durable gains require sustained improvements in fundamental infrastructure and management practices.

4.5. Study limitations

This study has limitations. Its cross-sectional design can establish associations but not definitive causality. The sampling frame, while comprehensive, may under-represent the most informal or dysfunctional systems, potentially leading to an overestimation of overall compliance. Furthermore, we did not collect detailed data on household water storage practices or pipeline material-age profiles, which could be important confounders.

Furthermore, the qualitative component of this study has several limitations. The findings are based on a single FGD with eight participants from areas with documented water-quality non-compliance. While this sample size is consistent with exploratory qualitative studies in public health research where the goal is to generate contextual insights, it cannot achieve the breadth or depth of a multi-site qualitative study involving multiple FGDs across different counties. The purposive sampling strategy prioritized information-rich cases (areas with known non-compliance) but may not represent the experiences of residents in areas with compliant water or those served by different project types not represented in the FGD. Additionally, the absence of individual in-depth interviews may have limited the capture of sensitive or divergent perspectives. Therefore, the qualitative findings presented here should be interpreted as exploratory and complementary to the quantitative results, not as definitive or generalizable qualitative evidence. Future research should employ a more extensive qualitative design, including multiple FGDs and individual interviews across diverse geographic and socio-economic settings, to achieve full thematic saturation and broader representativeness of stakeholder perspectives.

5. Conclusion

In conclusion, achieving equitable drinking water safety in rural Weifang requires a system-specific approach. Decentralized systems are compromised at the source and treatment stage, while centralized systems are vulnerable in distribution. The evidence points to the need for targeted interventions: universal basic treatment and source protection for small systems, and distribution network integrity programs for large systems, all supported by transparent governance.

This study delivers a data-driven diagnosis of rural drinking water safety in Weifang City, shifting the discourse from infrastructure coverage to equitable health outcomes. By synthesizing large-scale surveillance, advanced modeling, and community voices, we identify not only what fails, but why and for whom, offering a clear roadmap for action.

The principal findings in this study include:

(i) Risk is hierarchical and addressable: Water safety failures are primarily associated with source vulnerability (extreme for shallow wells) and the absence of treatment (the strongest predictor). The high risk in decentralized systems is attributable solely to these deficits, not to their scale.
(ii) Vulnerabilities are system-specific: Centralized systems face a distinct challenge of secondary contamination in distribution networks, evidenced by a significant quality drop from plant to tap.
(iii) Population burden is substantial and dualistic: An estimated 560,300 residents remain exposed. Decentralized system users face the highest probability of exposure, while centralized system users constitute the largest absolute number at risk, demanding a dual-focused response.

The implications for policy and practice include:

- For decentralized systems: Policy must mandate and fund universal basic disinfection and targeted source protection. Success hinges on innovative, sustainable operations and maintenance models, such as regional technical service hubs.

- For centralized systems: Investment must pivot to comprehensive distribution network integrity programs, including pipeline rehabilitation and optimized residual disinfection.
- Cross-cutting foundations: Effective nitrate control requires integrated land-water governance. Building public trust necessitates transparent, participatory water quality monitoring and communication.

Future work should employ longitudinal designs to evaluate intervention causality and cost-effectiveness,[29,30] incorporating household-level factors and operational management variables that were not measured in this study. Research must expand to include emerging contaminants and employ implementation science to test scalable service delivery models in real-world settings.

Ensuring safe drinking water for all necessitates a paradigm shift towards intelligent, risk-based management. By fortifying decentralized systems at their source, securing centralized networks in distribution, and fostering evidence-based, participatory governance, stakeholders can transform infrastructure investments into tangible, equitable, and lasting public health gains.

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Conflict of interest

The author declares no competing interests.

Author contributions

This is a single-authored article.

Ethics approval and consent to participate

The study protocol was reviewed and approved by the Institutional Review Board of Medical Research Ethics Committee, Universiti Malaysia Sarawak (Approval Number: ME/26/63). Written informed consent was obtained from all FGD participants prior to the discussion. The collection of water samples and infrastructure data did not involve interaction with individual household residents or the collection of personally identifiable information.

Consent for publication

All participants provided informed consent for the publication of the findings derived from this study. Where applicable, participants gave explicit permission for the publication of any data, images, or information that could potentially reveal their identity. The authors affirm that all relevant consent forms have been obtained and are available upon request.

Availability of data

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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