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MORALITY BEFORE KNOWLEDGE

Comparative characterization of water quality based on physicochemical parameters from various water sources

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ABSTRACT

Background: Water quality varies substantially across source types, yet field-based comparative assessments spanning natural, household-consumable, and potentially contaminated water within a single urban highland setting remain scarce in Indonesia. This study characterized and compared the physicochemical quality of 14 water samples across three source categories in Bandung, West Java, and evaluated their alignment with regulatory standards and product-labeled claims. **Methods:** Samples were collected through grab sampling and measured in situ using a portable multiparameter pH meter for pH, electrical conductivity (EC), total dissolved solids (TDS), salinity, and temperature. Descriptive statistics and Pearson correlation analysis were performed using IBM SPSS Statistics. **Findings:** Considerable variation was observed across source categories: mean pH 6.69 ± 0.77, EC 183.24 ± 141.00 µS/cm, TDS 134.86 ± 95.93 ppm, salinity 128.13 ± 90.55 ppm, and temperature 23.24 ± 1.17 °C. Six of 14 samples recorded pH below the minimum threshold of 6.5, including tap water (5.20), unboiled gallon water (5.80), two packaged mineral water brands, and both domestic wastewater samples. A very strong positive correlation was found between EC and TDS ($r = 0.984$, $p < 0.001$), confirming EC as a reliable field proxy for TDS estimation. **Conclusion:** Two packaged mineral water products marketed with alkaline pH claims showed discrepancies of more than one pH unit between measured and labeled values. These findings confirm that water source category is a primary determinant of physicochemical quality, underscoring the need for strengthened monitoring of distributed water supply systems and post-market verification of pH claims in Indonesia. **Novelty/Originality of this article:** The novelty lies in the first integrated field-based comparison across three functionally distinct water source categories combined with systematic verification of alkaline pH label claims in the Indonesian context.

KEYWORDS: comparative assessment; packaged drinking water; physicochemical parameters; water quality; water source categories.

1. Introduction

Water is fundamental to life, ecosystems, and public health. Covering approximately 70% of the planet's surface and constituting 65–90% of the mass of living organisms, making it not merely a background medium, but the chemical foundation of all known life (Dargaville & Hutmacher, 2022; Frenkel-Pinter et al., 2021). Despite consisting of only three atoms, water possesses remarkably complex properties that no other molecule can replicate in supporting carbon-based life (Chaplin, 2001). Beyond its biological role, water structures and sustains entire ecosystems; regulating nutrient cycles, moderating local climates, and providing habitat for aquatic biodiversity that underpins global food webs

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(Postel & Richter, 2003). At the human scale, access to water of adequate quality is a determinant of public health: contaminated or chemically imbalanced water is linked to waterborne disease, developmental impairment, and long-term physiological harm (WHO, 2022). Yet the presence of water alone does not guarantee its suitability for these functions, it is the physicochemical composition of water that ultimately determines whether it supports or undermines life, ecosystems, and human health.

Despite water's fundamental importance to life, the quality of available water sources is increasingly threatened by anthropogenic pressures. Rapid urbanization, industrialization, and population growth have intensified the discharge of domestic wastewater, agricultural runoff, and industrial effluents into natural water bodies, with an estimated 80% of wastewater released into the environment globally without prior treatment (Lin et al., 2022). The interplay between urbanization, inadequate treatment infrastructure, and increasing pollution loads creates a compounding cycle of water quality deterioration across diverse source types, from natural surface waters to distributed household supply systems (Song et al., 2025). Understanding the extent and nature of this deterioration across different water source categories therefore requires systematic physicochemical characterization.

Assessing water quality, therefore requires systematic measurement of its physicochemical properties, which collectively capture the chemical and physical state of a water body and its suitability for intended use (Debassi et al., 2025; Shah et al., 2023). Among the most widely applied indicators are pH, electrical conductivity (EC), total dissolved solids (TDS), salinity, and temperature, each reflecting the cumulative influence of geological substrate, atmospheric inputs, and anthropogenic activity on water composition (Mishra et al., 2023). Monitoring these parameters provides an integrated picture of water system health: pH indicates acid-base balance and governs the solubility of metals and nutrients; EC and TDS reflect the total ionic load dissolved in water; salinity indicates salt concentration; and temperature influences the rate of chemical reactions within the water body (Rahman et al., 2021).

Physicochemical assessment of water quality has been conducted across diverse settings worldwide, reflecting growing recognition that source type, land use, and the degree of anthropogenic influence collectively shape the chemical and physical profiles of water bodies. In urban river systems receiving domestic and industrial inputs, parameters such as EC and TDS have been shown to consistently exceed permissible limits, while natural upstream sources retain relatively stable pH and low ionic loads, a contrast that underscores the diagnostic value of comparative multi-source assessment (Moridi et al., 2024; Suriadikusumah et al., 2021). At the drinking water supply level, studies in developing country urban contexts have further documented that pH, EC, and TDS vary significantly across different supply sources, from natural sources to distributed tap water, with deterioration patterns closely linked to treatment infrastructure and distribution networks (Latif et al., 2024; Mengstie et al., 2023). In Indonesia, domestic wastewater remains a major, largely untreated source of physicochemical pollution, with greywater from household activities contributing disproportionately to surface water contamination (Widyarani et al., 2022). National surveys have additionally shown that a substantial proportion of drinking water sources across Indonesian cities fail to meet the pH standards mandated by the Ministry of Health, with compliance rates varying markedly between urban locations (Irianti et al., 2024).

As one of Indonesia's most densely populated highland cities, Bandung, West Java, presents a particularly relevant setting for this investigation. The city encompasses a diverse range of coexisting water source types, from forested highland catchments and urban river systems to commercially distributed packaged water and domestic wastewater, within a geographically compact area. Studies in the Bandung region have documented significant water quality degradation in major river systems, with industrial and domestic effluents contributing to persistent exceedances of permissible limits (Fitriana et al., 2023), while contamination has also been reported across multiple source types used directly by communities including wells, tap water, and refill bottled water (Sari et al., 2018). Despite this diversity of source types and documented quality variation, field-based comparative studies that simultaneously characterize the physicochemical profiles of natural, household-consumable, and potentially contaminated water sources within a single urban highland setting remain absent from the literature. Furthermore, while field-measured pH values of packaged drinking water have been documented in the Indonesian context (e.g., household- and access-point-level water quality surveys), no study has yet systematically verified these field measurements against the pH values printed on product labels, an omission that carries practical implications for consumer health literacy and regulatory oversight.

The Indonesian packaged drinking water market has expanded substantially over the past decade, driven in part by declining public trust in piped water quality and growing consumer interest in premium and functional water products (Puspita et al., 2023). Within this expanding market, alkaline bottled water, marketed with elevated pH claims typically ranging from 8.6 to 9.5, has emerged as a rapidly growing premium segment, with brands positioning their products around perceived health benefits associated with high-pH consumption. Consumer purchasing decisions for such products are shaped substantially by socio-economic factors and by perceptions of water safety that often diverge from the actual physicochemical quality of the water available to households (Zikrina et al., 2024). However, systematic field-based verification of pH claims on commercially available packaged water products under real-world consumer-access conditions remains largely absent from the peer-reviewed literature. This gap carries direct public health and consumer protection implications: if labeled pH values are established under controlled production conditions but shift substantially during storage, transport, or after container opening, consumers making health-motivated purchasing decisions may not receive the physicochemical profile promised on the label (Mitku & Endeshaw, 2022). Addressing this gap through independent field-based assessment is therefore not only scientifically warranted but practically consequential for both consumer literacy and evidence-based regulatory oversight in the Indonesian market.

The public health and consumer protection stakes of verifying such claims are further underscored by the regulatory apparatus that actually governs packaged drinking water in Indonesia. Under Indonesian law, packaged drinking water/*air minum dalam kemasan* (AMDK) is legally classified as a category of processed food/*pangan olahan*, placing its composition, safety, and label claims under the food-regulatory authority of the National Agency of Drug and Food Control/*Badan Pengawas Obat dan Makanan* (BPOM) rather than under a dedicated water-quality regulator. Within this food-safety framework, Ministry of Industry Regulation No. 62/2024 requires all AMDK products to comply with mandatory indonesian national standards/*standar nasional Indonesia* (SNI) prior to market registration, with high-pH water formally defined and regulated as a distinct AMDK category under SNI 8982:2021, which sets minimum composition and safety-testing requirements specific to this product type. As a processed food product, high-pH AMDK is further classified by BPOM as a medium-to-high-risk category under BPOM Regulation No. 23/2023, while BPOM Regulation No. 1/2022, which governs claims on processed food labels and advertisements more broadly, requires that any health-related claim, including pH-related claims, be substantiated and consistent with a product's actual composition. Mandatory SNI 8982:2021 certification for new AMDK registrations, however, only took effect from April 2025 onward, meaning that products registered earlier may not have undergone equivalent standardized verification, and units bearing pre-existing labels may remain in circulation well beyond that date. Because AMDK is regulated as a food product rather than as water per se, routine environmental water-quality monitoring does not automatically extend to it, leaving independent, field-based verification of the kind undertaken in this study, particularly valuable for checking whether marketed pH values correspond to actual product composition at the point of consumer access.

These five parameters do not operate independently but are governed by a shared set of physicochemical principles established in the water quality literature, providing the interpretive lens through which the following results are read. pH reflects the carbonatebicarbonate equilibrium and the concentration of dissolved carbon dioxide in water, a balance that in turn governs the solubility and reactivity of dissolved metals and nutrients (Saalidong et al., 2022). EC and TDS are both direct measures of the same underlying quantity, the total concentration of dissolved ions, and are consequently expected to co-vary strongly across virtually all water types, a relationship well documented in the water quality literature (Rusydi, 2018; Thirumalini & Joseph, 2009). Salinity represents the dissolved-salt component of this same ionic pool, while temperature does not itself add ions to water but modulates the solubility, dissociation, and mobility of those already present, thereby shaping the magnitude of EC, TDS, and salinity readings without altering their underlying source (Mishra et al., 2023; Rahman et al., 2021). Read together rather than in isolation, a shift in one parameter is therefore rarely an isolated event: it typically signals a corresponding, mechanistically linked shift in the others, and it is this joint behavior, rather than any single parameter alone, that this study uses to characterize and differentiate water source categories in the results that follow.

This study aims to characterize and compare the physicochemical quality of water from three distinct source categories: natural water, household-consumable water, and potentially contaminated water, within a single urban highland setting in Bandung, Indonesia. Because these categories differ in intended use and human exposure pathway, ranging from direct consumption in the case of household-consumable water to indirect environmental exposure in the case of natural surface water and potentially contaminated sources, the scope of this assessment extends beyond drinking-water suitability alone. Drinking water standards and World Health Organization (WHO) guidelines are nonetheless applied uniformly across all 14 samples as a common, policy-relevant benchmark, providing a consistent basis for comparing physicochemical profiles and gauging the relative degree of anthropogenic influence across source types, irrespective of whether a given source is intended for direct consumption. In doing so, the study seeks to contribute field-based comparative evidence to water quality monitoring in the Indonesian context, and to assess the extent to which measured physicochemical profiles align with regulatory standards and product-labeled claims.

2. Methods

2.1 Study area

This study was conducted at two primary locations in Bandung, West Java, Indonesia: Taman Hutan Raya (THR) Ir. H. Djuanda, representing a peri-urban forested highland environment, and Teras Cikapundung, representing an urban riverside public space in the heart of Bandung city. Both sites were selected to capture contrasting environmental contexts (natural highland and urban riverine) within the same metropolitan area, enabling a comparative assessment of water quality across source categories with differing degrees of anthropogenic influence.

2.2 Water sample categories

A total of 14 water samples were collected and grouped into three categories based on source type and intended use. The first category, natural water, comprised highland spring water (Taman Hutan Raya) and urban river water (Teras Cikapundung). The second category, household-consumable water, included five brands of commercially packaged mineral water, gallon water (boiled and unboiled), and tap water. The third category, potentially contaminated water, comprised domestic wastewater (post-washing with soap and post-rinsing), and pond water from both locations. This classification framework was adopted to enable systematic comparison of physicochemical profiles across source types with fundamentally different origins, treatment histories, and contamination potentials. To provide a clear overview of the sampling scheme and to support unambiguous crossreferencing throughout the Results and Discussion, each sample was assigned a unique alphanumeric code according to its source category, as summarized in Table 1.

Table 1. Sample codes and source categories of the 14 collected water samples

Sample Code	Source Category	Sample Description
NW-01	Natural water	Highland spring water (Taman Hutan Raya)
NW-02	Natural water	Urban river water (Teras Cikapundung)
HC-01	Household-consumable water	Tap water
HC-02	Household-consumable water	Gallon water (unboiled)
HC-03	Household-consumable water	Gallon water (boiled)
HC-04	Household-consumable water	Packaged mineral water — Brand A
HC-05	Household-consumable water	Packaged mineral water — Brand B
HC-06	Household-consumable water	Packaged mineral water — Brand C
HC-07	Household-consumable water	Packaged mineral water — Brand D
HC-08	Household-consumable water	Packaged mineral water — Brand E
PC-01	Potentially contaminated water	Domestic wastewater (post-soap washing)
PC-02	Potentially contaminated water	Domestic wastewater (post-rinsing)
PC-03	Potentially contaminated water	Pond water (Taman Hutan Raya)
PC-04	Potentially contaminated water	Pond water (Teras Cikapundung)

2.3 Data collection

Water samples were collected using a grab sampling approach, whereby physicochemical parameters were measured directly at each sampling point without prior storage or transport. All measurements were conducted in situ using a portable multiparameter digital pH meter (Eutech Waterproof pH Tester EC-pHTEST3), which simultaneously recorded five parameters: pH, electrical conductivity (EC, µS/cm), total dissolved solids (TDS, ppm), salinity (ppm), and water temperature (°C). Prior to field deployment, the instrument was calibrated according to the manufacturer's standard procedure to ensure measurement accuracy and consistency across sampling sessions. Sampling was conducted across multiple dates in April 2026, with each sample measured once at its respective collection point. For commercially packaged water products, measurements were taken immediately upon opening the container under standardized conditions to minimize exposure to ambient air.

Sampling was scheduled for April 2026 to align with the academic research timeline of the study. This period falls within the tail end of Bandung's wet season, during which rainfall remains substantial before the region transitions toward drier conditions from May onward. Because sampling was conducted at a single time point without seasonal replication, short-term weather effects, particularly recent rainfall and surface runoff, cannot be fully separated from source-driven differences in the measured profiles, and would most plausibly affect the natural water samples (highland spring and river water) rather than the enclosed household-consumable or wastewater sources.

2.4 Data analysis

Data were analyzed using a descriptive comparative approach. Descriptive statistics, including mean, minimum, maximum, and range, were calculated for each physicochemical parameter across all samples and source categories to characterize the overall distribution and variation of water quality profiles. Measured values were subsequently compared against the drinking water quality standards established by the Regulation of the Minister of Health No. 12 Year 2023/*Peraturan Menteri Kesehatan Nomor No. 2 Tahun 2023* (Permenkes No. 2/2023) and the WHO (2022) to assess regulatory compliance and identify deviations across source types. For packaged mineral water products carrying alkaline pH label claims, field-measured pH values were compared directly against the values stated on product packaging to evaluate the accuracy of such claims. To explore inter-parameter relationships, Pearson correlation analysis was performed between physicochemical parameters, with particular attention to the relationship between electrical conductivity (EC) and total dissolved solids (TDS) as co-varying indicators of ionic load. Given the exploratory and descriptive nature of this study, with a single measurement per sample and no replication, findings are interpreted as preliminary evidence and discussed in relation to existing standards and literature rather than subjected to inferential statistical testing. All statistical analyses were performed using IBM SPSS Statistics version 27.

3. Results and Discussion

3.1 Physicochemical profiles across water source categories

Physicochemical measurements were obtained from 14 water samples distributed across three source categories: natural water (n = 2), household-consumable water (n = 8), and potentially contaminated water (n = 4). Descriptive statistics across all samples revealed considerable variation in physicochemical profiles, with mean pH of 6.69 ± 0.77, mean EC of 183.24 ± 141.00 µS/cm, mean TDS of 134.86 ± 95.93 ppm, mean salinity of 128.13 ± 90.55 ppm, and mean temperature of 23.24 ± 1.17 °C (Table 2). The large standard deviations observed for EC, TDS, and salinity reflect the high degree of physicochemical heterogeneity across source types, underscoring the diagnostic value of multi-source comparative assessment.

Table 2. Descriptive statistics of physicochemical parameters across all water samples

Parameter	Minimum	Maximum	Mean	SD
pH	5.20	7.58	6.69	0.77
EC (µS/cm)	15.20	499.00	183.24	141.00
TDS (ppm)	11.10	355.00	134.86	95.93
Salinity (ppm)	17.90	339.00	128.13	90.55
Temperature (°C)	20.60	24.10	23.24	1.17

Water temperature across all samples ranged from 20.6 °C (Tahura highland spring water) to 24.1 °C (Brand B packaged water), with a mean of 23.24 ± 1.17 °C, the narrowest range of all parameters measured. The lowest temperatures were recorded at Taman Hutan Raya, for both highland spring water (20.6 °C) and pond water (20.7 °C), consistent with the cooler microclimate of the forested highland environment at higher elevation. Urban samples generally reflecting ambient thermal conditions at lower elevations. Temperature variation across samples was modest and all values remained within acceptable ranges for aquatic life and human water use. Nevertheless, temperature is an important co-variable in physicochemical interpretation, it influences ionic mobility, gas solubility, and the rate of chemical reactions in water and may partially account for the lower EC and TDS values observed at highland locations relative to warmer urban sources (Rahman et al., 2021).

3.1.1 Potential of Hydrogen (pH)

pH values across the 14 water samples ranged from 5.20 to 7.58, with a mean of 6.69 ± 0.77 (Table 2). pH is notably one of the most important physicochemical parameters in water quality assessment, as it governs the behavior of other chemical parameters including metal solubility, oxidation-reduction reactions, and acid-base equilibria in aquatic systems (Saalidong et al., 2022). Permenkes No. 2/2023 sets the permissible pH range for drinking water at 6.5–8.5, indicated by the red dashed lines in Fig. 1. Of the 14 samples measured, six fell below this minimum threshold, indicating non-compliance across multiple source categories (Fig.1). Bars are color-coded by source category: green for natural water, yellow for household-consumable water, and blue for potentially contaminated water.

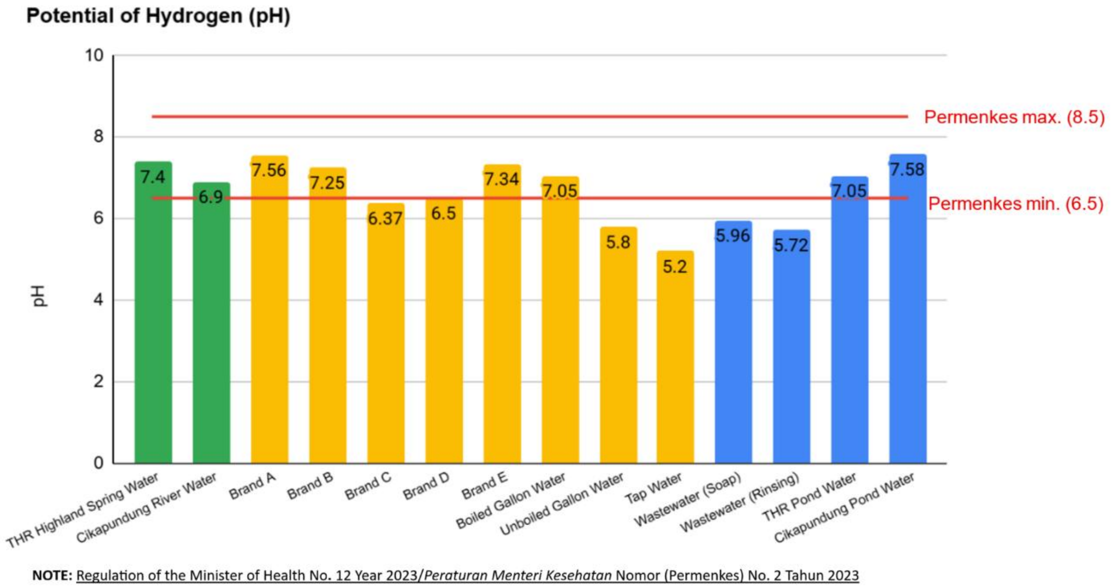

Fig. 1. pH value profiles of natural, household-consumable, and potentially contaminated water

Natural water, highland spring water from Taman Hutan Raya had a pH of 7.40, and urban river water from Teras Cikapundung had a pH of 6.90, both within the permissible range. The near-neutral pH of highland spring water reflects the natural buffering capacity of forested highland catchments, where geological substrates and organic matter regulate the acid-base equilibrium of water percolating through the system (Suriadikusumah et al., 2021). The slightly lower pH of urban river water is consistent with the gradual introduction of anthropogenic inputs that reduce the natural buffering capacity of open water bodies (Fitriana et al., 2023). Pond water from both locations recorded near-neutral to slightly alkaline values suggesting maintained buffering capacity in these semi-enclosed water bodies despite their proximity to human activity.

Household-consumable water, this category showed greatest pH variation among the three source categories. Tap water recorded the lowest pH of all 14 samples at 5.20, well below the Permenkes minimum threshold of 6.5. This is consistent with national survey findings documenting widespread pH non-compliance in distributed drinking water sources across Indonesian urban settings (Irianti et al., 2024), and raises concerns about the quality of municipal water supply infrastructure in the study area. Unboiled gallon of water similarly recorded a pH of 5.80, also below regulatory limits. In contrast, boiled gallon water exhibited a pH of 7.05, an increase of 1.25 pH units relative to the unboiled sample. This difference is attributable to the thermal volatilization of dissolved CO_2 during boiling: as temperature rises, dissolved carbon dioxide escapes from solution, reducing the formation of carbonic acid and thereby elevating pH. This finding confirms that boiling is an effective and accessible intervention for improving the pH of acidic gallon water prior to consumption.

Among packaged mineral water products, pH ranged from 6.37 (Brand C) to 7.56 (Brand A). Brand C, a demineralized product processed through reverse osmosis, recorded a pH of 6.37, slightly below the Permenkes threshold. This is consistent with the known characteristic of reverse osmosis-treated water: the removal of dissolved minerals including calcium and magnesium bicarbonates, which contribute to alkalinity, results in water with reduced buffering capacity and a tendency toward slight acidity (Janna et al., 2016). Brand D recorded pH 6.50, at the boundary of the permissible range, while Brands A, B, and E complied with pH standards.

A particularly noteworthy finding concerns two products marketed with alkaline pH label claims. Brand A, labeled as pH 8.6, recorded a field-measured pH of 7.56, a discrepancy of 1.04 pH units. Brand E, labeled as pH 8.8+, recorded a measured pH of 7.34, a deviation of at least 1.46 pH units from the minimum claimed value. While both values remain within the Permenkes permissible range, neither approaches the alkaline threshold implied by their labels. Studies on the physicochemical quality of commercially packaged mineral water have noted that labeled pH values may reflect controlled production conditions, and that pH can shift substantially during storage, transportation, or upon exposure to atmospheric CO_2 following container opening (Mitku & Endeshaw, 2022). This systematic overstatement of alkalinity in product labeling raises questions about post-market verification of pH claims and the adequacy of current consumer protection mechanisms for packaged drinking water in Indonesia.

Potentially contaminated water, post-soap washing wastewater recorded a pH of 5.96 and post-rinsing wastewater 5.72, both below the regulatory threshold and reflecting the acidic character of detergent and surfactant residues introduced through household washing activities (Widyarani et al., 2022). Notably, pond water from both locations met pH standards, suggesting that despite their classification as potentially contaminated sources, these water bodies maintain adequate acid-base regulation under current conditions. Overall, pH variation across source categories in this study reflects a clear gradient of anthropogenic influence: natural water sources and pond water maintained near-neutral pH values consistent with regulatory standards, while tap water, unboiled gallon water, demineralized packaged water, and domestic wastewater all recorded values below the permissible minimum of 6.5 set by Permenkes No. 2/2023. The discrepancy between labeled and measured pH values in alkaline packaged water products further underscores the importance of independent field-based verification of water quality claims, particularly in the context of consumer health literacy and regulatory oversight in Indonesia.

3.1.2 Electrical conductivity (EC) and total dissolved solids (TDS)

Electrical conductivity (EC), EC values across all 14 samples ranged from 15.2 µS/cm (Brand C) to 499 µS/cm (post-soap washing wastewater), with a mean of 183.24 ± 141.00 µS/cm. The large standard deviation relative to the mean reflects substantial ionic load heterogeneity across source categories, consistent with evidence that EC varies markedly depending on source type and degree of anthropogenic influence (Horiguchi et al., 2023). Among natural water sources, highland spring water recorded an EC of 66.9 µS/cm, consistent with water from a minimally disturbed forested catchment. Urban river water recorded a lower EC of 23.8 µS/cm, a counterintuitive finding given that urban streams typically exhibit higher ionic concentrations than their rural counterparts due to point and diffuse pollution inputs (Kaushal et al., 2021). This anomaly may reflect dilution from recent precipitation or the dominance of upstream natural inputs at the sampling point.

Pond water recorded moderate EC values at both locations, with the higher value at Teras Cikapundung (193.6 µS/cm) compared to Tahura (115.4 µS/cm), likely reflecting greater ionic inputs from surrounding urban activity. Within the household-consumable category, EC ranged widely from 15.2 µS/cm (Brand C, reverse osmosis-treated) to 319 µS/cm (boiled gallon water). Boiled gallon water recorded a higher EC than its unboiled counterpart (259 µS/cm), attributable to evaporative concentration of dissolved ions during boiling. Tap water (291 µS/cm) had higher EC than all packaged mineral water products, indicating elevated ionic loads in the municipal distribution network. Post-soap washing wastewater recorded the highest EC of all samples (499 µS/cm), followed by post-rinsing water (337 µS/cm), reflecting the high ionic contribution of detergent and surfactant compounds to domestic grey water (Cisneros-León et al., 2023).

Total dissolved solids (TDS), TDS values ranged from 11.1 ppm (Brand C) to 355 ppm (post-soap washing wastewater), with a mean of 134.86 ± 95.93 ppm. All values remained below the WHO maximum guideline of 500 ppm and the Permenkes No. 2/2023 threshold for drinking water, indicating that TDS alone does not constitute a compliance concern across any sample. The distribution of TDS values across categories closely mirrored that of EC, with the highest values concentrated in domestic wastewater and gallon or tap water, and the lowest in packaged mineral water and natural highland water. Notably, urban river water recorded a TDS of 84.8 ppm despite its anomalously low EC of 23.8 µS/cm, a divergence suggesting the presence of less ionically active dissolved particles, possibly particulate organic matter from urban surface runoff, that contribute to dissolved solid mass without proportionally elevating conductivity (Saalidong et al., 2022).

Among packaged products, TDS ranged from 11.1 ppm (Brand C) to 120 ppm (Brand B), reflecting differences in mineral content and purification method. Gallon water (boiled: 226 ppm; unboiled: 184 ppm) and tap water (207 ppm) recorded notably higher TDS than all packaged products, suggesting that refill and municipal water supply systems in the study area carry substantially higher dissolved solid loads than commercially purified alternatives. Post-soap washing wastewater recorded the highest TDS of all samples (355 ppm), approaching but not exceeding the WHO maximum guideline, while post-rinsing water recorded 239 ppm, both consistent with the residual ionic load of household detergent compounds (Cisneros-León et al., 2023). An exception was observed in urban river water, where TDS (84.8 ppm) was disproportionately high relative to its EC (23.8 µS/cm), yielding a TDS/EC ratio of 3.56, substantially higher than other samples. This divergence suggests the presence of non-ionic dissolved organic matter from domestic inputs that contributes to total dissolved solid mass without proportionally elevating ionic conductivity, a pattern documented in urban surface water bodies receiving untreated domestic effluent (Rusydi, 2018).

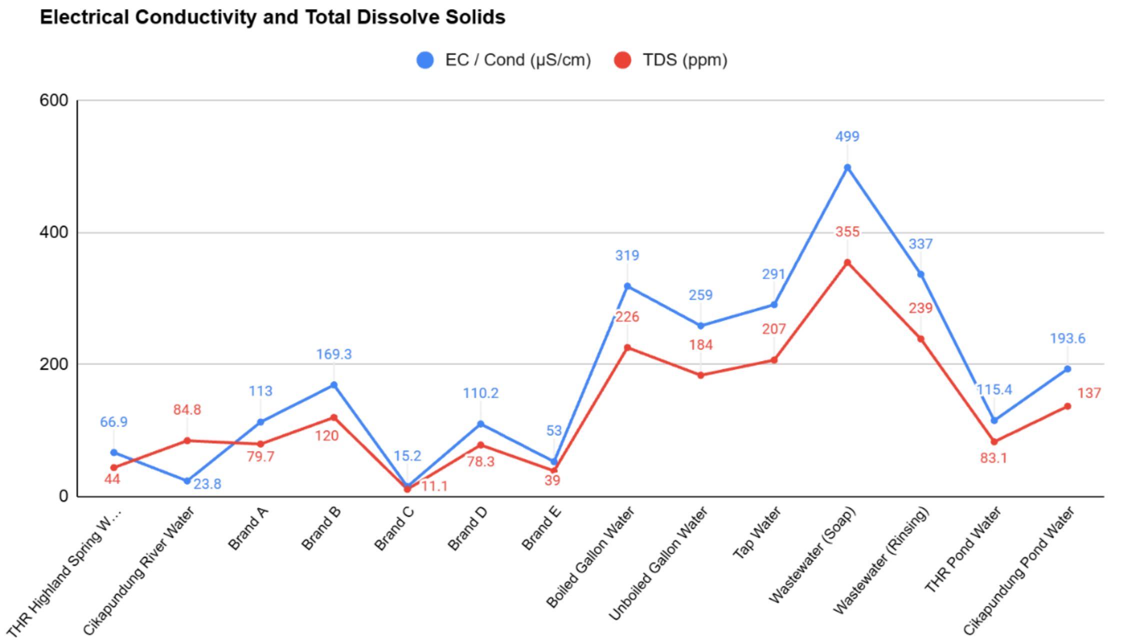

Fig. 2. EC and TDS value profiles of natural, household-consumable, and potentially contaminated water

Relationship between EC and TDS, pearson correlation analysis revealed a very strong positive relationship between EC and TDS across all 14 samples ($r = 0.984$, $p < 0.001$), indicating that 96.8% of the variance in TDS is explained by variation in EC ($r^2 = 0.968$). This near-perfect linear relationship (Fig.2), observed consistently across source types as diverse as natural highland spring water, reverse osmosis-treated packaged water, and domestic wastewater, confirms the shared ionic basis of both parameters: as dissolved ionic species accumulate in water, both the capacity to conduct electrical current and the total dissolved solid mass increase proportionally (Rusydi, 2018). The strength and consistency of this relationship across such heterogeneous source types further validates EC as a reliable field proxy for estimating TDS in water quality monitoring contexts where direct TDS measurement may not be available. This has particular practical relevance for routine monitoring by regional water quality agencies and community-level assessments, where portable EC meters offer a rapid, low-cost alternative to more resource-intensive TDS measurement, enabling broader coverage of monitoring sites without proportionally increasing analytical burden. The one notable exception to this pattern was urban river water, which exhibited a disproportionately high TDS relative to EC, a divergence attributable to non-ionic dissolved organic constituents rather than ionic pollution, and consistent with the complex pollutant composition of urban surface water receiving domestic inputs (Saalidong et al., 2022).

Such patterns are consistent with broader evidence that urban rivers and streams tend to carry a disproportionately allochthonous, non-ionic organic fraction relative to standing water bodies such as ponds and lakes. Dissolved organic matter (DOM) entering urban streams via surface runoff is typically dominated by humic-like and protein-like fractions originating from soil leaching, road and roof runoff, and diffuse domestic inputs, in contrast to the more autochthonous, biologically produced DOM characteristic of lentic systems (Romero González-Quijano et al., 2022). Because such organic macromolecules contribute measurable mass to a water sample without carrying a proportional ionic charge, their presence would elevate TDS readings, obtained gravimetrically or via correlation-based field proxies, without a corresponding rise in electrical conductivity, which specifically reflects the concentration of charged, mobile ionic species. This mechanism offers a plausible, literature-grounded explanation for the anomalously high TDS/EC ratio observed at the Teras Cikapundung sampling point, consistent with its position within a densely built urban catchment subject to road runoff, domestic greywater seepage, and limited riparian buffering compared to the forested highland catchment at Taman Hutan Raya. It is important to note, however, that this study did not directly characterize the composition of dissolved organic matter through spectroscopic, chromatographic, or carbon-specific analytical methods; the explanation offered here therefore represents a plausible mechanism consistent with the broader urban water quality literature rather than a compositional finding specific to this sample. Direct characterization of the non-ionic organic fraction, for example through dissolved organic carbon (DOC) quantification or optical/fluorescence-based DOM fingerprinting, represents a valuable direction for future work building on this preliminary field-based comparison, and would allow this divergence to be attributed with greater certainty to specific organic constituents rather than inferred indirectly from the TDS/EC divergence alone. This exception itself carries a monitoring implication: while EC serves as a reliable TDS proxy for most water sources, urban surface waters may require independent TDS measurement to accurately characterize their dissolved solid load, given the significant contribution of non-ionic organic constituents that EC cannot detect.

3.1.3 Salinity

Salinity values across all 14 samples ranged from 17.9 ppm (Brand C) to 339 ppm (post-soap washing wastewater), with a mean of 128.13 ± 90.55 ppm. All samples remained well within the freshwater classification threshold, with no sample approaching the brackish water range (Fig.3). The salinity pattern across source categories closely paralleled those of EC and TDS, reflecting the common ionic basis shared by all three parameters, dissolved salt species contribute simultaneously to electrical conductivity, total dissolved solid mass, and salinity concentration in water.

Natural water, highland spring water recorded a salinity of 38.8 ppm and urban river water 81.5 ppm, both low and consistent with freshwater systems minimally affected by saline anthropogenic inputs. The higher salinity of urban river water relative to highland spring water, despite its lower EC, again reflects the presence of dissolved organic constituents from domestic inputs that contribute to overall ionic concentration without proportionally elevating conductivity. Pond water from both locations recorded moderate salinity values, 71.3 ppm at Tahura and 130 ppm at Teras Cikapundung, with the higher value at the urban location consistent with greater exposure to dissolved salt inputs from surrounding activity.

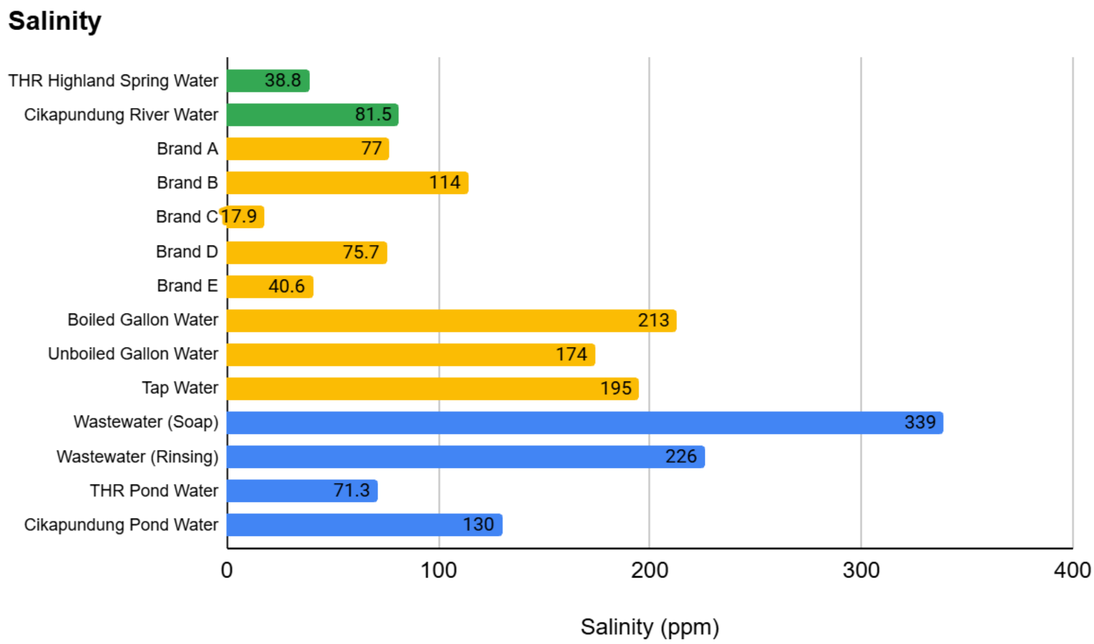

Fig. 3. Salinity value profiles of natural, household-consumable, and potentially contaminated water

Household-consumable water, among packaged mineral water products, salinity ranged from 17.9 ppm (Brand C) to 114 ppm (Brand B), mirroring the EC and TDS patterns and reflecting differences in mineral content and purification method. Boiled gallon water (213 ppm) recorded higher salinity than unboiled gallon water (174 ppm), consistent with the evaporative concentration effect documented for EC and TDS. Tap water recorded a salinity of 195 ppm, higher than all packaged mineral water products, reflecting the elevated dissolved ion load of the municipal distribution network.

Potentially contaminated water, post-soap washing wastewater recorded the highest salinity of all samples (339 ppm), followed by post-rinsing water (226 ppm). These elevated values are consistent with the salt-containing ionic species introduced by household detergents and surfactants, laundry and washing products typically contain sodium-based compounds that dissolve readily in water and contribute to elevated salinity (Mohan et al., 2024). The progressive reduction in salinity from post-soap to post-rinsing water confirms the dilution of these compounds through successive rinsing cycles, though rinsing water retained salinity levels substantially above those of natural and most household-consumable sources. Pond water at both locations recorded moderate salinity values well within freshwater classification, suggesting adequate dilution capacity in these semi-enclosed water bodies. Overall, salinity values across all 14 samples remained within the freshwater range and below any regulatory threshold, indicating that salinity alone does not constitute a health or compliance concern in the study area. Nevertheless, the consistent elevation of salinity in domestic wastewater relative to natural sources underscores the cumulative ionic contribution of household washing activities to water bodies receiving untreated grey water.

3.2 Implications for water quality standards and product-labeled claims

Comparative evaluation of measured pH values, revealed that five of the 14 samples recorded non-compliant values: tap water (5.20), unboiled gallon water (5.80), Brand C (6.37), post-soap washing wastewater (5.96), and post-rinsing wastewater (5.72). TDS and EC values across all samples remained within WHO maximum guidelines, indicating no compliance concern beyond pH. Natural water sources, boiled gallon water, and pond water from both locations all complied with pH standards, while domestic wastewater samples were non-compliant across pH parameters. These findings are consistent with national evidence of widespread pH non-compliance in Indonesian drinking water sources (Alfian et al., 2022; Irianti et al., 2024).

The non-compliance of tap water and unboiled gallon water with pH standards carries direct public health implications. These sources are commonly consumed by urban households in Indonesia, yet their acidic pH values render them unsuitable for direct consumption without prior treatment (Zikrina et al., 2024). Boiling has been demonstrated to improve water quality by facilitating the volatilization of dissolved gases, with the pH increase observed in boiled versus unboiled gallon water in this study, providing field-based confirmation of this effect (Zhai et al., 2020). Boiling prior to consumption is therefore recommended, particularly when the physicochemical quality of the source cannot be independently verified. Furthermore, consumers are advised to exercise caution in selecting refill gallon water depots, as studies in Indonesia have documented widespread quality failures in depot operations due to inadequate hygiene and sanitation practices among operators (Alfian et al., 2022).

The physicochemical variations documented across the household-consumable water category carry important social equity implications, as different socioeconomic groups in Bandung and other Indonesian urban settings rely differentially on these water sources. National survey data have shown that access to improved drinking water in Indonesia varies substantially across regions and income strata, ranging from 93.4% in DKI Jakarta to 41.1% in the least-served provinces, with poor households consistently facing the greatest access constraints (Afifah et al., 2018). In urban settings, this inequality manifests through household reliance on distinct water source types: higher-income households increasingly purchase branded packaged mineral water, middle-income households commonly use refill gallon water, while lower-income households often depend on tap water, unbranded refill gallons, or community wells; sources that in this study exhibited the highest rates of pH non-compliance (Ikhsan et al., 2022). The cost differential compounds this inequality, as packaged water is hundreds to thousands of times more expensive per unit volume than tap water, disproportionately burdening marginalized communities who may pay premium prices for perceived water safety while remaining exposed to lower-quality sources for daily use (Zikrina et al., 2024).

This socioeconomic patterning of water access has direct public health consequences. The finding that tap water and unboiled gallon water, the sources most commonly consumed by lower-income urban households, recorded the most acidic pH values in this study reinforces the concern that regulatory non-compliance in distributed water supply systems disproportionately affects those least able to afford alternatives. Boiling remains an accessible mitigation strategy, but its consistent practice requires household resources including cooking fuel and time, which are themselves unequally distributed. Moreover, the reliance on refill gallon water among households unable to afford branded packaged products creates additional vulnerability given the documented quality failures in refill depot operations (Alfian et al., 2022). These findings underscore that water quality is not only a technical or regulatory issue, but a fundamentally social one, and that policy responses to physicochemical non-compliance must simultaneously address the underlying inequities in water access that shape household exposure to water quality risks.

Beyond issues of access and affordability, the accuracy of information provided to consumers also warrants attention. A particularly consequential finding concerns the discrepancy between labeled and field-measured pH values for two alkaline packaged water products. Brand A (labeled pH 8.6) and Brand E (labeled pH 8.8+) recorded measured values of 7.56 and 7.34 respectively, deviations exceeding one pH unit in both cases. The growth of alkaline packaged water consumption in Indonesia, driven by health-related marketing claims, makes this discrepancy practically significant: consumers making health-based purchasing decisions may not be receiving the product as described (Puspita et al., 2023). These findings point to the need for more rigorous post-market verification of pH claims under field-representative conditions and suggest that current consumer protection mechanisms for packaged drinking water in Indonesia warrant strengthening (Mitku & Endeshaw, 2022).

Beyond household-consumable water, the physicochemical burden of untreated domestic wastewater warrants separate consideration. While domestic wastewater samples recorded TDS and EC values below WHO maximum guidelines, their absolute ionic loads were the highest of all samples measured, underscoring the physicochemical impact of untreated grey water on receiving water bodies. Without adequate treatment, the discharge of domestic wastewater into drainage and surface water systems progressively degrades natural water quality in urban areas, compounding the water quality challenges already documented in the Bandung region (Widyarani et al., 2022). This concern is particularly acute given Indonesia's persistent limitations in centralized wastewater infrastructure, which have prompted growing interest in decentralized community-led treatment systems as a more feasible alternative for urban settings (Cecilia et al., 2024). Strengthening decentralized greywater treatment at the household or community level, coupled with public education on responsible detergent use, would represent an important step toward mitigating this cumulative burden on Indonesian urban water systems.

3.3 Limitations and recommendations

This study has several limitations that should be acknowledged when interpreting the findings. First, each water sample was measured only once at a single point in time, without temporal replication across different days or seasons. Water quality parameters, particularly pH and EC, are known to vary with temperature fluctuations, precipitation events, and diurnal cycles, meaning that the values reported here reflect conditions for each source. Second, the sample size of 14 water sources, while sufficient for a preliminary comparative assessment, limits the statistical generalizability of the findings. The absence of replication precluded the use of inferential statistical tests beyond Pearson correlation, and findings should therefore be interpreted as exploratory rather than conclusive. Third, the physicochemical parameters measured in this study provide an incomplete picture of overall water quality. Parameters such as dissolved oxygen (DO), biological oxygen demand (BOD), heavy metal concentrations, turbidity, and microbiological indicators were not assessed, and their inclusion in future studies would provide a more comprehensive evaluation. Fourth, packaged mineral water products were measured immediately upon container opening under ambient field conditions, which may not fully replicate the conditions under which consumers typically access these products. Fifth, this study assessed only five brands of commercially packaged mineral water, which represents a limited subset of the products available in the Indonesian market, broader conclusions about the packaged water industry as a whole should be made with caution. Finally, the study was conducted at two specific sites in Bandung, and findings may not be directly transferable to other urban highland settings in Indonesia without further investigation.

Based on the findings and limitations of this study, the following recommendations are proposed for future research and practice. From a research perspective, future studies should incorporate temporal replication, collecting samples across multiple dates, seasons, or times of day, to capture variability in physicochemical profiles and strengthen the reliability of comparative assessments. Expanding the parameter set to include microbiological indicators, heavy metals, dissolved oxygen, and turbidity would provide a more complete characterization of water quality across source categories. A larger sample size with a formal statistical comparison between source categories using nonparametric tests such as the Kruskal-Wallis test, would allow more robust inferential conclusions. Future studies examining packaged mineral water products should include a broader range of commercially available brands and measure pH at multiple time points after container opening, including 30 minutes, one hour, and 24 hours, to capture the effect of ambient CO_2 exposure on pH drift over time. Studies should also assess whether pH values on product labels correspond to measurements taken under standardized post-opening conditions rather than controlled production environments. From a policy and public health perspective, the findings highlight the need for strengthened monitoring of distributed tap water and refill gallon water depots in Bandung and other Indonesian urban areas.

Regulatory authorities should consider implementing post-market verification mechanisms for physicochemical claims on packaged drinking water product labels, particularly alkaline pH claims, using field-representative measurement protocols. Public health communication should emphasize the effectiveness and accessibility of boiling as a household water treatment intervention, especially for consumers relying on acidic gallon or tap water sources. Finally, investment in domestic wastewater treatment infrastructure in urban areas is recommended to reduce the physicochemical burden of untreated grey water on natural water bodies.

4. Conclusions

This study provides a field-based comparative assessment of physicochemical water quality across three functionally distinct source categories, within an urban highland setting in Bandung, Indonesia. The findings demonstrate that water source category is a primary determinant of physicochemical profile, with natural highland water consistently exhibiting the most favorable quality and domestic wastewater the least. Six of 14 samples recorded pH values below the minimum threshold mandated by Permenkes RI No. 2/2023 and WHO guidelines, including tap water and unboiled gallon water indicating that pH non-compliance extends beyond obviously contaminated sources into the everyday drinking water supply. The very strong positive correlation between EC and TDS ($r = 0.984$, $p < 0.001$) confirms EC as a reliable and cost-effective field proxy for TDS estimation across diverse water source types. A notable finding of this study is the systematic discrepancy between field-measured pH values and alkaline pH label claims on two commercially packaged mineral water products, with deviations exceeding one pH unit in both cases, a finding that raises important questions about the accuracy of product labeling and the adequacy of current consumer protection mechanisms in Indonesia. Taken together, these findings underscore the importance of systematic physicochemical monitoring across diverse water source categories, and highlight the need for strengthened regulatory oversight of distributed water supply systems and packaged water product claims in Indonesian urban settings.

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Author Contribution

Y. K. S., conceived the study, designed the research methodology, conducted formal analysis, curated the data, and led the writing of the manuscript. D. F., I. R., and N. F., participated in field data collection and investigation. W. L., provided academic supervision, conceptual guidance throughout the study, and contributed to the critical review and editing of the manuscript. All authors have read and approved the final version of the manuscript.

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The authors declare no conflict of interest.

Declaration of Generative AI Use
During the preparation of this work, the authors used Claude to assist with language refinement, clarity improvement, and academic writing organization. After utilizing this tool, the authors thoroughly reviewed and edited the content as necessary and assumed full responsibility for the accuracy, integrity, and originality of the publication's content.

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