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FOOD SAFETY RISKS IN BOTTLED WATER PRODUCTION: A STRUCTURED EVIDENCE SYNTHESIS AND IMPLICATIONS FOR UZBEKISTAN

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ABSTRACT

This study synthesizes recent international evidence on food safety risks associated with bottled water production and examines their implications for Uzbekistan. A structured evidence synthesis of peer-reviewed literature and authoritative food-safety sources published between 2020 and 2026 was conducted using predefined eligibility criteria and thematic analysis. The evidence indicates that bottled-water safety can be affected by microbiological, chemical, physical, and emerging contaminants originating from source water, treatment processes, production equipment, packaging, storage, and distribution. Microbiological hazards, particularly contamination associated with inadequate source-water protection, sanitation failures, and persistent microorganisms in production environments, remain important concerns. Recent evidence also highlights chemical contaminants associated with source-water pollution and packaging materials, as well as emerging concerns regarding microplastics and other contaminants of emerging concern. Further evidence demonstrates the importance of preventive food safety management systems, including Good Hygiene Practices, Good Manufacturing Practices, HACCP, and broader food safety management systems, in controlling contamination throughout the production chain. For Uzbekistan, the findings indicate a need to strengthen source-water monitoring, hygienic production practices, laboratory capacity, regulatory surveillance, and implementation of preventive food safety management systems. The study identifies important gaps in Uzbekistan-specific evidence and recommends greater producer-level monitoring and research to support evidence-based regulation and continuous improvement of bottled-water safety.

Keywords: bottled water; food safety; microbiological hazards; chemical contamination; microplastics; HACCP; food safety management systems; Uzbekistan.

ANNOTATSIYA

Ushbu tadqiqot qadoqlangan ichimlik suvi ishlab chiqarish bilan bog‘liq oziq-ovqat xavfsizligi xatarlariga oid so‘nggi xalqaro ilmiy dalillarni tizimli ravishda umumlashtiradi hamda ularning O‘zbekiston uchun ahamiyatini tahlil qiladi. 2020–2026 yillarda e’lon qilingan ilmiy adabiyotlar asosida tuzilgan dalillar sintezi o‘tkazilib, tadqiqotlar oldindan belgilangan mezonlar asosida tanlandi va tematik yondashuv orqali tahlil qilindi. Tahlil qilingan dalillar shuni ko‘rsatadiki, butilkadagi ichimlik suvining xavfsizligiga mikrobiologik, kimyoviy, fizik va yangi paydo bo‘layotgan ifloslantiruvchi moddalar ta’sir qilishi mumkin. Ushbu xavflar suv manbai, suvni tozalash jarayonlari, ishlab chiqarish uskunalari, qadoqlash, saqlash va tarqatish bosqichlarida yuzaga kelishi mumkin. Mikrobiologik xavflar, xususan, suv manbalarining yetarli darajada himoyalanmaganligi, sanitariya talablarining buzilishi va ishlab chiqarish muhitida mikroorganizmlarning saqlanib qolishi bilan bog‘liq ifloslanishlar muhim muammolardan biri bo‘lib qolmoqda. So‘nggi tadqiqotlar, shuningdek, suv manbalarining ifloslanishi va qadoqlash materiallari bilan bog‘liq kimyoviy ifloslantiruvchi moddalar, shuningdek, mikroplastiklar va boshqa yangi paydo bo‘layotgan ifloslantiruvchi moddalarga e’tibor kuchayganini ko‘rsatmoqda. Dalillar Good Hygiene Practices (GHP), Good Manufacturing Practices (GMP), Hazard Analysis and Critical Control Points (HACCP) hamda oziq-ovqat xavfsizligini boshqarish tizimlari (FSMS) kabi profilaktik yondashuvlarning ishlab chiqarish zanjiri bo‘ylab ifloslanish xavflarini nazorat qilishdagi muhimligini ko‘rsatadi. O‘zbekiston uchun natijalar suv manbalarini monitoring qilish, ishlab chiqarishdagi gigiyenik amaliyotlarni takomillashtirish, laboratoriya salohiyatini oshirish, nazorat va monitoring mexanizmlarini kuchaytirish hamda profilaktik oziq-ovqat xavfsizligini boshqarish tizimlarini samarali joriy etish zarurligini ko‘rsatadi. Tadqiqot O‘zbekistonga xos ilmiy dalillarda muhim bo‘shliqlar mavjudligini aniqlaydi va butilkadagi ichimlik suvi xavfsizligini doimiy takomillashtirish hamda dalillarga asoslangan tartibga solishni qo‘llab-quvvatlash uchun ishlab chiqaruvchi darajasida monitoring va ilmiy tadqiqotlarni kengaytirishni tavsiya etadi.

Kalit so‘zlar: Qadoqlangan ichimlik suvi; oziq-ovqat xavfsizligi; mikrobiologik xavflar; kimyoviy ifloslanish; mikroplastiklar; HACCP; oziq-ovqat xavfsizligini boshqarish tizimlari; O‘zbekiston.

АННОТАЦИЯ

В настоящем исследовании систематизированы современные международные научные данные о рисках для безопасности пищевых продуктов, связанных с производством бутилированной питьевой воды, и проанализирована их значимость для Узбекистана. Был проведён структурированный синтез научных данных на основе рецензируемой литературы, опубликованной в период с 2020 по 2026 год. Исследования отбирались в соответствии с заранее установленными критериями и анализировались с использованием тематического подхода. Анализ имеющихся данных показывает, что безопасность бутилированной воды может подвергаться воздействию микробиологических, химических, физических и новых, потенциально значимых загрязнителей, источниками которых могут быть исходная вода, процессы водоподготовки, производственное оборудование, упаковочные материалы, условия хранения и дистрибуции. Микробиологические риски, особенно загрязнение, связанное с недостаточной защитой источников воды, нарушениями санитарных требований и сохранением микроорганизмов в производственной среде, остаются одной из важных проблем. Современные исследования также указывают на растущее внимание к химическим загрязнителям, связанным с

загрязнением источников воды и упаковочными материалами, а также к микропластикам и другим загрязнителям, вызывающим повышенный научный интерес. Полученные данные подчёркивают важность профилактических систем управления безопасностью пищевых продуктов, включая надлежащие гигиенические практики (GHP), надлежащие производственные практики (GMP), систему анализа опасностей и критических контрольных точек (HACCP), а также более широкие системы управления безопасностью пищевых продуктов (FSMS) для контроля рисков загрязнения на всех этапах производственной цепочки. Для Узбекистана результаты указывают на необходимость усиления мониторинга источников воды, совершенствования гигиенических практик на производстве, повышения лабораторного потенциала, укрепления государственного надзора и мониторинга, а также эффективного внедрения профилактических систем управления безопасностью пищевых продуктов. Исследование выявляет существенные пробелы в научных данных, непосредственно относящихся к Узбекистану, и рекомендует расширение мониторинга на уровне производителей и проведение дополнительных исследований для поддержки научно обоснованного регулирования и постоянного совершенствования безопасности бутилированной питьевой воды.

Ключевые слова: бутилированная питьевая вода; безопасность пищевых продуктов; микробиологические риски; химическое загрязнение; микропластики; HACCP; системы управления безопасностью пищевых продуктов; Узбекистан.

1. INTRODUCTION

Bottled water has become an important component of the global drinking-water market and is increasingly consumed as an alternative or supplement to tap and other drinking-water sources. Its widespread consumption is associated with perceptions of convenience, safety, controlled quality, and accessibility. However, bottled water should not automatically be regarded as free from food safety risks. The safety of the final product depends on the quality of the original water source, the effectiveness of treatment processes, the hygienic condition of production facilities, the integrity of packaging, and conditions during storage and distribution. Recent research has consequently shifted attention from the quality of bottled water as a final product toward the multiple contamination pathways that may occur throughout its production and supply chain. (Boas et al., 2024; Pourfadakari et al., 2022; WHO, 2026; Akhbarizadeh et al., 2020).

Microbiological hazards remain among the most important food safety concerns associated with bottled water. Recent studies have demonstrated that microorganisms may enter bottled water through contaminated source water, inadequate treatment, insufficient sanitation of production equipment, and poor hygienic practices during bottling. Microbial populations may also change during storage, with production conditions, packaging materials, and storage environments influencing microbial diversity and abundance. Recent research has particularly highlighted the importance of Pseudomonas aeruginosa and other microorganisms in bottled and mineral water, demonstrating that microbial safety requires continuous control rather than reliance on final-product testing alone. (Boas et al., 2024; Hamad et al., 2022; Shrestha et al., 2024; Silva et al., 2025).

Chemical contamination represents another important dimension of bottled water safety. Contaminants may originate from naturally occurring substances in groundwater and surface water, agricultural and industrial pollution, treatment processes, or materials that come into contact with water

during production and packaging. Recent literature has examined a broad range of chemical contaminants, including heavy metals, nitrate and nitrite, disinfection by-products, plastic-associated compounds, and other contaminants of emerging concern. In addition, growing scientific attention has been directed toward microplastics and nanoplastics in bottled water. These emerging concerns demonstrate that bottled water safety is not limited to conventional microbiological and chemical parameters but is increasingly connected to changes in analytical technologies and understanding of long-term exposure. (Akhbarizadeh et al., 2020; Pourfadakari et al., 2022; Bradley et al., 2023; Aslani et al., 2024; Guo et al., 2024; Kamel et al., 2026).

The production process therefore represents a critical determinant of bottled water safety. Contamination can potentially occur at several interconnected stages, beginning with source-water extraction and continuing through treatment, filtration, storage, bottling, packaging, transportation, and retail storage. Consequently, effective food safety control requires a preventive approach covering the entire production chain. Good Hygiene Practices (GHP), Good Manufacturing Practices (GMP), Hazard Analysis and Critical Control Points (HACCP), and broader food safety management systems (FSMS) provide established frameworks for identifying hazards, controlling critical risks, and maintaining hygienic production conditions. Recent evidence from water-bottling facilities also indicates that the effectiveness of such systems is influenced by organizational conditions and food safety culture, rather than by documented procedures alone. (Boas et al., 2024; Woreta et al., 2024; Lou et al., 2024; WHO, 2026; Pourfadakari et al., 2022).

Despite the expanding international literature, important differences remain in the availability and quality of evidence between countries and regions. A substantial proportion of recent research has focused on individual markets, specific contaminants, or aspects of bottled water quality. Evidence concerning the complete production-chain perspective is less consistently integrated, particularly for developing and transitioning economies. This creates a need to synthesize recent findings across different categories of food safety hazards and production stages to identify common contamination pathways and practical preventive measures. (Pourfadakari et al., 2022; Boas et al., 2024; Bradley et al., 2023).

This issue is particularly relevant to Uzbekistan, where bottled and packaged drinking water represents an important part of the domestic food and beverage sector. However, compared with the international literature, publicly accessible scientific evidence specifically addressing food safety risks in Uzbekistan's bottled-water production remains limited. The availability of international evidence therefore provides an opportunity to assess which preventive approaches may be relevant to the Uzbek context while recognizing that differences in water sources, production technologies, regulatory capacity, laboratory infrastructure, and industry practices may influence their applicability.

Accordingly, this study synthesizes peer-reviewed evidence published between 2020 and 2026 on food safety risks associated with bottled-water production. The review focuses on microbiological, chemical, physical, and emerging hazards; identifies the principal stages at which contamination may occur; examines the role of preventive food safety management systems; and evaluates the implications of the international evidence for Uzbekistan. By bringing these strands of evidence together, the study aims to identify practical priorities for strengthening bottled-water safety and highlight areas where further Uzbekistan-specific research is required. (Page et al., 2021).

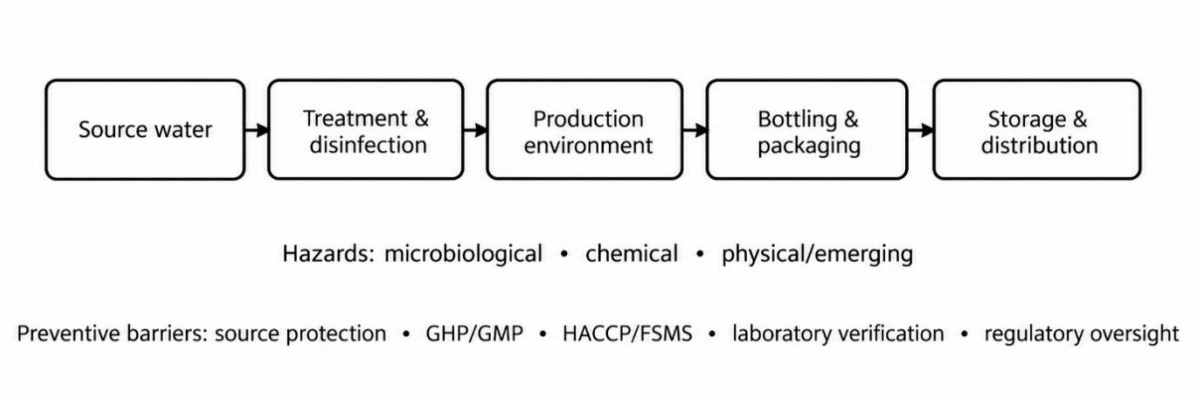

Figure 1. Conceptual framework linking bottled-water production stages, food-safety hazards and preventive barriers.

2. RESEARCH METHODOLOGY

2.1 Review design

This study employed a structured evidence synthesis to examine recent scientific evidence concerning food safety risks associated with bottled-water production and their implications for Uzbekistan. The review focused primarily on peer-reviewed literature published from January 2020 through 2026, supplemented where necessary by authoritative WHO and Codex materials. Evidence was synthesized thematically according to major food-safety hazard categories, contamination points within the production chain, and preventive food-safety management approaches. The review is reported as a structured evidence synthesis rather than a full systematic review because the original database-export files and complete retrieval counts were not retained; therefore, numerical PRISMA flow statistics are not reported.

PRISMA 2020 was used as a reporting reference for transparency in describing eligibility, screening, and synthesis decisions, but the study does not claim to be a fully reproducible systematic review. PRISMA 2020 provides reporting guidance and flow-diagram templates for systematic reviews (Page et al., 2021).

2.2 LITERATURE SEARCH STRATEGY

Relevant publications were identified from major scholarly indexing and publisher platforms, with PubMed and ScienceDirect used as principal searchable sources for the recent evidence base. Additional records were identified through publisher pages, reference-list checking, and authoritative publications from the World Health Organization (WHO) and Codex Alimentarius Commission where relevant to drinking-water and food safety. Codex standards were used only as regulatory context rather than as empirical study evidence (Codex Alimentarius Commission, 2019).

The principal search concept combined terms relating to bottled water, food safety, contamination, hazards, and production. The core search string was:

("bottled water" OR "bottled drinking water" OR "packaged drinking water" OR "mineral water") AND ("food safety" OR contamination OR hazard* OR microbiological OR chemical OR physical) AND (production OR processing OR bottling OR packaging)

Additional targeted searches used terms relating to Pseudomonas aeruginosa, Escherichia coli, heavy metals, nitrate, nitrite, microplastics, packaging migration, biofilms, disinfection by-products, HACCP, GMP, GHP, and food safety management systems.

The search and verification process was conducted during the preparation of this article in 2026. Preference was given to recent evidence from 2022–2026, while 2020–2021 studies were retained where they provided important evidence on emerging contaminants, analytical methods, or bottled-water risks. The final evidence set used in the synthesis comprises 32 references meeting the stated relevance criteria, including peer-reviewed empirical studies, reviews, and authoritative standards/guidance.

2.3 Inclusion and exclusion criteria

Studies were considered eligible when they:

1. were published between 2020 and 2026;
2. were peer-reviewed scientific publications or authoritative institutional documents;
3. addressed bottled, packaged, or mineral drinking water;
4. examined at least one food safety hazard, contamination pathway, production-stage risk, or preventive control measure; and
5. provided information relevant to bottled water safety or its management.

Studies were excluded when they:

1. were published before 2020, except for essential methodological or internationally established foundational sources;
2. focused exclusively on general drinking-water quality without relevance to bottled-water production;
3. were unrelated to food safety or contamination;
4. consisted solely of commercial or promotional material;
5. lacked sufficient information to determine their relevance to the research objectives; or
6. were duplicate publications.

2.4 Study selection and PRISMA procedure

Records were screened for topical relevance against the predefined criteria. Potentially relevant publications were assessed by title/abstract information and, where necessary, full-text or publisher/PubMed records. The final evidence set comprised 32 relevant sources used in qualitative synthesis. Because complete database retrieval logs were not retained, the review does not report reconstructed numbers of records identified, duplicates removed, or records excluded; doing so would create unsupported numerical results.

Accordingly, no numerical PRISMA flow diagram is presented. This avoids implying a level of systematic reproducibility that cannot be demonstrated from the retained search record.

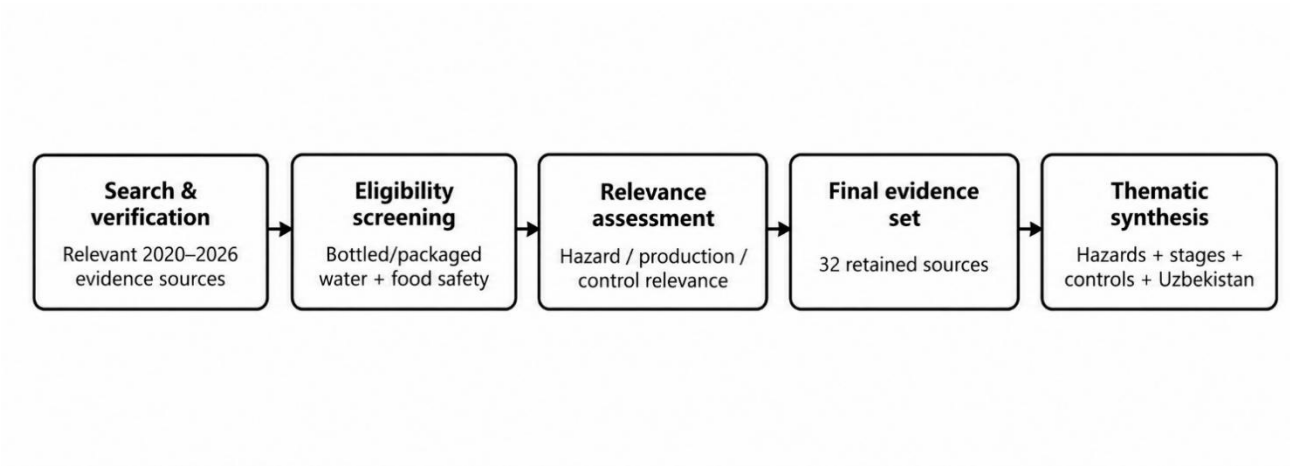

Figure 2. Structured evidence-selection workflow used to identify and retain the 32 sources included in the qualitative synthesis.

2.5 Data extraction

Information from the included publications was systematically extracted into an evidence matrix. The extracted variables included author and publication year, country or geographical region, study design, type of bottled water, hazard category, contamination source or production stage, principal findings, and recommended control measures.

The evidence was subsequently grouped into four principal categories:

a) microbiological hazards;

b) chemical hazards;

c) physical and emerging hazards; and

d) food safety management and preventive controls.

This categorization enabled comparison of evidence across different production stages and geographical settings.

2.6 Quality and relevance assessment

Methodological relevance and quality were considered during synthesis using predefined criteria appropriate to the type of source. Greater weight was given to empirical studies with clearly described sampling procedures, analytical methods, sample populations, controls, and transparent reporting of results. Reviews were used to establish broader evidence patterns and identify research gaps, while WHO/Codex materials were used for regulatory and guideline context. Studies with limited methodological detail were retained only where they provided useful contextual evidence, but their findings were not treated as definitive.

Because the evidence base contains heterogeneous laboratory investigations, field studies, reviews, and regulatory publications, findings were not statistically pooled in a meta-analysis. Instead, they were compared qualitatively according to hazard type, contamination pathway, production stage, and preventive control.

2.7 Thematic synthesis

The included evidence was analyzed using a thematic synthesis approach. Findings were initially organized according to the major hazard categories and then compared across stages of the bottled-water production chain.

The analysis focused on recurring themes concerning:

1. source-water contamination;
2. treatment and disinfection;
3. production-equipment hygiene and biofilm formation;
4. bottling and handling practices;
5. packaging-related contamination;
6. storage and distribution;
7. preventive food safety management systems; and
8. regulatory and institutional capacity.

The synthesis was used to identify recurring risk patterns, differences between studies, emerging concerns, evidence gaps, and implications for Uzbekistan.

2.8 Application to Uzbekistan

Finally, the international evidence was interpreted in relation to the Uzbek context. Attention was given to the relevance of identified hazards and control measures to source-water protection, production hygiene, laboratory monitoring, packaging, regulatory surveillance, and implementation of preventive food safety management systems in Uzbekistan.

This final stage does not assume that findings from other countries directly represent Uzbekistan. Instead, international evidence was used to identify potential priorities and areas requiring further country-specific investigation.

3. LITERATURE REVIEW AND EVIDENCE SYNTHESIS

3.1 Microbiological hazards in bottled water

Microbiological contamination remains one of the most important food safety concerns associated with bottled water production. Recent evidence indicates that bottled water can contain diverse microbial communities and that microbial characteristics may change throughout production and post-packaging storage. Source-water characteristics, treatment processes, bottling conditions, packaging materials, and storage conditions can all influence microbial abundance and diversity. A 2024 review of bottled-water microbiology emphasized that microbial populations may change during processing and post-packaging shelf life, demonstrating that microbiological quality cannot be considered exclusively at the point of source-water extraction or final-product testing. (Boas et al., 2024; Hamad et al., 2022; Shrestha et al., 2024; Silva et al., 2025).

Potential microbial contamination may originate from several interconnected sources. Inadequately protected source water can introduce microorganisms into the production system, while insufficient treatment or disinfection may allow organisms to survive. Contamination can also occur through production equipment, storage tanks, filing systems, bottles, closures, and personnel. Biofilms are of particular importance because microorganisms can attach to surfaces and persist within production environments, potentially providing a continuing source of contamination. Recent research on drinking

water microbial ecology has similarly demonstrated that treatment and distribution environments exert strong selective pressures on microbial communities and that biofilms can contain substantial numbers of microorganisms. (Boas et al., 2024; Hamad et al., 2022; Shrestha et al., 2024).

Recent empirical evidence further demonstrates that microbiological risks remain relevant in commercial bottled water production. For example, a 2024 investigation of water-bottling factories in Ethiopia found that 43% of tested samples showed positive total plate counts, while deficiencies were also identified in hygiene practices, production areas, and food safety management systems. The study illustrates how microbiological quality can be influenced not only by the quality of the water itself but also by the effectiveness with which preventive controls are implemented within the manufacturing environment. (Woreta et al., 2024).

The evidence therefore suggests that microbial safety should be approached as a production-chain issue rather than as an isolated final-product parameter. Effective source-water protection, validated treatment, hygienic equipment design, environmental sanitation, personnel hygiene, and appropriate microbiological monitoring are interconnected components of microbial risk control. (Boas et al., 2024; Silva et al., 2025; Woreta et al., 2024).

3.2 Chemical hazards

Chemical contamination represents a second major category of bottled-water food safety risk. Unlike many microbiological hazards, chemical contaminants may persist over relatively long periods and may originate from both environmental and production-related sources. Recent studies have investigated heavy metals and other chemical contaminants in bottled water, highlighting the importance of evaluating exposure in addition to simple compliance with individual concentration limits. (Pourfadakari et al., 2022; Bradley et al., 2023; Aslani et al., 2024; Askari et al., 2024).

Environmental contamination of groundwater and surface-water sources can introduce metals and other inorganic contaminants into water before it enters the bottling facility. Agricultural activities, industrial emissions, geological characteristics, and inadequate protection of water sources may therefore influence the chemical profile of bottled water. A 2024 health-risk assessment of bottled water in Iran, for example, examined eight heavy metals using both deterministic and probabilistic approaches, demonstrating the continuing relevance of heavy-metal exposure as a bottled-water safety issue. (Olowoyo et al., 2022; Mirzaei et al., 2023; Aslani et al., 2024; Alshishani et al., 2026).

Chemical hazards may also arise during treatment and manufacturing. Disinfection processes are essential for microbiological control but can generate chemical by-products when treatment conditions and water chemistry are not appropriately controlled. Evidence from water-bottling factories has demonstrated the potential occurrence of disinfection-related by-products alongside microbiological quality problems, reinforcing the need to balance microbial control with chemical safety. (Woreta et al., 2024; Kamel et al., 2026; Rasheduzzaman et al., 2025).

Packaging is another potential source of chemical contamination. Bottled water is frequently stored in plastic containers, particularly polyethylene terephthalate (PET), and water may remain in contact with packaging materials for extended periods. Consequently, packaging composition, production conditions, storage temperature, exposure to light, and duration of storage may influence the migration or formation of chemical substances. The literature on bottled-water contamination increasingly treats

packaging as part of the overall food safety system rather than as an independent post-production issue. (Akhbarizadeh et al., 2020; Wang et al., 2021a; Guo et al., 2024; Wang et al., 2021b).

3.3 Emerging and physical hazards

The recent literature has expanded the scope of bottled-water safety beyond conventional microbiological and chemical parameters. Microplastics (MPs) and nanoplastics have emerged as important areas of scientific investigation because bottled water can potentially become contaminated through source water, packaging materials, bottling operations, and degradation of plastic containers. (Gambino et al., 2022; Muhib et al., 2023; Acarer, 2023; Yang et al., 2024).

A review reported the detection of different polymer types, including PET, polyethylene, polypropylene, polystyrene, PVC and other plastics, in drinking-water and food-packaging contexts. The review identified mechanical stress, ultraviolet radiation, ageing, material quality and environmental deposition as potential contributors to plastic particle contamination. It also emphasized methodological difficulties in comparing results because analytical approaches differ considerably between studies. (Gambino et al., 2022; Muhib et al., 2023; Acarer, 2023).

More recent evidence has strengthened interest in this issue. Yang et al. (2024) systematically reviewed microplastics in drinking water and reported wide variation in measured concentrations, emphasized the need for standardized sampling and analytical methods, and identified important gaps concerning particles smaller than 10 μm and nanoplastics.

The emergence of microplastics illustrates an important characteristic of contemporary bottled-water safety research: scientific attention is expanding as analytical technologies become more sensitive. However, the presence of an emerging contaminant should not automatically be interpreted as evidence of a confirmed human health risk. Current literature continues to identify uncertainties concerning exposure levels, analytical standardization, toxicological significance, and long-term health effects. Therefore, emerging contaminants should be treated as important research and monitoring priority while avoiding conclusions that exceed the available evidence. (Gambino et al., 2022; Muhib et al., 2023; Yang et al., 2024; Bradley et al., 2023).

3.4 Contamination across the bottled-water production chain

The evidence reviewed indicates that food safety risks are distributed across multiple stages of bottled-water production rather than being concentrated at a single point. The production chain can be conceptualized as: (Akhbarizadeh et al., 2020; Wang et al., 2021b; Chow et al., 2021; Martínez et al., 2024; Boas et al., 2024).

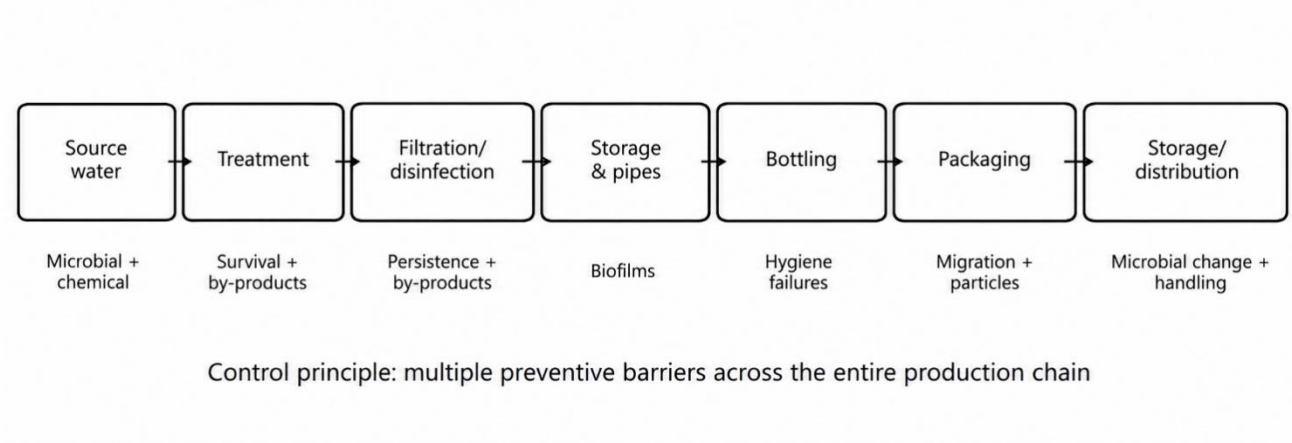

Figure 3. Bottled-water production chain and principal contamination points.

At the source-water stage, contamination may arise from environmental pollution, agricultural activities, industrial activities, geological conditions, or inadequate protection of water sources. The quality of source water therefore determines the initial hazard profile entering the production system. (Acarer, 2023; Gambino et al., 2022; Pourfadakari et al., 2022).

During treatment and filtration, the principal concern is the effectiveness and validation of processes intended to remove or control contaminants. Inadequate treatment may permit microorganisms or chemical contaminants to remain in the water, while poorly controlled disinfection may introduce or increase chemical by-products. (Woreta et al., 2024; Boas et al., 2024; Kamel et al., 2026).

The storage and production-equipment stages present additional risks because tanks, pipes, filters, filling equipment and other water-contact surfaces may provide locations for microbial attachment and biofilm development. Recent research on microbial ecology emphasizes the importance of environmental and surface-associated microbial communities in determining drinking-water quality. (Boas et al., 2024; Shrestha et al., 2024).

During bottling and packaging, contamination may occur through equipment, personnel, bottle surfaces, closures or environmental exposure. Packaging also introduces a potential pathway for physical particles and chemical migration. Finally, storage and distribution can influence product quality through temperature, light exposure, storage duration and handling conditions. (Boas et al., 2024; Guo et al., 2024; Wang et al., 2021b).

These findings support a preventive approach in which food safety controls are applied throughout the entire production chain rather than relying primarily on testing of finished products. (Boas et al., 2024; Pourfadakari et al., 2022).

3.5 Food safety management systems and preventive controls

The effectiveness of bottled water safety depends not only on individual technological interventions but also on the organizational systems used to control hazards. Good Hygiene Practices (GHP), Good Manufacturing Practices (GMP), sanitation procedures, HACCP, and broader Food Safety Management Systems (FSMS) provide complementary mechanisms for preventing and controlling contamination. (Woreta et al., 2024).

Recent evidence from water-bottling facilities demonstrates the importance of implementation in practice. A 2024 study of seven water manufacturers found that manufacturers operated under varying

contextual risk levels and that lower FSMS activity was associated with poorer food safety outcomes. The study also identified deficiencies in hygiene practices, cleaning routines, employee hand hygiene, information exchange, and implementation of preventive measures. Importantly, the researchers concluded that certification alone does not necessarily guarantee strong food safety performance; the functionality and practical implementation of the system are critical. (Woreta et al., 2024).

This finding has broader implications for bottled water producers. A documented HACCP plan or ISO 22000 certification may establish a formal framework, but food safety performance ultimately depends on whether procedures are understood, implemented, monitored, verified, and continuously improved. Management commitment, employee training, communication, sanitation practices, laboratory capacity, supplier relationships and regulatory oversight can therefore influence the effectiveness of formal food safety systems. (Woreta et al., 2024; WHO, 2026).

3.6 Synthesis of the evidence

Taken together, the 2020–2026 literature demonstrates that bottled-water food safety is a multidimensional and interconnected problem. Microbiological hazards remain central, but they coexist with chemical contamination, packaging-related risks, and emerging concerns such as microplastics. The reviewed evidence consistently indicates that contamination can occur at multiple stages from source-water extraction through production, packaging, storage and distribution. (Boas et al., 2024; Woreta et al., 2024; WHO, 2026; Pourfadakari et al., 2022).

Three broad conclusions emerge from the evidence. First, source-water quality is fundamental because contamination entering the production system may increase the burden placed on subsequent treatment processes. Second, production hygiene and preventive controls are essential, particularly because microorganisms can persist in equipment and production environments. Third, food safety management must extend beyond certification or final-product testing and should incorporate continuous monitoring, verification, employee competence, management commitment and corrective action. (Boas et al., 2024; Woreta et al., 2024).

The evidence also reveals an important geographical imbalance. While recent international research provides substantial information about specific contaminants and production risks, evidence directly examining bottled-water production in Uzbekistan remains comparatively limited. Consequently, international findings can provide a basis for identifying potential priorities for Uzbekistan, but they cannot substitute for country-specific monitoring and primary research.

This evidence gap provides the basis for the next stage of the analysis: assessing how international findings can be translated into practical food safety priorities for Uzbekistan.

4. ANALYSIS AND SYNTHESIZED RESULTS

The evidence synthesized in this review indicates that bottled-water safety is determined by a combination of hazard characteristics, production-stage vulnerabilities, and the effectiveness of preventive food safety controls. Rather than identifying a single dominant contamination source, the literature demonstrates that microbiological, chemical, physical, and emerging risks can interact across the bottled-water production chain. (Boas et al., 2024; Pourfadakari et al., 2022; Woreta et al., 2024).

4.1 Distribution of identified food safety hazards

The reviewed literature can be broadly classified into four major evidence categories: microbiological hazards, chemical hazards, physical hazards, and emerging contaminants. Microbiological risks constitute a substantial proportion of recent research, reflecting continued concern regarding pathogenic and indicator microorganisms, biofilm formation, and changes in microbial communities during production and storage. Chemical hazards form another major research category, particularly studies investigating heavy metals, inorganic contaminants, disinfection-related compounds, and substances associated with packaging. (Boas et al., 2024; Pourfadakari et al., 2022; Bradley et al., 2023; Hamad et al., 2022; Silva et al., 2025).

More recent publications have expanded the evidence base toward emerging contaminants, particularly microplastics and other substances associated with plastic packaging. However, the evidence in this area is less consistent because analytical methodologies, detection limits, sampling approaches, and definitions of particle size vary substantially between studies. (Akhbarizadeh et al., 2020; Gambino et al., 2022; Muhib et al., 2023; Acarer, 2023; Askari et al., 2024; Aslani et al., 2024; Kamel et al., 2026).

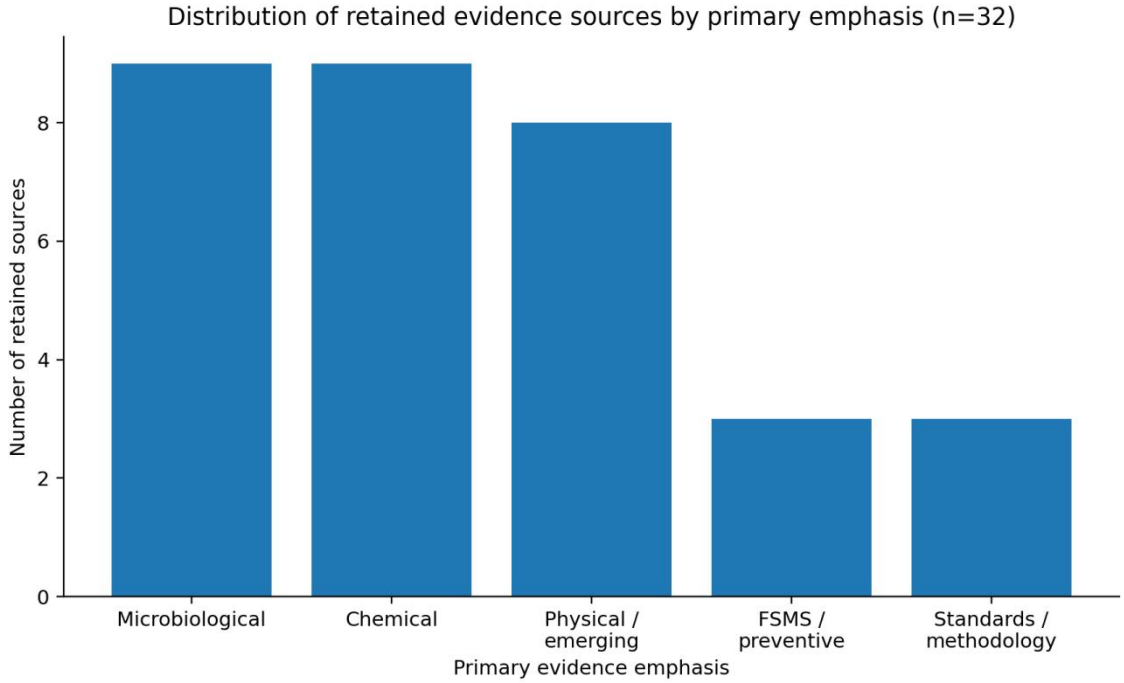

Figure 4. Evidence sources included in the synthesis by primary hazard emphasis, 2020–2026.

Note: Categories are based on the primary emphasis of the 32 retained evidence sources; sources addressing multiple hazards were assigned to the category that best represented their principal analytical focus.

Primary evidence category	Number of retained sources
Microbiological hazards	9
Chemical hazards	9
Physical/emerging contaminants	8
FSMS/preventive controls	3
Standards/methodology	3

4.2 Microbiological risks as a persistent production-chain concern

The analysis demonstrates that microbiological contamination is not restricted to source water. Recent studies indicate that contamination may be introduced or amplified during treatment, storage, bottling and post-production handling. This is particularly important because bottled water may support microbial persistence or changes in microbial populations during storage even when the original source water meets quality requirements. (Boas et al., 2024; Schalli et al., 2023; Silva et al., 2025).

A recent large-scale investigation of mineral water analyzed 1,150 samples across seasons and container types and specifically examined Pseudomonas aeruginosa and heterotrophic bacteria. The study illustrates the value of examining microbiological quality across different production and storage conditions rather than relying on a single sampling point. The persistence of such organisms reinforces the importance of environmental hygiene, equipment sanitation and appropriate microbiological monitoring. (Silva et al., 2025).

The evidence therefore supports a shift from a final-product testing model toward preventive process control. Source-water monitoring, validated treatment, cleaning and disinfection procedures, hygienic filling operations, personnel hygiene, and environmental monitoring should function as interconnected barriers. (Lou et al., 2024; Woreta et al., 2024; WHO, 2026; Boas et al., 2024).

4.3 Chemical contamination and the importance of source-water control

The analysis also indicates that chemical hazards require a different control strategy from microbiological hazards. Whereas microbial contamination may sometimes be reduced rapidly through validated treatment and sanitation, chemical contaminants may persist and may enter the production process through the source water itself. (Bradley et al., 2023; Askari et al., 2024; Aslani et al., 2024; Mianeh et al., 2025; Alshishani et al., 2026).

Recent studies have identified heavy metals and other inorganic contaminants in bottled-water samples and have increasingly applied health-risk assessment approaches rather than assessing compliance with concentration limits alone. This suggests that bottled-water safety assessments should consider both the occurrence of contaminants and potential cumulative exposure. (Askari et al., 2024; Mirzaei et al., 2023; Olowoyo et al., 2022; Alshishani et al., 2026; Zhou et al., 2026).

Further evidence indicates that source-water protection is therefore a critical preventive measure. Treatment technologies cannot be regarded as a substitute for adequate protection of the water source. Where contamination originates upstream from the bottling facility, producers may face continuing challenges in maintaining chemical quality even when downstream treatment is effective. (WHO, 2026; Aslani et al., 2024; Mianeh et al., 2025; Pourfadakari et al., 2022).

4.4 Packaging and emerging contamination pathways

An important development in the 2020–2026 literature is the increasing attention given to packaging-related contamination. Plastic packaging can potentially contribute both chemical substances and particulate contamination to bottled water. Microplastics have consequently become an emerging research area within bottled water safety. (Akhbarizadeh et al., 2020; Wang et al., 2021a; Guo et al., 2024; Rasheduzzaman et al., 2025; Wang et al., 2021b).

However, the analysis indicates that the scientific evidence concerning the health significance of microplastics remains less mature than evidence concerning established microbiological and chemical

hazards. Differences in sampling, extraction, identification and quantification methods make direct comparison between studies difficult. (Gambino et al., 2022; Muhib et al., 2023; Acarer, 2023; Yang et al., 2024).

Therefore, the presence of microplastics should currently be interpreted primarily as an emerging food-safety and research concern, rather than treated in the same evidentiary category as well-established microbial hazards. This distinction is important for evidence-based regulatory decision-making. (Gambino et al., 2022; Muhib et al., 2023; Yang et al., 2024).

4.5 Production-stage vulnerabilities

A comparison of the reviewed evidence demonstrates that different hazards are associated with different stages of the production chain.

Production stage	Principal risks identified	Priority controls
Source-water collection	Microbial, chemical and environmental contamination	Source protection and monitoring
Treatment	Microbial survival; treatment-related chemical risks	Process validation and verification
Filtration/disinfection	Microbial persistence; disinfection by-products	Validated treatment and monitoring
Storage tanks and pipelines	Biofilms and microbial persistence	Cleaning, sanitation and environmental monitoring
Bottling/filling	Microbial contamination and hygiene failures	GHP, GMP and personnel hygiene
Packaging	Chemical migration and plastic particles	Packaging-material control
Storage/distribution	Microbial changes, chemical migration and physical contamination	Temperature, handling and storage controls

The evidence indicates that these stages should not be treated independently. A weakness at one stage can increase the burden placed on subsequent controls. For example, poor source-water quality can increase treatment requirements, while inadequate sanitation of filling equipment can reintroduce microorganisms after successful treatment. (Boas et al., 2024; Woreta et al., 2024; WHO, 2026).

Risk domain	Evidence from recent literature	Primary preventive control	Priority for Uzbekistan
Microbiological	Microbial communities can change across bottling and storage; P. aeruginosa and other bacteria remain relevant.	Source protection; sanitation; hygienic filling; environmental monitoring	Risk-based microbiological surveillance and stronger production hygiene
Chemical	Heavy metals, nitrate/nitrite, PFAS, phthalates and disinfection-related compounds occur in bottled-water studies.	Source-water protection; validated treatment; chemical monitoring	Expand laboratory capacity and source-water chemical surveillance

Risk domain	Evidence from recent literature	Primary preventive control	Priority for Uzbekistan
Packaging/emerging	Plastic packaging can contribute chemical and particulate contamination; microplastics remain an emerging concern.	Packaging specifications; supplier control; storage controls; standardized testing	Packaging-material control and targeted emerging-contaminant research
FSMS	Formal systems may not translate into effective implementation in practice.	HACCP/GHP/GMP verification; training; auditing; corrective action	Assess functionality and implementation, not certification alone

4.6 Food safety management systems

The analysis identifies preventive food safety management systems as a common control principle across the recent literature. GHP, GMP, HACCP and FSMS provide different but complementary layers of control. (Woreta et al., 2024; Page et al., 2021; WHO, 2026).

Importantly, the evidence suggests that the existence of a formal system does not necessarily demonstrate effective food safety performance. Recent research in water-bottling facilities has identified differences between documented food safety procedures and their practical implementation. Hygiene practices, cleaning procedures, employee behaviour, communication and monitoring can determine whether formal controls function effectively. (Woreta et al., 2024).

This finding has relevance for developing food industries where regulatory requirements may exist, but laboratory capacity, trained personnel, monitoring infrastructure or enforcement resources may be uneven. Consequently, food safety management should be assessed not only through certification status but also through measurable implementation and verification. (Woreta et al., 2024; WHO, 2026).

4.7 Evidence gap and implications for Uzbekistan

The most significant finding from the geographical analysis is the limited availability of recent, publicly accessible evidence specifically concerning bottled-water production in Uzbekistan compared with the broader international literature. The international evidence provides extensive information about individual hazards and preventive controls, but relatively little evidence is available to determine the prevalence of specific contaminants or production failures within Uzbek bottling facilities.

This represents both a limitation and an important research opportunity. International evidence suggests that Uzbekistan should prioritize source-water monitoring, hygienic production environments, microbiological surveillance, chemical testing, packaging control, and implementation of preventive FSMS. However, the relative importance of each risk in Uzbekistan cannot be established confidently without systematic national monitoring. (Boas et al., 2024; Woreta et al., 2024; Alshishani et al., 2026).

Therefore, the most appropriate interpretation is not that international findings demonstrate specific contamination levels in Uzbekistan, but that they identify priority areas for national surveillance and primary research.

4.8 Overall synthesis

Overall, the analysis demonstrates that bottled water safety should be understood as a multi-barrier system. No single treatment technology, laboratory test, certification scheme, or regulatory requirement can independently guarantee safety. (WHO, 2026; Woreta et al., 2024; Boas et al., 2024).

The strongest evidence supports an integrated approach combining:

1. protected and regularly monitored water sources;
2. validated treatment and disinfection processes;
3. effective sanitation and hygienic production practices;
4. microbiological and chemical verification;
5. control of packaging and storage conditions;
6. functional HACCP/FSMS-based preventive management; and
7. effective regulatory oversight and laboratory capacity.

For Uzbekistan, the evidence therefore supports strengthening the entire preventive system rather than concentrating exclusively on testing the finished bottled-water product. (Woreta et al., 2024; WHO, 2026; Boas et al., 2024).

5. IMPLICATIONS AND PRIORITIES FOR UZBEKISTAN

The evidence synthesized in this review indicates that bottled-water safety in Uzbekistan should be approached as a preventive, production-chain food-safety issue rather than solely as a matter of final-product testing. International studies demonstrate that microbiological and chemical hazards can originate from source water, treatment processes, production equipment, packaging, storage and distribution. However, these international findings should not be interpreted as evidence that the same contamination levels occur in Uzbekistan; instead, they provide a scientific basis for identifying priority areas for national surveillance, industry intervention and further research (Boas et al., 2024; Alshishani et al., 2026).

5.1 Strengthening source-water protection and monitoring

Source-water quality should represent the first major priority because contamination entering the production system can increase the burden placed on subsequent treatment and control measures. Bottled-water studies have shown that source characteristics and environmental conditions can influence microbiological and chemical profiles, while chemical-risk studies demonstrate the importance of assessing contaminants in relation to exposure rather than relying only on isolated compliance measurements (Pourfadakari et al., 2022; Askari et al., 2024; Alshishani et al., 2026). For Uzbekistan, producers and regulators should therefore implement risk-based monitoring programmes that integrate microbiological indicators with relevant chemical parameters according to the vulnerability and characteristics of individual water sources.

5.2 Improving hygienic control within bottling facilities

Compliance of the original water source does not necessarily guarantee microbiological safety of the final product. Microorganisms may persist or be introduced through tanks, pipelines, filtration systems, filling equipment, bottles, closures and personnel, while biofilms may provide persistent reservoirs within production environments (Boas et al., 2024; Shrestha et al., 2024). The 2025 large-

scale mineral-water study further demonstrates the continuing relevance of Pseudomonas aeruginosa in commercial bottled water (Silva et al., 2025). Uzbek producers should therefore strengthen Good Hygiene Practices (GHP), Good Manufacturing Practices (GMP), sanitation, personnel hygiene and environmental monitoring throughout the production environment.

5.3 Strengthening laboratory surveillance and analytical capacity

The reviewed evidence demonstrates the importance of reliable laboratory capacity for both microbiological and chemical surveillance. Recent studies have examined heavy metals, nitrate and nitrite, PFAS, phthalates and other contaminants in bottled water, while emerging-contaminant research increasingly depends on sensitive and standardized analytical methods (Aslani et al., 2024; Chow et al., 2021; Guo et al., 2024; Yang et al., 2024). Uzbekistan should therefore strengthen laboratory capacity for validated microbiological and chemical testing and develop surveillance systems capable of identifying recurring contamination patterns rather than responding only to individual non-compliant samples.

5.4 Moving from certification towards effective FSMS implementation

The evidence concerning food safety management systems has particular relevance for Uzbekistan. Woreta et al. (2024) found that practical implementation of food-safety systems in water-bottling facilities did not necessarily correspond to formal system status and identified weaknesses in hygiene, cleaning, employee hand hygiene, information exchange and preventive measures. Accordingly, HACCP and broader FSMS implementation should be assessed on functionality rather than certification status alone. Audits should verify whether hazards are correctly identified, controls are operational, monitoring records are reliable, corrective actions are implemented, and employees understand their responsibilities.

5.5 Strengthening packaging and storage controls

Packaging should be incorporated explicitly into bottled-water food-safety management. Evidence indicates that packaging can be a pathway for chemical migration and particulate contamination, while storage conditions may influence microbial characteristics and contaminant behaviour (Akhbarizadeh et al., 2020; Guo et al., 2024; Wang et al., 2021b). Producers should strengthen controls over packaging specifications, suppliers, storage temperature, light exposure and storage duration. Microplastics should be treated as an emerging monitoring and research priority, while avoiding the unsupported conclusion that their presence alone establishes a confirmed human-health risk (Yang et al., 2024; Muhib et al., 2023).

5.6 Developing Uzbekistan-specific evidence

The most important implication of this review is the need for country-specific primary research. International evidence can identify potential hazards and control strategies, but it cannot establish the prevalence or magnitude of those hazards in Uzbek bottled-water production. Future studies should therefore sample different regions, water sources, producers and packaging types and examine relationships among source characteristics, production practices, packaging, storage and final-product

quality. Longitudinal studies would also help determine seasonal variation in microbiological and chemical quality.

5.7 Priority actions for Uzbekistan

a) Protect and systematically monitor water sources using risk-based microbiological and chemical assessment.

b) Strengthening GHP, GMP and sanitation controls throughout bottling facilities, especially at water-contact surfaces and filling stages.

c) Expand laboratory capacity and surveillance using validated analytical methods and trend monitoring.

d) Evaluate FSMS implementation in practice rather than relying solely on certification or documented procedures.

e) Develop Uzbekistan-specific primary research to establish the prevalence, sources and significance of bottled-water hazards.

These priorities should be implemented as an integrated system rather than as isolated interventions. The evidence supports strengthening the entire preventive food-safety chain, from source-water protection through production, packaging, storage, distribution and regulatory verification (Boas et al., 2024; Woreta et al., 2024).

6. CONCLUSIONS

This structured evidence synthesis demonstrates that food safety in bottled-water production is a multidimensional issue involving microbiological, chemical, physical and emerging hazards across the production and supply chain. Recent evidence indicates that microbiological risks remain particularly important, while chemical contaminants and packaging-associated substances require continued surveillance and improved analytical capacity. Emerging contaminants such as microplastics warrant further investigation, although current evidence does not justify treating their presence as equivalent to established microbial hazards (Boas et al., 2024; Yang et al., 2024).

The evidence also indicates that effective bottled-water safety depends on preventive control throughout the production chain rather than reliance on final-product testing alone. Source-water protection, validated treatment, hygienic production, environmental sanitation, packaging control, laboratory verification and functional food-safety management systems should operate as interconnected barriers (Woreta et al., 2024; Alshishani et al., 2026).

For Uzbekistan, the principal conclusion is that international evidence provides a useful basis for identifying priorities but cannot substitute for country-specific monitoring. The immediate priorities are therefore to strengthen source-water surveillance, production hygiene, laboratory capacity, packaging controls and practical FSMS implementation while developing a stronger national evidence base through systematic primary research. These measures would provide a more evidence-based foundation for regulatory oversight and continuous improvement of bottled-water safety in Uzbekistan.

7. LIMITATIONS AND FUTURE RESEARCH

This review has several limitations. First, it is based on secondary evidence and therefore does not provide direct measurements of contamination in bottled-water products or production facilities in

Uzbekistan. International findings may not be directly transferable because water sources, production technologies, regulatory systems, laboratory capacity and industry practices differ between countries.

Second, the evidence base is heterogeneous in study design, geographical setting, sampling strategy, analytical method and measured parameter. This limits direct comparison of contamination levels and was the principal reason for using qualitative thematic synthesis rather than statistical meta-analysis. Differences in analytical methods are particularly important for microplastics, for which sampling, extraction, identification and quantification procedures vary substantially (Yang et al., 2024).

Third, the review prioritised literature published from 2020 to 2026. This improves currency but may exclude older empirical studies that could provide useful historical or methodological context. Older sources were retained only where they were considered essential to the scientific or regulatory framework.

Fourth, Uzbekistan-specific peer-reviewed evidence remains limited. The absence of extensive publicly accessible evidence should not be interpreted as evidence that hazards are absent. Instead, the current evidence base supports identification of research and surveillance priorities rather than national prevalence estimates.

Future research should prioritise primary studies across different Uzbek regions, water sources, producers and packaging types. Longitudinal sampling should investigate seasonal variation, while production-chain studies should examine contamination from source water through treatment, bottling, packaging, storage and distribution. Research should also evaluate the practical effectiveness of HACCP, GMP, GHP and FSMS implementation using facility audits, microbiological and chemical testing, employee assessments and food-safety-culture measures. Finally, standardized methods for emerging contaminants should be developed or adopted to improve comparability and support future risk assessment.

Overall, future research should move from identifying potential hazards toward quantifying their occurrence, determining their sources, evaluating the effectiveness of preventive controls and establishing evidence-based priorities specific to Uzbekistan.

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