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CHRONIC HEALTH RISKS ASSOCIATED WITH NITRATE AND NITRITE IN UNPURIFIED CHLORINATED DRINKING WATER IN THE AUTONOMOUS PROVINCE OF VOJVODINA

POVEZANI HRONIČNI ZDRAVSTVENI RIZICI ZBOG PRISUSTVA NITRATA I NITRITA U NEPREČIŠĆENOJ HLORISANOJ PIJAĆOJ VODI AUTONOMNE POKRAJINE VOJVODINE

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Abstract

Introduction. This study aimed to analyse nitrate and nitrite concentrations in unpurified chlorinated drinking water across the Autonomous Province of Vojvodina and to assess the associated chronic health risks for both adult and paediatric populations. **Material and Methods**. A retrospective analysis was performed using data from 2023 obtained from seven authorized, certified, and accredited public health institutions. A total of 11,919 samples of unpurified chlorinated drinking water were analysed. Nitrate and nitrite concentrations were determined using a spectrophotometric analytical method. Valued below the analytical detection limit were imputed as one-half of the respective detection limits. Health risk assessment was conducted by calculating the Hazard Quotient for adults and children in accordance with the United States Environmental Protection Agency methodology. **Results**. Elevated nitrite concentrations were identified in 456 samples (3.83%), with a mean concentration of 0.030 mg/L and a maximum value of 1.005 mg/L (national limit: 0.03 mg/L). Elevated nitrate concentrations were detected in 129 samples (1.08%), with a mean concentration of 5.229 mg/L and a maximum concentration of 139 mg/L (national limit: 50 mg/L). A Hazard Quotient value below one indicates the absence of non-carcinogenic health risk. For the average nitrate concentration, Hazard Quotient values were within acceptable limits for both adults (8.46E-02) and children (3.49E-01); however, Hazard Quotient values calculated using maximum nitrate concentrations exceeded the safety threshold (2.25E+00 for adults and 9.27E+00 for children). In contrast, Hazard Quotient for nitrites remained well below one for both average and maximum concentrations in both population groups. **Conclusion.** While average nitrate and nitrite concentrations in chlorinated drinking water do not pose a chronic health risk, elevated maximum nitrate concentrations represent a potential long-term health concern, particularly for children.

Key words: Nitrates; Nitrites; Drinking Water; Water Pollution; Halogenation; Water Quality; Risk Assessment; Public Health; Environmental Medicine

Sažetak

Uvod. Studija ima za cilj analizu koncentracija nitrata i nitrita u neprečišćenoj hlorisanoj vodi za piće na teritoriji Autonomne Pokrajine Vojvodine i procenu povezanih zdravstvenih rizika za decu i odrasle. **Materijal i metode.** Sprovedena je retrospektivna analiza podataka iz 2023. godine, prikupljenih iz sedam ovlašćenih, sertifikovanih i akreditovanih Zavoda za javno zdravlje. Istraživanje je obuhvatilo 11.919 uzoraka neprečišćene hlorisane pijaće vode. Koncentracije nitrata i nitrita određene su spektrofotometrijskom analitičkom tehnikom. Vrednosti ispod granice detekcije modelovane su kao polovina laboratorijske granice detekcije. Hazardov koeficijent za odrasle i decu izračunat je primenom metodologije Agencije za zaštitu životne sredine Sjedinjenih Američkih Država. **Rezultati.** Povišene koncentracije nitrita pronađene su u 456 uzoraka (3,83%), sa prosekom od 0,030 mg/L i maksimumom od 1,005 mg/L (nacionalna vrednost: 0,03 mg/L). Povišeni nivoi nitrata zabeleženi su u 129 uzoraka (1,08%), sa prosekom od 5,229 mg/L i maksimumom od 139 mg/L (nacionalna vrednost: 50 mg/L). Koeficijent opasnosti ispod jedan ukazuje na odsustvo rizika od nekancerogenih efekata. Za prosečne koncentracije nitrata, koeficijent opasnosti bio je prihvatljiv (8,46E – 02 za odrasle i 3,49E – 01 za decu), dok za maksimalne koncentracije nije bio prihvatljiv (2,25E + 00 za odrasle i 9,27E + 00 za decu). Za nitrite, koeficijent opasnosti bio je znatno ispod jedan, što je prihvatljivo za prosečne i maksimalne koncentracije i za odrasle i za decu. **Zaključak.** Prosečne koncentracije nitrata i nitrita ne predstavljaju zdravstveni rizik; međutim, maksimalne koncentracije nitrata mogu predstavljati potencijalni hronični zdravstveni rizik, naročito za decu.

Ključne reči: nitrati; nitriti; voda za piće; zagađenje vode; hlorinacija; kvalitet vode; procena rizika; javno zdravlje; medicina životne sredine

Introduction

Safe and sufficient drinking water is fundamental to public health and overall well-being [1], as emphasized by global initiatives such as the 2015 United Nations Sustainable Development Goals [1,2]. Water is indispensable for human survival and it must comply with strict safety standards to ensure freedom from microbial, physical, and chemical contamination [3]. Among chemical contaminants, nitrate is one of the

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Abbreviations

EPA – Environmental Protection Agency
EU – European Union
HQ – Hazard Quotient
ISO – International Organization for Standardization
NPCW – Unpurified Chlorinated Drinking Water
SRPS – Serbian Standards
WHO – World Health Organization
APV – Autonomous Province of Vojvodina

most prevalent in groundwater, second only to pesticides. Other nitrogenous compounds – including nitrite, ammonia, and organic nitrogen – are likewise critical indicators of water quality and are closely monitored worldwide [4]. The nitrate cycle illustrates the generation and transformation of nitrogen compounds through both natural processes and anthropogenic activities. Atmospheric nitrogen is initially converted into plant-available forms by soil microorganisms. Through ammonification, organic nitrogen is transformed into ammonia, which is subsequently oxidized during nitrification to produce nitrite and nitrate. These compounds may infiltrate groundwater or be assimilated by plants and microorganisms, eventually returning to the atmosphere as nitrogen gas and completing the cycle [2]. Within drinking water distribution systems, nitrite may also form through the metabolic activity of *Nitrosomonas* bacteria, particularly under conditions of low oxygen availability and water stagnation in galvanized steel pipes. Additionally, the use of chloramine for residual disinfection may promote nitrite formation if treatment processes are inadequately controlled [5]. Major sources of nitrate and nitrite contamination in aquatic systems include agricultural practices – especially the application of synthetic fertilizers and manure – nitrogen-rich wastes from human activities, industrial emissions, and effluents from wastewater treatment facilities. Due to incomplete crop uptake, it is estimated that approximately 50% of applied fertilizer nitrogen may leach into soil, thereby increasing nitrate concentrations in surface and groundwater [5,6]. A thorough understanding of nitrate contamination sources is therefore essential for developing effective strategies to mitigate nitrate pollution [7].

Diet represents the primary source of nitrate exposure in humans, with vegetables such as spinach and beetroot accounting for approximately 80–90% of total intake. Drinking water contributes an estimated 15–20%, while other food sources, including animal-derived products, provide the remaining proportion. Nitrate metabolism involves the nitrate-nitrite-nitric oxide pathway, which depends on the oral microbiota and salivary glands. Following absorption in the stomach and small intestine, approximately 75% of ingested nitrate is excreted in urine, while up to 25% is actively concentrated in the salivary glands at levels up to tenfold higher than plasma concentrations. In the oral cavity, anaerobic bacteria located on the posterior tongue convert 5–7% of nitrate into nitrite, which is subsequently converted into nitric oxide in the stomach and systemically absorbed [8].

Although nitrates are generally considered to have low intrinsic toxicity, their metabolic conversion to nitrites may result in adverse health effects [9]. Nitrite exposure can induce methemoglobinemia, commonly referred to as "blue baby syndrome". In 2010, the International Agency for Research on Cancer classified nitrates and nitrites as Group 2A agents, indicating they are probably carcinogenic to humans [10]. Furthermore, nitrate and nitrite may serve as precursors for endogenous formation of genotoxic N-nitroso compounds, potentially increasing cancer risk when present in drinking water [9]. Beyond methemoglobinemia, the most consistent epidemiological evidence links nitrate exposure in drinking water to colorectal cancer, neural tube defects, and thyroid dysfunction, with some studies suggesting adverse effects even at concentrations below established regulatory limits [6]. Conversely, long-term exposure to nitrate exposure at permissible concentrations has shown inconsistent associations with bladder cancer risk [11].

Despite guidelines established by the World Health Organization (WHO) for safe nitrate and nitrite concentrations in drinking water, numerous countries continue to report exceedances, even in the absence of acute health effects such as methemoglobinemia or thyroid disorders [12]. Since the adoption of the Nitrates Directive, the European Union has prioritized the reduction of nitrate contamination in groundwater as major environmental and public health objective [13]. Regulatory limits for nitrate and nitrite vary slightly across international frameworks. European Union Directive 2020/2184 (EU) sets maximum values of 50 mg/L (11.3 mg/L as nitrogen) for nitrate and 0.5 mg/L (0.152 mg/L as nitrogen) for nitrite [14]. The United States Environmental Protection Agency (EPA) applies stricter limits, permitting 10 mg/L nitrate as nitrogen (44 mg/L nitrate) and 1 mg/L nitrite as nitrogen (3.3 mg/L nitrite) [15]. WHO guidelines recommend maximum concentrations of 50 mg/L for nitrate (11.3 mg/L as nitrogen) and 3 mg/L for nitrite (0.91 mg/L as nitrogen) [5]. In Serbia, national regulations are harmonized with these standards, establishing maximum allowable concentrations of 50 mg/L for nitrate (11.3 mg/L as nitrogen) and 0.03 mg/L for nitrite (0.009 mg/L as nitrogen) [16]. Notably, the Serbian nitrite limit is the most stringent among international standards, including those of the EU, WHO, and U.S. EPA.

The aim of this study was to evaluate nitrate and nitrite concentrations in untreated chlorinated drinking water across the districts of the Autonomous Province of Vojvodina during 2023 and to assess the associated health risks for adults (≥18 years) and young children (≤5 years).

Material and Methods

Sampling and Analyses

This investigation included 11,919 samples of unpurified chlorinated drinking water (NPCW) collected during 2023. All procedures - sampling, transport, and laboratory analysis - were conducted within seven authorized, certified, and accredited Public Health Institution laboratories operating in the territory of the Autonomous Province of Vojvodina.

Sampling locations were selected in accordance with stakeholder requirements (local governments and public utility companies) and formed part of the regular, scheduled drinking water health surveillance program. The sampling framework encompassed both urban and rural areas, as well as locations identified as having an increased contamination risk, particularly regions with intensive agricultural activity. Nitrate and nitrite concentrations were determined using accredited spectrophotometric analytical techniques. Sampling procedures followed internationally recognized standard: SRPS EN ISO 5667-1:2023, ISO 5667-3:2018, and SRPS ISO 5667-5:2008 [17–19]. Laboratory analyses were performed using accredited methods in compliance with ISO/IEC 17025 requirements by competent public health institutions responsible for drinking water safety monitoring [20,21]. For analytical results below the method detection limit, concentrations were modeled by assigning a value equal to one-half of the respective laboratory detection limit.

Health Risk Assessment

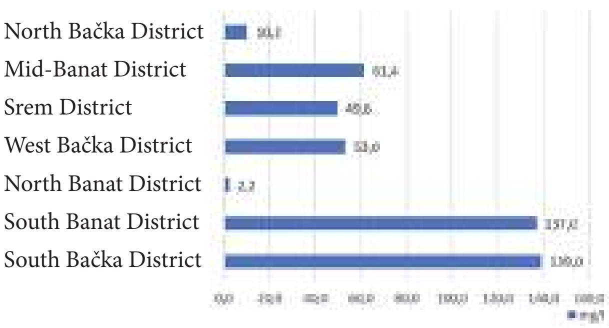
According to the US EPA, human health risk assessment is defined as a systemic process for estimating the likelihood and severity of adverse health effects resulting from exposure to hazardous substances [22]. In this study, non-carcinogenic health risks associated with nitrate and nitrite exposure were assesses using the Hazard Quotient (HQ) approach, following US EPA guidelines [23].

Exposure pathways included ingestion and dermal absorption from untreated chlorinated drinking water. Risk estimates were calculated for two population groups: children ≤ 5 years of age and adults ≥18 years. Demographic and exposure parameters were derived from data provided by the Statistical Office of the Republic of Serbia and relevant international sources.

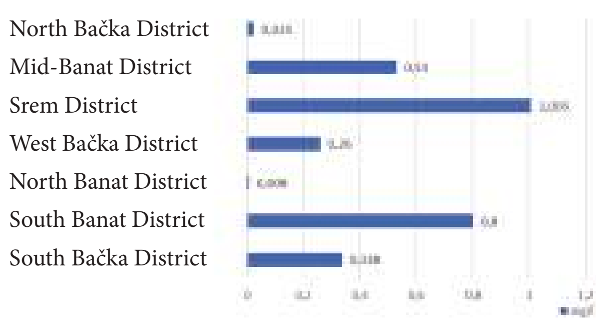
Quantitative health risk equations used for ingestion and dermal exposure pathways are presented in **Table 1.**

Results and Discussion

Of the 11,919 NPCW samples analyzed, elevated nitrate concentrations were detected in 129 samples (1%), while elevated nitrite concentrations were identified in 456 samples (4%). The highest nitrate concentrations exceeding permissible limits were recorded in the South Bačka District (139 mg/l) and the South Banat District (137 mg/l). In contrast, the maximum nitrite concentration was observed in the Srem District (1.005 mg/l) **(Graphs 1 and 2)**.



Graph 1. Maximum nitrate concentrations by district



Graph 2. Maximum nitrite concentrations by district

Table 1. Quantitative health risk equation

Pathway	Formula
Ingestion	CDI_ing = (Cw × IR × EF × ED)/(BW × AT)
Dermal	CDI_derm = (Cw × SA × PC × ET × EF × ED × CF)/(BW × AT)
Total CDI	CDI_tot = CDI_ing + CDI_derm
Hazard Index (HI)	HI = CDI_tot/RfD (or sum across contaminants)

CDI ing – chronic daily intake by ingestion; Cw – concentration of contaminant in water; IR – ingestion rate; EF – exposure frequency; ED – exposure duration; BW – body weight; AT – Averaging time; CDI derm – chronic daily absorbed dose via dermal contact; SA – Skin surface area exposed; PC – Dermal permeability coefficient; ET – Exposure time; CF – volumetric conversion factor for water; RfD – Reference dose; HI – Hazard Index .

Table 2. Chronic hazard index for average and maximum nitrate and nitrite concentrations in drinking water for children up to 5 years old and adults over 18 years old in the territory of APV in 2023

	Concentration (mg/L)	HI, after ingestion	HI, after dermal absorption	Total HI
For average nitrate concentration values				
Children	5.22	3.49E-01	1.98E-06	3.49E-01
Adults		8.46E-02	3.77E-07	8.46E-02
For average nitrite concentration values				
Children	0.0369	2.46E-03	1.40E-08	2.46E-03
Adults		5.97E-04	2.71E-09	5.97E-04
For maximum nitrate concentration values				
Children	139	9.27E+00	5.26E-05	9.27E+00
Adults		2.25E+00	1.01E-05	2.25E+00
For maximum nitrite concentration values				
Children	1.005	6.70E-02	3.80E-07	6.70E-02
Adults		1.63E-02	7.37E-08	1.63E-02

HI – chronic hazard index; IR 1.6 L/day for children and 2 L/day for adults [15]; EF - 365 days/year; ET - 0.5 h/day [16]; ED - 5 years for children/ 75.61 years for adults [17]; BW - 15 kg for children [14] and 75.61 kg for adults; AT - ED*365 days [18]; RfD - 1.6 mg/kg/day [19]; SA - 1.815 m^2 for adults and 0.76 m^2 for children [20]; PC - 0.00001 m/hour [21]; ET - is specified as 0.5 hours/day for adults and children; CF for water is 0.001 L/cm^3 [21].

Table 3. Hazard Quotient for average and maximum concentrations of nitrates and nitrites in drinking water for children up to 5 years old and adults over 18 years old by districts of the Autonomous Province of Vojvodina in 2023

District	Population	Concentration (mg/L)	HQ, after ingestion	HQ, after dermal absorption	Total HQ
South Bačka District	For average nitrate concentration values				
	Children	12.3	8.20E-01	4.65E-06	8.20E-01
	Adults		1.99E-01	9.02E-07	1.99E-01
	For average nitrite concentration values				
	Children	0.042	2.80E-03	1.58E-08	2.80E-03
	Adults		6.79E-04	3.08E-09	6.79E-04
	For maximum nitrate concentration values				
	Children	139	9.26E+01	5.25E-05	**9.27E+00**
	Adults		2.25E+00	1.01E-05	**2.25E+00**
	For maximum nitrite concentration values				
	Children	0.417	2.78E-02	1.57E-07	2.78E-02
	Adults		6.74E-03	3.05E-08	6.74E-03
West Bačka District	For average nitrate concentration values				
	Children	3.8	2.53E-01	1.43E-06	2.53E-01
	Adults		6.14E-02	2.78E-07	6.14E-02
	For average nitrite concentration values				
	Children	0.012	8.00E-04	4.53E-09	8.00E-04
	Adults		1.94E-04	8.80E-10	1.94E-04
	For maximum nitrate concentration values				
	Children	53	3.53E+00	2.00E-05	**3.53E+00**
	Adults		8.57E-01	3.88E-06	8.57E-01
	For maximum nitrite concentration values				
	Children	0.26	1.73E-02	9.83E-08	1.73E-02
	Adults		4.20E-03	1.90E-08	4.20E-03
Nort Bačka District	For average nitrate concentration values				
	Children	2.1	1.40E-01	7.94E-07	1.40E-01
	Adults		3.40E-02	1.54E-07	3.40E-02
	For average nitrite concentration values				
	Children	0.001	6.67E-05	3.78E-10	6.67E-05
	Adults		1.62E-05	7.33E-11	1.62E-05
	For maximum nitrate concentration values				
	Children	10.2	6.80E-01	3.85E-06	6.80E-01
	Adults		1.65E-01	7.48E-07	1.65E-01
	For maximum nitrite concentration values				
	Children	0.025	1.67E-03	9.45E-09	1.67E-03
	Adults		4.04E-04	1.83E-09	4.04E-04

HQ – Hazard Quotient; IR 1.6 L/day for children and 2 L/day for adults [24]; EF – 365 days/year; ET – 0.5 h/day [25]; ED – 5 years for children/75.61 years for adults [26]; BW – 15 kg for children [27] and 75.61 kg for adults; AT- ED*365 days [28]; RfD – 1.6 mg/kg/day [29]; SA – 1.815 m^2 for adults and 0.76 m^2 for children [30]; PC – 0.00001 m/hour [31]; ET – is specified as 0.5 hours/day for adults and children; CF for water is 0.001 L/cm^3 [31].
a - Adult exposure duration (ED, years); North Bačka – 76.55; West Bačka – 74.6; South Bačka – 74.75; North Banat – 75.65; Central Banat – 75.25; South Banat – 75.65; Srem – 76.

For nitrates, the average HQ (combined ingestion and dermal exposure) for the adult population was 8.46E-02, which is below the threshold value of one and therefore considered acceptable. However, the maximum nitrate HQ reached 2.25E+00, exceeding the safety threshold and indicating a potential health risk **(Table 2).**

In the children's population (≤5 years), the average nitrate HQ was 3.49E-01, suggesting that average nitrate concentrations do not pose a health risk. In contrast,

Table 4. Hazard Quotient for average and maximum concentrations of nitrates and nitrites in drinking water for children up to 5 years old and adults over 18 years old by districts of the Autonomous Province of Vojvodina in 2023

District	Population	Concentration (mg/L)	HQ, after ingestion	HQ, after dermal absorption	Total HQ
Srem District			For average nitrate concentration values		
	Children	3.6	2.40E-01	1.36E-06	2.40E-01
	Adults		5.82E-02	2.64E-07	5.82E-02
			For average nitrite concentration values		
	Children	0.0125	8.33E-04	4.72E-09	8.33E-04
	Adults		2.02E-04	9.17E-10	2.02E-04
			For maximum nitrate concentration values		
	Children	49.6	3.31 E+00	1.88E-05	**3.31 E+00**
	Adults		8.02E-01	3.63E-06	8.02E-01
			For maximum nitrite concentration values		
	Children	1.005	6.70E-02	3.80E-07	6.70E-02
	Adults		1.63E-02	7.37E-08	1.63E-02
South Banat District			For average nitrate concentration values		
	Children	5	3.33E-01	1.89E-06	3.33E-01
	Adults		8.09E-02	3.66E-07	8.09E-02
			For average nitrite concentration values		
	Children	0.011	7.33E-04	4.15E-09	7.33E-04
	Adults		1.78E-04	8.07E-10	1.78E-04
			For maximum nitrate concentration values		
	Children	137	9.13E+00	5.18E-05	**9.13E+00**
	Adults		2.22E+00	1.00E-05	**2.22E+00**
			For maximum nitrite concentration values		
	Children	0.8	5.33E-02	3.02E-07	5.33E-02
	Adults		1.29E-02	5.86E-08	1.29E-02
Central Banat District			For average nitrate concentration values		
	Children	3.36	2.24E-01	1.27E-06	2.24E-01
	Adults		5.43E-02	2.46E-07	5.43E-02
			For average nitrite concentration values		
	Children	0.06	4.00E-03	2.26E-08	4.00E-03
	Adults		9.70E-04	4.40E-09	9.70E-04
			For maximum nitrate concentration values		
	Children	61.43	4.10E+00	2.32E-05	**4.10E+00**
	Adults		9.93E-01	4.50E-06	9.93E-01
			For maximum nitrite concentration values		
	Children	0.53	3.53E-02	2.00E-07	3.53E-02
	Adults		8.57E-03	3.88E-08	8.57E-03
North Banat District			For average nitrate concentration values		
	Children	1.32	8.80E-02	4.99E-07	8.80E-02
	Adults		2.13E-02	9.68E-08	2.13E-02
			For average nitrite concentration values		
	Children	0.0052	3.47E-04	1.96E-09	3.47E-04
	Adults		8.41E-05	3.81E-10	8.41E-05
			For maximum nitrate concentration values		
	Children	2.2	1.47E-01	8.31E-07	1.47E-01
	Adults		3.56E-02	1.61E-07	3.56E-02
			For maximum nitrite concentration values		
	Children	0,008	5.33E-04	3.02E-09	5.33E-04
	Adults		1.29E-04	5.86E-10	1.29E-04

HQ – Hazard Quotient; IR – 1.6 L/day for children and 2 L/day for adults [24]; EF – 365 days/year; ET – 0.5 h/day [25]; BW – 15 kg for children [27] and 75.61 kg for adults; AT-ED*365 days [28]; RfD – 1.6 mg/kg/day [29]; SA – 1.815 m^2 for adults and 0.76 m^2 for children [30]; PC – 0.00001 m/hour [31]; ET – is specified as 0.5 hours/day for adults and children; CF for water is 0.001 L/cm^3 [31].

a - Adult exposure duration (ED, years); North Bačka – 76.55; West Bačka – 74.6; South Bačka – 74.75; North Banat – 75.65; Central Banat – 75.25; South Banat – 75.65; Srem – 76.

the maximum nitrate HQ reached 9.27E+00, substantially exceeding the threshold of one and indicating a significant potential health risk for children **(Table 2).**

For nitrites, the HQ values for adults were 5.97E-04 for average concentration and 1.63E-02 for maximum concentrations. Both values are well below the threshold value of one, indicating no health risks **(Table 2).**

Similarly, in children, the HQ values for nitrites were 2.46E-03 (average) and 6.70E-02 (maximum), remaining below the safety threshold and suggesting no health risk from nitrite exposure in this age group **(Table 2).**

Across all scenarios, ingestion was identified as the dominant exposure pathway for both nitrate and nitrite, with dermal absorption contributing minimally to total exposure **(Table 2).**

District-level HQ analysis revealed that both adults and children are at increased risk associated with maximum nitrate concentrations in the South Bačka and South Banat districts. In contrast, in the West Bačka, Srem, and Central Banat districts, elevated risk was observed primarily for children, reflecting their higher susceptibility to nitrate exposure **(Tables 3 and 4).**

Overall, HQ values indicate that average nitrate and nitrite exposures are safe for both children and adults across the Autonomous Province of Vojvodina. However, maximum nitrate concentrations – particularly in specific districts – exceed acceptable risk thresholds, underscoring the importance of incorporating HQ-based risk management into routine drinking water safety evaluation and management strategies.

Discussion

Comparison of the present findings with international data indicates that nitrate contamination of drinking water remains a widespread concern across Europe and beyond. According to the European Environment Agency, all 27 European Union Member States report groundwater bodies with nitrate concentrations exceeding 50 mg/L. Moreover, a substantial proportion of groundwater monitoring stations in Spain, Portugal, Germany, Malta, Luxembourg, Cyprus, and Belgium record nitrate levels above the maximum allowable concentration [13]. Water quality assessments further identify the Czech Republic, the Netherlands, and Slovenia as countries facing particularly severe challenges, with 70%-90% of monitored water bodies classified as poor quality [9]. In England, approximately 55% of the national territory has been designated as a Nitrate Vulnerable Zone, primarily due to elevated nitrate concentrations in groundwater and rivers [32].

A broader international comparison reveals considerable variability in nitrate and nitrite concentrations. Notably, Poland and Malta reported high average nitrate concentrations of 41.2 mg/L and 58.1 mg/L, respectively, with Poland reaching the maximum value of 194.8 mg/L. In the same study, the average nitrite concentration in Poland was 0.044 ± 0.036 mg/L, with a maximum recorded value of 0.123 mg/L. Marked regional differences were also observed in the United Kingdom, where England exhibited an average nitrate concentration of 22.94 mg/L, compared with a substantially lower average of 2.07 mg/L in Scotland. In Morocco, the reported average nitrate concentration was 24.73 mg/L, with maximum values reaching 82.02 mg/L [27].

Data from Serbia underscore the magnitude of the problem. In 2014, drinking water analyses conducted in rural areas near Požarevac identified nitrate and nitrite as the principal causes of unsafe water quality, with nitrate concentrations reaching 1138.9 mg/dm^3 and nitrite concentrations up to 0.40 mg/dm^3 [33]. A 2019 study conducted across settlements in the South Bačka Administrative District detected exceedances of permissible nitrite concentrations in 23 of 386 samples (5.96%) of untreated chlorinated water [9]. More, recently, in 2022, elevated nitrite concentrations were identified as a major hazard in the Autonomous Province of Vojvodina, occurring in 13% of unpurified chlorinated water samples [34]. In 2023, 783,104 individuals, representing approximately 45% of the total population of Vojvodina, were supplied with non-purified but disinfected drinking water [35].

In contrast to concentration-based monitoring, relatively limited research has focused on health risk characterization using the Hazard Quotient. Nevertheless, studies from several countries highlight the value of this approach. In Turkey, groundwater investigations in Mersin Province demonstrated generally low overall risk but identified localized areas – particularly between Tarsus and Çeşmeli – where HQ values exceeded 4.00, indicating a significant health risk for children [36]. Similarly, in Italy, health risk assessments conducted in the Poirino Plateau revealed substantially higher risks for children, primarily through oral exposure pathways, compared with dermal exposure, particularly in areas affected by nitrate-contaminated shallow aquifers [37]. Comparable findings have been reported in Poland, where a study assessing nitrate ingestion risk found that 50% of the analyzed samples posed an unsafe HQ (>1) for children, compared with 40% for adolescents and 33% for adults. Reported HQ values reached 6.90 for children and 4.87 for adolescents, indicating pronounced age-related vulnerability. Studies from Iran and China further corroborate these concerns, with reported HQ values for children in China reaching as high as 19.86

[27]. Although drinking water safety in the Republic of Serbia is regulated by national legislation defining mandatory analytical parameters, monitoring frequency, and permissible limit values, formal health risk assessment methodologies are not yet integrated into routine regulatory practice [38]. Alignment with international standards requires strengthening national capacities, improving healthcare financing strategies, and harmonizing regulatory frameworks with regional and global best practices [39]. In this context, the implementation of chronic hazard index-based approaches is essential for identifying localized high–risk areas and supporting evidence-based prioritization of mitigation measures. Effective management of nitrate and nitrite contamination necessitates an integrated, multidisciplinary approach. Such strategies should account for local environmental conditions and include optimized fertilizer application practices based on soil testing, promotion of natural attenuation processes such as denitrification and plant uptake, and, where necessary, the implementation of appropriate of water purification technologies [40].

Several limitations of this study should be acknowledged. First, the risk assessment was limited to children under 5 years of age and adults over 18 years, excluding other potentially vulnerable population groups. Second, the study did not evaluate the combined health risk associated with nitrate-nitrite metabolic conversion, which may underestimate total exposure-related risk. Finally, the assessment considered only drinking water exposure and did not account for total dietary intake, which represents an important additional source of nitrate and nitrite exposure.

Conclusion

The findings of the present study clearly demonstrate a significant public health concern in specific regions of the Autonomous Province of Vojvodina, where maximum Hazard Quotient values for nitrates exceed established safety thresholds. Elevated maximum nitrate concentrations are associated with increased health risk for both children under 5 years of age and adults over 18 years. The results further confirm that ingestion is the predominant exposure pathway for nitrate and nitrite in both population groups, while dermal absorption contributes minimally to overall risk. Beyond emphasizing the importance of drinking water purification, these findings highlight the urgent need for systemic incorporation of health risk assessment methodologies into routine drinking water monitoring and regulatory frameworks.

Future research should prioritize the integration of health risk assessment into legislative and professional practice and support development of a unified national database linking drinking water quality parameters with health statistics data at the national, provincial, district, and local levels.

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