Microbial and Chemical Contamination of Irrigation Water in Horticultural Production: Implications for Food Safety and Consumer Health - A Systematic Review

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Abstract

Irrigation water is a major pathway for microbial and chemical contamination of horticultural produce, posing significant risks to food safety and consumer health. This systematic review synthesized evidence published between 2013 and 2023 on irrigation water quality and associated health risks in horticultural production systems. Following PRISMA guidelines, 237 records were identified from 4 databases. After screening and eligibility assessment, 80 peer-reviewed studies were included. Microbial contamination of irrigation water was widespread, with total and faecal coliforms and Escherichia coli concentrations commonly ranging from 1.9 to 8.0 log CFU/100 mL. Generic E. coli prevalence reached 84.8% in some production systems. Pathogenic bacteria including Salmonella spp., Shigella spp., Listeria monocytogenes, and Campylobacter were detected in up to 64% of wastewater samples. Viral pathogens, including norovirus and rotavirus, were detected in 20.8–37.5% of irrigation water samples and up to 60.4% of irrigated leafy vegetables. Heavy metals such as cadmium, lead, and chromium often exceeded WHO/FAO permissible limits, with cadmium concentrations surpassing standards by up to 1.82-fold. Quantitative microbial risk assessments estimated infection risks exceeding the WHO health target of 10^{-6} DALYs in multiple exposure scenarios. These findings highlight irrigation water as a critical control point for reducing produce-associated health risks.

Keywords: *Irrigation water, Horticulture production, Microbial contamination, Food safety, Consumer health*

1.0 Introduction

The first published report implicating fresh produce as a source of human foodborne infection was in 1912 (Monaghan et al., 2008). Since then, food-borne pathogens have been identified as the cause of about 9.4 million illnesses, 55,961 hospitalizations, and 1,351 deaths in the US each year. Noroviruses (58%), non-typhoidal Salmonella spp. (11%), and *Clostridium perfringens* (10%) are the major causes of foodborne illness worldwide (Hoffman et al., 2015). According to World Health Organization (WHO) report in 2015, there were about 600 million food-borne illnesses and 420,000 associated deaths globally in 2010 (WHO, 2015). Similarly, per the findings of Hashemi et al. (2023), the reported incidence of norovirus-associated foodborne illness ranged from 11 to 2,643 cases in Asia, and from 418 to 9,200,000 cases in the USA and Europe. Recent findings by Centers for Disease Control and Prevention (CDC) (2025) indicate that The CDC estimates that approximately 48 million people experience foodborne illness annually in the United States, resulting in about 128,000 hospitalizations and 3,000 deaths. . The Shiga-toxin-producing *Escherichia coli* O14:H4 outbreak in Germany demonstrated the complexity of the modern produce supply chain. After a detailed investigation, the source of contamination was identified to have been caused by fenugreek seeds imported from Egypt (BfR, 2011). During the outbreak period, a total of 4,321 cases were reported to the Robert Koch Institute (RKI, 2011) including 3,469 Enterohemorrhagic *Escherichia coli* (EHEC) cases and 852 Hemolytic Uremic Syndrome (HUS) cases with 50 fatalities. Also, foodborne hazards are responsible for 137,000 deaths and 91 million acute illnesses in Africa every year, mostly affecting children under age 5 (WHO, 2019).

Warriner et al. (2009) noted that foodborne illness outbreaks linked to the fresh-cut chain were specifically due to the inability to control the dissemination of human (and animal) pathogens within the environment; failure of pre-and post-harvest interventions to remove field-acquired contamination; and lack of traceability to track contaminated produce back to the source. Douti et al. (2021) reported that in a study by the Small Grants Programme (SGP) of the United Nations Development Programme (UNDP)/Global Environmental Facility (GEF) between 2007 and 2008, most of the vegetables consumed in Ghana's capital, Accra were chemically and faecally contaminated. Findings of Douti et al. (2021) in a study in one of Ghana's largest irrigation sites (the Vea catchment) indicated that the population of total coliform load ranged between 3.56 and 3. 98 log CFU/100 ml, faecal coliform ranged from 3.20 and 3. 96 log CFU/100 ml, and E. coli levels were between 3.00 log CFU/100 ml and 3.95 log CFU/100 ml in the reservoir. Irrigation water is increasingly being recognized as a major risk factor for microbiological contamination of produce commodities. Legislators, public health authorities, and other relevant stakeholders have recognized the need to focus on the prevention of foodborne illnesses rather than responding to and managing incidents. Research shows that one of the ways to prevent foodborne illnesses associated with produce is to safeguard all relevant steps along the food supply chain (Castro-ibanez et al., 2017). Furthermore, to ensure produce safety throughout the production-supply chain and minimize the occurrence of future produce-associated outbreaks, it is imperative to control microbiological hazards along all points including irrigation water resources/applications (Oluwadara et al., 2023) monitor now.

Despite growing global awareness of foodborne illnesses linked to fresh produce, irrigation water remains a poorly controlled and insufficiently monitored source of microbial and chemical contamination in horticultural production systems, particularly in low- and middle-income countries. Evidence from global outbreaks and regional studies, including Ghana, shows that contaminated irrigation water serves as a critical pathway for introducing human pathogens and chemical hazards into fresh produce supply chains. The absence of consistent water quality monitoring, weak enforcement of safety standards, and limited preventive interventions along the production–supply continuum continue to expose consumers to significant public health risks. Consequently, a comprehensive synthesis of existing evidence on irrigation water contamination and its implications for food safety is urgently needed to inform policy, guide best management practices, and reduce produce-associated disease burdens. In light of the documented prevalence of foodborne illnesses linked to fresh produce and the recognition of irrigation water as a significant risk factor for microbial contamination, this systematic review aims to investigate the microbial and chemical contamination of irrigation water in horticultural production. By examining the implications for food safety and consumer health, the review seeks to provide insights and recommendations to improve water quality management practices, mitigate microbial contamination risks, and enhance the safety and quality of fresh produce.

2.0 METHODS

2.1 Literature search strategy

A systematic literature search was conducted to identify peer-reviewed studies examining the use of wastewater and other irrigation water sources in horticultural production and their implications for microbial contamination, food safety, and consumer health. The search was performed across multiple electronic databases, including Scopus and ScienceDirect, as well as publisher-indexed journal platforms such as MDPI and Elsevier, which host a wide range of relevant environmental, agricultural, and food safety journals.

The search was restricted to studies published between January 2013 and January 2023 to ensure the inclusion of contemporary and policy-relevant evidence. Only English-language publications were considered to maintain consistency in interpretation and analysis.

A structured search strategy was developed using a combination of controlled vocabulary and free-text terms. Key search terms included *"irrigation water," "wastewater reuse," "horticultural production," "fresh produce," "microbial contamination," "pathogenic bacteria," "foodborne pathogens,"* and *"food safety."* These terms were combined using Boolean operators (AND/OR) to maximize sensitivity while maintaining relevance. In addition to database searching, the reference lists of included studies were manually screened to identify any additional relevant articles not captured during the initial search.

2.2 Study selection process

Study selection was conducted in a stepwise screening process to ensure methodological rigor and relevance. Initially, all retrieved records were imported into a reference management system, and duplicate articles were identified and removed.

In the first screening stage, titles and abstracts were reviewed to exclude studies that were clearly irrelevant to irrigation water quality, horticultural production, or food safety. Studies that appeared relevant or potentially relevant were retained for further evaluation.

In the second stage, full-text articles were retrieved and assessed in detail against predefined inclusion and exclusion criteria. This assessment focused on the study objectives, methodology, and relevance to the research question. The study selection process adhered strictly to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, and the selection outcomes are illustrated in the PRISMA flow diagram (Figure 1).

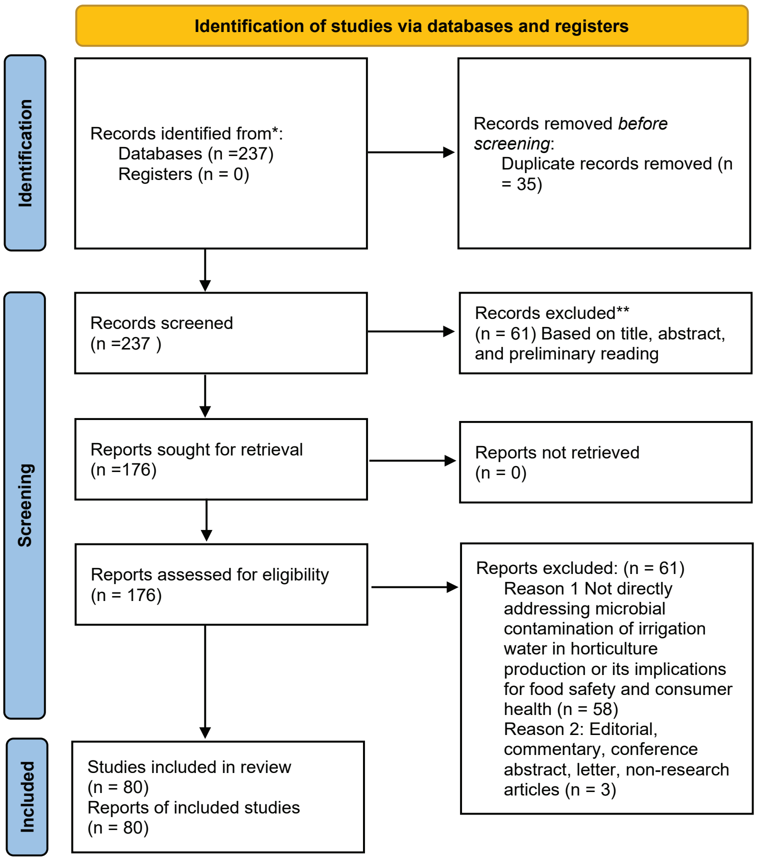

Figure 1. Identification of studies via databases and registers

2.3 Inclusion and exclusion criteria

Eligibility criteria were established a priori to ensure the selection of high-quality studies directly addressing microbial contamination of irrigation water in horticultural production systems and its implications for food safety and consumer health. All included studies directly addressed the research objectives and provided empirical evidence on irrigation water contamination in horticultural production systems. The final dataset represents a diverse range of geographic regions, irrigation water sources, and microbial hazards, thereby providing a comprehensive basis for assessing food safety risks associated with irrigation water use. These criteria is presented in Table 1.

Table 1. Inclusion and exclusion criteria for study selection

Criterion Type	Category	Description
Inclusion	Study design	Primary research studies, including experimental, observational, case–control, cohort, cross-sectional, and intervention studies
	Study focus	Studies assessing microbial contamination of irrigation water used in horticultural or fresh produce production
	Outcomes	Studies reporting implications for food safety, public health, or consumer health risks
	Publication type	Articles published in peer-reviewed scientific journals
	Language	Studies published in the English language

Criterion Type	Category	Description
	Time frame	Studies conducted and/or published within the last 10 years
Exclusion	Publication type	Editorials, commentaries, letters, conference abstracts, opinion pieces, and review articles
	Peer-review status	Unpublished studies, gray literature, theses, reports, and other non–peer-reviewed sources
	Relevance	Studies not directly addressing irrigation water contamination or horticultural production systems
	Language	Studies published in languages other than English
	Time frame	Studies published outside the defined 10-year period

2.4 Data extraction

Data extraction was performed using a standardized data extraction form developed specifically for this review to ensure consistency and minimize bias. For each included study, the following information was extracted: author(s), year of publication, country or region of study, study design, irrigation water source, type of horticultural crop, microbial and/or chemical contaminants assessed, analytical methods employed, key findings, and stated conclusions. Extracted data were cross-checked to ensure accuracy and completeness. The extracted information was subsequently organized into thematic categories to facilitate synthesis and comparison across studies.

2.5 Quality assessment and risk of bias

The methodological quality and potential risk of bias of the included studies were assessed during the full-text review stage. This qualitative assessment focused on several key domains, including clarity of study objectives, appropriateness of study design, adequacy of sample size, robustness of sampling and laboratory methods, transparency of data analysis, and consistency of result reporting.

Although a formal scoring system was not applied, this structured appraisal allowed identification of methodological strengths and limitations within individual studies. The quality assessment informed the interpretation of results and ensured that conclusions were drawn with appropriate consideration of study reliability and validity.

2.6 Data synthesis and Analysis

Given the heterogeneity in study designs, sampling approaches, microbial indicators, and outcome measures, a quantitative meta-analysis was not feasible. Consequently, a narrative synthesis approach was employed. The synthesis focused on identifying recurring patterns and themes, including sources and types of irrigation water contamination, prevalence of key microbial pathogens, regional differences, and reported food safety risks. Findings were compared and contrasted across studies to highlight consistencies, discrepancies, and knowledge gaps.

3.0 RESULTS

3.1 Results of the Literature Search

The database search yielded a total of 237 articles identified as potentially relevant to irrigation water use in horticultural production and food safety. After removing 35 duplicate records, 202 unique articles remained for screening. Title and abstract screening resulted in the exclusion of 61 articles that did not focus on microbial or chemical contamination of irrigation water or its relevance to food safety and consumer health. The remaining 141 articles underwent full-text assessment. Following comprehensive evaluation, an additional 61 articles were excluded for failing to meet the inclusion criteria. Ultimately, 80 studies met all eligibility requirements and were included in the systematic review. These studies formed the basis for data extraction, quality assessment, and synthesis.

3.2 Quality Assessment Results

The included studies demonstrated moderate to high methodological quality. Most studies employed appropriate sampling and laboratory analytical methods for assessing microbial contamination of irrigation water. However, variability was observed in sampling frequency, microbial indicators assessed, and reporting of methodological limitations. These factors were considered when interpreting the findings.

3.3 Characteristics of Included Studies

A data extraction graph (Figure 2) was designed using Microsoft Excel to extract relevant information from the included article which was thoroughly read. The 80 articles used for the study were published in Water, Air, and Soil Pollution (5 publications), Water Science and Technology (4 publications), Water Resources Research (4 publications), Water Research (3 publications), Sustainability (Switzerland), Water and Environment Journal, Sustainable Cities and Society (3 publications each) (Figure 3)

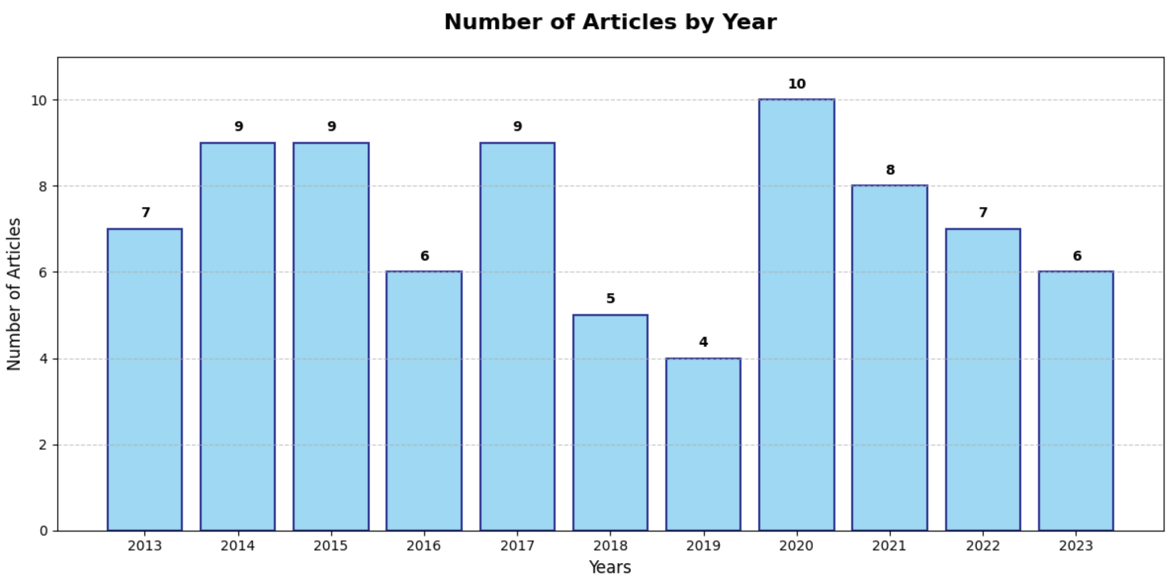

Figure 2: Number of articles published per year (2013- 2023)

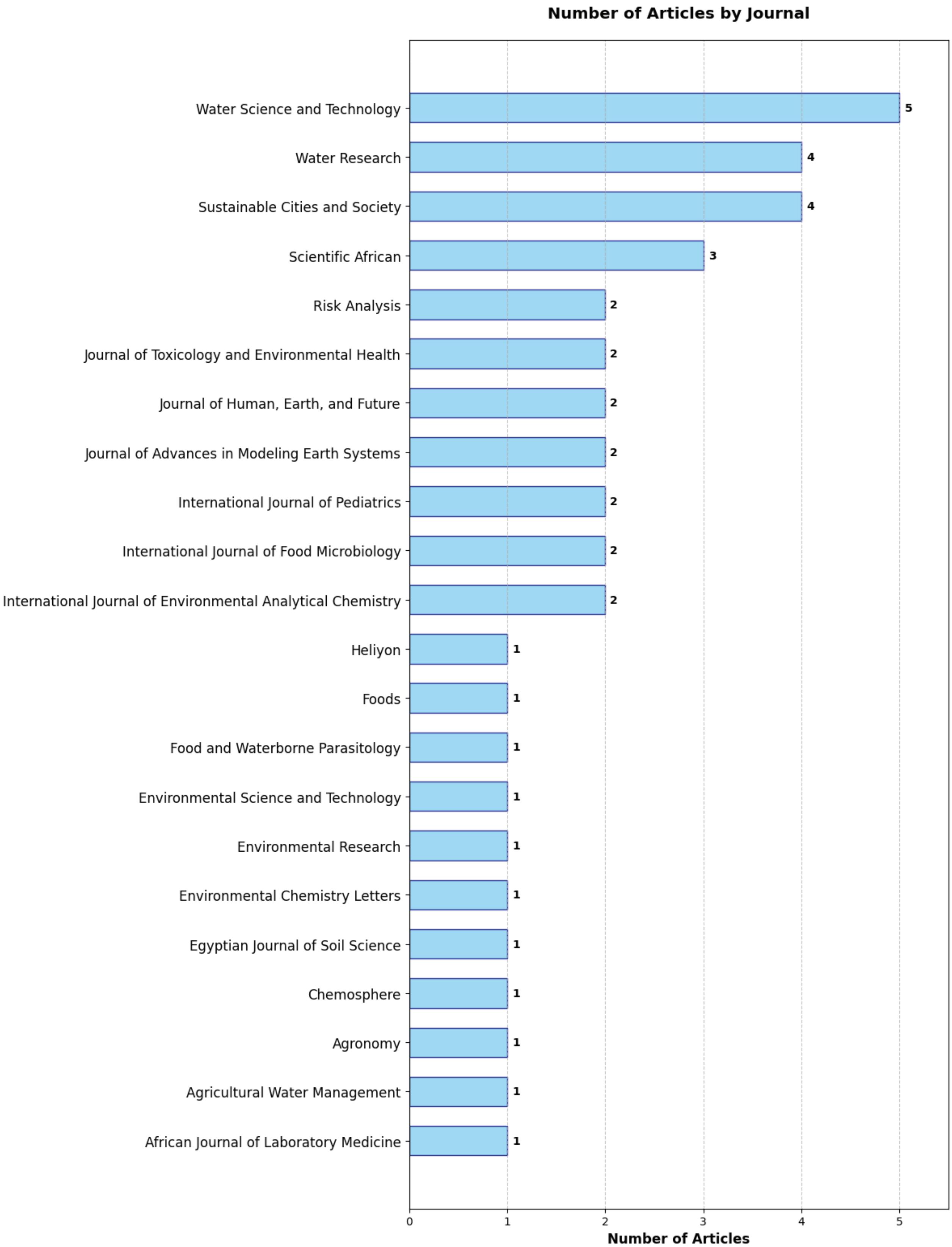

Figure 3. List of journal articles used for the review

3.4 Water sources for irrigation

Water scarcity and increasing food demand have necessitated the exploration of various water sources for irrigation. Freshwater from surface water and groundwater, recycled water, brackish water, desalinated water, and rainwater harvesting are all viable options. However, each source comes with its own challenges, such as water quality concerns, sustainability issues, and economic feasibility. These challenges must be addressed to ensure sustainable agriculture in the face of water scarcity. Freshwater sources, such as surface water and groundwater, have traditionally been major sources of irrigation water. Surface water, including rivers, lakes, and reservoirs, provides a readily available supply (Malakar et al., 2019). However, concerns regarding water quality and sustainable management strategies must be addressed (Leng et al., 2017). Groundwater, on the other hand, plays a vital role globally, but challenges such as overexploitation and water quality degradation require sustainable management practices (Qin and Horvath, 2020). Implementing effective groundwater management strategies has been demonstrated in several studies. Abbas et al. (2020) and Paudel et al. (2016) have highlighted successful strategies for groundwater management. These studies provide insights into sustainable practices such as groundwater recharge, water demand management, and regulatory frameworks. One effective groundwater management strategy is groundwater recharge, which involves replenishing depleted groundwater resources. This can be achieved through techniques such as artificial recharge, where surface water is deliberately directed into aquifers, allowing it to infiltrate and recharge groundwater levels. Abbas et al. (2020) discuss the implementation of artificial recharge systems, such as infiltration basins and injection wells, to replenish groundwater resources effectively. Another strategy is water demand management, which aims to reduce the overall demand for groundwater by promoting water conservation practices and optimizing water use efficiency. Paudel et al. (2016) highlight the importance of adopting efficient irrigation techniques, such as drip irrigation or precision sprinkler systems, to minimize water wastage and improve water use efficiency in agriculture. Implementing water pricing mechanisms and awareness campaigns to encourage responsible water consumption can also contribute to effective water demand management. Furthermore, regulatory frameworks play a crucial role in groundwater management. Siebert et al. (2013) emphasized the significance of establishing and enforcing regulations that govern groundwater extraction and usage. This includes setting limits on abstraction rates, implementing permits or licenses for groundwater use, and monitoring compliance to ensure sustainable groundwater management practices. The outcome of the review suggest that groundwater management strategies encompass approaches such as groundwater recharge, water demand management, and regulatory frameworks. These strategies, as highlighted by Abbas et al. (2020), Paudel et al. (2016), and Siebert et al. (2013), demonstrated the importance of sustainable water use practices, conservation measures, and effective governance to ensure the long-term availability and quality of groundwater resources.

However, ensuring water quality through regulatory frameworks, monitoring techniques, and risk assessment strategies is essential (WHO, 2017). The benefits of recycled water for irrigation include a consistent water supply, reduced dependence on freshwater sources, and nutrient enrichment (Chen et al., 2013). Overcoming challenges related to public perception, regulatory barriers, and treatment costs is crucial for its wider adoption (Kerich, 2020). Brackish water, with salinity levels between freshwater and seawater, presents an alternative irrigation source. It can be sourced from aquifers and coastal regions. Desalination techniques, such as reverse osmosis, electrodialysis, and thermal desalination, offer efficient ways to remove salts and impurities (Paudel et al., 2016). Successful implementation of brackish water desalination for irrigation has been demonstrated in various studies, highlighting its economic viability and water supply reliability (Chen et al., 2013; Paudel et al., 2016). Effective management of brackish water quality and disposal of brine by-products are crucial considerations (An et al., 2015). Desalinated water, obtained through various desalination technologies like reverse osmosis, multi-stage flash distillation, and electrodialysis, is another viable water source for irrigation (Shatat and Riffat, 2014). However, the by-products and potential environmental impacts associated with desalination processes require careful consideration (Chen et al., 2013). Managing water quality and salinity levels in desalinated water for irrigation purposes is essential (Vidic et al., 2013). Cost-effectiveness and energy requirements also play a significant role in determining its feasibility (Zhang and Hanaoka, 2021). Rainwater harvesting is an innovative approach to irrigation. Different systems and techniques for collecting, storing, and treating harvested rainwater are available (Ward et al., 2019). Maintaining water quality and quantity through appropriate storage and treatment methods are essential considerations (Zaman et al., 2018). Rainwater harvesting offers advantages such as reduced demand for other water sources and the potential for self-sufficiency in irrigation (Zaman et al., 2018). Technological advancements in utilizing water sources for irrigation are crucial for sustainable practices. Efficient irrigation techniques, precision agriculture, smart irrigation systems, water conservation technologies, remote sensing, and GIS applications all contribute to optimized water use (Shafi et al., 2019). These advancements help in maximizing irrigation efficiency, minimizing water wastage, and improving crop productivity. Looking ahead, the future prospects of water sources for irrigation involve addressing the challenges posed by climate change and implementing adaptation strategies (UNESCO, 2018). Integrated water resources management, supported by policy and regulatory frameworks, plays a critical role in sustainable irrigation practices (FAO, 2020). Innovations in water reuse and treatment technologies are continuously emerging, further improving the efficiency and effectiveness of irrigation systems (An et al., 2015).

3.5 Microbial and chemical indicator assessment in irrigation water used for horticultural produce

3.5.1 Microbial pathogens and indicator organisms in irrigation water

The presence of microbial pathogens in irrigation water is a major public health concern due to their potential to contaminate horticultural produce and cause foodborne illnesses. Numerous studies have documented the occurrence of pathogenic bacteria, viruses, and indicator organisms in irrigation water sourced from surface water, groundwater, wastewater, and reused water.

Several bacterial pathogens of public health relevance have been detected in irrigation water, including *Yersinia enterocolitica* (Saxena et al., 2015), verocytotoxin-producing *Escherichia coli* (VTEC), particularly *E. coli* O157:H7 (Razzuoli et al., 2018), *Salmonella* spp. (Liang et al., 2015; Stokdyk et al., 2020), and *Shigella* spp. (Ntuli et al., 2017). The detection of these organisms highlights the risk of direct crop contamination during irrigation and the potential for subsequent human infections. Opportunistic pathogens such as *Pseudomonas aeruginosa* and *Legionella pneumophila* have also been reported, posing additional risks to crop safety and consumer health.

To assess microbiological water quality, bacterial indicators of fecal contamination—such as total coliforms, fecal coliforms, and *E. coli*—are commonly used as proxies for pathogen presence. Several studies have shown strong associations between bacterial indicators and enteric viruses in surface waters (Hughes et al., 2017; Salvador et al., 2020). Viruses are among the most significant causes of waterborne disease globally and are frequently detected in both domestic and recreational surface waters. Enteric viruses such as rotavirus, noroviruses, and adenoviruses are leading causes of gastrointestinal illness worldwide (Hughes et al., 2017; Katukiza et al., 2014; Rezaeinejad et al., 2014), transmitted primarily via the fecal–oral route. These infections are responsible for over

500,000 deaths annually, particularly among children in developing countries (Murphy et al., 2017; Al-Badani et al., 2014; Nnukwu et al., 2017).

Empirical studies have demonstrated high levels of microbial contamination in irrigation water. For instance, Decol et al. (2017) reported an 84.81% prevalence of generic *E. coli* in irrigation water used for leafy green vegetables in Brazil, while lower prevalence rates of 59% were observed in Spain and Belgium (Castro, 2015; Holvoet et al., 2014). Water source and irrigation method significantly influence microbial load, with pond water often showing higher *E. coli* concentrations than water from irrigation heads (Leifer et al., 2018; Castro-Ibáñez et al., 2015a).

In sub-Saharan Africa, where freshwater scarcity has increased reliance on alternative water sources for irrigation, microbial contamination is widespread (Adewumi et al., 2010; World Bank, 2013). In Ghana, approximately 60% of water bodies are polluted due to industrial discharges, illegal mining, agricultural runoff, and domestic waste disposal (Ampomah, 2017). Studies across the country have consistently reported elevated levels of fecal indicators and pathogens. Ninkuu et al. (2015) recorded fecal and total coliforms and *Salmonella* spp. ranging from 1.9 to 3 CFU/100 ml and 3.2 CFU/100 ml, respectively, in northern Ghana. Similarly, Douti et al. (2021) reported total coliforms (3.80–3.84 CFU/100 ml), fecal coliforms (3.50–3.63 CFU/100 ml), and *E. coli* (0.42–3.19 CFU/100 ml) in the Vea irrigation dam.

Extremely high fecal coliform densities have been reported in urban irrigation sources, reaching up to 4×10^6 CFU/100 ml in shallow wells and 4×10^8 CFU/100 ml in streams in Kumasi, and up to 2×10^7 CFU/100 ml in Accra (Mensah et al., 2001; Keraita et al., 2003). These values far exceed WHO guideline limits and indicate substantial risks to food safety and public health. Quantitative microbial risk assessment (QMRA) studies further demonstrate the health implications of microbial contamination. Safe reuse of greywater for irrigation was achieved only when concentrations of *Staphylococcus aureus*, *Salmonella enterica*, and *Shigella* spp. were kept below 10^6, 500, and 5 CFU/100 ml, respectively, under best-practice scenarios, in line with the WHO acceptable risk threshold of 10^{-6} DALYs (Decol et al., 2017).

3.5.2 Chemical indicators and their influence on crop safety and microbial contamination

Chemical parameters of irrigation water—including pH, alkalinity, soluble salts, and heavy metals—play a critical role in determining crop growth, soil health, and food safety. In addition to their direct effects on plant physiology, these parameters influence microbial survival, persistence, and transport within irrigation systems and agricultural soils.

Alkalinity reflects the capacity of water to neutralize acids and, when elevated, can lead to soil alkalization. High alkalinity reduces nutrient availability, particularly of micronutrients, and can impair crop growth and productivity. Prolonged use of alkaline irrigation water may result in salt accumulation, nutrient imbalances, and ion toxicity, adversely affecting plant physiology and soil microbial processes (Pereira et al., 2016).

Soluble salts—such as sodium, calcium, magnesium, and chloride—are another critical chemical parameter. Elevated salinity levels can cause osmotic stress, restrict water uptake, disrupt nutrient balance, and reduce crop yield (Ali Khan et al., 2022). Excess sodium can lead to soil sodicity, degrading soil structure, reducing infiltration rates, and creating conditions that indirectly influence microbial persistence and pathogen survival. The pH of irrigation water strongly affects soil pH, nutrient solubility, and microbial activity. Acidic irrigation water may induce micronutrient toxicities or deficiencies, while alkaline water can limit the availability of essential nutrients such as iron, zinc, and phosphorus (Ley et al., 2020). Microbial communities are highly sensitive to pH, and specific pathogens may thrive within particular pH ranges, increasing the risk of crop contamination (Kamran et al., 2013; Khalid et al., 2018; Rai et al., 2019).

Heavy metals such as cadmium and lead have also been detected in irrigation water and represent a dual threat to crop safety and human health (Hezbullah et al., 2016). These metals can accumulate in soils and plant tissues, posing chronic health risks through dietary exposure, while also exerting selective pressure on microbial communities and potentially promoting metal-tolerant pathogenic strains.

The interaction between chemical parameters and microbial contamination is complex. While high salinity or extreme pH conditions may inhibit certain pathogens, other microorganisms can adapt and persist under such conditions. Consequently, chemical stressors do not necessarily eliminate microbial risks and may, in some cases, enhance pathogen survival or transmission.

Effective monitoring and management of irrigation water chemistry are therefore essential. Regular assessment of pH, alkalinity, salinity, and heavy metals can guide corrective measures such as water treatment, blending, filtration, and pH adjustment. Complementary soil management practices, including adequate drainage and leaching, are also necessary to prevent salt accumulation and maintain conditions conducive to safe and sustainable horticultural production.

Table 2. Microbial and chemical water quality studies on horticultural Produce

Authors/Years	Aims/Objective of the study	Environmental sampling/organic or inorganic farm	Methodology	Findings	Gaps identified
Pavione et al. (2013)	To highlight key-variables for better knowledge for future refinement of irrigation water quality, ratios of pathogen to indicator organisms, and pathogen reduction between harvesting and consumption.	lettuce, spinach, and rocket produce green pepper, cucumber, tomato kale, broccoli, silver beet watercress, parsley, cauliflower, cabbage	Crop contamination levels were estimated using predictive models derived from field experiments.	The importance of having ponds in series in order to reduce risks associated with wastewater irrigation.	Data obtained were limited to effluents of stabilization ponds.
Makkaew et al. (2016)	Examined the degree of E. coli contamination on lettuces following spray and drip irrigation in the field experiment, and submersion irrigation in the laboratory, using partially treated domestic wastewater.	Lettuce	Submersion technique was used.	All lettuce samples from spray beds were positive for E. coli. Results from the laboratory scale showed that the microbial quality of irrigating wastewater affect microbial safety of crops at harvest.	Potential influence of lettuce leaf morphology should be considered.
El-Senousy et al. (2013)	To evaluate in different types of fresh produce and in irrigation water for human norovirus (NoV) detection	green onion, watercress, radish, leek, and lettuce s	Two different virus concentration procedures, polyethylene-glycol precipitation (PEG) and organic flocculation (OF), were employed	PEG provided significantly (p b 0.05) better virus recoveries than OF for both irrigation water and salad vegetable virus analysis. In experimentally contaminated salad vegetables, virus recoveries ranged from 28.0% to 48.0% and from 14.0% to 18.8% by PEG precipitation and OF, respectively.	

Quarcoo et al. (2022)	assessed Escherichia coli counts, antibiotic resistance patterns and resistant genes on irrigated lettuce	Lettuce	A cross-sectional study was conducted	Escherichia coli was found in all 25 composite lettuce samples analyzed. Counts expressed in CFU/g ranged from 186 to 3000, with the highest counts found in lettuce irrigated from open drains (1670) and tap water using hose pipes (3000).	Support farmers to implement measures for improving vegetable safety
Mengesha et al. (2023)	To evaluate microbial contamination of irrigation water and vegetables in Addis Ababa, Akaki River	kale, lettuce, cabbage, and spinach	The analysis of E. coli non-E. coli, total coliform (TC), fecal coliform (FC), and total aerobic plate count (TAC) were determined using standard methods	All fresh vegetables were contaminated with total coliforms, fecal coliforms, and total aerobic plate counts in both dry and wet seasons. The overall mean counts of E. coli and non-E. coli in the water samples were 2.09 and >3.48 log10 CFU 10 mL−1, respectively	
Machado-Moreira et al. (2021)	analyzed the survival of *E. coli* and L. innocua on lettuce plants watered with contaminated irrigation water via a single irrigation event and within stored irrigation water	Lettuce	direct enumeration, enrichment and qPCR were used for the assessment	E. coli was detected in water samples up to 7 days after inoculation and L. innocua was detected up to 28 days by direct enumeration.	

Corbel et al. (2015)	To analyzed the impact on the growth and physiology of tomato, Solanum lycopersicum cultivar MicroTom	Tomato, soil, cyanobacterial extract	Agricultural soil was irrigated daily with a cyanobacterial extract diluted at environmental concentrations of microcystin–leucine–arginine, from 0.005 to 0.1 mg equivalent MC-LR L-1, for 90 days.	Long-term irrigation of a soil–plant system with water containing realistic environmental concentrations of microcystins accelerated the development of tomato plants.	Further research into the mechanisms involved in microcystins accelerating plants development
Farhadkhani et al. (2018)	To assess the impact of irrigation with secondary treated wastewater (STWW) on soil properties as well as the safety of various types of crops as compared with tap water (TW) irrigation through a furrow system.	maize and onion	combination of culture and molecular methods were used	. Although the microbial quality of soil was affected by STWW irrigation, a relatively low concentration of E. coli was detected in soil. No microbial contamination in terms of E. coli was found on harvested maize and onion. E. coli contamination of lettuce and spring onion was found for both irrigation schemes	
Soleimani et al. (2023)	To investigate the effect of three types of irrigation on the accumulation and ecological risk of heavy metals in agricultural soils.	Coriander and Basil vegetables, Radish	plasma optical emission spectrometry (ICP-OES) model was used to determine the concentration of heavy metals	The different irrigation sources increased the concentration of all heavy metals in the soil, and the accumulation of Cr, Ni, and Cd significantly elevated more than others.	

Agboola and Bisi-Johnson (2023)	To examine the incidence of L. monocytogenes in selected irrigation water and irrigated vegetables in Osun State and to provide information on the seasonal distribution of the bacteria strain in	Leaves of Amaranthus hybridus and fruits of Solanum lycopersicum	PALCAM Agar (selective medium) after enrichment with frazer broth and Polymerase Chain Reaction (PCR) with genes that codes for genus Listeria (Prs) and virulence in L. monocytogenes were used	All the isolates were positive for Prs, Hly A and prf A which codes for the genus Listeria, listeriolysin and virulence regulator respectively. irrigation water play a role in dissemination of Listeria monocytogenes in the sampled vegetables
Zongo et al. (2023)	remediating a highly weathered, irrigated sodic Lixisol under prolonged urban crop production by clean water and gypsum application and (2) to determine the remediation effects on soil microbial indices	Maize	A three-factorial on-farm experiment with maize (Zea mays L.) was used	microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) were 20% lower than at the low-degradation site, while fungal ergosterol was even 40% lower, leading to a 33% lower ergosterol/MBC ratio. Wastewater irrigation increased MBN but decreased ergosterol content.

Bai et al. (2023)	To investigate the effects of four irrigation treatments via subsurface drip irrigation on the seed yield and quality of Hedysarum fruticosum, a dominant leguminous shrub in the desert areas of China.	Lettuce, maize and onion	Total and fecal coliforms and Escherichia coli were monitored as indicator bacteria in STWW, irrigated soil and harvested crops. The presence of pathogenic E. coli O157, Salmonella and Shigella was also monitored in all samples using a combination of cul-ture and molecular methods	The results showed that seed yield increased as irrigation frequency increased regardless of growth season. The yearly average seed yields were 98.0, 107.7, 179.3, and 265.5 kg hm^{-2} for W0, W1, W2, and W3 irriga-tion, respectively. These results suggest that irrigation may be a practical way to increase the seed supply of H.fruticosum either from improved seed yield or increased WUE
Cui et al. (2022)	to study the changes in soil physicochemical properties and tomato yield and quality indicators by irrigating tomatoes on cadmium-contaminated soil with two different water qualities through drip irrigation devices	Tomato, Reclaimed water, tap water		Soil nutritional status was increased with the irrigated reclaimed water irrigation. The yield of the tomatoes increased by 52.03–94.03% than tap water irrigation.

Al Nahhas and Aboualchamat (2020)	To inspect the parasitological contamination of some raw vegetables used in salads.	radish, spearmint, lettuce, tarragon, coriander, parsley, watercress, and arugula	Vegetables were purchased, washed and sediments were obtained for microscopic examination. Genomic DNA was isolated from contaminated samples	34.4% of the studied samples were contaminated with one or more species of parasites. Lettuce was the most commonly contaminated vegetable type (29.5%), while tarragon leaves showed the lowest level of contamination (2.3%).	Further research is needed to identify the precise source of contamination and applying strict control of vegetable cultivation areas. conduct awareness campaigns on parasite contamination and its different sources.
Raja et al. (2022)	for identification of the bacterial strains in wastewater and wastewater irrigated vegetable and crops	pumpkin, sugarcane, maize, brinjal, lettuce, spinach, cabbage and radish	XLT-4 cultural media was used for culture-based detection of different bacterial pathogens. PCR based diagnosis was also carried out.	Wastewater irrigated vegetables and crops were highly contaminated with pathogenic bacterial strains. Various biochemical identification tests (catalase, urease, oxidase and lactase) confirmed the presence of pathogenic bacterial species in analyzed samples.	
Tariq (2021)	to investigate the concentrations of highly toxic metals such as Nickel (Ni), chrome (Cr), lead (Pb), zinc (Zn), cadmium (Cd), and copper (Cu) in wastewater, farmlands soils and vegetables (chard, celery, cress and leek), and also their possible human health risk in the area of Erbil city	chard, celery, cress and leek	Atomic absorption spectrophotometer was conducted. Bio-concentration factor (BCF), daily intake (DI) and health risk index (HRI) were calculated in order to estimate the human health risk	The water, soil and vegetable samples were contaminated with Ni, Cd, Cr, Cu, Pb, and Zn. Leek had the highest concentrations of Cd, Cu, and Zn, while Cress and Chard had the lowest concentrations of Cd, Cu, and Zn. Except for Ni and Cu, all checked metals in all selected vegetables exceeded WHO/FAO safe limits.	Further consideration on the findings and preventive actions should be taken to avoid usage of untreated wastewater in irrigation.

Amin et al. (2013)	To study the accumulation of eight heavy metals (Cu, Ni, Zn, Cr, Fe, Mn, Co and Pb) in green vegetables like Allium cepa, Allium sativum, Solanum lycopersicum and Solanum melongena, irrigated with wastewater in Mardan	Tomat, Onion Garlic, Brinjal	Atomic Absorption spectrophotometer was performed	Studied metals in vegetable grown on wastewater irrigated soil were significantly higher than those of tube well water irrigated soil and WHO/FAO permissible limits ($P < 0.05$)
Ahmadi-Jouibari et al. (2021)	To extract preconcentration and determination of potentially toxic elements (PTEs) in vegetables and soil samples irrigated with treated sewage from two different regions of Iran.	spinach (Spinacia oleracea), coriander (Coriandrum sativum), basil (Ocimum basilicum) and radish (Raphanus sativus	A microextraction approach termed as vortex assisted liquid phase microextraction based on deep eutectic solvent (VALPME-DES) combined with graphite furnace atomic absorption spectrometry (GFAAS) was used	The correlation coefficient (r^2) of the calibration curves was in the range of 0.995–0.998. The limit of detections was in the range of 0.03 and 0.1 µg kg−1 for different metal ions. The risk of arsenic carcinogenicity was higher than the acceptable levels in all four types of vegetables.
Orlofsky et al. (2016)	To evaluate the impact of treated wastewater (TWW) irrigation for produce safety	Tomatoes	Human pathogens and opportunistic bacterial pathogens, protozoa and viruses were monitored in two field trials using a combination of microscopic, cultivation-based, and molecular (qPCR) techniques	Microbial contamination on the surface of tomatoes was not associated with the source of irrigation waters. Indicator bacteria and the opportunistic pathogens were detected in water, soil and on tomato surfaces from all irrigation treatment schemes.

Farhadkhani et al. (2020)	to determine Campylobacter risk for the consumers of TWW-irrigated vegetables	Iceberg lettuce (Lactucas sativa L.) and spring onion (Allium fistulosum)	field experiments as well as quantitative microbial risk assessment (QMRA) model was used	Campylobacter was detected in 64% (16/25) of TWW samples, whereas analysis of TWW-irrigated soil and vegetable samples yielded no positive result for Campylobacter	Further experiments to determine the safety of TWW-irrigated crops from the other pathogens point of view
Alghobar and Suresha (2017)	To evaluate metal accumulation in soil and tomatoes irrigated with sewage water	Tomatoes, sewage water (SW), mixed water (sewage water and pure water) (MW), treated sewage water (TSW) and groundwater (GW), K, Na, Cl Ca, Mg, and SO4	plasma optical emission spectrometry (ICP–OES	Concentrations of heavy metals in soils with different kinds of irrigation water were lower in background values and non-significant. The total N, total P, Ca, K, Na, and Zn mg/kg1 in tomatoes crop were significantly higher than the groundwater treated plants.	
Abegunrin et al. (2016)	to evaluate soil physico-chemical properties, growth parameters and water use pattern of two indigenous vegetables irrigated with three kinds of wastewater in southwest Nigeria	Eggplant and Spinach abattoir wastewater (AW), bathroom, laundry wastewater (BW) cassava effluent (CE) and rainwater (RW)	a 2 × 4 factorial (wastewater versus vegetable) pot experiment, laid out in randomized complete block design (RBCD) with three replications in a screen house	The wastewaters had moderate to very high degree of restriction for use in relation to salinity and sodicity. The CE wastewater had the most negative impact on both soil function and plant growth	
Holvoet et al. (2014)	To assess the Relationships among hygiene indicators and enteric pathogens in irrigation water, soil and lettuce	lettuce crop	total psychrotrophic aerobic plate count (TPAC) was used	A low prevalence of Campylobacter (8/88) was noted in lettuce. Presence of elevated levels of E. coli increased the probability for the presence of pathogens	

Dao et al. (2018)	To verify to what degree irrigation water quality is correlated with contamination of lettuce with Escherichia coli, total coliforms, and Salmonella spp., and (ii) assessing effects of post-harvest handling on pathogen development during the trade chain.	Lettuce		Irrigation water did not meet the standards of the World Health Organization (WHO) for safe irrigation water, and in 30% of the cases, irrigation water was contaminated with Salmonella spp. Loads of total coliforms on lettuce leaves ranged from 2.9 × 103 CFU g−1 to 1.3 × 106 CFU g−1, while E. coli averaged 1.1 × 102 CFU g−1 . Results on post-harvest handling revealed that microbial loads increased along the trade chain
Saab et al. (2022)	evaluated the potential health risks of irrigating vegetables (radishes, parsley, onions, and lettuce) using three water sources (groundwater, river water, and treated wastewater) and three irrigation methods (drip, sprinkler, and surface) over two growing seasons	radishes, parsley, onions, and lettuce, groundwater, river water, and treated wastewater	The BOD and the presence of metals was analyzed in accordance with standard methods (APHA, 1998), and chemical oxygen demand (COD) and the total suspended solids (TSS), and the pH and EC measurements were determined in accordance by APHA (2005)	For water with less than 2 log E. coli CFU/100 mL, no pathogens (Escherichia coli, salmonella, parasite eggs) were detected in irrigated vegetables, irrespective of the irrigation method. The trends in the bioaccumulation factor and the estimated dietary intakes of metals were in the order of Cu < Cd < Ni < Cr < Zn

Xu et al. (2022)	Investigated the distribution and migration characteristics of heavy metals in vegetable–soil systems of facilities in a typical sewage irrigation area of the Xi River, Shenyang City, and northern China.	cabbage, coriander, chlorella, lettuce, Chinese lettuce, asparagus leaves, celery, and spinach, radish, tomato, Hun River water	Spatial interpolation and a potential ecological risk assessment were applied to evaluate the soil quality. Bioaccumulation factors (BCFs) were used to analyze the absorption and transportation capacity of Cd, Cu, Pb, and Zn by different parts of different vegetables	The average concentration of Cd exceeded the standard values by 1.82 times and accumulated by 11 times. Cd also contributed the most in terms of the estimated potential ecological risk index	
Emilse et al. (2021)	assess the presence of norovirus, rotavirus and infective enterovirus in leafy green vegetables and irrigation waters collected from a farm located at the province of Cordoba, ´ Argentina, and -QMRA model was applied to estimate the risk of rotavirus infection arising from the consumption of raw vegetables irrigated with the studied water	Vegetables: Chicory Lettuces Inorganic farms Underground and municipal water	The concentration of viruses in irrigation water samples was performed using the method of polyethylene glycol (PEG) precipitation Nucleic acid extraction and cDNA synthesis Viral RNA was extracted from the viral concentrates	The frequency of detection of norovirus, rotavirus and infective enterovirus in irrigation waters was 37.5%, 20.8% and 37.5% and in crops 60.4%, 22.7% and 35.6% respectively The estimated risk of rotavirus infection associated with raw consumption of the vegetables harvested in that rural farm was 0.2 per person per day.	Soil quality Stool samples Ecoli Faecal coliforms salmonella Questionnaire to know KAP

Affum et al. (2020)	assessed the quality, sources, and distribution of heavy metals in surface soils, MWD stream and groundwater, and edible tissues of leafy and non-leafy vegetables from a major urban farm in the Sekondi-Takoradi metropolis, Ghana Human health risk due to exposure to the metals in frequently consumed vegetables	Soil Water Edible part of the plant	Samples worked on irrigation water, cultivating soil, and edible portions of vegetable The water, vegetable, and soil samples were acid digested in a Milestone microwave (ETHOS 900 microwave digester, Connecticut, USA) using standard acid digestion protocol	The mean concentration of Cd, Hg, and Fe ranged from 0.008 - 0.027, 0.001–0.013, and 4.517–36.178 mg/kg fw in edible parts of non-leafy vegetables, respectively and 0.011–0.035, 0.002–0.011, and 3.617–13.695 mg/ kg fw in exotic or indigenous leafy vegetables. The vegetables were less impacted with the metals if compared to similar vegetables produced from other urban farms, locally and in some countries in Africa, Asia, and Europe. Water resource on the farm were not suitable for vegetable crop irrigation.	Other parameters in the water Emerging contamination were lacking and need to be assessed

Haldar et al. (2022)	To assess the risk, periurban farmers who use surrounding water bodies of Khulna city, Bangladesh, for crop irrigation were selected for the study. study aimed to highlight the concerns associated with the current irrigation practice and thus, an initial screening-level risk assessment was performed using a deterministic model with point estimates of pathogen concentrations. This study aimed to assess the risks related to indirect wastewater irrigation among peri-urban farmers based on a questionnaire survey among farmers and a determination of the microbial quality of surface water resources around the Bengal delta city of Khulna	As, Co, Ni, Cd, Cr, Cu and Pb Al, Fe, Mn, Ti and Zn Total coliform (TC), Faecal coliform (FC), E. coli and Enterococcus	Filtration (MF) method was used for microbial analysis. Quantitative Microbial Risk Assessment (QMRA) was used to quantify the risk associated to the exposure	As, Co, Ni, Cd, Cr, Cu and Pb, concentrations were below the detection limit, whereas Al, Fe, Mn, Ti and Zn were present but below the FAO recommendation limit for safe irrigation. The mean concentrations of microbial parameters were above the thresholds of WHO guidelines for crop irrigation intended for human consumption. During the farmers' survey, around 45% reported health-related issues and more than 26% reported suffering from water-borne diseases after getting in contact with polluted surface water.	Samples were only taken from the water to test for microbial and heavy metals. No virus and Nonemerging contaminants were assessed An in-depth QMRA considering other microorganisms, such. as bacteria, viruses, protozoa, and helminth eggs, would provide a comprehensive image of the risks associated with indirect wastewater irrigation. Moreover, chemical pollution such as organic micropollutants, in addition to the heavy and other metals studied here, could further complete the picture of risks and treatment measures needed. Consumers and market vendors should also be considered in a complete risk assessment and strategies to reduce the risk of infection and chemical pollution.

3.6 Irrigated water impact on crop quality, growth, and safety of horticultural produce

The quality of irrigation water plays a vital role in the overall growth and development of crops. Water contaminated with pathogens, pollutants, or excessive salts can have detrimental effects on plant health and productivity. Pathogens present in irrigation water, such as bacteria, viruses, and nematodes, can directly infect crops and cause diseases, leading to reduced yield and compromised quality (Machado-Moreira et al., 2021). Additionally, the presence of larvae of worms, such as fruit flies or root-knot nematodes, in irrigation water can result in infestations and damage to the crops. Contaminants present in irrigation water, such as heavy metals, pesticides, and organic pollutants, can also impact crop quality. Heavy metal contamination can accumulate in plant tissues and pose risks to human health upon consumption of the contaminated produce (Ahmadi-Jouibari et al., 2021; Amir et al., 2021; Mcheik et al., 2017). Pesticides present in irrigation water may be absorbed by plants, leading to residue accumulation, which can exceed safety limits and compromise food quality and safety (Sharafi et al., 2022). Similarly, organic pollutants, including polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs), can contaminate crops through irrigation water and pose health risks to consumers (Alghobar et al., 2017).

The transmission of pathogens and contaminants from irrigation water to crops can occur through various routes. Splash or spray irrigation methods can directly contaminate the aboveground parts of the plant, while contaminated soil resulting from irrigation practices can lead to the uptake of pathogens or contaminants by plant roots. Pathogens may also adhere to the surface of produce, such as fruits and vegetables, during overhead irrigation or when contaminated water comes into contact with edible portions of the crops (Emilse et al., 2021)rotavirus and infective enterovirus in leafy green vegetables and irrigation waters collected from a farm located at the province of Córdoba, Argentina, and to estimate the quantitative risk of infection by consuming these vegetables. During June 2014–July 2015, vegetables (n = 101. The presence of larvae of worms in irrigation water can result in infestation of crops, leading to physical damage and reduced market value. The consequences of these transmissions can significantly impact crop quality and safety. Pathogenic bacteria, such as Escherichia coli and Salmonella species, can cause foodborne illnesses when consumed through contaminated produce (O. Alegbeleye et al., 2023; Emilse et al., 2021) constituting significant public health risks especially for the fresh produce category. This review discusses some available guidelines or regulations for microbiological safety of irrigation water, and provides a summary of some common methods used for characterizing microbial contamination. The goal of such exploration is to understand some of the considerations that influence formulation of water testing guidelines, describe priority microbial parameters particularly with respect to food safety risks, and attempt to determine what methods are most suitable for their screening. Furthermore, the review discusses factors that influence the potential for microbiologically polluted irrigation water to pose substantial risks of pathogenic contamination to produce items. Some of these factors include type of water source exploited, irrigation methods, other agro ecosystem features/practices, as well as pathogen traits such as die-off rates. Additionally, the review examines factors such as food safety knowledge, other farmer attitudes or inclinations, level of social exposure and financial circumstances that influence adherence to water testing guidelines and other safe water application practices. A thorough understanding of relevant risk metrics for the application and management of irrigation water is necessary for the development of water testing criteria. To determine sampling and analytical approach for water testing, factors such as agricultural practices (which differ among farms and regionally. The presence of larvae of worms, such as fruit fly larvae or root-knot nematodes, can cause structural damage to crop and affect their overall appearance, marketability, and nutritional value. Furthermore, the accumulation of contaminants in crops can result in the presence of harmful substances exceeding regulatory limits, compromising both quality and safety. To mitigate these risks and ensure high-quality and safe horticultural produce, several measures can be implemented. Water quality monitoring and testing should be conducted regularly to assess the microbial and chemical composition of irrigation water. Proper filtration and treatment methods, such as sedimentation, disinfection, and activated carbon filtration, can help reduce pathogens and contaminants in irrigation water (Allende et al., 2015)but the low prevalence of pathogens makes the use of faecal indicators, particularly E. coli, a more practical approach. Where growers have to utilise water sources of moderate quality, they can reduce the risk of contamination of the edible portion of the crop (i.e., the leaves. Implementing good agricultural practices (GAPs), including proper irrigation management, crop rotation, and integrated pest management, can minimize the risk of pathogen and worm infestations. Additionally, adherence to regulatory standards for pesticide use and employing sustainable agricultural practices can help mitigate the presence of chemical contaminants in crops.

3.7 Health risk assessment of wastewater irrigation for horticulture Production

The utilization of irrigated water for horticulture production is essential for meeting the increasing demand for fresh produce. However, it is crucial to assess the potential chemical risks associated with the use of such water to ensure the safety and quality of agricultural products. Irrigated water sources can contain a wide range of chemical contaminants, including pesticides, heavy metals, pathogens, and emerging pollutants. Pesticides are commonly used in agricultural practices to control pests and diseases. However, improper application or runoff can result in their presence in irrigation water. Studies have demonstrated the potential accumulation of pesticide residues in horticultural crops, posing risks to human health and the environment (Alberti et al., 2022; Sharafi et al., 2022)climate change is expected to have effects on rainfall patterns, which are likely to impact urban food production. The main aim of this paper is to evaluate how issues related to water sources for UA have been addressed in the scientific literature from two different socioeconomic and environmental realities, Brazil and Italy. The method involved a systematic literature review, considering the PRISMA guidelines. The Web of Science database and papers' reference lists were used for retrieving original articles, published in 2000–2020 interval, indexed on scientific databases, and containing data on the typology and quality of water sources used in UA studies. After applying the eligibility criteria, 191 papers were selected – Brazil (108. Effective risk assessment methods, such as residue analysis and exposure modeling, have been employed to evaluate the pesticide-related risks associated with irrigated water (Abdelmoula et al., 2021; Mok et al.,2014). Heavy metals, including lead, cadmium, mercury, and arsenic, can also contaminate irrigated water from various sources, such as industrial activities, urban runoff, and natural weathering of rocks and soils. These metals have the potential to accumulate in horticultural crops and pose health risks upon consumption. Studies have highlighted the importance of assessing heavy metal concentrations in both irrigation water and plant tissues to estimate exposure levels and potential health hazards (Affum et al., 2020; Amin et al., 2013; Sharafi et al., 2022; Tariq, 2021; Xu et al., 2022)Ni, Zn, Cr, Fe, Mn, Co and Pb. Analytical techniques such as atomic absorption spectroscopy and inductively coupled plasma mass spectrometry have been utilized for accurate determination of heavy metal concentrations (Abegunrin et al., 2016). Pathogens, including bacteria, viruses, and parasites, can contaminate irrigated water, posing risks to both crop safety and consumer health. Waterborne disease outbreaks associated with contaminated irrigation water have been reported in various regions (Allende et al.,2015; Holvoet et al., 2014; Orlofsky et al., 2016; Pavione et al., 2013; Raja et al., 2022; Toze, 2006)yellowish for E. coli and small pink colonies for Shigella. Risk assessment of pathogen exposure involves monitoring the presence of specific pathogens, quantifying their levels, and evaluating the likelihood of infection based on exposure pathways (Clark et al., 2019; Gonzales-Gustavson et al., 2019; Mok et al.,2014)a practice that may expand with climate change. There are a number of health risks associated with wastewater irrigation for human food crops, particularly with surface irrigation techniques common in the developing world. The World Health Organization (WHO. Techniques such as polymerase chain reaction and immunological assays have been employed for pathogen detection and quantification (O. Alegbeleye et al., 2023)constituting significant public health risks especially for the fresh produce category. This review discusses some available guidelines or regulations for microbiological safety of irrigation water, and provides a summary of some common methods used for characterizing microbial contamination. The goal of such exploration is to understand some of the considerations that influence formulation of water testing guidelines, describe priority microbial parameters particularly with respect to food safety risks, and attempt to determine what methods are most suitable for their screening. Furthermore, the review discusses factors that influence the potential for microbiologically polluted irrigation water to pose substantial risks of pathogenic contamination to produce items. Some of these factors include type of water source exploited, irrigation methods, other agro ecosystem features/practices, as well as pathogen traits such as die-off rates. Additionally, the review examines factors such as food safety knowledge, other farmer attitudes or inclinations, level of social exposure and financial circumstances that influence adherence to water testing guidelines and other safe water application practices. A thorough understanding of relevant risk metrics for the application and management of irrigation water is necessary for the development of water testing criteria. To determine sampling and analytical approach for water testing, factors such as agricultural practices (which differ among farms and regionally. Emerging pollutants, including pharmaceuticals, personal care products, and endocrine-disrupting compounds, are another concern in irrigated water. These contaminants may enter water sources through various pathways, including wastewater discharges and agricultural runoff. Limited studies have investigated the risks associated with emerging pollutants in irrigated water for horticulture production (Becerra-Castro et al., 2015; Saab et al., 2022)in particular for irrigation, is an increasingly common practice, encouraged by governments and official entities worldwide. Irrigation with wastewater may have implications at two different levels: alter the physicochemical and microbiological properties of the soil and/or introduce and contribute to the accumulation of chemical and biological contaminants in soil. The first may affect soil productivity and fertility; the second may pose serious risks to the human and environmental health. The sustainable wastewater reuse in agriculture should prevent both types of effects, requiring a holistic and integrated risk assessment. In this article we critically review possible effects of irrigation with treated wastewater, with special emphasis on soil microbiota. The maintenance of a rich and diversified autochthonous soil microbiota and the use of treated wastewater with minimal levels of potential soil contaminants are proposed as sine qua non conditions to achieve a sustainable wastewater reuse for irrigation. The use of polluted water to irrigate is an increasing problem in the developing world. Lebanon is a case in point, with heavily polluted irrigation waters, particularly in the Litani River Basin. This study evaluated the potential health risks of irrigating vegetables (radishes, parsley, onions, and lettuce. The assessment of exposure and analysis of emerging pollutants require advanced analytical methods, such as liquid chromatography-mass spectrometry and high-resolution mass spectrometry (Ahmadi-Jouibari et al., 2021; O. Alegbeleye et al., 2023) constituting significant public health risks especially for the fresh produce category. This review discusses some available guidelines or regulations for microbiological safety of irrigation water, and provides a summary of some common methods used for characterizing microbial contamination. The goal of such exploration is to understand some of the considerations that influence formulation of water testing guidelines, describe priority microbial parameters particularly with respect to food safety risks, and attempt to determine what methods are most suitable for their screening. Furthermore, the review discusses factors that influence the potential for microbiologically polluted irrigation water to pose substantial risks of pathogenic contamination to produce items. Some of these factors include type of water source exploited, irrigation methods, other agro ecosystem features/practices, as well as pathogen traits such as die-off rates. Additionally, the review examines factors such as food safety knowledge, other farmer attitudes or inclinations, level of social exposure and financial circumstances that influence adherence to water testing guidelines and other safe water application practices. A thorough understanding of relevant risk metrics for the application and management of irrigation water is necessary for the development of water testing criteria. To determine sampling and analytical approach for water testing, factors such as agricultural practices (which differ among farms and regionally. Risk analysis plays a crucial role in evaluating and managing the chemical risks associated with irrigated water used in horticulture production. Exposure assessment involves estimating the levels of chemical contaminants in irrigated water, the uptake of these contaminants by crops, and the potential exposure of consumers to these contaminants through ingestion. Various exposure modeling approaches, such as deterministic and probabilistic models, have been used to estimate exposure levels and assess associated risks (Yeboah et al., 2022). Risk characterization involves integrating exposure assessment data with toxicological information to determine the potential health risks and establish appropriate risk management strategies (Emilse et al., 2021; Gonzales-Gustavson et al., 2019)rotavirus and infective enterovirus in leafy green vegetables and irrigation waters collected from a farm located at the province of Córdoba, Argentina, and to estimate the quantitative risk of infection by consuming these vegetables. During June 2014–July 2015, vegetables (n = 101. However, the use of appropriate risk analysis methods, including exposure assessment and risk characterization, is essential for evaluating and managing these risks.

According to the literature, the risk assessment can be performed using: (i) microbiological, chemical and heavy metal laboratory tests; (ii) epidemiological studies; (iii) quantitative microbiological risk assessment (QMRA); (iv), target hazard quotient (THQ). Microbiological studies are considered as a source of information for types of studies (ii) and (iii) and are only appropriate if health assessments and appropriate protective measures are taken to avoid a health risk. Epidemiological studies are a direct measure of the associated risk, but their complexity and target population requirements and high costs may limit the technique. The QMRA is considered an indirect risk measurement that has been widely used, but its results are associated with the specific scenarios evaluated. The combined use of the three i) microbiological, chemical, and heavy metal laboratory tests; (ii) epidemiological studies; (iii) quantitative microbiological risk assessment (QMRA) has been employed by most studies. target hazard quotient (THQ) analysed the health risk associated with the consumption of a given media (Soil, water, food etc.) contaminated with heavy metal pollutions. Summary Wastewater reuse or irrigation and health risk studies on vegetables/plants is summarised in the below Table 3.

Table 3. Wastewater reuse or irrigation and health risk studies on vegetables/plants

Reference	Key objectives	Key risks assessed	Key findings
Alegbeleye and Sant'Ana (2021)	To explore some fundamental principles of conducting QMRAs for irrigation-water-related fresh produce safety risks and discuss some of the most relevant risk parameters usually incorporated into these QMRAs	A quantitative microbial risk assessment model was used	Water contamination data alone is not sufficient to assess human health risks associated with consumption of produce commodities contaminated via irrigation water and all other relevant data points and risk parameters should be considered.
Gonzales-Gustavson et al. (2019)	to develop a Quantitative Microbial Risk Assessment for viral gastroenteritis caused by norovirus GII and adenovirus, associated with the ingestion of lettuce irrigated with tertiary effluents	A stochastic QMRA model was used to estimate the annual disease burden from the consumption of lettuce irrigated with tertiary treated water from two different WWTPs.	High concentrations of NoVGII and HAdV were present in sewage. Sensitivity analysis showed that virus reduction due to whole treatment, virus concentration in raw sewage and ingestion of lettuce were major inputs influencing the variability in the risk assessment.
Barker et al. (2014)	To assess the risk of gastroenteritis illness (caused by rotavirus, norovirus and Ascaris lumbricoides) associated with the consumption of street food salads.	A quantitative microbial risk assessment model was used. Three different risk assessment models were constructed, based on availability of microbial concentrations of water, produce, and street.	The Water model consistently predicted lower estimates of risk. Risks from both rotavirus and norovirus exceeded the health target but risks from Ascaris did not
Liang et al. (2019)	Investigate the toxic metals (cadmium (Cd), lead (Pb), chromium (Cr), arsenic (As), and mercury (Hg)) concentrations in different foodstuffs (cereals, vegetables (cauliflower, white gourd, cabbage, eggplant, potato, cucumber, carrot, haricot bean, onion), fruits, fish, and meat) and then estimate the potential health risks of toxic metals via consumption	The method for health risk assessment is based on non-carcinogenic effects, and the risk was expressed as a target hazard quotient (THQ)	The study found that the risk contribution from vegetable intake (38.8%) was significant in comparison to that from other foodstuffs. The study recommends biological risk assessment to quantify the health risk of consumption. The study recommends future studies to consider different routes as there are many routes for the migration of heavy metals into humans, such as food, water, air, so the potential health risks might be underestimated.

Antwi-Agyei and Ensink (2016)	Identifying and quantifying key exposures associated with the transmission of faecal pathogens in wastewater irrigated agriculture.	Risk factors for soil and irrigation water contamination Farmers' infection risk to pathogens. Quantitative microbial risk assessment of E. coli concentration	The results showed that irrigation water was significantly more contaminated than farm soil, though exposure to soil was found to pose the key risk to farmers due to hand-to mouth events (10 events/day). This study also showed that there was potential health risk to wastewater irrigation farmers and consumers of wastewater irrigated produce, and hence the need to intervene appropriately to reduce these risks
Bougnom et al. (2019) Ouagadougou (Burkina Faso)	Wastewater used for urban agriculture in West Africa as a reservoir for antibacterial resistance dissemination	A range of parasitic infections including hookworm and Giardia lamblia infection	Eleven pathogen-specific and 56 orthologous virulence factor genes were detected in the wastewater samples.
El-Senousy et al. (2013)	To evaluate in different types of fresh produce and in irrigation water for human norovirus (NoV) detection	Two different virus concentration procedures, polyethylene-glycol precipitation (PEG) and organic flocculation (OF), were employed	PEG provided significantly (p b 0.05) better virus recoveries than OF for both irrigation water and salad vegetable virus analysis. In experimentally contaminated salad vegetables, virus recoveries ranged from 28.0% to 48.0% and from 14.0% to 18.8% by PEG precipitation and OF, respectively.
Clark et al. (2019)	To quantify in multiple rain three pathogen groups in rooftop runoff from three roof types from locations with differing amounts of tree cover.	A quantitative microbial risk assessment	Bacterial loads were highest from wood shake and asphalt shingle roofs. Enterococci were the most frequently detected bacteria from all roof types.

Barker (2014)	to assess the risk of norovirus gastroenteritis associated with consumption of raw vegetables irrigated with highly treated municipal wastewater, using Melbourne,	Quantitative microbial risk assessment was used	Estimates of norovirus concentrations in raw sewage ranged from 104 per milliliter to 107 per milliliter and treated effluent from 1 × 10−3 per milliliter to 3 per milliliter (95th percentiles). Estimates of annual disease burden were highly variable, ranging from 8 log10 below the health target to 2 log10 higher
Soleimani et al. (2023)	To investigate the effect of three types of irrigation on the accumulation and ecological risk of heavy metals in agricultural soils.	plasma optical emission spectrometry (ICP-OES) model was used to determine the concentration of heavy metals	The different irrigation sources increased the concentration of all heavy metals in the soil, and the accumulation of Cr, Ni, and Cd significantly elevated more than others.
Amha et al. (2015)	To determine the risk of Salmonella infections resulting from the consumption of edible crops irrigated with treated wastewater	A quantitative microbial risk assessment model was used (Quantitative polymerase chain reaction (qPCR) was used to enumerate Salmonella spp. in post-disinfected samples)	Lettuce showed the highest risk of infection in all scenarios considered, while cucumber showed the lowest risk. the absence of indicator bacteria (E. coli) does not always indicate the absence of Salmonella spp. in the treated wastewater
Malchi et al. (2014)	To quantify pharmaceutical compounds (PCs) uptake by treated wastewater-irrigated root crops (carrots and sweet potatoes) grown in lysimeters and to evaluate potential risks.	The health risk associated with consumption of wastewater-irrigated root vegetables was estimated using the threshold of toxicological concern (TTC) approach.	In both crops, nonionic PCs were detected at significantly higher concentrations than ionic PCs. PCs in leaves were found at higher concentrations than in the roots.
Amha et al. (2015)	To determine the risk of Salmonella infections resulting from the consumption of edible crops irrigated with treated wastewater	A quantitative microbial risk assessment model was used (Quantitative polymerase chain reaction (qPCR) was used to enumerate Salmonella spp. in post-disinfected samples)	Lettuce showed the highest risk of infection in all scenarios considered, while cucumber showed the lowest risk. the absence of indicator bacteria (E. coli) does not always indicate the absence of Salmonella spp. in the treated wastewater

Malchi et al. (2014)	To quantify pharmaceutical compounds (PCs) uptake by treated wastewater-irrigated root crops (carrots and sweet potatoes) grown in lysimeters and to evaluate potential risks.	The health risk associated with consumption of wastewater-irrigated root vegetables was estimated using the threshold of toxicological concern (TTC) approach.	In both crops, nonionic PCs were detected at significantly higher concentrations than ionic PCs. PCs in leaves were found at higher concentrations than in the roots.
Sharafi et al. (2022)	to investigate the effect of various water resources on the accumulation of heavy metals (HMs) in the three most widely consumed edible vegetables in Iran	Total Target Hazard Quotient (TTHQ) of toxic metals in vegetables was less than the allowable limits (TTHQ= 1). Also, TWE was the best irrigation water type since the HMs content of vegetables was low	Inductive coupled plasma optical emission spectrometry (ICP-OES)
Gonzales-Gustavson et al. (2019)	to develop a Quantitative Microbial Risk Assessment for viral gastroenteritis caused by norovirus GII and adenovirus, associated with the ingestion of lettuce irrigated with tertiary effluents from these WWTPs	stochastic QMRA model was adopted	The results show that the disease burden of NoV GII and HAdV for the consumption of lettuce irrigated with tertiary effluent from either WWTP was higher than the WHO recommendation of 106 DALYs for both viruses.

3.7.1 Quantitative microbial risk assessment (QMRA)

Quantitative microbial risk assessment (QMRA) is a mathematical modelling approach or tool for evaluating the risks associated with consuming horticultural produce contaminated by irrigation water (Alegbeleye et al., 2021; Amha et al., 2015; Haldar et al., 2022; Owusu-Ansah et al., 2017a probabilistic QMRA to determine the risk of Salmonella infections resulting from the consumption of edible crops irrigated with treated wastewater was conducted. Quantitative polymerase chain reaction (qPCR; Haas et al., 1993). Different studies (Farhadkhani et al., 2020; Owusu-Ansah et al., 2017) have documented QMRA methodological techniques. When applied to horticultural produce, QMRA allows for the estimation of the likelihood of pathogen contamination and subsequent adverse health effects resulting from consumption. By considering various factors such as pathogen prevalence, concentration, and dose-response relationships, QMRA provides a quantitative estimation of the probability of illness and the severity of potential health outcomes. To conduct a QMRA related to irrigation water contamination, key steps include hazard identification, exposure assessment, dose-response modeling, and risk characterization. Hazard identification involves identifying and selecting relevant pathogens of concern, such as Salmonella, Escherichia coli, or norovirus, which may be transmitted through contaminated irrigation water. Exposure assessment quantifies the level of exposure to pathogens by considering factors like irrigation practices, water quality, crop type, and consumption patterns. Dose-response modeling establishes the relationship between pathogen dose and the probability of illness, enabling the calculation of risk estimates. Finally, risk characterization combines all the information to provide a comprehensive assessment of the potential health risks associated with consuming contaminated produce. Few studies in developing countries have performed QMRA based on indicator organisms. However, using indicator organisms requires making assumptions about the correlation between pathogens and indicators, which contributes to the risk assessment's ambiguity. By utilizing QMRA, researchers and policymakers can obtain objective information on the potential health risks and make informed decisions to ensure food safety. QMRA enables the identification of critical control points in the production and distribution process, allowing for targeted interventions to reduce pathogen transmission. It provides a quantitative basis for establishing microbiological criteria and setting appropriate safety standards for irrigation water quality. Various studies have employed QMRA to assess the risks associated with irrigation water contamination and its impact on horticultural produce. For example, a study by (Alegbeleye et al., 2021) used QMRA to evaluate the health risks associated with consuming lettuce contaminated with Escherichia coli O157:H7 from contaminated irrigation water. The study incorporated exposure assessment, dose-response modeling, and risk characterization to estimate the probability of illness and provide valuable insights for risk management strategies. Another study by Owusu-Ansah et al. (2017) applied QMRA to assess the risks of consuming strawberries contaminated with norovirus through irrigation water. The researchers conducted exposure assessment and dose-response modeling to quantify the likelihood of infection and illness. The study highlighted the importance of implementing effective control measures to minimize norovirus contamination in irrigation water. Different types of QMRA models have been utilized in these studies, including probabilistic models, Bayesian models, and quantitative exposure models. Probabilistic models allow for the incorporation of uncertainties and variability in input parameters, providing a more realistic representation of the risks. Bayesian models, on the other hand, enable the integration of prior knowledge with observed data, enhancing the accuracy of risk estimates. Quantitative exposure models facilitate the estimation of the level of exposure to pathogens and help identify critical control points in the production chain.

Recent risk assessment studies have recommended using Disability Adjusted Life Years (DALYs) to compare the impact of various illnesses (Farhadkhani et al., 2020; Gonzales-Gustavson et al., 2019) and its use in agriculture requires the guarantee of acceptable public health risks. The use of fecal indicator bacteria to evaluate safety does not represent viruses, the main potential health hazards. Viral pathogens could complement the use of fecal indicator bacteria in the evaluation of water quality. In this study, we characterized the concentration and removal of human adenovirus (HAdV. The DALY metric estimates the loss of healthy life years in a specific population to quantify the overall disease burden (Owusu-Ansah et al., 2017). The DALY approach is a novel way of assessing environmental health risks that combines disease burden estimate with risk assessment. This is calculated as the sum of the years of life lost to death and the years spent living with a disability (Barker, 2014). Most studies have employed a constant number of DALYs per 1000 cases (Barker et al., 2014)Ghana, the consumption of street food is increasing. Raw salads, which often accompany street food dishes, are typically composed of perishable vegetables that are grown in close proximity to the city using poor quality water for irrigation. This study assessed the risk of gastroenteritis illness (caused by rotavirus, norovirus and Ascaris lumbricoides. DALYs have been used all around the world to estimate the severity of potential health risks, mortality rates, diseases, and disorders. In my opinion, QMRA is an essential tool for understanding and managing the risks associated with consuming horticultural produce contaminated by irrigation water. It provides a systematic framework for quantifying risks, enabling evidence-based decision-making and effective risk communication. By incorporating scientific knowledge and data-driven analyses, QMRA enhances our understanding of the potential health impacts and aids in the development of preventive measures and control strategies.

3.8 Farm-to-fork microbial contamination

Farm-to-fork microbial contamination refers to the transmission and persistence of microbial pathogens throughout the entire food production and consumption chain. The farm-to-fork continuum encompasses multiple stages, including primary production, harvesting, processing, distribution, and consumption. Each stage presents opportunities for the introduction and amplification of microbial pathogens, posing risks to food safety and public health. Understanding the dynamics of microbial contamination along this continuum is crucial for implementing effective control measures and ensuring the production of safe and high-quality food. At the primary production stage, microbial contamination can arise from various sources, including contaminated irrigation water, soil, animals, and human handlers. Pathogens such as Salmonella, Escherichia coli, Listeria monocytogenes, and Campylobacter are commonly associated with primary production and can contaminate crops through direct contact or indirect routes. For example, a study by Amha et al. (2015) investigated the prevalence of Salmonella in fresh produce and found that contaminated irrigation water was a significant contributing factor. During harvesting, the risk of microbial contamination increases due to factors such as improper handling practices, cross-contamination, and inadequate sanitation. Processing and post-harvest handling operations also play a significant role in farm-to-fork microbial contamination. Processing facilities provide environments conducive to pathogen growth and survival if proper hygiene practices and sanitation protocols are not followed. For instance, a study by Franz et al. (2018) investigated the prevalence of Listeria monocytogenes in ready-to-eat salads and identified processing facilities as potential contamination sources. During distribution and transportation, there is a potential for further microbial contamination if temperature control, packaging integrity, and hygiene practices are not maintained. Cross-contamination between different batches or products can occur during storage, loading, or unloading processes. A study by Alegbeleye and Sant'Ana (2021) examined the microbial quality of fresh produce during distribution and highlighted the importance of proper handling and transportation practices to prevent contamination. Finally, at the consumption stage, mishandling of food by consumers, inadequate cooking, or improper storage can contribute to the transmission of microbial pathogens. Insufficient knowledge of safe food handling practices, such as inadequate handwashing, can further exacerbate the risks of foodborne illnesses. However, addressing farm-to-fork microbial contamination requires a comprehensive approach that involves the implementation of preventive measures at each stage of the continuum. Good Agricultural Practices (GAPs) should be implemented during primary production to minimize microbial contamination in the field, including proper irrigation water management, hygiene practices, and control of animal and wildlife interactions. Harvesting practices should prioritize hygiene, worker training, and proper cleaning and sanitation procedures to reduce the risk of contamination. In processing facilities, adherence to Good Manufacturing Practices (GMPs), Hazard Analysis and Critical Control Points (HACCP) systems, and rigorous sanitation protocols are essential. Maintaining proper temperature control, effective cleaning, and sanitization, and implementing traceability systems can help minimize the risk of microbial contamination during processing and post-harvest handling. During distribution and transportation, proper temperature management, adherence to sanitary standards, and appropriate packaging materials are crucial to prevent pathogen growth and cross-contamination. Promoting consumer education on safe food handling practices, such as proper storage, thorough cooking, and effective hand hygiene, is also essential to reduce the risk of foodborne illnesses at the consumption stage. According to the WHO, (2016), farm-to-fork microbial contamination is a complex issue that requires a multi-faceted approach involving collaboration between stakeholders throughout the food supply chain. By implementing robust food safety practices, conducting regular monitoring, and testing, and promoting awareness among producers, processors, distributors, and consumers, one can effectively mitigate the risks of microbial contamination and ensure the safety and quality of food.

3.8 Future scenario analysis and research direction

The previous discussions on various aspects of water sources for irrigation, chemical and microbial pathogens in irrigation water, impact on crop quality, quantitative microbial risk assessment (QMRA), and farm-to-fork microbial contamination provide valuable insights into the current state of knowledge and challenges in ensuring food safety and quality. As the demand for agricultural products continues to rise, ensuring sustainable and safe water sources for irrigation is of paramount importance. Future research should focus on the development and implementation of innovative irrigation technologies that minimize water usage, such as precision irrigation systems and smart water management approaches. Additionally, studying the efficiency and effectiveness of alternative water sources, such as treated wastewater, recycled water, and desalinated water, in maintaining crop productivity and minimizing potential risks to human health and the environment will be crucial. Investigating the long-term effects of climate change on water availability and quality for irrigation purposes is another area that warrants attention. Future research should aim to enhance our understanding of the prevalence, persistence, and transmission routes of microbial pathogens in irrigation water. Studies investigating the effectiveness of various water treatment methods, such as filtration, disinfection, and advanced oxidation processes, in reducing pathogen loads in irrigation water are needed. Furthermore, exploring the impact of climate change and extreme weather events on the dynamics of microbial pathogens in irrigation water will provide valuable insights into potential risks and the need for adaptive management strategies. Integrating molecular techniques, such as metagenomics and quantitative PCR, can facilitate the rapid detection and identification of specific pathogens in irrigation water, enabling targeted interventions to minimize contamination risks. Additionally, Future research should focus on elucidating the specific mechanisms by which irrigation water quality affects crop growth, quality, and safety. Understanding the interactions between water quality parameters (e.g., nutrient levels, pH, salinity, and pesticide residues) and crop responses will enable the development of tailored irrigation strategies for optimal plant health and productivity. Assessing contaminants of emerging concern (CEC) including micro- and nano-plastics, personal care products, cyanotoxins, perfluoroalkyl acids, estrogen, and viruses in irrigatable irrigation water and their impact on soil are also critical as few studies have looked into that. Assessing the impact of long-term exposure to suboptimal water quality on crop nutrient content, sensory attributes, and post-harvest shelf life will provide valuable insights into the overall quality and marketability of horticultural produce. Additionally, studying the potential accumulation and persistence of microbial pathogens, contaminants, and larvae of worms on crops irrigated with different water sources will contribute to developing effective control measures and post-harvest interventions. For QMRA analysis, future research in QMRA should focus on refining and expanding the existing models to incorporate site-specific factors, regional variations, and emerging pathogens. Developing predictive models that integrate the dynamics of microbial pathogens throughout the farm-to-fork continuum will enable more accurate assessments of the risks associated with consuming contaminated horticultural produce. Incorporating climate change scenarios and the effects of agronomic practices, irrigation water sources, and post-harvest interventions in QMRA models will provide a more comprehensive understanding of the potential health risks and inform risk management strategies. Additionally, conducting longitudinal studies to collect high-quality data on pathogen occurrence, survival, and transfer dynamics will improve the accuracy of QMRA models and enhance their utility in decision-making processes. Succinctly, future research should focus on developing integrated and holistic approaches to mitigate farm-to-fork microbial contamination. This includes the development and evaluation of novel interventions and technologies to reduce microbial risks at each stage of the food production and consumption chain. Exploring the potential of biocontrol agents, natural antimicrobials, and innovative packaging materials to inhibit pathogen growth and improve the safety and shelf life of horticultural produce is an area that warrants attention.

4.0 CONCLUSION

Microbial contamination of irrigation water in horticulture production has emerged as a critical concern for food safety and consumer health. Throughout the review, various aspects related to this issue have been explored: including water sources for irrigation, microbial pathogens in irrigation water, the impact on crop quality, quantitative microbial risk assessment (QMRA), and farm-to-fork microbial contamination. The analysis reveals that irrigation water serves as a significant source of microbial pathogens, with various studies highlighting the presence of pathogens such as pathogenic Escherichia coli, Salmonella species, Shigella spp., etc, Viruses and among other microbial pathogens. These pathogens can contaminate horticultural produce at different stages, posing risks to both crop quality and consumer health. However, to address this challenge, it is crucial to focus on effective water management strategies and the development of innovative irrigation technologies. Treatment methods such as filtration, disinfection, and advanced oxidation processes show promise in reducing pathogen loads. Additionally, understanding the impact of irrigation water quality on crop growth and safety is vital. Suboptimal water quality can affect nutrient uptake, plant health, and the accumulation of contaminants on crops. Tailored irrigation practices and improved post-harvest interventions can enhance crop productivity while minimizing health risks. Quantitative microbial risk assessment (QMRA) plays a significant role in assessing the risks associated with consuming contaminated horticultural produce. These models provide objective information on pathogen occurrence and impact values, aiding in risk management strategies. However, further research is needed to refine and expand QMRA models, incorporating site-specific factors, regional variations, and emerging pathogens. Mitigating farm-to-fork microbial contamination requires a comprehensive approach involving collaboration among stakeholders. GAPs, GMPs, and promoting consumer education on safe food handling practices are essential. By integrating these measures, we can ensure the safety and quality of horticultural produce throughout the entire food supply chain. The review also found that the microbial contamination of irrigation water poses significant challenges, but with ongoing research, the development of innovative strategies, and the implementation of best practices, we can minimize risks and ensure the production of safe and high-quality horticultural produce for consumers. By addressing these issues, we can enhance food safety, protect consumer health, and contribute to sustainable agricultural practices.

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