

Article

Biogenic Compounds and ATP Measurement as Indicators for Assessing Operational Risk and Biological Stability of Tap Water

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Abstract

This study assessed the quality and physicochemical and biological stability of tap water in the Rzeszow distribution system during the 2023–2024 autumn–winter season. Samples were collected at the water treatment plant and from taps in selected public buildings. The results showed that the water met drinking water standards and was chemically and physically stable (Langelier index Saturation Index from -0.5 to 0.5 ; turbidity <0.8 NTU), minimising the risk of scale formation and operational problems. However, complete biological stability was not achieved, as the concentrations of both nitrogen ($N > 0.2$ mg/L) and phosphorus (>0.01 mg/L) exceeded the recommended thresholds, only biodegradable organic carbon remained low (BDOC < 0.25 mg C/L). This underscores that maintaining full biological stability throughout a distribution system remains a highly challenging task due to nutrient availability. The absence of indicator bacteria (*Escherichia coli*, *coliform bacteria*) does not guarantee complete safety, as increases in total bacterial counts were observed in indoor systems. The results underscore the importance of regular and comprehensive monitoring—including ATP and phosphorus measurements—to ensure water safety and protect public health.

Keywords: tap water quality; drinking water monitoring; water stability; distribution system; ATP measurement; phosphorus

1. Introduction

The high-quality and sufficient drinking water is essential for public health and human well-being. The European Union (EU) policy on drinking water quality (the recast Drinking Water Directive (DWD) [1] entered into force in January 2021) ensures that water intended for human consumption can be consumed safely, leading to a high level of human health protection.

Therefore, one of the main pillars of EU drinking water policy is to ensure efficient and effective monitoring, assessment and enforcement of drinking water quality in order to avoid the loss of recommended water quality for consumers using mainly the collective water supply system.

Thus, it is extremely important to properly operate and manage the whole collective water supply system. Therefore, it requires continuous monitoring of water quality at all stages, beginning from water collection, through treatment at water treatment plant (WTP), pumping, ending with its distribution (taking into account both the external water supply network and internal building installations).



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Therefore, the quality of tap water and the possibility of secondary contamination of drinking water are influenced by many diverse factors, including the origin and sanitary condition of the treated raw water [2–4], treatment technology and disinfectants used [5], water corrosivity, type of installation pipe materials used [6,7], the method of operation and technical condition of the installation and devices [8] and also the time of water residence inside the water supply network called water age [9].

The age of water is defined as the time from the moment when water is pumped into the water supply system until it is consumed by consumers. Lack of water intake for a long time and stagnation can significantly affect the growth of microorganisms, which in turn leads to a deterioration of organoleptic parameters such as taste, odour and colour, throughout the distribution system. Furthermore, these factors directly contribute to a reduction in the concentration of disinfectants in water [10], which are used to protect systems against secondary microbial growth. In addition, water temperature and the content of organic substances in water also have a significant impact regarding water deterioration.

However, the most common causes of changes in water quality in the distribution network, which are responsible for secondary contamination of drinking water present in the water supply network, are corrosion products, sediments (processes causing the formation of mineral deposits) and the so-called biofilm [11,12].

Biofilm is formed by layers of various multiplying microorganisms adhering to the internal surfaces of pipes, whose specific structure protects them from the action of disinfectants [13]. Therefore, pathogenic microorganisms, such as *Escherichia coli*, *Pseudomonas aeruginosa*, *Legionella pneumophila* or *Clostridium perfringens* present in the biofilm, significantly pose a significant health risk to consumers (including acute gastroenteritis and diarrhea), especially those with compromised immune systems, the elderly and children. Additionally, as a result of the reduced water intake or even shutdown of internal building installations, the risk of pathogens, such as *Legionella* bacteria, drastically increases [14,15].

In order to avoid it, the water quality control system is based on a list of parameters and parametric values. For example, in Poland, the applicable implementing act on drinking water quality is regulated by the Regulation of the Minister of Health of 7 December 2017 on the quality of water intended for human consumption [16], in compliance with EU regulations. According to this document, water should not contain pathogenic microorganisms, parasites or other living organisms [17]. Nevertheless, in practice, virtually every water supply system undergoes changes in the chemical and biological composition of water during its transport from the WTP to consumers. Therefore, in some undesirable cases, water can become a carrier of pathogenic microorganisms and contain exceeded concentrations of selected substances present in tap water.

Therefore, in order to prevent and reduce such incidents, the water introduced into the water supply system must be chemically and biologically stable in order to minimise the risk of secondary contamination in the supply system. Lack of stability is defined as the risk associated with failure to maintain the required values of physicochemical parameters of water quality in the water supply network (Table 1).

Table 1. The measures and technologies in assessing and ensuring chemical and biological stability of drinking water in a distribution system [17–24].

Stability Assessment	Method	Technology	Stability Criterion	Purpose
Physical	Turbidity	Water turbidity measurement	<0.8–1 NTU	Evaluation of water clarity
Chemical	Langelier Saturation Index (LSI) Ryznar Stability Index (RSI) Strocker Index (SI)	Measurement of alkalinity and pH	$-0.5 < \text{LSI} < 0.5$ $6 < \text{RSI} < 7$ $\text{SI} = 0$	Evaluation of the scaling or corrosive tendency of water
	Biogenic compounds: Assimilable and Biodegradable Dissolved Organic Carbon (AOC/BDOC), phosphates and the sum of inorganic nitrogen compounds	Measurement of content: TOC DOC P-PO_4^{3-} N-NH_4^+ N-NO_2^- N-NO_3^-	The stability conditions $\text{BDOC} \leq 0.25 \text{ mg C/L}$ $\text{N}_{\text{inorg.}} \leq 0.2 \text{ mg N/L}$ $\text{P} \leq 0.01 \text{ mg P-PO}_4^{3-} / \text{L}$	Estimation of biological stability of water as an acceptable level; water quality requires monitoring (possibility of changes in water quality in the system); biologically unstable water indicates a high probability of secondary water contamination.
Biological	Biofilm monitoring	Pipe coupons, sensors	Qualitative studies of biofilm using instrumental methods	Assessment of biofilm formation and prediction of possible secondary water contamination
	Microbiological quality of water	Measurement of the total number of bacteria—HTP method using R2A Agar <i>Escherichia coli</i> and <i>Enterococcus</i> —using the membrane filtration procedure	The total number of bacteria at $37^\circ\text{C} < 20 \text{ CFU/mL}$ $22^\circ\text{C} < 200 \text{ CFU/mL}^*$ <i>Escherichia coli</i> : 0 CFU/100 mL <i>Enterococcus</i> : 0 CFU/100 mL	Water safely for drinking purposes

* It is recommended that the total number of microorganisms is not exceed: 100 CFU/1 mL in water entering the water supply network and 200 CFU/1 mL at the consumer's tap.

Effective prevention of secondary water contamination during distribution is particularly challenging, especially in old, extensive, and oversized water supply systems. In practice, experience shows that systems designed to detect outbreaks of waterborne diseases are generally ineffective in countries at all levels of socioeconomic development. Failure to detect such outbreaks does not guarantee their absence and such drinking water should not be considered safe. Increased public awareness and their growing expectations regarding the quality of life, and consequently, the quality of water [25], force water and sewage companies to adapt treatment technologies and produce good quality drinking water that meets applicable standards [26], mostly by strict monitoring and assessment of tap water [24]. However, it should be emphasised that constant monitoring is also extremely important at consumer drinking water collection points. Thus, water quality monitoring plays a key role in ensuring consumer safety. Therefore, strict and comprehensive monitoring should encompass the entire drinking water distribution system, from the water treatment plant, through the water distribution subsystem, to the end consumer.

Therefore, given the challenges of secondary contamination in drinking water distribution systems, this study aimed to assess changes in tap water quality at selected collection points in the city of Rzeszów. A comprehensive assessment of physicochemical and biological stability was conducted to determine whether water intended for human consumption remains safe for residents. The analysis also included additional parameters not routinely

included in standard water quality monitoring but that may indicate an increased risk of compromised sanitary safety.

2. Materials and Methods

2.1. Study Area—Water Sampling

The study was performed on a water supply network in Rzeszów—the largest city in Southeastern Poland. The analysed water supply network has a total length of approximately 900 km, consisting of main pipelines (50 km), distribution pipelines (530 km) and household connections (330 km). The main pipelines are made of cast iron and steel, while the distribution pipelines consist of cast iron, steel, PE and PVC. Household connections are mainly made of galvanized steel, cast iron, PE and PVC. The analysed water supply network consists of four mains transporting treated water. The water treatment plant is supplied with surface water. A detailed flow chart of the water treatment process is presented in Figure 1.

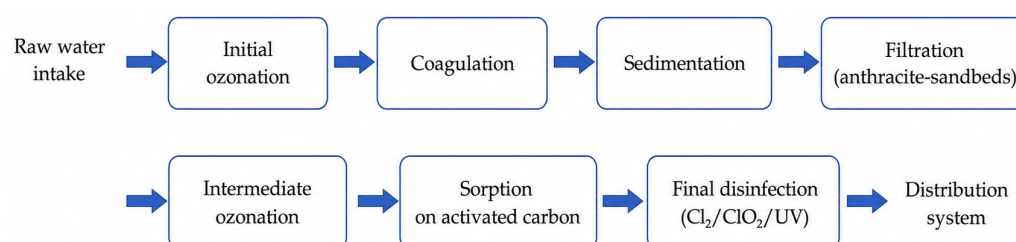


Figure 1. Technological scheme of the water treatment process.

Sampling was conducted during the autumn and winter seasons under aseptic conditions at both the water treatment plant and selected points within the drinking water distribution network (public buildings) (Figure 2). Sampling points P-1–P-6 are routinely used by sanitary authorities for water quality assessment in the city, confirming their representativeness. Samples were collected twice per month in accordance with the guidelines for water sampling for laboratory analysis specified in PN-EN ISO 19458 [27]. The autumn–winter period was selected due to variable hydraulic conditions, lower water temperatures and extended water residence time, which may enhance the occurrence and detection of water quality changes within the distribution system. Water samples were collected directly from tap outlets into sterile, autoclaved 1-L glass bottles. Prior to sampling, tap outlets were flame-sterilized and flushed at full flow for 5 min. Samples were transported to the laboratory under refrigerated conditions and analysed immediately upon arrival.

2.2. Chemical Analysis

Research procedures for determining the physicochemical quality of water were carried out in accordance with the standards and guidelines of the producers (Table 2).

Table 2. Standards and analytical procedures applied in the physicochemical water quality assessment.

Parameter	Unit	Analytical Method/Standard
pH	-	ELMETRON CX-505 (ELMETRON GP, Zabrze, Poland)
Colour	mg Pt/L	Spectrophotometric method using a Hach-Lange DR 5000 spectrophotometer (Hach Company, Loveland, CO, USA)
Turbidity	NTU	2100P ISO TURBIDIMETER HACH (Hach Company, Loveland, CO, USA)

Table 2. Cont.

Parameter	Unit	Analytical Method/Standard
TOC	mg C/L	TOC analyser Sievers 5310 C (SUEZ, Boulder, CO, USA);
Ammonium nitrogen	mg N-NH ₄ ⁺ /L	Spectrophotometric method 8155 (sachet tests—Ammonia Salicylate (1) and Cyanurate (2)) using a Hach-Lange DR 5000 spectrophotometer
Nitrite nitrogen	mg N-NO ₂ ⁻ /L	Colorimetric method by Nitrite Test Merck 1.14408 (Merck KGaA (Darmstadt, Germany))
Nitrate nitrogen	mg N-NO ₃ ⁻ /L	Spectrophotometric method 8039 (sachet tests—NitraVer5) using a Hach-Lange DR 5000 spectrophotometer
Phosphates	mg P-PO ₄ ³⁻ /L	Spectrophotometric method 8048 (sachet tests—PhosVer3) using a Hach-Lange DR 5000 spectrophotometer

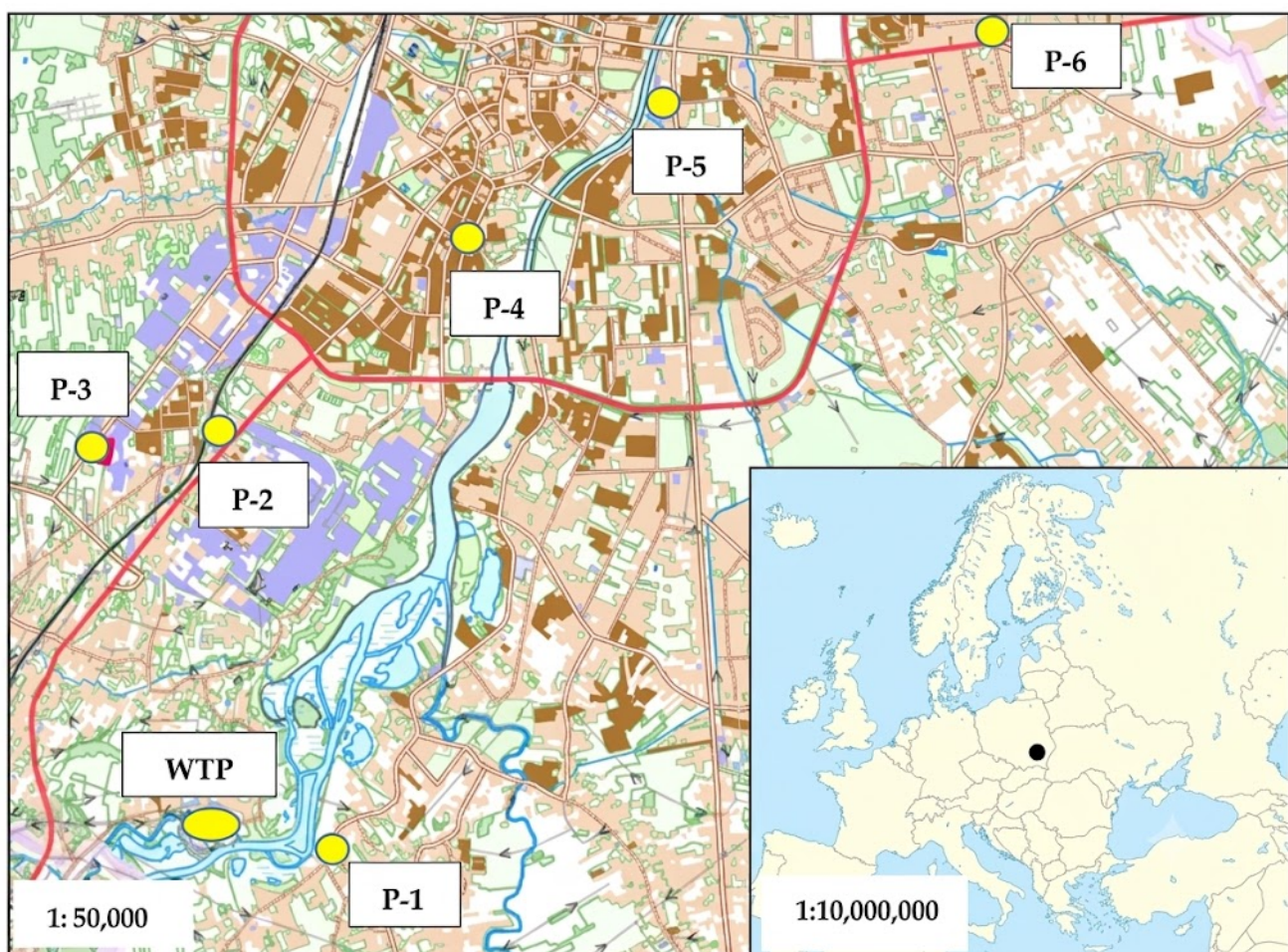


Figure 2. Localisation of water intake measurement points (P1–P6) and the water treatment plant (WTP) within the water supply network of the city of Rzeszow (distances of individual measurement points from the WTP are as follows: P-1—0.9 km; P-2 and P-3—2.4 km; P-4—4.1 km; P-5—5.4 km; and P-6—7.3 km).

2.3. Microbial Analysis

Research procedures for determining the microbiological quality of water were carried out in accordance with the standards and manufacturers' guidelines (Table 3).

Table 3. Methods of assessing the microbiological quality of tap water.

Parameter	Unit	Analytical Method/Standard
The total number of bacteria at 37 °C and at 22 °C	CFU/mL	HTP method using R2A Agar (CM0906) manufactured by Oxoid Thermo Scientific (Oxford, UK) (incubation for 7 days)
<i>Escherichia coli</i>	CFU/100 mL	Membrane filtration procedure using Chromocult® Coliform Agar (MERCK, Warsaw, Poland)
<i>Enterococcus</i>	CFU/100 mL	Membrane filtration procedure using Slanetz and Bartley Agar (MERCK, Poland)
ATP concentration	RLU/100 µL	Luminometric method; determination according to protocol Promega https://pl.promega.com/resources/protocols/technical-manuals/0/glomax-2020-luminometer-protocol/ (accessed on 1 December 2025) LuminUltra 20/20

2.4. Assessment of Tap Water Stability

2.4.1. Physical Stability of Water

The physical stability of water was assessed based on turbidity values. Water was considered physically stable when turbidity did not exceed 0.8 NTU, in accordance with criteria proposed in the literature [28,29].

2.4.2. Chemical Stability of Water

Chemical stability of water was assessed using the Langelier Saturation Index (LSI), calculated according to Equations (1) and (2):

$$LSI = pH_n - pH \quad (1)$$

$$pH_n = 11.39 - 2\log A \quad (2)$$

where pH is the measured pH of the tested water, pH_n is the pH corresponding to the calcium carbonate equilibrium, and A denotes the concentration of bound carbon dioxide (CO_2) expressed in mg/L. Based on the obtained LSI values, the chemical stability of water was classified as follows:

LSI < 0—chemically unstable water with a tendency to precipitate $CaCO_3$;

LSI $\approx$ 0 (−0.5 < LSI < 0.5)—chemically stable water;

LSI > 0—chemically unstable water with a tendency to dissolve $CaCO_3$ deposits.

2.4.3. Biological Stability of Water

Biologically stable water is defined as water in which the microflora does not change during distribution, or at least to an extent that does not adversely affect consumer safety or aesthetic perception or does not cause technical system failure, either on a spatial or temporal scale, at any point of drinking water distribution, including the consumer's tap. The biological stability of the water was assessed based on the content of biogenic compounds: carbon, nitrogen and phosphorus. According to the literature data [30,31], the following threshold values for biological stability were adopted: biologically dissolved organic carbon (BDOC) $\leq$ 0.25 mg C/L; inorganic nitrogen ($N_{inorg.}$) $\leq$ 0.2 mg N/L; and phosphorus (P) $\leq$ 0.01 mg P- PO_4^{3-} /L. The biodegradable organic carbon content was estimated based on data presented in [30], assuming that the BDOC and DOC content in water is described by the relationship: BDOC = 9% DOC, with DOC accounting for 80% TOC. Water was considered biologically stable if at least two of the three criteria were met (Table 4).

Table 4. Assessing criteria for the biological stability of water [32].

Biologically stable water—acceptable level of water safety if:	
$\text{BDOC} \leq 0.25 \text{ mg C/L AND } \text{N}_{\text{inorg.}} \leq 0.2 \text{ mg N/L AND } \text{P} \leq 0.01 \text{ mg P-PO}_4^{3-} / \text{L}$	OR
$\text{BDOC} \leq 0.25 \text{ mg C/L AND } \text{N}_{\text{inorg.}} \leq 0.2 \text{ mg N/L AND } \text{P} > 0.01 \text{ mg P-PO}_4^{3-} / \text{L}$	OR
$\text{BDOC} \leq 0.25 \text{ mg C/L AND } \text{N}_{\text{inorg.}} > 0.2 \text{ mg N/L AND } \text{P} \leq 0.01 \text{ mg P-PO}_4^{3-} / \text{L}$	OR
$\text{BDOC} > 0.25 \text{ mg C/L AND } \text{N}_{\text{inorg.}} \leq 0.2 \text{ mg N/L AND } \text{P} \leq 0.01 \text{ mg P-PO}_4^{3-} / \text{L}$	
Water requires monitoring, if:	
$\text{BDOC} > 0.25 \text{ mg C/L AND } \text{N}_{\text{inorg.}} > 0.2 \text{ mg N/L AND } \text{P} \leq 0.01 \text{ mg PO}_4^{3-} / \text{L}$	OR
$\text{BDOC} > 0.25 \text{ mg C/L AND } \text{N}_{\text{inorg.}} \leq 0.2 \text{ mg N/L AND } \text{P} > 0.01 \text{ mg PO}_4^{3-} / \text{L}$	OR
$\text{BDOC} \leq 0.25 \text{ mg C/L AND } \text{N}_{\text{nieorg.}} > 0.2 \text{ mg N/L AND } \text{P} > 0.01 \text{ mg PO}_4^{3-} / \text{L}$	
Biologically unstable water—high probability of secondary water contamination, if:	
$\text{BDOC} > 0.25 \text{ mg C/L AND } \text{N}_{\text{inorg.}} > 0.2 \text{ mg N/L AND } \text{P} > 0.01 \text{ mg PO}_4^{3-} / \text{L}$	

3. Results and Discussion

3.1. Analysis of the Physicochemical Quality of Tap Water

Water leaving the water treatment plant (WTP) and samples collected at various intake points within the distribution network (P-1–P-6) met the requirements for water intended for human consumption (Tables 3 and 4). The average turbidity values of the analysed water samples ranged from 0.23 to 0.56 NTU, remaining below the 0.8 NTU threshold adopted for the assessment of physical stability. Therefore, analysed water can be classified as physically stable. Single exceedances of the stability criterion were observed at sampling points P-1 and P-6 during the autumn period; however, turbidity values did not exceed the regulatory limit of 1 NTU for drinking water (Tables 5 and 6).

The colour of tap water was acceptable to consumers and did not exceed 15 mg Pt/L in any of analysed samples. Mean values ranged from 0.33 to 1.67 mg Pt/L, with the highest value (8 mg Pt/L) recorded at point P-1 in autumn, which also had the highest total organic carbon (TOC) levels (3.44 mg/L in autumn; 5.99 mg/L in winter). Elevated values may result from local processes in the distribution network, such as leaching of organic matter from sediments due to flow changes or biofilm detachment, which can increase organic content, support heterotrophic microbial growth and promote disinfection by-product formation, reducing microbiological stability [33]. Seasonal fluctuations were also observed in physicochemical parameters, particularly electrical conductivity, which indicated moderate salinity typical of treated surface waters. Values were lower in winter (517–545 $\mu\text{S/cm}$) than in autumn (650–673 $\mu\text{S/cm}$), most likely due to reduced water temperature, lower biological activity and limited ionic transformations. The corresponding seasonal trends were observed for inorganic ions: average chloride and sulfate concentrations were 31 mg Cl^- / L and 38 mg $\text{SO}_4^{2-} / \text{L}$, respectively, in winter, compared with 43 mg Cl^- / L and 42 mg $\text{SO}_4^{2-} / \text{L}$, respectively, in autumn (Wilcoxon test: $p = 0.016$ for both chlorides and sulfates). Similarly, total and carbonate hardness decreased from 308 and 202 mg CaCO_3 / L in autumn to 263 and 168 mg CaCO_3 / L in winter (Wilcoxon test: $p = 0.016$). Overall, winter values decreased on average by 18% for conductivity, 38% for chlorides, 10% for sulfates, 15% for total hardness and 17% for carbonate hardness (Tables 5 and 6). These results demonstrate clear seasonal fluctuations in water mineralisation, which was statistically confirmed by the Wilcoxon signed-rank test applied to conductivity and major ion concentrations ($p < 0.05$). These fluctuations are primarily driven by lower temperatures

and reduced biogeochemical activity in winter. Lower mineralisation can enhance chemical stability, but very low calcium and bicarbonate levels may increase corrosion risk in the distribution network [34].

Table 5. Summary of physicochemical parameters of tap water during the autumn period ($n = 6$).

Parameter	Unit	WTP	P-1	P-2	P-3	P-4	P-5	P-6
		Mean $\pm$ SD and Range (Min–Max)						
pH	-	7.83 $\pm$ 0.12 (7.70–7.92)	7.80 $\pm$ 0.21 (7.48–8.05)	7.87 $\pm$ 0.14 (7.75–8.04)	7.51 $\pm$ 0.47 (7.30–7.89)	7.79 $\pm$ 0.29 (7.28–8.03)	7.63 $\pm$ 0.35 (7.11–7.92)	7.65 $\pm$ 0.41 (6.97–8.01)
Colour	mg Pt/L	<5.00	2.00 $\pm$ 3.46 (0.00–8.00)	1.40 $\pm$ 1.14 (0.00–3.00)	0.80 $\pm$ 1.30 (0.00–3.00)	0.20 $\pm$ 0.45 (0.00–1.00)	0.40 $\pm$ 0.55 (0.00–1.00)	0.60 $\pm$ 0.89 (0.00–2.00)
Conductivity	μ S/cm	655 $\pm$ 84.9 (562–727)	672 $\pm$ 118.5 (529–778)	650 $\pm$ 96.29 (542–730)	673 $\pm$ 115.6 (529–759)	669 $\pm$ 105.2 (552–751)	668 $\pm$ 81.03 (577–742)	669 $\pm$ 95.53 (553–748)
Turbidity	NTU	<0.2	0.53 $\pm$ 0.21 (0.34–0.85)	0.34 $\pm$ 0.16 (0.17–0.56)	0.38 $\pm$ 0.12 (0.22–0.54)	0.40 $\pm$ 0.18 (0.21–0.69)	0.36 $\pm$ 0.06 (0.31–0.45)	0.56 $\pm$ 0.29 (0.26–0.92)
Nitrites	mg N-NO ₂ /L	<0.05	0.00 $\pm$ 0.00 (0.00–0.00)	0.0003 $\pm$ 0.00 (0.00–0.002)	0.00 $\pm$ 0.00 (0.00–0.00)	0.00 $\pm$ 0.00 (0.00–0.00)	0.00 $\pm$ 0.00 (0.00–0.00)	0.0038 $\pm$ 0.00 (0.00–0.019)
Ammonium nitrogen	mg N-NH ₄ ⁺ /L	- *	0.01 $\pm$ 0.00 (0.00–0.03)	0.02 $\pm$ 0.00 (0.00–0.06)	0.00 $\pm$ 0.00 (0.00–0.01)	0.01 $\pm$ 0.00 (0.00–0.05)	0.02 $\pm$ 0.00 (0.00–0.10)	0.01 $\pm$ 0.00 (0.00–0.03)
Nitrates	mg N-NO ₃ /L	1.79 $\pm$ 0.16 (1.69–2.03)	1.48 $\pm$ 0.48 (1.00–2.00)	1.66 $\pm$ 0.38 (1.30–2.20)	1.38 $\pm$ 0.48 (0.90–2.10)	1.60 $\pm$ 0.24 (1.30–1.90)	1.40 $\pm$ 0.29 (1.00–1.70)	1.58 $\pm$ 0.71 (1.00–2.70)
Alkalinity	mval/L	-	3.98 $\pm$ 0.36 (3.4–4.4)	4.02 $\pm$ 0.50 (3.40–4.70)	4.02 $\pm$ 0.52 (3.30–4.70)	4.12 $\pm$ 0.56 (3.20–4.70)	4.06 $\pm$ 0.60 (3.10–4.70)	4.00 $\pm$ 0.59 (3.40–4.70)
Total hardness	mg CaCO ₃ /L	279 $\pm$ 25.73 (250–300)	318 $\pm$ 34.93 (280–368)	322 $\pm$ 33.81 (274–360)	314 $\pm$ 46.76 (302–380)	324 $\pm$ 48.25 (280–405)	301 $\pm$ 48.83 (251–380)	298 $\pm$ 28.05 (266–332)
Chlorides	mg Cl ⁻ /L	36 $\pm$ 4.72 (29–40)	45 $\pm$ 9.42 (38–56)	46 $\pm$ 9.13 (35–54)	46 $\pm$ 7.60 (39–57)	45 $\pm$ 10.06 (35–58)	42 $\pm$ 9.17 (33–55)	42 $\pm$ 6.20 (35–49)
Phosphates	mg P-PO ₄ ³⁻ /L	-	0.14 $\pm$ 0.14 (0.01–0.30)	0.16 $\pm$ 0.13 (0.06–0.31)	0.20 $\pm$ 0.35 (0.01–0.83)	0.13 $\pm$ 0.11 (0.03–0.28)	0.09 $\pm$ 0.06 (0.02–0.18)	0.17 $\pm$ 0.20 (0.01–0.51)
Sulphates	mg SO ₄ ²⁻ /L	39 $\pm$ 6.14 (32–44)	40 $\pm$ 11.37 (23–47)	42 $\pm$ 7.29 (32–48)	43 $\pm$ 7.52 (33–50)	43 $\pm$ 7.16 (39–50)	43 $\pm$ 7.07 (33–48)	44 $\pm$ 6.23 (35–49)
Free chlorine	mg Cl ₂ /L	-	0.01 $\pm$ 0.01 (0.00–0.02)	0.05 $\pm$ 0.02 (0.03–0.06)	0.03 $\pm$ 0.02 (0.02–0.06)	0.02 $\pm$ 0.02 (0.00–0.03)	0.03 $\pm$ 0.01 (0.02–0.03)	0.06 $\pm$ 0.05 (0.02–0.11)
TOC	mg C/L	1.83 $\pm$ 0.12 (1.7–1.9)	2.16 $\pm$ 0.74 (1.74–3.44)	2.16 $\pm$ 0.17 (1.99–2.40)	1.96 $\pm$ 0.16 (1.77–2.20)	2.02 $\pm$ 0.07 (1.94–2.05)	2.17 $\pm$ 0.29 (1.81–2.60)	1.91 $\pm$ 0.15 (1.86–2.11)
BDOC	mg C/L	0.13 (0.12–0.14)	0.16 (0.12–0.25)	0.16 (0.14–0.17)	0.14 (0.13–0.16)	0.15 (0.14–0.15)	0.16 (0.13–0.19)	0.14 (0.12–0.15)

* Note: “-” denotes missing data.

Table 6. Summary of physicochemical parameters of tap water during the winter period ($n = 6$).

Parameter	Unit	WTP	P-1	P-2	P-3	P-4	P-5	P-6
		Mean $\pm$ SD and Range (Min–Max)						
pH	-	7.63 $\pm$ 0.33 (7.27–7.87)	7.51 $\pm$ 0.26 (7.26–7.78)	7.88 $\pm$ 0.17 (7.69–8.00)	7.90 $\pm$ 0.19 (7.70–8.08)	7.90 $\pm$ 0.10 (7.81–8.01)	7.89 $\pm$ 0.11 (7.78–7.99)	7.88 $\pm$ 0.11 (7.77–7.99)
Colour	mg Pt/L	<5.00	0.33 $\pm$ 0.58 (0.00–1.00)	1.67 $\pm$ 2.89 (0.00–5.00)	1.00 $\pm$ 1.73 (0.00–3.00)	0.33 $\pm$ 0.58 (0.00–1.00)	0.33 $\pm$ 0.58 (0.00–1.00)	1.00 $\pm$ 1.73 (0.00–3.00)
Conductivity	μ S/cm	545 $\pm$ 125.5 (453–688)	528 $\pm$ 69.5 (451–586)	517 $\pm$ 73.4 (455–598)	535 $\pm$ 88.2 (444–620)	534 $\pm$ 85.6 (447–618)	527 $\pm$ 78.1 (455–610)	538 $\pm$ 86.9 (462–633)
Turbidity	NTU	<0.20	0.35 $\pm$ 0.07 (0.27–0.41)	0.40 $\pm$ 0.07 (0.32–0.46)	0.34 $\pm$ 0.21 (0.16–0.57)	0.23 $\pm$ 0.10 (0.12–0.32)	0.23 $\pm$ 0.15 (0.13–0.40)	0.38 $\pm$ 0.19 (0.23–0.59)
Nitrites	mg N-NO ₂ /L	<0.05	0.00 $\pm$ 0.00 (0.00–0.00)	0.00 $\pm$ 0.00 (0.00–0.00)	0.00 $\pm$ 0.00 (0.00–0.00)	0.00 $\pm$ 0.00 (0.00–0.00)	0.00 $\pm$ 0.00 (0.00–0.00)	0.00 $\pm$ 0.00 (0.00–0.00)
Ammonium nitrogen	mg N-NH ₄ ⁺ /L	0.00 $\pm$ 0.00 (0.00–0.00)	0.01 $\pm$ 0.01 (0.00–0.02)	0.00 $\pm$ 0.00 (0.00–0.00)	0.00 $\pm$ 0.00 (0.00–0.00)	0.00 $\pm$ 0.00 (0.00–0.00)	0.00 $\pm$ 0.00 (0.00–0.00)	0.00 $\pm$ 0.01 (0.00–0.01)

Table 6. Cont.

Parameter	Unit	WTP	P-1	P-2	P-3	P-4	P-5	P-6
		Mean $\pm$ SD and Range (Min–Max)						
Nitrates	mg N-NO ₃ /L	1.79 $\pm$ 0.02 (1.76–1.80)	1.73 $\pm$ 0.25 (1.50–2.00)	2.03 $\pm$ 0.42 (1.70–2.50)	1.80 $\pm$ 0.00 (1.80–1.80)	1.43 $\pm$ 0.21 (1.20–1.60)	1.77 $\pm$ 0.40 (1.40–2.20)	1.83 $\pm$ 0.25 (1.60–2.10)
Alkalinity	mval/L	- *	3.42 $\pm$ 0.53 (2.90–3.40)	3.53 $\pm$ 1.04 (2.70–4.70)	3.33 $\pm$ 0.85 (2.50–4.20)	3.30 $\pm$ 0.75 (2.50–4.00)	3.20 $\pm$ 0.80 (2.40–4.00)	3.37 $\pm$ 0.70 (2.70–4.10)
Total hardness	mg CaCO ₃ /L	257 $\pm$ 33.32 (221–287)	261 $\pm$ 38.28 (218–292)	274 $\pm$ 39.34 (238–316)	279 $\pm$ 60.54 (224–344)	275 $\pm$ 57.07 (220–334)	231 $\pm$ 33.13 (200–266)	262 $\pm$ 43.86 (224–310)
Chlorides	mg Cl ⁻ /L	30 $\pm$ 5.77 (27–37)	31 $\pm$ 6.43 (26–38)	30 $\pm$ 7.94 (24–39)	31 $\pm$ 8.72 (25–41)	31 $\pm$ 8.39 (26–41)	31 $\pm$ 8.39 (26–41)	32 $\pm$ 4.58 (28–37)
Phosphates	mg P-PO ₄ ³⁻ /L	-	0.18 $\pm$ 0.23 (0.05–0.45)	0.11 $\pm$ 0.06 (0.07–0.18)	0.11 $\pm$ 0.09 (0.06–0.22)	0.07 $\pm$ 0.02 (0.06–0.07)	0.15 $\pm$ 0.20 (0.03–0.38)	0.4 $\pm$ 0.44 (0.05–0.9)
Sulphates	mg SO ₄ ²⁻ /L	38 $\pm$ 7.64 (31–46)	38 $\pm$ 10.02 (30–49)	39 $\pm$ 10.15 (30–50)	38 $\pm$ 9.29 (30–48)	37 $\pm$ 9.71 (29–48)	39 $\pm$ 10.02 (31–50)	37 $\pm$ 10.97 (28–49)
Free chlorine	mg Cl ₂ /L	-	0.04 $\pm$ 0.04 (0.01–0.09)	0.15 $\pm$ 0.08 (0.07–0.23)	0.11 $\pm$ 0.04 (0.06–0.16)	0.05 $\pm$ 0.04 (0.02–0.09)	0.09 $\pm$ 0.04 (0.06–0.13)	0.02 $\pm$ 0.02 (0.00–0.05)
TOC	mg C/L	1.94 $\pm$ 0.23 (1.69–2.14)	3.25 $\pm$ 1.83 (1.74–5.99)	1.97 $\pm$ 0.42 (1.63–2.44)	1.94 $\pm$ 0.27 (1.78–2.25)	1.83 $\pm$ 0.32 (1.62–2.20)	1.81 $\pm$ 0.29 (1.63–2.15)	1.92 $\pm$ 0.58 (1.55–2.58)
BDOC	mg C/L	0.14 $\pm$ 0.02 (0.12–0.15)	0.23 $\pm$ 0.17 (0.13–0.43)	0.14 $\pm$ 0.03 (0.12–0.18)	0.14 $\pm$ 0.02 (0.13–0.16)	0.13 $\pm$ 0.02 (0.12–0.16)	0.13 $\pm$ 0.02 (0.12–0.15)	0.14 $\pm$ 0.04 (0.12–0.19)

* Note: “-” denotes missing data.

Tap water reaching consumers was classified as very hard (>181 mg CaCO₃/L [33]). However, hardness levels in the range of 60–500 mg CaCO₃/L are considered acceptable for drinking water [16]. Water hardness has both aesthetic and operational significance, affecting the taste of water as well as the performance of distribution systems and household appliances. Calcium and magnesium ions are essential for proper functioning of the human body, and insufficient intake can lead to adverse health effects. Consequently, drinking water with high hardness can serve as an important dietary source of these elements. Although high water hardness is considered beneficial for human health, depending on pH and alkalinity, it may lead to increased detergent consumption, promote scale formation and contribute to corrosion processes within distribution system components, thereby reducing their operational lifespan [35]. During the analysed period, average pH values ranged from 7.51 to 7.90, indicating stable, slightly alkaline water. The assessment of chemical stability demonstrated that during the autumn and winter periods, tap water is stable and shows no tendency to form or dissolve CaCO₃, as confirmed by the average Langelier Saturation Index values of -0.27 and -0.17 ($0.5 < \text{LSI} < 0.5$) (Table 7). It should also be noted that the distribution network is continuously undergoing modernisation and replacement of old pipe sections, which reduces the impact of corrosion and scale formation on the quality of water in consumers’ taps.

Table 7. Langelier Saturation Index (LSI) values in tap water in autumn and winter ($n = 6$).

	P-1	P-2	P-3	P-4	P-5	P-6
	Mean $\pm$ SD and Range (Min–Max)					
Autumn period	-0.29 ± 0.28 ($-0.55 \div 0.16$)	-0.37 ± 0.21 ($-0.59 \div -0.11$)	-0.20 ± 0.30 ($-0.47 \div 0.25$)	-0.31 ± 0.26 ($-0.52 \div 0.14$)	-0.13 ± 0.43 ($-0.54 \div 0.37$)	-0.35 ± 0.14 ($-0.50 \div -0.12$)
Winter period	-0.14 ± 0.21 ($0.00 \div 0.38$)	-0.33 ± 0.28 ($-0.64 \div -0.02$)	-0.22 ± 0.21 ($-0.41 \div -0.02$)	-0.22 ± 0.21 ($-0.37 \div 0.03$)	-0.17 ± 0.20 ($-0.30 \div 0.05$)	-0.21 ± 0.16 ($-0.32 \div 0.03$)

According to commonly applied criteria, water is considered biologically stable if at least two of the three indicator parameters—nitrogen (<0.2 mg/L), phosphorus (<0.01 mg/L) and BDOC (<0.25 mg C/L)—remain within recommended ranges. In the analysed samples, these criteria were met only for BDOC, indicating that the water is biologically unstable due to exceedances recorded for both nitrogen and phosphorus. Exceedances were observed for both parameters, with mean phosphorus concentrations ranging from 0.07 to 0.40 mg P- PO_4^{3-} /L, and the highest values recorded at point P-6, where elevated microbial counts were also observed (Figure 3) [36]. The increased phosphorus concentration at point P-6 may be associated with sediment accumulation or secondary release from biofilms, particularly under conditions of variable flow and extended water retention times.

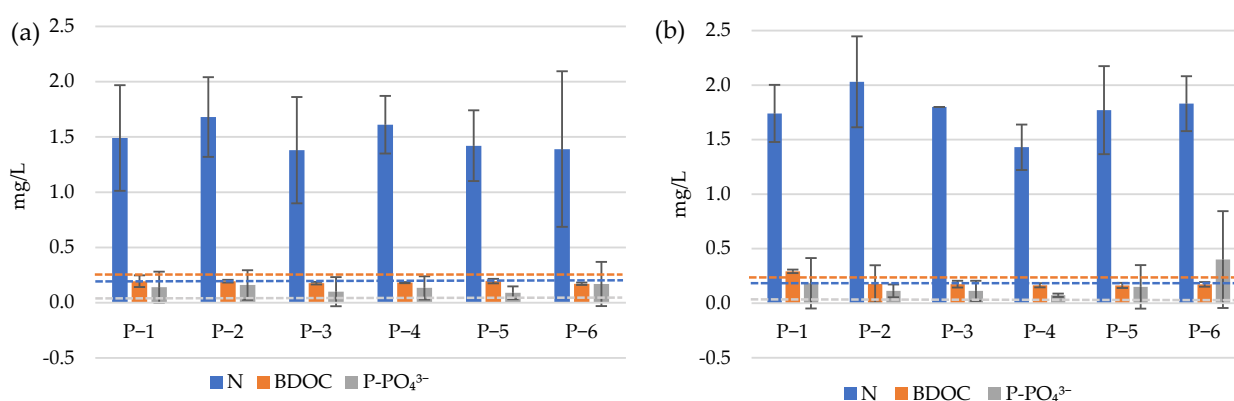


Figure 3. Concentrations of biogenic compounds (ΣN , BDOC and P- PO_4^{3-}) in tap water collected at sampling points P-1–P-6 during autumn (a) and winter (b). Dashed lines indicate threshold values recommended for biological stability assessment.

Although phosphorus is not included among the regulated parameters for drinking water quality, its monitoring may serve as a complementary tool for assessing biological and operational risks in distribution systems, particularly in the context of biofilm development and the use of phosphate-based corrosion inhibitors [37,38]. The literature data confirm that phosphorus is a component that limits the growth of microorganisms in drinking water [39]. Importantly, the response of a water distribution system to such changes is highly system-specific and depends on individual technical and operational conditions, including pipe age and material, hydraulic regime (residence time and flow velocity), raw water quality, applied treatment technologies and operational practices such as flushing, disinfection, and inhibitor dosing. Therefore, monitoring should include both regulated parameters (NH_4^+ , NO_2^- and NO_3^-) and indicators of biological stability, such as phosphorus and biofilm-related metrics [12], which may enable early detection of potential operational or water quality issues.

Free chlorine concentrations in the analysed water samples showed a higher descriptive trend during winter (0.03–0.15 mg Cl_2 /L) compared to during autumn (0.01–0.06 mg Cl_2 /L) (Tables 5 and 6). Although this seasonal shift was not statistically significant ($p = 0.142$), the Wilcoxon test, it is likely attributed to reduced chlorine consumption at lower temperatures, which limits its decay in the distribution network. Variations between sampling points suggest that local hydraulic conditions and water quality, as well as the technical state, age and degradation of pipelines, influence chlorine retention. Although the observed concentrations are low, they align with operational practices aimed at maintaining minimal disinfectant levels to control microbial growth. Chlorine decay rates in distribution systems are affected by water quality, the presence of biofilm and pipe material characteristics. Higher temperatures accelerate chlorine decay, while low flow

rates, longer residence times and aging infrastructure contribute to more rapid decreases in chlorine concentration [40,41]. It should also be emphasized that chlorination may lead to the formation of disinfection by-products (DBPs), such as trihalomethanes (THMs) and haloacetic acids (HAAs), which may pose health risks if present at elevated concentrations [42,43]. However, in the studied water supply system, the applied purification technology and low chlorine doses limited the formation of DBPs. During the study period, the sum of chlorites and chlorates remained below 0.2 mg/L (permissible value: 0.7 mg/L), and the maximum concentration of total THMs was only 9.7 µg/L, i.e., less than 10% of the permissible level (100 µg/L), which confirms the negligible health risk associated with disinfection by-products in the distributed water [44].

3.2. Microbiological Parameters in the Assessment of the Sanitary Quality of Tap Water

Microbiological contamination of water is a significant source of many waterborne diseases. The most significant microbiological threat is associated with contamination of water by human or animal feces. These can be a source of pathogenic bacteria (*Campylobacter jejuni*, pathogenic strains of *Escherichia coli*, *Salmonella typhi*, *Shigella* spp., *Vibrio cholerae*, *Yersinia enterocolitica*, *Aeromonas* spp., *Helicobacter pylori*, *Legionella*, *Leptospira* and *Mycobacterium avium*), viruses (adenoviruses, astroviruses, enteroviruses, hepatitis A and E viruses, noroviruses and rotaviruses), protozoa (*Cryptosporidium parvum*, *Giardia intestinalis*, *Entamoeba histolytica* and *Cyclospora cayetanensis*) and intestinal parasites (helminths) [45–47]. This widely confirmed information is particularly important in the context of secondary contamination of tap water, usually associated with microbiological quality.

In practice, only the presence and number of indicator microorganisms—primarily bacteria such as *Escherichia coli*, coliforms and fecal streptococci—are tested in water supplied to consumers. This approach is consistent with applicable European and national regulations (including Poland) for the quality of water intended for human consumption. These include Directive (EU) 2020/2184 of the European Parliament and of the Council of 16 December 2020 on the quality of water intended for human consumption and the Regulation of the Minister of Health of 7 December 2017 on the quality of water intended for human consumption.

The results of the indicator bacteria analyses confirmed the very good bacteriological quality of the water produced by Rzeszowskie Wodociągi. No *Escherichia coli* or fecal streptococci were detected in any of the analysed samples. Furthermore, no indicator bacteria—coliforms, *Escherichia coli* or fecal streptococci—were detected in the water at any of the test points. An analysis of the results of tests for the total number of bacteria also indicates the very good bacteriological quality of the water supplied to the water supply network. However, the quality of this water deteriorates during its transport to the consumer. Changes in bacteriological quality were detected primarily at the terminal points of the distribution system, particularly within the internal installations of buildings (Figures 4 and 5; Tables 8 and 9). Based on the total number of bacteria at 37 °C and 22 °C, a deterioration in the microbiological quality of water was indicated at one tested point in the network, also during the colder season of the temperate climate (winter). Significantly worse water quality was recorded in the autumn season. At these points, exceedances of the normative values for the parameter of the total number of bacteria at 37 and 22 °C were recorded. Water used by consumers does not meet sanitary standards and may pose a potential health risk, like total number of bacteria in 37 °C and 22 °C.

Although a significant proportion of microorganisms developing within the water supply network are harmless heterotrophs and theoretically should not pose a direct threat to consumer health, it should be emphasized that these microbial communities may also include opportunistic bacteria capable of causing infections in humans. Such

microorganisms pose the greatest risk to immunocompromised individuals, patients in intensive care units and people hospitalized in postoperative wards. The detection of bacteria incubated at 37 °C may indicate the presence of members of the Enterobacteriaceae family, including *Proteus*, *Serratia* and coliform bacteria: *Citrobacter*, *Enterobacter*, *Hafnia*, *Klebsiella* and *E. coli*. Other bacteria detected include *Aeromonas*, *Pseudomonas* (*P. cepacia*, *P. fluorescens*, *P. maltophilia*), *Staphylococcus* and *enterococci*. Due to the types of bacteria detected, testing water at 37 °C can provide information about possible contamination with sewage or intestinal microorganisms, which in turn may indicate the presence of bacteria that are potentially pathogenic to humans [48,49].

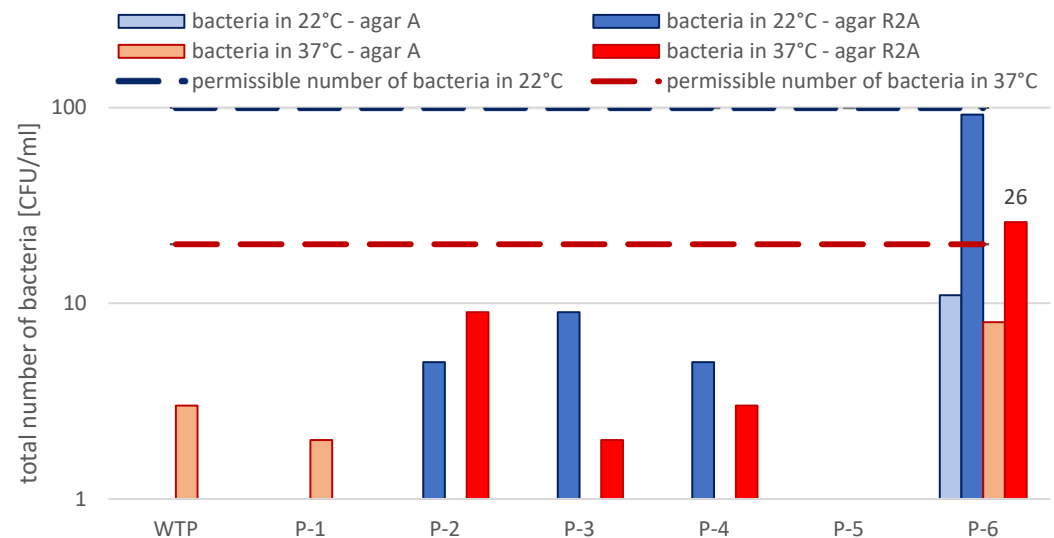


Figure 4. Average values of the total number of bacteria in tap water collected at sampling points (P-1–P-6) and at the water treatment plant (WTP) during the winter season.

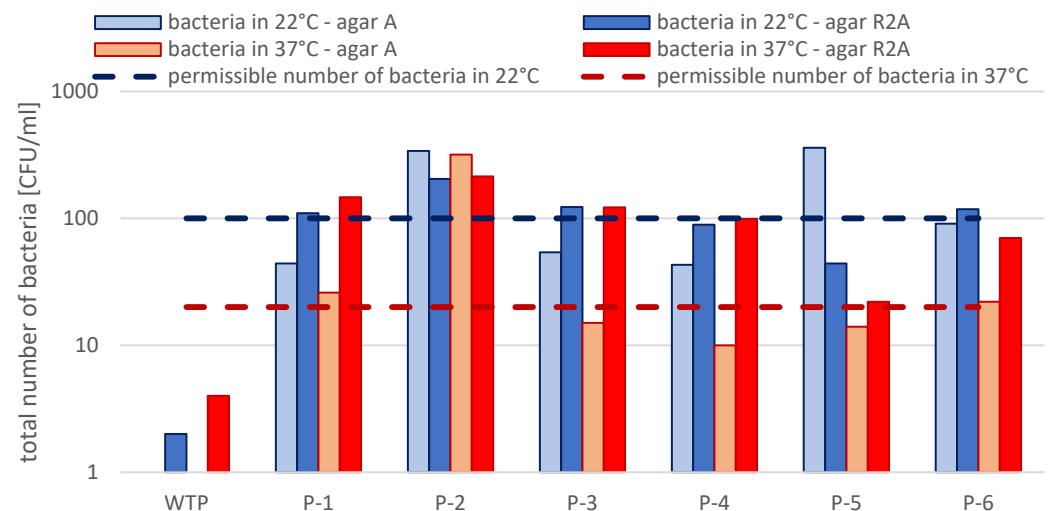


Figure 5. Average values of the total number of bacteria in tap water collected at sampling points (P-1–P-6) and at the water treatment plant (WTP) during the autumn season.

Table 8. Summary of microbiological parameters of tap water during the winter period ($n = 6$).

Sample	Unit	Bacteria in 22 °C (A Agar)	Bacteria in 22 °C (R2A Agar)	Bacteria in 37 °C (A Agar)	Bacteria in 37 °C (R2A Agar)
Mean $\pm$ SD and Range (Min–Max)					
WTP	CFU/mL	0 $\pm$ 0.44 (0–1)	2 $\pm$ 0.44 (0–1)	1 $\pm$ 1.64 (0–4)	0 $\pm$ 0.44 (0–1)
P-1		0 $\pm$ 00 (0–0)	1 $\pm$ 0.70 (0–2)	2 $\pm$ 1.34 (1–4)	1 $\pm$ 0.44 (0–1)
P-2		1 $\pm$ 0.84 (0–2)	11 $\pm$ 11.77 (0–30)	0 $\pm$ 0.44 (0–1)	8 $\pm$ 6.06 (0–17)
P-3		0 $\pm$ 0.44 (0–1)	14 $\pm$ 14.35 (0–30)	0 $\pm$ 0.54 (0–1)	2 $\pm$ 1.22 (0–33)
P-4		0 $\pm$ 1.64 (0–4)	5 $\pm$ 5.21 (1–13)	0 $\pm$ 0.44 (0–1)	3 $\pm$ 1.80 (0–4)
P-5		0 $\pm$ 0.45 (0–1)	2 $\pm$ 1.78 (0–4)	1 $\pm$ 0.54 (0–1)	1 $\pm$ 0.44 (0–1)
P-6		1 $\pm$ 13.03 (0–31)	93 $\pm$ 92.30 (14–250)	10 $\pm$ 9.63 (0–23)	26 $\pm$ 22.03 (1–61)

Table 9. Summary of microbiological parameters of tap water during the autumn period ($n = 6$).

Sample	Unit	Bacteria in 22 °C (A Agar)	Bacteria in 22 °C (R2A Agar)	Bacteria in 37 °C (A Agar)	Bacteria in 37 °C (R2A Agar)
Mean $\pm$ SD and Range (Min–Max)					
WTP	CFU/mL	0 $\pm$ 00.41 (0–1)	1 $\pm$ 1.21 (0–3)	1 $\pm$ 1.64 (0–4)	0 $\pm$ 0.81 (0–2)
P-1		16 $\pm$ 23.69 (1–59)	110 $\pm$ 76.53 (3–255)	2 $\pm$ 1.34 (1–4)	23 $\pm$ 31.38 (2–78)
P-2		116 $\pm$ 0.827638 (1–680)	173 $\pm$ 405.18 (1–1000)	0 $\pm$ 0.44 (0–1)	265 $\pm$ 605.81 (2–1500)
P-3		27 $\pm$ 35.39 (0–95)	110 $\pm$ 176.32 (2–470)	0 $\pm$ 0.54 (0–1)	13 $\pm$ 22.65 (1–59)
P-4		15 $\pm$ 34.54 (0–85)	85 $\pm$ 96.17 (0–260)	0 $\pm$ 0.44 (0–1)	9 $\pm$ 12.27 (0–26)
P-5		120 $\pm$ 288.88 (0–710)	39 $\pm$ 74.11 (2–190)	1 $\pm$ 0.54 (0–1)	12 $\pm$ 26.06 (0–65)
P-6		32 $\pm$ 67.98 (1–170)	113 $\pm$ 80.23 (1–212)	10 $\pm$ 9.63 (0–23)	18 $\pm$ 27.42 (0–56)

The total bacterial count (TBC) parameter is increasingly recognised as useful in assessing the sanitary condition of a water distribution system. Although specific values for the allowable bacterial count at 22 °C are not provided, changes in the TBC value signal the emergence of conditions conducive to biofilm formation, including water stagnation (dead sections of pipes excluded from active water flow), significant content of biogenic compounds used by microorganisms in the water, biofilm and other deficiencies in water network maintenance. Although the total bacterial count parameter is not considered an indicator of water safety for health, it is increasingly regarded as useful in assessing the sanitary condition of the water distribution system. Changes in the indicator value signal the emergence of conditions conducive to biofilm formation, including water stagnation (dead sections of pipes, excluded from active water flow), a significant content of biogenic compounds used by microorganisms in water, biofilm and other deficiencies in the maintenance of the water supply network. An important advantage of determining the total number of microorganisms is the ability to detect changes from the expected value, based on regular analyses carried out during long-term monitoring [50].

Physicochemical parameters are increasingly assessed using rapid analytical tests. On the other hand, the problem of assessing microbiological contamination is still solved using traditional, labour-intensive and time-consuming culture methods. It takes at least 24 h from the moment the test is performed to obtain the first result. Therefore, it is necessary to develop and implement rapid, reliable and reproducible microbiological tests. Luminometric determination of ATP concentration could potentially be used. The studies did not reveal any exceptional patterns of microbiological contamination at any of the water sampling points (Figure 6 and Table 10).

It should be emphasized that rapid methods such as luminometric ATP determination cannot yet replace the culture method. When using this determination, it is particularly

important not to look for correlations between ATP measurement and the total number of bacteria. On culture media, it is only possible to determine the number of viable cultivable bacteria (in the case of reference nutrient agar, only heterotrophic bacteria), while ATP measurement applies to all viable microorganisms (heterotrophic bacteria, iron bacteria, bacteria, fungi, protozoa, etc.) [51]. This distinction is particularly important in the context of ensuring the sanitary safety of tap water for all consumers. In order to fully exploit the potential of this indicator, regular measurements at sampling points are necessary, as in the case of the total bacterial count parameter. Only under such conditions is it possible to detect deviations that may indicate changes occurring within the distribution network or irregularities at the water treatment stage [52].

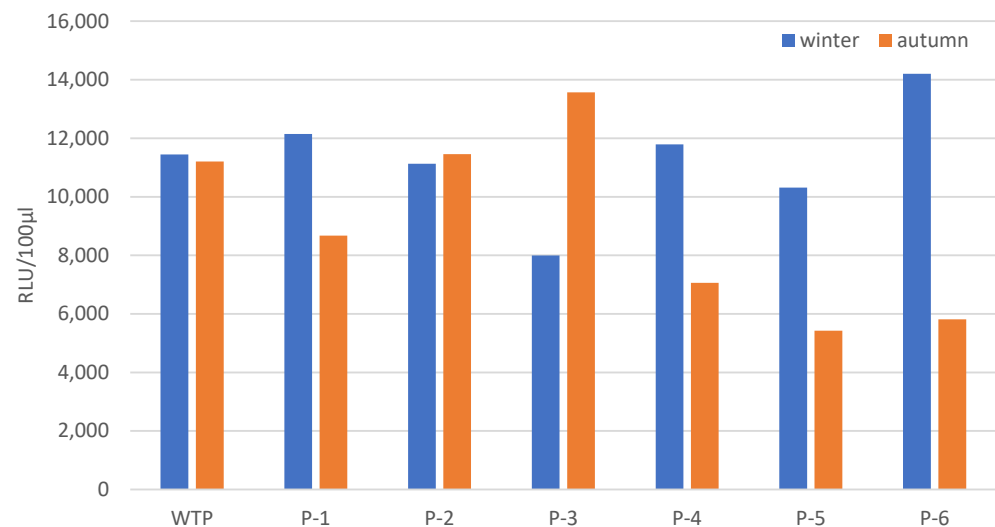


Figure 6. ATP (average amount) in tap water collected at sampling points (P-1–P-6) and at the water treatment plant (WTP) during the in autumn and winter seasons.

Table 10. Summary of microbiological ATP parameters of tap water during the autumn period.

Sample	Unit	Autumn	Winter
		Mean $\pm$ SD (Min–Max)	
WTP	RLU/100 μ L	11,209 $\pm$ 9654.83 (4382–18,039)	11,445 $\pm$ 7609.17 (6065–16,826)
P-1		8670 $\pm$ 7061.82 (1321–19,643)	12,145 $\pm$ 3342.72 (9396–15,866)
P-2		11,454 $\pm$ 11,292.03 (1500–29,703)	11,130 $\pm$ 777.59 (10,233–11,613)
P-3		13,569 $\pm$ 22,960.07 (1102–54,427)	7996 $\pm$ 1495.02 (6278–8999)
P-4		7059 $\pm$ 4470.81 (1218–13,574)	11,786 $\pm$ 3275.90 (8861–15,326)
P-5		5424 $\pm$ 2832.17 (1404–9277)	10,314 $\pm$ 4707.68 (6676–15,631)
P-6		5811 $\pm$ 2755.59 (1171–8135)	14,203 $\pm$ 8637.07 (4309–20,233)

The ATP concentration in water also depends on the ATP content of the cell, which varies according to the type of microorganism and the environment in which the cell is located. Average ATP values per cell in drinking water differ mainly depending on the sampling location within the water supply system, yet are very comparable. Nevertheless, ATP concentrations in drinking water are significantly lower than those observed in source water or biofilm samples. This may be related to the oligotrophic nature of drinking water. This also occurs due to the use of chemical disinfection. The presence of disinfectants such as chlorine or ozone also accelerates the breakdown of extracellular ATP molecules, thereby influencing the final measured total ATP concentrations. Changes in ATP content in water can also result from changes in its pH. Although the pH ranges tested correspond to those

within which the ATP assay is optimal, pH fluctuations can result in slight fluctuations in this indicator [53].

Luminometric ATP testing is a rapid and relatively inexpensive method for assessing the microbiological quality of water. It is a general indicator. Continuous ATP monitoring may enable the early identification of potential hazards and can be applied to various types of water [54]. This is indicated despite the weak correlations between the culture method and the ATP determination, especially in waters with low microbiological activity—the growth of bacterial colonies on the culture medium at the level of several to several dozen CFU/mL [55]. Since surface waters are commonly used as sources of drinking water, rapid detection of changes in microbiological quality may facilitate timely corrective actions, such as adjustment of disinfectant doses, detection of accidental contamination events and rapid response by water utility services [56].

In the context of the health safety of tap water consumers, attempts have been made for over a decade to investigate the relationship between ATP measurements and results obtained using conventional culture-based methods. This is primarily due to the rapid availability of results provided by luminometric ATP determination, but also to the underestimation of the number of bacteria growing in laboratory conditions. The fraction of bacterial cells detected using heterotrophic plate count (HPC) methods represents less than 1% of the total bacterial concentration in drinking water [57,58]. Furthermore, feces can be a source of nonbacterial pathogens (e.g., viruses, protozoa, helminths) that do not always correlate with coliform bacteria, and some free-living amoebae can act as reservoirs for bacterial pathogens, making their detection difficult [17]. Furthermore, opportunistic pathogens such as *Pseudomonas aeruginosa*, *Legionella pneumophila* and *Mycobacterium avium* complex are not of fecal origin and may pose a public health risk [59,60]. ATP measurements have been successfully applied in several case studies to assess the biological stability of tap water [61]. Total ATP concentrations in drinking water have been reported to range from 8 to 120 pg ATP/mL (<10 pg/mL) [62–64]. Zamorska et al. reported slightly higher ATP values. In water intended for human consumption, total ATP levels have been reported at levels not exceeding 10,000 RLU/mL (ca. 50 pg ATP/mL) [56]. Based on the literature data and the authors' own experience, it seems that values above 10,000 RLU may constitute a threshold value above which remedial measures should be taken (e.g., temporary change of chlorine dose). At the current stage of research on the luminometric method, it is considered a method accompanying standard methods [61,65]. At the same time, it should be emphasised that each company should conduct preliminary analyses that take into account, for example, the periodically changing quality of the water taken for treatment. ATP measurements can be readily implemented as part of routine monitoring programs, similarly to the approach already applied by water utilities in the Netherlands using flow cytometry [66]. Collecting large amounts of data on water quality in distribution systems over space and time allows for the description of natural variations in each drinking water distribution system under normal conditions and provides a reference point for detecting abnormal changes. Applying such an approach in the long term would provide a solid basis for determining the degree of acceptable range of water quality fluctuations specific to a given distribution network or when action is necessary to protect water quality during distribution. If abnormal changes occur, continuous monitoring using flow cytometry should be supplemented with other methods, such as high-throughput sequencing or screening for specific pathogenic organisms.

Some bacteria are resistant to disinfection due to their ability to produce spores; others are associated with biofilm, can live in the cells of other organisms or occur in the form of aggregates, which limits direct contact between the disinfectant and bacterial cells, thereby reducing disinfection efficiency [67]. As a result, some of the microorganisms present

in the water pass through water treatment systems and enter distribution systems. It is increasingly recognised that biofilms can reduce water quality through the processes they mediate or through their release from pipe walls into the water column, causing not only a deterioration in the water quality perceived by consumers (e.g., odour), but also potentially posing a threat to public health in the event of the release of pathogens [68]. Numerous studies confirm that the microbiome of biofilms differs from that of plankton [69], yet water quality standards and disinfection programmes focus exclusively on the quality of planktonic microorganisms.

The results of microbiological analyses clearly show that testing for indicator bacteria alone does not guarantee the sanitary safety of tap water users. This issue appears to be particularly important when the water intake point is a tap frequently used by large number of people. We are referring here to public bathrooms in public facilities such as healthcare centres, shopping centres, schools and municipal offices.

4. Conclusions

Water supplied through the distribution network complied with the applicable drinking water quality requirements specified in the Regulation of the Minister of Health, both in terms of physicochemical and microbiological parameters. The results indicate the high effectiveness of treatment processes and confirm the maintenance of stable water quality throughout the distribution system.

Seasonal fluctuations in mineral and chemical parameters of water, including conductivity, total and carbonate hardness, and chloride and sulfate concentrations, indicate the influence of climatic factors and limited biogeochemical processes during the winter period. The analysed water exhibited chemical, physical and biological stability. LSI values range from -0.5 to 0.5 and turbidity <0.8 NTU indicated no tendency toward CaCO_3 scale formation or dissolution. However, complete biological stability was not achieved, as the parameters for nutrient concentrations exceeded the recommended thresholds (nitrogen >0.2 mg/L and phosphorus >0.01 mg/L). Only BDOC remained below the limit (<0.25 mg C/L). This highlights that maintaining full biological stability in a distribution system is an exceptionally difficult challenge, requiring strict control over nutrient availability.

Regarding the literature data, elevated ATP concentration values were observed in the tested tap water, i.e., above 10,000 RLU/100 μL . This indicates the quality of the water during its transport to the consumer and the presence of microorganisms that may affect the organoleptic characteristics of the water (taste, odour and appearance), the condition of the installation pipes (biological corrosion) and the sanitary quality (pathogenic bacteria). The absence of indicator bacteria, such as *E. coli*, *fecal coliforms*, does not guarantee complete sanitary safety, as an increase in total bacterial counts was detected within internal building installations. In this context, ATP analysis can be a valuable complement to traditional microbiological methods, enabling faster detection of microbiological changes occurring within the distribution network. Regular and comprehensive water quality monitoring is crucial for the early detection of microbiological threats and ensuring public health protection and consumer safety.

The obtained results indicate the need to include analyses of biofilm collected from consumer taps as a complementary element in the assessment of microbiological water quality and supporting the determination of public health risks. Furthermore, it seems crucial to continue research into the potential use of ATP measurement in water quality monitoring. This will require closer collaboration with water treatment plants, for example through the implementation of online ATP monitoring systems.

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Abbreviations

EU	European Union
DWD	Drinking Water Directive
WTP	water treatment plant
BDOD	biologically dissolved organic carbon
TOC	total organic carbon
DOC	dissolved organic carbon
THMs	trihalomethanes
HAAs	haloacetic acids
TBC	total bacterial count
PE	polyethylene
PVC	polyvinyl chloride

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