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COMPARATIVE HYGIENIC ANALYSIS AND ECOLOGICAL SAFETY ASSESSMENT OF DRINKING WATER IN CENTRALIZED, PACKAGED AND AUTOMATED SUPPLY SYSTEMS

B. B. Rakhimov
M. Mamatqulova
M. Nakshamova
Sultonov Erkin Yoqubjon o‘g‘li
Tashkent State Medical University, Tashkent, Uzbekistan
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Abstract: Households increasingly combine piped water with packaged and vended water, but these supply systems are rarely compared using both hygienic and environmental criteria. Aim. To compare the hygienic quality, health risk and ecological safety of drinking water from centralized, packaged and automated (vending machine) supply systems. Methods. In a matched cross-sectional study, water from all three systems was sampled on the same day in 30 mahallas of Samarkand region in a warm and a cold season (180 samples). Physicochemical (including Pb, Cd, As, Cu and Zn) and microbiological indicators, the water quality index (WQI), hazard index (HI) and arsenic cancer risk (CR) for adults and children were determined, and environmental burdens per 1 m^3 of delivered water were estimated by a screening life cycle assessment. The results were combined into an integrated hygienic–ecological safety index (HESI). Results. The WQI rated tap water as good (40.9) and packaged (13.9) and vended water (10.3) as excellent, yet only 55.0% of packaged and 30.0% of vended samples were physiologically adequate. Microbiological non-compliance was 13.3%, 10.0% and 35.0%, respectively ($p = 0.002$), and was higher in the warm season. The HI for children slightly exceeded 1 only for tap water (1.07). Arsenic CR was acceptable (9.3×10^{-6} to 3.3×10^{-5}) but exceeded 10^{-4} in all systems with the 2025 US EPA toxicity values. Single-use PET water produced 168 kg CO_2-eq and 21.3 kg of plastic waste per 1 m^3, compared with 0.38 kg CO_2-eq for tap water, while vending machines withdrew 3.81 m^3 of water per 1 m^3 delivered. The HESI was 88.0 for tap, 83.4 for returnable 19-L, 73.3 for vended and 59.5 for single-use PET water. Conclusion. Improving the reliability of centralized supply, regulating vending machines and promoting returnable containers offer the greatest combined health and environmental benefit.
Keywords: drinking water; centralized water supply; packaged water; water vending machines; water quality index; health risk assessment; hazard index; life cycle assessment; plastic waste; ecological safety

1. Introduction

Access to safe drinking water is a basic determinant of health and a target of Sustainable Development Goal 6.1. In 2022, 2.2 billion people still lacked safely managed drinking water services (World Health Organization [WHO] & United Nations Children's Fund, 2023). At the

same time, households increasingly use several sources in parallel: piped water, packaged water and water from automated vending machines (WVMs). This choice is often driven by distrust of tap water rather than by objective evidence of its quality (Cohen & Ray, 2018; Doria, 2006).

Each system has specific hygienic weaknesses. Centralized water supply systems (CWS) are exposed to secondary contamination in ageing networks with intermittent supply, a problem well documented in low- and middle-income countries and in Central Asia (Bain et al., 2014; Bekturganov et al., 2016). Packaged water may release antimony and plastic particles from polyethylene terephthalate (PET) containers (Mason et al., 2018; Westerhoff et al., 2008). WVMs usually treat piped water by reverse osmosis (RO); they are frequently contaminated because of poor maintenance and produce demineralized water (Chaidez et al., 1999; Hile et al., 2021; Kozisek, 2020; Yeremin et al., 2023).

The systems also differ in environmental cost. Life cycle assessments (LCAs) show that bottled water requires hundreds to thousands of times more energy than tap water and has a much larger carbon footprint (Fantin et al., 2014; Garfí et al., 2016; Gleick & Cooley, 2009). A study in Barcelona estimated that switching from bottled to tap water would reduce resource and ecosystem impacts by more than three orders of magnitude with a minimal increase in health risk (Villanueva et al., 2021). Plastic packaging adds to global plastic waste (Geyer et al., 2017), and RO units discharge concentrate and withdraw more water than they deliver (Jones et al., 2019). Nevertheless, hygienic evaluations based on standards, water quality indices (WQI) and the risk methodology of the US Environmental Protection Agency (US EPA, 1989) are rarely applied to all systems used by the same population (Chidiac et al., 2023), and they are almost never combined with environmental indicators. In Uzbekistan, piped and packaged water are regulated by O'z DSt 950:2011 (Uzstandard, 2011) and Resolution No. 861 (Cabinet of Ministers of the Republic of Uzbekistan, 2019), whereas vended water has no specific requirements and local data are scarce (Utamuradova et al., 2024).

The aim of this study was to perform a comparative hygienic analysis and ecological safety assessment of drinking water from centralized, packaged and automated systems in Samarkand region. The objectives were (1) to compare the quality of matched samples, (2) to estimate health risks for adults and children, (3) to quantify environmental burdens per unit of delivered water and (4) to combine these results into an integrated index.

2. Materials and Methods

2.1. Study design and sampling

A matched cross-sectional study was carried out in 30 mahallas (neighbourhood communities; 20 urban and 10 peri-urban) of Samarkand city and adjacent districts. They were randomly selected among mahallas in which a household connection to the public supply, retail packaged water and a WVM within 500 m were all available. Sampling was conducted in the warm season (July–August 2025) and in the cold season (January–February 2026).

In each mahalla and season, three samples were taken on the same day. Tap water was collected from a household kitchen tap after 2–3 min of flushing (International Organization for Standardization [ISO], 2006d). Packaged water was purchased from a local retail outlet, alternating

single-use PET bottles (0.5–1.5 L) and returnable 19-L containers (30 samples of each type). Water from the nearest WVM was collected directly from the nozzle without flushing, to reflect consumer conditions. In total, 180 samples (60 per system) were analysed; 48 WVM samples (80.0%) came from machines with RO and ultraviolet (UV) units. Samples were transported at 4–8 °C and analysed within 6 h (microbiology) and 24 h (chemistry). In addition, 300 households (10 per mahalla) were interviewed about their main source of drinking water and the containers they used.

2.2. Laboratory analyses

Organoleptic and physicochemical indicators were determined by the methods of O'z DSt 950:2011 and Standard Methods (Baird et al., 2017). Lead, cadmium, arsenic, copper and zinc were determined by inductively coupled plasma mass spectrometry (ISO, 2016); limits of quantification were 0.05–0.5 µg/L, and recoveries of certified reference materials were 92–106%. Heterotrophic plate count at 22 °C (HPC; ISO, 1999), total coliforms and Escherichia coli (ISO, 2014), intestinal enterococci (ISO, 2000) and Pseudomonas aeruginosa (ISO, 2006c) were determined by membrane filtration or pour-plate methods. A harmonized criterion was applied to all systems: absence of the four indicator organisms in 100 mL (tap water) or 250 mL (packaged and vended water) and HPC ≤ 100 CFU/mL (Codex Alimentarius Commission, 2001; WHO, 2022).

2.3. Water quality index and health risk assessment

A weighted arithmetic WQI was calculated from 11 parameters (pH, TDS, hardness, Na^+, Cl^-, SO_4^{2-}, NO_3^-, F^-, Fe, turbidity and oxidizability), using O'z DSt 950:2011 values as standards. Values of 0–25, 26–50, 51–75, 76–100 and > 100 denote excellent, good, poor, very poor and unsuitable water, respectively (Brown et al., 1970; Tyagi et al., 2013).

Ingestion risk was assessed by the US EPA (1989) method. The chronic daily intake was CDI = (C × IR × EF × ED)/(BW × AT), with IR of 2 and 1 L/day, BW of 70 and 15 kg and ED of 24 and 6 years for adults and children, respectively. EF was 365 days/year, and AT was ED × 365 days for non-carcinogenic and 70 × 365 days for carcinogenic effects (US EPA, 2011). The hazard quotient was HQ = CDI/RfD and the hazard index HI = ΣHQ; values above 1 indicate a potential hazard. Reference doses (RfD, mg/kg/day) were 1.6 for nitrate as nitrogen (NO_3^-/4.427), 0.06 for fluoride, 5×10^{-4} for cadmium, 3×10^{-4} for arsenic, 0.04 for copper and 0.3 for zinc (US EPA, n.d.). For lead, which has no RfD, the widely used value of 3.5×10^{-3} was applied for comparability. It is derived from a tolerable weekly intake that has since been withdrawn (Joint FAO/WHO Expert Committee on Food Additives [JECFA], 2011). The lifetime cancer risk of arsenic (CR = CDI × SF, childhood plus adulthood) was calculated with SF = 1.5 $(mg/kg/day)^{-1}$. A sensitivity analysis applied the 2025 IRIS values (SF = 32 $(mg/kg/day)^{-1}$; RfD = 6×10^{-5} mg/kg/day; US EPA, 2025). CR of 10^{-6}–10^{-4} was considered acceptable.

2.4. Ecological safety assessment and integrated index

A screening-level LCA following ISO 14040 and ISO 14044 principles (ISO, 2006a, 2006b) was performed. The functional unit was 1 m^3 of drinking water delivered to the consumer, and the boundaries were cradle to consumer, without end-of-life credits. Five indicators were estimated: cumulative energy demand (CED), greenhouse gas (GHG) emissions, plastic waste, total water withdrawal and RO concentrate discharged. Data sources were the water utility (non-revenue water

31%), metering of 20 WVMs over 30 days (mean RO recovery 38%), weighing of containers, distributors (40 refills per 19-L container) and published LCAs (Fantin et al., 2014; Garfí et al., 2016; Gleick & Cooley, 2009). A grid emission factor of 0.50 kg CO_2/kWh was assumed. Packaged water was weighted by the volume shares reported in the household survey (72% from 19-L containers, 28% from single-use PET bottles).

Four hygienic sub-scores were expressed as the percentage of samples meeting the criteria for microbiological safety, chemical safety (HI for children ≤ 1), physiological adequacy (TDS 100–1000 mg/L and hardness 1.5–7.0 mmol/L) and organoleptic acceptability. Three ecological sub-scores were normalized linearly between zero burden (100 points) and a worst-case reference (0 points). The references were single-use PET water for GHG emissions (168 kg CO_2-eq/m^3) and plastic waste (21.3 kg/m^3), and 5 m^3/m^3 for water withdrawal. The integrated index was HESI = 0.6H + 0.4E, where H and E are the means of the hygienic and ecological sub-scores; equal weights were tested in a sensitivity analysis.

2.5. Statistical analysis

Because samples were matched by mahalla and day, continuous variables were compared with the Friedman test followed by Bonferroni-corrected Wilcoxon signed-rank tests. Binary outcomes were compared with Cochran's Q test followed by exact McNemar tests, and seasons with the χ^2 test. Analyses were performed in R version 4.4.1 (R Core Team, 2024); $p < 0.05$ was considered significant.

3. Results and Discussion

3.1. Sources of drinking water and physicochemical composition

In the household survey, tap water was the main source of drinking water for 41.3% of households, WVM water for 34.0% and packaged water for 24.7%. Thus, more than half of the connected households relied on non-centralized sources for drinking.

Tap water was moderately mineralized (TDS 526 ± 92 mg/L; hardness 5.51 ± 0.98 mmol/L). It met O'z DSt 950:2011 for all indicators except hardness, which exceeded 7.0 mmol/L in 8.3% of samples (Table 1). TDS was 2.4 times lower in packaged water and 4.0 times lower in vended water. The distribution of vended water was bimodal: RO machines delivered water with a mean TDS of 62 mg/L, and non-RO machines 404 mg/L. As a result, 63.3% of WVM samples had TDS below 100 mg/L and the mean pH fell to 6.84. Only 30.0% of vended and 55.0% of packaged samples were physiologically adequate, compared with 91.7% of tap samples. Long-term consumption of water poor in calcium and magnesium is undesirable, and minimum levels are recommended in several countries (Kozisek, 2005, 2020; WHO, 2022).

All toxic elements were far below WHO guideline values. Their highest levels occurred in tap water, reflecting groundwater composition and pipe corrosion. However, vended water contained 3.7 times more copper and 3.4 times more zinc than packaged water. This is consistent with the leaching of brass fittings and pumps by aggressive, poorly buffered RO permeate (Greenlee et al., 2009). Fluoride was below 0.7 mg/L in all samples. The WQI rated tap water as good (40.9) and packaged (13.9) and vended water (10.3) as excellent. Conventional indices reward low

concentrations and therefore rate demineralized water as the best (Chidiac et al., 2023), so the WQI alone is unsuitable for comparing systems with different treatment technologies.

Table 1. Organoleptic and physicochemical indicators of drinking water from centralized, packaged and automated supply systems (mean ± SD, n = 60 per system)

Indicator	Standard[a]	Centralized (CWS)	Packaged (PACK)	Vending machines (WVM)
pH	6.0–9.0	7.46 ± 0.21	7.18 ± 0.34	6.84 ± 0.47
Turbidity, mg/L	≤ 1.5	0.60 ± 0.31	0.21 ± 0.12	0.19 ± 0.11
Total dissolved solids, mg/L	≤ 1000	526 ± 92	221 ± 118	132 ± 158
Total hardness, mmol/L	≤ 7.0	5.51 ± 0.98	2.12 ± 1.21	1.34 ± 1.62
Calcium, mg/L	–	76.2 ± 13.9	28.6 ± 17.4	17.8 ± 22.6
Magnesium, mg/L	–	20.8 ± 5.1	8.4 ± 5.6	5.5 ± 6.9
Sodium, mg/L	≤ 200	39.8 ± 9.6	19.9 ± 14.2	12.6 ± 15.1
Chlorides, mg/L	≤ 350	47.5 ± 11.8	16.9 ± 10.3	12.8 ± 14.9
Sulfates, mg/L	≤ 500	146.2 ± 32.4	44.1 ± 27.6	31.5 ± 41.2
Nitrates (NO_3^-), mg/L	≤ 45	15.1 ± 6.8	4.8 ± 3.2	4.6 ± 5.9
Fluoride, mg/L	0.7–1.5	0.37 ± 0.09	0.19 ± 0.16	0.10 ± 0.12
Total iron, mg/L	≤ 0.3	0.13 ± 0.08	0.04 ± 0.03	0.03 ± 0.02
Permanganate oxidizability, mg O_2/L	≤ 5.0	1.88 ± 0.62	0.86 ± 0.41	0.64 ± 0.33
Lead, µg/L	≤ 10[b]	3.8 ± 2.1	1.2 ± 0.8	1.5 ± 1.1
Cadmium, µg/L	≤ 3[b]	0.42 ± 0.21	0.15 ± 0.09	0.18 ± 0.12
Arsenic, µg/L	≤ 10[b]	1.4 ± 0.7	0.8 ± 0.5	0.4 ± 0.3
Copper, µg/L	≤ 2000[b]	38 ± 22	6 ± 4	22 ± 15
Zinc, µg/L	–	64 ± 35	12 ± 8	41 ± 27
TDS < 100 mg/L, n (%)	–	0 (0)	7 (11.7)	38 (63.3)
Hardness < 1.5 mmol/L, n (%)	–	0 (0)	24 (40.0)	41 (68.3)

Indicator	Standard[a]	Centralized (CWS)	Packaged (PACK)	Vending machines (WVM)
Physiologically adequate[c], n (%)	–	55 (91.7)	33 (55.0)	18 (30.0)
WQI (class)	–	40.9 (good)	13.9 (excellent)	10.3 (excellent)

Note: [a] O'z DSt 950:2011; [b] WHO (2022) guideline values; [c] TDS 100–1000 mg/L and total hardness 1.5–7.0 mmol/L. Differences between systems were significant for all continuous indicators (Friedman test, $p < 0.001$). In post hoc tests, packaged and vending machine water did not differ in turbidity, nitrates, iron, lead or cadmium ($p > 0.05$). WQI – water quality index; TDS – total dissolved solids.

3.2. Microbiological quality

Microbiological non-compliance was found in 13.3% of tap, 10.0% of packaged and 35.0% of vended samples (Figure 1; Cochran's Q = 12.44, p = 0.002). Vended water failed more often than tap water (adjusted p = 0.044) and packaged water (adjusted p = 0.012), whereas tap and packaged water did not differ. In tap water, coliforms (8.3%) and E. coli (3.3%) predominated, which points to faecal ingress into the network (Bain et al., 2014). In vended water, elevated HPC (26.7%) and P. aeruginosa (15.0%) prevailed. This pattern is typical of biofilms on filters, tanks and nozzles (Flemming & Wingender, 2010) and agrees with studies in the United States (Chaidez et al., 1999; Hile et al., 2021). Among packaged waters, 19-L containers failed more often than PET bottles (4 of 30 vs 2 of 30 samples), reflecting the risks of washing and refilling.

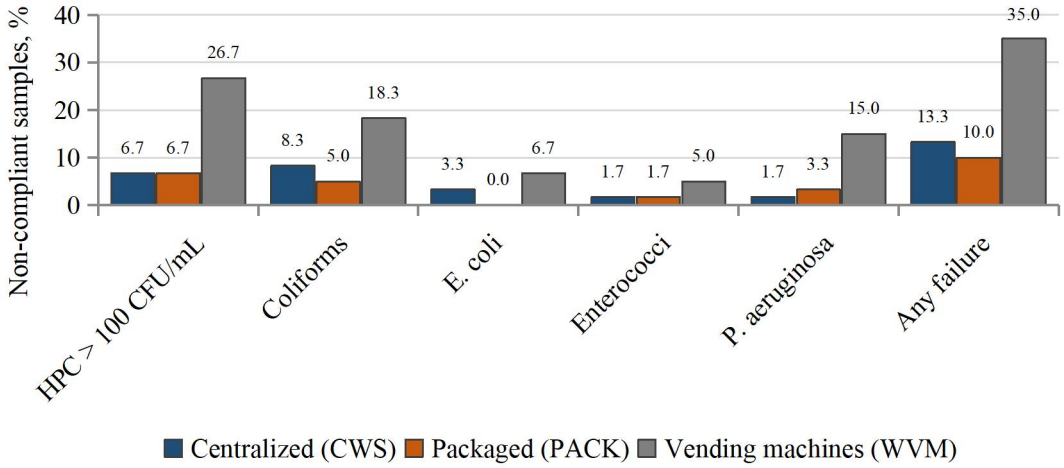


Figure 1. Frequency of microbiological non-compliance of drinking water from centralized, packaged and automated supply systems, % of samples (n = 60 per system)

Non-compliance was higher in the warm season than in the cold season (26.7% vs 12.2%; $\chi^2 = 5.98$, p = 0.014). The difference was most marked for vending machines (46.7% vs 23.3%), although it

was not significant within this system (p = 0.058). This calls for more frequent sanitation of machines in summer.

3.3. Health risk assessment

All individual HQs were below 1 (Table 2). The HI for adults ranged from 0.15 (WVM) to 0.46 (CWS). For children, it was 0.34 for vended, 0.49 for packaged and 1.07 for tap water, and it exceeded 1 in 36.7% of tap water samples. Fluoride (38.4%) and arsenic (29.1%) were the main contributors (Figure 2). These substances act on different target organs, and no target-organ-specific HQ exceeded 1. Moreover, fluoride was below its optimal range. The slight exceedance for children is therefore a screening signal for monitoring rather than evidence of harm. Nitrate contributed little when correctly expressed as nitrogen. Applying the RfD to NO_3^- concentrations, as is often done, would overestimate its HQ about 4.4-fold (Ward et al., 2018).

Table 2. Hazard quotients, hazard index and carcinogenic risk associated with ingestion of drinking water from the three supply systems

Parametr	RfD,mg/kg/day	CWS adults	CWS children	PACK adults	PACK children	WVM adults	WVM children
HQ nitrate (as N)	1.6	0.061	0.142	0.019	0.045	0.019	0.043
HQ fluoride	0.06	0.176	0.411	0.090	0.211	0.048	0.111
HQ lead	3.5×10^{-3}	0.031	0.072	0.010	0.023	0.012	0.029
HQ cadmium	5×10^{-4}	0.024	0.056	0.009	0.020	0.010	0.024
HQ arsenic	3×10^{-4}	0.133	0.311	0.076	0.178	0.038	0.089
HQ copper	0.04	0.027	0.063	0.004	0.010	0.016	0.037
HQ zinc	0.3	0.006	0.014	0.001	0.003	0.004	0.009
HI = ΣHQ	–	**0.46**	**1.07**	**0.21**	**0.49**	**0.15**	**0.34**
Samples with HI > 1, %	–	0	36.7	0	1.7	0	0

Parametr	RfD,mg/kg/day	CWS adults	CWS children	PACK adults	PACK children	WVM adults	WVM children
CR arsenic, SF = 1.5	–	2.1×10^{-5}	1.2×10^{-5}	1.2×10^{-5}	6.9×10^{-6}	5.9×10^{-6}	3.4×10^{-6}
CR arsenic, SF = 32[a]	–	4.4×10^{-4}	2.6×10^{-4}	2.5×10^{-4}	1.5×10^{-4}	1.3×10^{-4}	7.3×10^{-5}

Note: RfD – oral reference dose; HQ – hazard quotient; HI – hazard index; CR – cancer risk (adults: exposure duration 24 years; children: 6 years; averaging time 70 years); SF – oral slope factor, $(mg/kg/day)^{-1}$; [a] sensitivity analysis with the 2025 IRIS values for inorganic arsenic (US EPA, 2025). CWS – centralized, PACK – packaged, WVM – vending machine water.

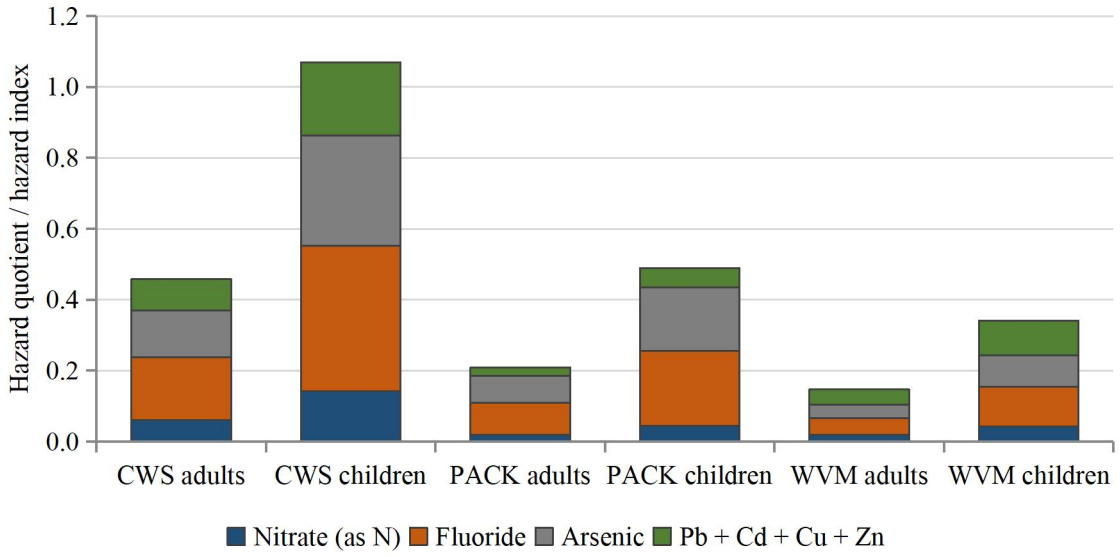


Figure 2. Contribution of individual contaminants to the hazard index (HI) for adults and children by supply system; the gridline at 1.0 corresponds to the threshold of potential non-carcinogenic effects

The lifetime arsenic CR was 3.3×10^{-5} for tap, 1.9×10^{-5} for packaged and 9.3×10^{-6} for vended water, all within the acceptable range. With the 2025 IRIS values, it increased to 6.9×10^{-4}, 4.0×10^{-4} and 2.0×10^{-4}, respectively. The HI for children rose to 2.32 for tap and 1.20 for packaged water. Arsenic concentrations were 7–25 times below the WHO guideline value, so the risk classification now depends strongly on the choice of toxicity values. Arsenic should therefore be a priority parameter in monitoring all systems.

3.4. Ecological safety and integrated assessment

Environmental burdens differed by up to three orders of magnitude (Table 3). Delivering 1 m^3 of tap water required 7.2 MJ and emitted 0.38 kg CO_2-eq. Single-use PET water required 5600 MJ and emitted 168 kg CO_2-eq, mainly because of bottle manufacture and distribution (Fantin et al.,

2014; Gleick & Cooley, 2009). Returnable 19-L containers reduced these burdens about sevenfold. A person drinking 2 L/day of single-use PET water generates about 15.5 kg of plastic waste per year (Geyer et al., 2017).

Vending machines had a low carbon footprint (3.2 kg CO_2-eq/m^3) but the poorest water efficiency. With 38% RO recovery and network losses, 3.81 m^3 of water was withdrawn per 1 m^3 delivered. The 1.63 m^3 of concentrate (TDS ≈ 845 mg/L) was discharged, which increases the salt load in an arid region (Jones et al., 2019).

Table 3. Environmental burdens per 1 m^3 of drinking water delivered to the consumer and integrated hygienic–ecological safety scores

Indicator	CWS	PET 0.5–1.5 L	19-L returnable	PACK, weighted[a]	WV M
Environmental burdens					
Cumulative energy demand, MJ/m^3	7.2	5600	820	2158	62
Greenhouse gas emissions, kg CO_2-eq/m^3	0.38	168	24.5	64.7	3.2
Plastic waste, kg/m^3	< 0.01	21.3	1.9	7.3	1.4
Total water withdrawal, m^3/m^3	1.45	2.90	2.20	2.40	3.81
RO concentrate discharged, m^3/m^3 (TDS, mg/L)	–	n.a.	n.a.	n.a.	1.63 (845)
Safety scores (0–100)					
Hygienic sub-index (H)	82.5	87.5	84.2	85.8	72.9
Ecological sub-index (E)	96.2	17.5	82.2	64.1	73.8
HESI = 0.6H + 0.4E	**88.0**	**59.5**	**83.4**	**77.1**	**73.3**
HESI = 0.5H + 0.5E	89.3	52.5	83.2	74.9	73.3

Note: [a] weighted by the household survey (72% of packaged water volume consumed from 19-L containers and 28% from single-use PET bottles); the hygienic sub-index of pooled packaged water is based on all 60 samples. n.a. – not assessed; RO – reverse osmosis; HESI – hygienic–ecological safety index.

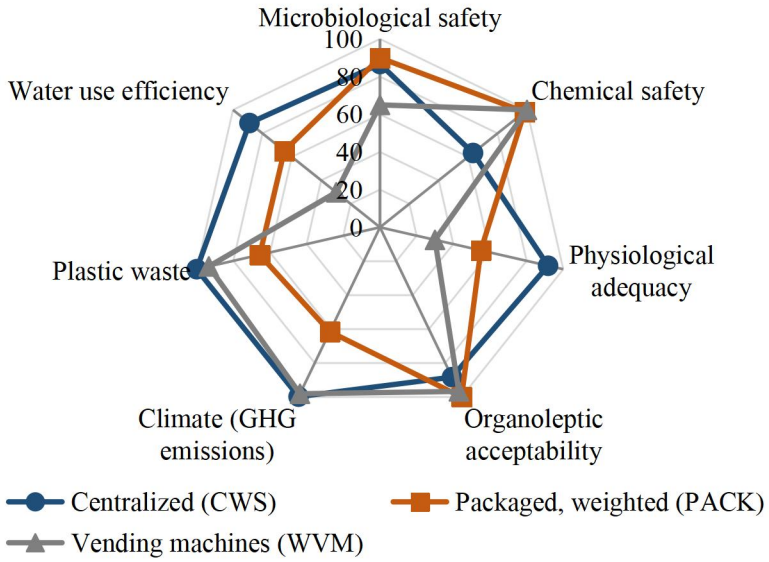


Figure 3. Hygienic and ecological safety profile of drinking water supply systems (sub-scores on a 0–100 scale; higher values indicate greater safety)

Each system showed a distinct weakness (Figure 3). Tap water was weakest in chemical safety for children and in microbiological reliability. Packaged water was weakest in ecological indicators and physiological adequacy. Vended water was weakest in microbiological safety, physiological adequacy and water efficiency. On hygienic indicators alone, packaged water ranked first (H = 85.8). After ecological indicators were included, centralized water had the highest HESI (88.0), followed by returnable 19-L (83.4), pooled packaged (77.1), vended (73.3) and single-use PET water (59.5). The ranking was unchanged with equal weights. This agrees with Villanueva et al. (2021), who found tap water preferable from a combined health and environmental perspective, provided its quality is controlled.

4. Conclusion

1. Packaged and vended water had lower mineralization and better WQI values than tap water, but only 55.0% and 30.0% of their samples, respectively, were physiologically adequate. The WQI alone is therefore insufficient for comparing supply systems.

2. Microbiological non-compliance was highest in vended water (35.0%, compared with 13.3% for tap and 10.0% for packaged water), with a predominance of HPC and P. aeruginosa, and it increased in the warm season.

3. Non-carcinogenic risk was acceptable except for a slight excess of the HI for children consuming tap water (1.07), without target-organ-specific exceedance. The arsenic cancer risk was acceptable with the established slope factor but exceeded 10^{-4} in all systems with the 2025 IRIS values.

4. Single-use PET water had about 440 times higher GHG emissions than tap water and generated 21.3 kg of plastic waste per 1 m^3, while vending machines withdrew 3.81 m^3 of water per 1 m^3 delivered. Centralized water had the highest HESI (88.0). Improving its reliability, regulating the

maintenance, remineralization and water efficiency of vending machines and promoting returnable containers are recommended as priority measures.

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