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Microbial hazards in rainwater harvesting systems: bacterial sources, indicators, and health implications – a review

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Abstract
Introduction and Objective. Rainwater harvesting systems (RWHS) are an important element of sustainable water management in urbanized areas, by supporting retention and adaptation to climate change. The widespread use of RWHS, however, is limited due to concerns about the microbiological purity of the water. The aim of the review is to illustrate the current state of knowledge regarding microbiological hazards and methods of their assessment in the rainwater of RWHS.
Review Methods. A comprehensive literature search was conducted using Scopus, ScienceDirect, and PubMed databases. Publications from 2000–2026 were analyzed, with special consideration of the studies published after 2015. Key words included: rainwater harvesting, RWHS, microbiological contamination, faecal indicator bacteria, FIB, microbial source tracking, MST, quantitative microbial risk assessment, QMRA.
Brief description of the state of knowledge. RWHS systems are an effective tool for rainwater management and protection of its resources in integrated water resource management systems. However, the fundamental limitation to their broader implementation is mainly microbiological hazards, effectively limiting the use of rainwater for domestic and consumption purposes.
Summary. The review organizes the knowledge on the safety of water from RWHS, considers microbiological hazards, FIB indicator bacteria, markers for identification of sources of microbiological contamination (MST), and QMRA microbiological risk assessment methods. It also discusses the limitations associated with FIB, the significance of MST, and the role of QMRA. Current data indicate that untreated water from RWHS is often suitable for use in non-consumption activities; however, it usually exceeds the standards set for drinking water. The water from RWHS intended for drinking most often requires treatment and continuous monitoring.

Key words
public health, microbiological contamination, RWHS – rainwater harvesting system, FIB – faecal indicator bacteria, QMRA – quantitative microbiological risk assessment, MST – microbial source tracking

INTRODUCTION

Water resource management is a key process in water protection, ensuring the sustainable use of these resources in accordance with societal needs. However, it must also consider the protection of ecosystems and biodiversity, account for the impact of climate change, and incorporate water quality monitoring and control to ensure safety for people and the environment [1, 2]. In this context, alongside the monitoring of commonly occurring pollutants, attention should be paid to the health risks associated with micropollutants in water sources [3], as this is an important element of public health protection within sustainable water resource management. In the social dimension, this also encompasses ecological education, actions to protect water and reduce risks associated with extreme hydrometeorological phenomena and pollution, as well as the implementation of appropriate water use regulations [4].

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There are various known models of rainwater management that align with the principles of best management practices (BMP), green infrastructure (GI), and low-impact development (LID) solutions [2, 5–9]. Recently, urban areas have seen a rapid development of smart systems for rainwater management and wastewater treatment [10, 11]. An example is the 'sponge city' concept developed in China, which posits that urban systems can and should absorb, retain, purify, and reuse rainwater [10]. This approach, based on LID solutions, has been implemented in numerous pilot projects [12, 13]. These systems, which integrate water infiltration, storage, retention, and drainage processes, enable the utilization of up to 80% of precipitation while simultaneously providing numerous ecological benefits [14].

Environmental and economic benefits of RWHS. Rainwater harvesting systems (RWHS), which encompass the collection of runoff from roofs and impermeable surfaces, its storage, and subsequent use, constitute an essential element of modern water resource management [15]. According to Ghaffarian et al. [16], the widespread implementation of RWHS in urban areas could satisfy up to 80–90% of household water demand. RWHS are of particular importance in countries with limited water resources, where water deficits force the substitution of potable water with rainwater for non-consumptive applications [17]. The use of relatively clean rainwater for applications that do not require drinking-water quality helps to mitigate severe water shortages and reduce the volume of stormwater runoff in municipal drainage systems [18, 19].

The implementation of RWHS brings numerous economic benefits, mainly by increasing water availability and lowering the costs of water supply and consumption, especially in countries with limited resources [20, 21]. Furthermore, RWHS contribute to energy savings, reduced CO_2 emissions [22], stormwater runoff control [23], decreased pollutant loads, and improved groundwater quality owing to natural filtration processes [18].

Additionally, in rural areas, where water is used for both domestic and agricultural purposes (such as farming and animal husbandry), RWHS must exhibit high water-collection efficiency, which remains a significant challenge [24].

Integrating RWHS with stormwater management strategies – including rainwater treatment and monitoring, as well as green infrastructure and bioretention systems – can further benefit ecosystems, enhance biodiversity, improve water use efficiency, and support better living conditions for humans and animals, in alignment with sustainable development goals [2, 18].

RWHS functioning, limitations, and uncertainties. The functioning of RWHS is strongly dependent on climatic conditions, primarily the amount and intensity of precipitation, the size and type of the catchment area, the level and type of water demand, and other extensively studied factors that impact technical and economic optimization in stormwater management [25–27]. Accounting for these conditions is crucial, as the incorrect estimation or omission of these factors can significantly distort the assessment of the environmental and economic benefits resulting from RWHS implementation [27–29].

RWHS also exhibit other important limitations [30], resulting from the high variability of hydrological conditions, difficulties in real-time system optimization, and a limited capacity to adapt to changes in water demand. This necessitates the design, development, and implementation of smart technologies – such as predictive models, sensors, and control and optimization algorithms – to improve RWHS performance [31]. These advancements will ensure that households receive water of appropriate quantity and quality, enabling a more stable, safe, and efficient use of rainwater [30, 31].

However, a primary limitation of RWHS is the widespread perception that, due to the risks of microbiological and chemical contamination alongside insufficient rainwater monitoring and quality control [32], these systems cannot be recognized as a potential source of potable water [15, 31, 33]. Consequently, the successful implementation of RWHS largely depends on public attitudes and the social acceptance of this technology [34]. Key influencing factors include the real and perceived costs of rainwater harvesting [35], water quality concerns [36], a lack of reliable knowledge about RWHS [34, 36], and apprehensions regarding unfavourable regulations and maintenance costs [35]. Incentives, support programmes, and favourable regulations also play a vital role in promoting RWHS implementation [37]. Nevertheless, recent research on social attitudes [38] indicates that despite initial concerns, many users become advocates for rainwater harvesting and its economical utilization once the systems are installed.

Environmental and structural determinants of microbiological water quality in RWHS. In RWHS, the microbiological quality of water results from complex interactions between environmental and structural factors. These include the properties of the catchment surface, local sources of contamination, rainfall characteristics, and various physicochemical and biological processes occurring within the storage tanks [39]. These factors determine the significant qualitative and quantitative variability of the microbiome across different systems. The type of roofing material dictates the specifics of retention and subsequent wash-off of microorganisms by surface runoff. It has been shown that water running off metal roofs generally features lower concentrations of microorganisms, including pathogens, compared to other types of roof coverings [40]. However, it should be noted that the ultimate impact of the roof type on microbiological safety is closely linked to many additional variables.

Atmospheric deposition constitutes another significant source of contamination – not only chemical but also microbiological. Dust, aerosols, and organic matter originating from the atmosphere accumulate on roof surfaces, serving as a specific carrier for microorganisms [39]. Rainfall washes off the material previously deposited on the roof while simultaneously scavenging airborne contaminants and transporting them to the RWHS. The intensity and extent of this process is primarily influenced by the length of the antecedent dry period and current meteorological conditions. Furthermore, one of the primary sources of pathogens introduced into RWHS is animal faecal contamination. This primarily involves bacteria such as *Campylobacter* spp., *Salmonella* spp., and pathogenic strains of *Escherichia coli*, which are washed from roof surfaces and lead to a drastic increase in their concentration in the harvested water. The scale of this phenomenon depends mainly on the frequency and duration of animal (e.g., bird) presence on roofs, the time of faeces accumulation during dry periods, and the intensity of the initial runoff phase [41].

During water storage, microorganisms associated with organic and inorganic matter undergo sedimentation and accumulate at the bottom of the tank. This leads to the formation of a secondary reservoir of potential pathogens – including opportunistic bacteria such as *Pseudomonas aeruginosa* and *Legionella* spp. – which can be re-released into the water column as a result of mechanical or hydraulic disturbances. Additionally, a biofilm forms on the internal surfaces of the installation and tank walls. Studies indicate that the tank's construction material is of key importance for the composition of the microbiome, both in the water and within the biofilm structure itself [42]. Mitigating the load of these contaminants involves accounting for the so-called first-flush effect. The initial portion of water running off after a dry period carries a significantly elevated load of microbiological contaminants, after which its quality improves rapidly. This phenomenon dictates the design requirements of RWHS, which should be equipped with first-flush diverters to minimize the load on the main storage tank. As demonstrated, the intensity of this effect depends primarily on the characteristics of the rainfall itself, the length of the preceding dry period, as well as the type and technical condition of the roof covering [43].

Microbiological risks associated with RWHS and their significance for public health. Alongside chemical pollutants, a key factor determining the suitability of rainwater for domestic applications is microbiological risk, which poses a significant threat to human health [36, 44]. Because the microbiological quality of water in RWHS varies due to diverse contamination sources, unambiguously determining its safe applications can be challenging [45]. Identifying contaminants and their sources is essential to ensure the safe utilization of rainwater and to develop effective treatment strategies [36, 37]. This approach aligns with the principles of sustainable water management, which aims to minimize exposure to human pathogens [36, 46].

While the comprehensive monitoring of all human pathogens is the optimal solution, their high diversity and variability in RWHS make this approach costly, analytically complex, and impractical for routine application [47]. Therefore, faecal indicator bacteria (FIB) and genetic markers for microbial source tracking (MST) are commonly used to support pathogen detection and contamination source identification, thereby aiding health risk assessment in RWHS [48, 49].

A common approach for assessing the microbiological quality of water is the simultaneous analysis of multiple FIB groups alongside selected pathogens in rainwater [50]. Although this approach provides a comprehensive characterization of contaminants, its diagnostic value remains limited [51]. This limitation stems from the lack of a clear correlation between the presence of FIB and the occurrence of human pathogens, which undermines the reliability of traditional indicators in RWHS risk assessment [52].

To address these limitations, bacteria of the genus *Bacteroides* spp. have been proposed as an alternative indicator of faecal contamination due to their significant abundance in the human gut microbiota and high host specificity [53]. Of particular importance is the HF183 marker, which is specific to human faecal contamination and commonly found in RWHS [54].

Recent research indicates that, compared to conventional FIB, MST markers like HF183 enable the precise identification of contamination sources and improve the reliability of health risk assessments [55]. This approach reflects current trends of integrating molecular methods (e.g., qPCR, eDNA) into the environmental monitoring of water systems [56].

Despite their limitations, FIB remain an important element of RWHS microbiological monitoring, especially for assessing seasonal variability, treatment effectiveness, maintenance planning, and system design [45]. Consequently, integrating traditional FIB with MST tools currently constitutes the most comprehensive and recommended approach for assessing microbiological safety in RWHS [57].

Faecal indicator bacteria as a tool for assessing water quality in RWHS. Commonly used faecal indicator bacteria (FIB) include coliform bacteria (total coliforms – TC), *Escherichia coli* (*E. coli*), enterococci, and *Clostridium perfringens* (*C. perfringens*). These microorganisms are utilized to assess the microbiological quality of environmental waters, including rainwater harvested in RWHS, as well as to indirectly assess the risk of enteric pathogens [55].

Coliform bacteria include four genera belonging to the family *Enterobacteriaceae*: *Escherichia*, *Enterobacter, Klebsiella*, and *Citrobacter*, which typically constitute less than 1% of the healthy human gut microbiota. Modern metagenomic profiling reveals that *Enterobacteriaceae* are a minor fraction – for example, *E. coli* reaches an abundance of 0.1% or greater in only 15% of healthy stool microbiomes, while the gastrointestinal community is primarily dominated by the *Firmicutes* and *Bacteroidetes phyla* [58]. This group and the total microbial count are utilized as indicators for assessing microbiological purity and the integrity of water distribution systems [59]. Currently, it is widely recognized that the presence of total coliforms (TC) does not always unambiguously indicate fresh faecal contamination. This is because a portion of the microorganisms classified in this group can naturally reside and multiply in environments free from faecal contamination [55]. Therefore, a more effective and frequently used indicator of faecal contamination is *E. coli* of faecal origin, which accounts for over 95% of the faecal coliforms isolated from water. For monitoring purposes, the target is typically thermotolerant *E. coli* originating from the intestines of warm-blooded animals, capable of lactose fermentation at 44.5–45.5 °C [55].

Identifying the origin of rainwater contamination is of particular importance, as human-derived contamination carries a higher risk of containing human-specific pathogens [60]. The majority of *E. coli* strains present in human faeces are not host-specific, which significantly limits the precise determination of the source of faecal contamination. However, certain strains – such as phylogroup B2 (subgroup VIII, serotype O81), isolated mainly from humans, and phylogroup B1 carrying the hly virulence gene, more often associated with animals – have been described. These strains are considered potential markers for identifying faecal contamination sources in MST studies; however, their environmental application remains limited due to the high genetic variability of *E. coli* [61].

The concentration of *E. coli* in rainwater remains strongly dependent on environmental factors, particularly climate change, air temperature, and the intensity and frequency of precipitation. These factors influence both bacterial survival in the environment and the surface runoff processes responsible for transporting faecal contaminants into RWHS [62].

Similar dependencies are observed with enterococci, which – alongside *E. coli* – constitute a commonly used indicator of microbiological water contamination. In contrast to *E. coli*, they exhibit higher resistance to adverse environmental conditions and can occur independently of fresh faecal contamination [55]. Enterococci are widely recognized as a significant indicator for identifying faecal contamination and, indirectly, for assessing the potential presence of enteric pathogens, especially in rainwater quality analyses and sanitary risk assessments. Two species dominate the population of human faecal enterococci: *Enterococcus faecium* and *Enterococcus faecalis* [63]. These bacteria naturally colonize the large intestines of humans and the gastrointestinal tracts of other warm-blooded animals, reaching high concentrations in excreted feces.

In accordance with the guidelines of the World Health Organization [64] and the regulations in force in many countries, including Poland, concerning the quality of water intended for human consumption, *E. coli*, coliform bacteria, and enterococci must be absent in a 100 mL sample of drinking water [50].

Clostridium perfringens was one of the first bacterial species recognized as an indicator of faecal contamination in the aquatic environment [65]. This bacterium usually occurs in higher concentrations in human faeces than in animal faeces, although its presence is not limited solely to intestinal sources. *C. perfringens* has been isolated from the gastrointestinal tracts of fish, pigs, and ducks, as well as from soil and marine sediments [60]. Due to its ability to form highly resistant spores and survive for long periods in the aquatic environment, it is recognized as a useful indicator of long-term and cumulative faecal contamination [66]. The dissemination of *C. perfringens* spores in the environment, its limited host specificity, and the weak correlation of its abundance with other FIB render its usefulness as an independent microbiological indicator debatable. However, it has been shown that using *C. perfringens* alongside other FIB increases the effectiveness of predicting the presence of pathogens in the aquatic environment, including within RWHS [55].

Microbial source tracking markers and pathogens in RWHS as indicators of health threats. Contemporary research indicates a limited correlation between the presence of FIB and the occurrence of other pathogens in RWHS, which undermines the usefulness of these traditional faecal indicators as the sole tool for microbiological risk assessment [52]. Consequently, increasing attention is being paid to microbial source tracking (MST) markers, which enable the identification of contamination sources and provide a more accurate assessment of health threats. This information is crucial for assessing the potential for the safe utilization of harvested rainwater and, if necessary, for developing appropriate treatment strategies [45].

The genus Bacteroides has been proposed as an MST marker and an alternative to conventional FIB in evaluating faecal contamination during water quality studies [67]. Bacteria of *Bacteroides* spp. are a dominant component of the gut microbiota of humans and other warm-blooded animals, constituting approximately 30–50% of faecal bacteria. Their high host specificity makes them particularly valuable indicators for monitoring the microbiological quality of water in RWHS [65, 67]. In water samples, host-associated 16S rDNA target genes can be utilized to detect and quantify *Bacteroides* spp., serving as MST markers for identifying and tracking faecal contamination originating from humans and animals [68].

Numerous *Bacteroides*-based MST markers have been described, including HF183, HF134, BacHum-UCD, HuBac, and Human-Bac1 [68]. Among them, HF183 is the most thoroughly investigated and widely used marker for detecting human faecal contamination due to its high sensitivity and specificity, as well as its ability to distinguish human-derived contamination from that of animal origin [68]. The occurrence of the HF183 marker has been frequently reported in RWHS gutters and storage tanks [48, 54].

Apart from *Bacteroides*-associated markers, several other MST markers have been utilized to detect human faecal contamination in surface and groundwater, including harvested rainwater. These include CPQ_064, crAssphage CPQ_056, human polyomaviruses (HPyV), pepper mild mottle virus (PMMoV), and Lachno3 [69]. However, the quantitative determination of viral markers in harvested rainwater remains challenging due to methodological and environmental limitations that influence their detection and persistence in water matrices [70]. The detection frequencies and concentrations of FIB and MST markers reported in RWHS worldwide are summarized in Tables 1 and 2.

Table 1. Occurrence of faecal indicator bacteria (FIB) in rainwater harvesting systems

Microorganisms	Methods	Positive samples n (%)	Concentration (CFU/100 mL)	Year (Reference) Country
E. coli	C-BM; IDEXX	9 (64)	<1 – 20	[71] USA
Total coliforms		14 (100)	43 –> 2420	
E. coli	MF; C-BM	38 (57)	0 – 9200	[72] Australia
Enterococcus spp.		55 (82)	0 – 32000	
C. perfringens		33 (49)	0 – 120	
E. coli	MF; C-BM	NM	up to 50	[73] Poland
Enterococcus spp.			up to 77	
C. perfringens			detected only in spring	
Total bacteria			7×10^5 in summer, 3.5×10^5 in spring	
Clostridium perfringens	C-BM	17 (81)	4 –> 300	[74] Czech Republic
E. coli	C-BM; IDEXX	70 (11.9)	33.2 (mean)	[75] USA
Total coliforms		381 (64.9)	480.4 (mean)	

Table 2. Occurrence of microbial source tracking markers (MST) in rainwater harvesting systems

Microorganisms / Marker	Methods	Positive samples n (%)	Concentration (gene copies /100 mL)	Year (Reference) Country
HF183 marker	qPCR	60 (100)	1.54×10^2 – 6.59×10^4	[54] South Africa
HF183 marker	qPCR	25 (76)	0 – 44	[48] South Africa

In these studies, individual FIB were most frequently quantified using membrane filtration and culture-based methods, which were occasionally supplemented with molecular qPCR analysis. The qPCR method enables the detection of both viable and non-culturable microorganisms, which often results in higher recorded concentrations [45].

Published data indicate significant variability in the microbiological quality of harvested rainwater in RWHS. The primary factors recognized as influencing the variability of FIB concentrations include: (1) meteorological conditions (especially wind direction and speed), (2) the location and time of sampling, (3) the type of catchment area and roof materials, as well as the construction of storage tanks, (4) the presence of animals, and (5) the applied laboratory methods [40, 52].

The most frequently detected FIB were coliform bacteria, *Escherichia coli*, and *Enterococcus* spp., where positive detection rates generally exceeded 60%, and concentrations often exceeded the World Health Organization (WHO) guidelines for drinking water quality (Tab. 1). Only a limited number of samples collected from RWHS tanks, including those studied in Singapore and Australia, yielded negative results for *E. coli* or *Enterococcus* spp. [76, 77]. *Clostridium perfringens*, considered an indicator of the persistence of faecal contamination in the environment, was detected in 49–91% of samples at concentrations reaching 300 CFU/100 mL [74].

While the MST marker HF183 is frequently utilized to identify anthropogenic sources of faecal contamination in environmental waters, there is currently a significant data gap regarding its quantitative occurrence and detection frequency specifically within RWHS. The limited available data (Tab. 2), originating predominantly from a single research group, confirm its presence in RWH systems but do not provide a sufficient basis to establish a generalized detection frequency. This highlights the need for further targeted research in this area.

Investigations into the associations between MST markers (mainly HF183) and FIB (mainly *E. coli* and *Enterococcus* spp.) have yielded inconclusive results [56] demonstrating both positive and negative correlations. Similar inconsistencies were observed when investigating their relationships with various other pathogens [48, 54]. These results suggest that while MST markers are useful for indicating contamination sources, they may not reflect all associated health threats – such as those posed by pathogens present in animal faeces [78].

Therefore, there is a need for the direct monitoring of opportunistic and pathogenic microorganisms in RWHS. Molecular studies of rainwater most frequently indicate the presence of *Campylobacter*, *Salmonella*, *Legionella*, *Pseudomonas*, *Cryptosporidium*, and *Giardia*. Additionally, dangerous pathogenic genera, such as *Mycobacterium* (e.g., *Mycobacterium tuberculosis*), *Yersinia* spp., and *Listeria* (*Listeria monocytogenes*), have been found [45]. Cross-sectional Australian studies on RWHS primarily identified microorganisms such as *E. coli*, total and fecal coliforms, *Campylobacter*, *Salmonella*, *Legionella*, *Pseudomonas*, *Cryptosporidium*, enterococci, *Giardia*, *Aeromonas*, and the *Mycobacterium avium* complex (MAC) [76]. The latest reviews of microbiological contaminants in RWHS [79] confirmed the occurrence mainly of *E. coli*, *Salmonella* spp., *Campylobacter* spp., and *Legionella*. These reviews also highlight the main sources of contamination (e.g., urban bird droppings), their regional differentiation, and the widespread presence of antibiotic-resistant strains (e.g., to ampicillin, ciprofloxacin, and tetracycline), which constitutes an additional threat to public health in urban RWHS.

Quantitative microbial risk assessment (QMRA) of rainwater in RWHS. Identifying detected pathogens and their contamination sources is essential for developing appropriate strategies to prevent contamination and assessing the human health risks associated with RWHS water utilization. Quantitative Microbial Risk Assessment (QMRA) is a tool used to estimate the probability of adverse health effects resulting from human exposure to pathogenic microorganisms in water, including in RWHS. QMRA enables the assessment of the microbiological safety of RWHS water used for various purposes (e.g., irrigation, toilet flushing, hygiene activities), as well as the evaluation of greywater or drinking water post-treatment. It also allows for the assessment of potential pathogen exposure risks and the comparison of various RWHS management scenarios, such as different utilization methods, water treatment technologies, consumer behaviours, or regulatory policies [48,80].

Risk modelling within the QMRA framework consists of four main stages: (1) hazard identification, (2) exposure assessment, (3) dose-response modelling, and (4) risk characterization. The aim of the first stage is to determine which pathogens posing a health threat to consumers can occur in rainwater. The second stage, exposure assessment, estimates the pathogen load to which a person may be exposed under a specific rainwater utilization scenario. The third stage analyzes the probability of infection (or illness) based on the ingested dose and pathogen type. Integrating data from all stages allows for the development of a predictive model aimed at estimating the health risk of infection with a specific pathogen based on defined exposure scenarios within a particular environment or activity [81,82]. For example, Ahmed et al. [47] demonstrated that when utilizing rainwater for toilet flushing, the annual risk of *Campylobacter* infection was 3×10^{-4}, which exceeds the permissible infection risk threshold of 10^{-4} pppy set by the WHO [64].

Despite the wide application of QMRA as a tool supporting microbiological water safety planning and decision-making processes, this risk assessment is burdened by the inherent variability of microbiological processes. Additionally, it faces significant uncertainties regarding the estimation of pathogen presence and the underlying modelling assumptions [83].

A relationship between illness and the occurrence of microorganisms in rainwater has been established for numerous pathogens, including *Clostridium botulinum*, *Campylobacter* spp., *Salmonella typhimurium*, *Legionella pneumophila*, *Mycobacterium avium* complex (MAC), *Naegleria* spp., *Salmonella arechevalata*, *Cryptosporidium*, and *Giardia* – which are major etiological agents of gastroenteritis worldwide [45].

Epidemiological studies based on QMRA, published by Hamilton et al. [45], evaluated the associations between RWHS use and gastrointestinal diseases in various contexts. They found no statistically significant differences in the risk of gastrointestinal diseases between individuals consuming RWHS rainwater and those using so-called 'improved water sources'. According to the WHO definition [64], improved water sources are those protected from external contamination, particularly faecal matter. Significantly, the analysis demonstrated a lower health risk associated with rainwater consumption compared to water from unimproved sources. However, it must be noted that these findings may not apply to young children, the elderly, or immunocompromised individuals. Furthermore, drinking rainwater may carry a higher risk of campylobacteriosis compared to alternative sources [45]. Conversely, a study involving a large cohort of children found no increased risk of gastroenteritis among those drinking rainwater compared to those consuming treated tap water [84]. Similar results were reported for diarrheal diseases [85], although another study found that rainwater consumption was strongly associated with diarrheal diseases, accounting for 77% of reported cases [86].

In summary, consuming water from RWHS poses a lower risk of gastrointestinal disease compared to alternative or unimproved water sources. However, assessing the risk of RWHS water utilization relative to improved water sources is highly dependent on source water quality and cannot be generalized as an absolute metric [45]. Table 3 presents exemplary annual microbiological risk values for various applications of treated and untreated RWHS water across several pathogens, as determined using QMRA. According to the WHO [64], the acceptable risk level for drinking water quality is 10^{-4} infections per person per year (i.e., a maximum of one infection per 10,000 inhabitants annually). These values are subsequently adjusted using the Disability-Adjusted Life Years (DALY) metric, establishing a benchmark of 10^{-6} DALYs per person per year (pppy) [45]. Adopting an annual risk threshold of 10^{-6} DALYs pppy aligns with WHO guidelines [45, 64].

Table 3. Annual risk values for different RWHS uses reported in QMRA studies

Reference pathogen	Water use / Exposure scenario	Annual Infection Risk (pppy) WHO Benchmark: 10^{-4}	Annual DALYs (pppy) WHO Benchmark: 10^{-6}	Reference
Campylobacter ssp.	Drinking	—	3.40×10^{-4}	[87]
	Bathing	—	6.50×10^{-7}	
	Food washing	—	4.00×10^{-7}	
	Hose irrigation	—	2.10×10^{-7}	
	Toilet flushing	—	1.40×10^{-7}	
Salmonella spp.	Drinking	$1.3 \times 10^{-1} – 6.9 \times 10^{-1}$	—	[46]
	Bathing	$2.5 \times 10^{-4} – 1.3 \times 10^{-3}$	—	
	Hose irrigation – aerosol	$7.1 \times 10^{-8} – 4.1 \times 10^{-7}$	—	
	Crops irrigation (cucumber, tomato, lettuce)	1.39×10^{-4} – 1.62×10^{-3}	—	[88]
G. lamblia	Drinking	$2.0 \times 10^{-1} – 1.3 \times 10^{0}$	—	[46]
	Bathing	$3.9 \times 10^{-4} – 2.4 \times 10^{-3}$	—	
	Hose irrigation – aerosol	$1.1 \times 10^{-7} – 6.9 \times 10^{-7}$	—	
	Crops irrigation (cucumber, tomato, lettuce)	5.53×10^{-4} – 5.49×10^{-3}	—	[88]
Campylobacter jejuni	Bathing in treated rainwater (sand filtration and UV disinfection)	7.9×10^{-8}	—	[89]
Salmonella enterica		7.7×10^{-9}	—	
Cryptosporidium spp.		1.4×10^{-3}	—	
Giardia spp.		4.4×10^{-6}	—	
E. coli O157:H7		1.3×10^{-4}	—	
L. pneumophila		2.7×10^{-7}	—	

The consumption of untreated RWHS water has been associated with risk levels exceeding WHO recommendations. However, studies have shown that applying non-chlorine treatment methods lowers this risk to 2×10^{-6} DALYs pppy, bringing it closer to WHO reference values [87]. For non-potable applications of RWHS water, the infection risk for *Campylobacter* spp. – often used as a reference microorganism in QMRA – remained at approximately 10^{-7}, thus meeting WHO criteria [87, 90].

The risk of infection from *Salmonella* spp., *Giardia lamblia*, and *Legionella pneumophila* during non-consumptive uses of RWHS water also remained low. Conversely, the direct consumption of untreated water containing *Salmonella* spp. or *G. lamblia* poses an unacceptable risk level for drinking water [46].

Fortunately, implementing various RWHS water treatment methods significantly reduced the infection risk for *Campylobacter jejuni*, *Salmonella enterica*, *Legionella pneumophila*, and *Giardia* spp. to well below the reference limit (Tab. 3). The risk only exceeded this acceptable threshold for *Cryptosporidium* spp. and *E. coli* O157:H7 [89].

CONCLUSIONS

Health risks associated with the use of water from RWHS are primarily linked to the direct consumption of untreated water, particularly in the presence of *Salmonella* spp. and *Giardia lamblia*. For non-potable applications, this risk is generally low. Furthermore, when evaluating the risk using *Campylobacter* spp. as a reference bacterium, the estimated risk may even comply with the WHO criteria for non-potable water.

Water treatment processes in RWHS significantly reduce microbiological risks to acceptable levels for a range of pathogens, including *C. jejuni*, *S. enterica*, and *L. pneumophila*. However, *Cryptosporidium* spp. and *E. coli* O157:H7 can still present an unacceptable risk. Consequently, the efficacy of treatment methods should be evaluated strictly in the context of specific pathogens and the intended end-use scenarios.

The weak correlation between traditional faecal indicator bacteria (FIB) and actual pathogens in water, as demonstrated in the literature, necessitates supplementing routine FIB monitoring with assessments based on appropriately selected reference microorganisms within the Quantitative Microbial Risk Assessment (QMRA) framework. Incorporating *Campylobacter* spp. into QMRA models allows for a more accurate estimation of the actual health risks associated with rainwater reuse than relying solely on FIB detection. Unfortunately, the lack of reliable data regarding the variability of *Campylobacter* spp. concentrations in RWHS, combined with insufficient source identification, necessitates the probabilistic modelling of concentration variance rather than the use of point estimates. This data gap limits the overall reliability of QMRA and the accuracy of estimating infection probabilities within the population.

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