https://doi.org/10.17221/132/2025-HORTSCI

Hydroponics and food safety: Key risks and solutions – A review

*Sachin Adhikari**

Kansas State University, Olathe, Kansas, United States

**Corresponding author: adhikarisachin7@gmail.com*

Citation: Adhikari S. (2026): Hydroponics and food safety: Key risks and solutions – A review. Hort. Sci. (Prague), 53: 259–267.

Abstract: Hydroponics is an innovative and sustainable approach to crop production that eliminates the need for soil by supplying plants with nutrient-enriched water solutions. However, the recirculation of nutrient solutions introduces specific microbiological risks that may compromise food safety. This review evaluates contamination pathways and examines current mitigation strategies in hydroponic systems. Various hydroponic systems, including deep water culture (DWC), nutrient film technique (NFT), drip systems, ebb-and-flow systems, wick systems, and aeroponic systems, remain vulnerable to pathogen accumulation and spread. Outbreaks associated with *Salmonella enterica*, *Listeria monocytogenes*, and *Escherichia coli* O157:H7 highlight the importance of strict hygiene, continuous monitoring, and effective water treatment practices. Among available disinfection approaches, ultraviolet (UV-C, 254 nm) irradiation has emerged as a residue-free, energy-efficient alternative for nutrient solution treatment. Nevertheless, its efficacy is influenced by operational factors such as turbidity and the applied dose. The review highlights current knowledge gaps in the optimization and validation of UV-C treatment under commercial-scale conditions and underscores the importance of integrated and multi-barrier safety strategies to ensure safe and sustainable hydroponic production.

Keywords: controlled environment agriculture; urban food systems; foodborne pathogens; UV-C; recirculating systems

The global food system is facing increasing pressure due to rapid population growth, urbanisation, climate change, and the ongoing loss of arable land (Webb et al. 2017; Wang et al. 2019). The global population is projected to reach approximately 9.7 billion by 2050, requiring an estimated 70% increase in food production to meet future demand (Hunter et al. 2017; Prosekov, Ivanova 2018; United Nations Department of Economic and Social Affairs 2024). Conventional soil-based agriculture is increasingly constrained by land scarcity, soil degradation, water scarcity, and environmental pollution, highlighting the need for alternative and more sustainable food production systems (Murali et al. 2011).

Hydroponics, a soilless cultivation method in which plants are grown in nutrient-enriched water solutions, has emerged as a promising approach to address these challenges (Douglas 1975; Savvas 2003). Hydroponic production systems include deep water culture (DWC), nutrient film technique (NFT), drip systems, ebb-and-flow systems, wick systems, and aeroponics, which are commonly used in controlled environment agriculture (CEA). By enabling precise control of water, nutrients, and environmental conditions, hydroponic systems can achieve higher yields, improved resource-use efficiency, and year-round production compared with conventional agriculture (Resh 2022; Jan et al. 2020). Consequently, hydroponic production has become an important component of controlled environment agriculture and urban food systems. Despite these advantages, these systems are not inherently free from food safety risks. Fresh fruits and vegetables, particularly leafy greens, are frequently consumed raw

© The authors. This work is licensed under a Creative Commons Attribution-NonCommercial 4.0 International (CC BY-NC 4.0).

https://doi.org/10.17221/132/2025-HORTSCI

and are major contributors to foodborne disease outbreaks (Kamarasu et al. 2025). In hydroponic production, the recirculation of nutrient solutions can facilitate the introduction, persistence, and spread of human pathogens throughout the system (Ivey et al. 2025). Pathogens such as *Salmonella enterica*, *Listeria monocytogenes*, and *Escherichia coli* have been repeatedly associated with outbreaks linked to leafy greens produced in both conventional and controlled environments (Ivey et al. 2025; Viazis et al. 2025). Water quality, equipment sanitation, and human handling represent critical contamination pathways that must be effectively managed to ensure consumer safety (Sela Saldinger et al. 2023).

To mitigate microbial risks in hydroponic systems, multiple control strategies are employed, including good agricultural practices (GAPs), sanitation protocols, biological control agents, and physical or chemical water disinfection methods. Conventional approaches such as chlorination and heat treatment are effective but may introduce chemical residues, alter nutrient composition, or increase operational costs (Adhikari 2025). Consequently, interest has increased in non-chemical technologies, such as UV-C (254 nm), that provide effective pathogen control while remaining residue-free and energy-efficient. UV-C inactivates microorganisms by damaging nucleic acids, thereby preventing replication (Goto et al. 2015). Multiple studies demonstrate that UV-C reduces microbial loads in irrigation water and fresh produce while limiting biofilm and algal formation in recirculating systems (Lee et al. 2015; Huang et al. 2018). However, the application of UV-C technology in recirculating hydroponic systems has received limited attention. In particular, its role in food safety management, operational constraints, and integration with existing agricultural practices requires further investigation. This review examines the relationship between hydroponic food production and food safety, with a focus on microbial risks and mitigation strategies. It synthesises current knowledge on hydroponic systems and evaluates existing and emerging approaches to enhance microbial safety. By integrating recent literature and highlighting knowledge gaps, this review provides practical insights for researchers, producers, and policymakers seeking to promote safe and sustainable hydroponic food production.

LITERATURE SELECTION METHODOLOGY

This narrative review was conducted through a structured literature search using keyword combinations such as "controlled environment agriculture", "urban food systems", "foodborne pathogens", "nutrient solution disinfection", "UV-C", recirculating systems", along with related terms. The search covered publications from 2000 to 2025 and was performed using major databases, including Scopus, Web of Science, PubMed, Google Scholar, and other relevant academic databases.

Peer-reviewed journal articles focusing on hydroponic production systems, food safety challenges, and mitigation strategies were prioritised, while non-peer-reviewed sources were included only if essential. Studies unrelated to the focus were excluded. Both experimental and review articles were considered to provide comprehensive coverage of the topic. The retrieved literature was screened for relevance and thematically grouped to identify key trends, knowledge gaps, and emerging solutions, with a particular focus on hydroponics and pathogen control strategies.

URBAN FOOD SYSTEMS AND HYDROPONICS

Traditional food production and distribution systems exert significant environmental pressure, including biodiversity loss, climate change, freshwater pollution, deforestation, and nutrient accumulation (Jaramillo, Destouni 2015; Lenka et al. 2015). Concurrently, rapid population growth and urbanisation intensify pressure on cities, contributing to land scarcity, rising food prices, and environmental degradation. Collectively, these factors threaten the long-term sustainability of urban food systems (Gulyas, Edmondson 2021). By 2050, about 68% of the global population is expected to live in urban areas, compared with 55% in 2018 (UN DESA 2018). This demographic shift underscores the urgency of developing resilient and well-structured urban food systems to ensure food security (Matacena 2016). Currently, urban food systems rely heavily on industrialised and global food supply chains (Forster et al. 2015; Vieira et al. 2018). Although these systems enable large-scale food distribution, they generate substantial greenhouse gas emissions and contribute to significant food waste at the production, transportation, and distribution stages (Goldstein et al. 2016).

https://doi.org/10.17221/132/2025-HORTSCI

Urban agriculture (UA) has emerged as a strategic approach to address food security in densely populated regions (Jones 2002). It encompasses crop production, animal husbandry, and aquaculture within cities and peri-urban areas, as well as non-food production such as flowers, trees, and potted plants (Weidner et al. 2019). Urban agriculture also includes the processing and marketing of agricultural products (Yuan et al. 2022). It is practised at multiple scales, including community gardens, small commercial farms, and household-level rooftop and balcony production. Urban agriculture can increase access to fresh foods, support local supply, reduce transport distances, and lower greenhouse emissions (Jones 2002; Coelho et al. 2018). Despite these benefits, urban agriculture faces several constraints, including limited space, soil contamination, high land costs, and limited water availability. Hydroponic systems provide a viable solution to many of these limitations by enabling high-density crop production in controlled environments, including rooftops and vertical farming systems (Talib et al. 2018). By facilitating localised food production, hydroponics reduces food miles and improves access to fresh and nutritious produce (Rajaseger et al. 2023). Moreover, hydroponic cultivation mitigates several challenges commonly associated with open-field agriculture, including soil degradation, climatic variability, pest pressures, and water scarcity (Sardare, Admane 2013).

TYPES OF HYDROPONIC SYSTEMS

Hydroponic systems can be classified according to the methods used to deliver water, nutrients, and oxygen to plant roots (Table 1). Each system presents distinct operational advantages and limitations that influence crop performance and system management. Therefore, understanding these differences is essential for selecting the most appropriate system for crop type, production scale, and management objectives.

CHALLENGES FOR SAFE PRODUCTION IN HYDROPONICS

In recent years, fruits and vegetables have been increasingly recognised as major contributors to foodborne disease outbreaks (Bennett et al. 2018). Leafy greens, in particular, present a higher risk because they are frequently consumed raw, which increases the likelihood of transmitting foodborne pathogens compared to cooked vegetables (Uyttendaele et al. 2015). Over the past decade, the rising incidence of foodborne illnesses has been a major concern for food safety (Taban, Halkman 2011). Epidemiological data indicate that leafy greens are frequently implicated in foodborne outbreaks. Between 2010 and 2020, a total of 66 outbreaks linked to leafy greens resulted in 2 032 illnesses, 580 hospitalisations, and 15 deaths, primarily associated with pathogens such as *Salmonella enterica*, *Listeria monocytogenes*, and Shiga toxin-producing *Escherichia coli* (Dorick et al. 2024). Similarly, a multistate outbreak of *E. coli* O157:H7 in the United States in 2020 resulted in 40 illnesses and 20 hospitalisations. Although investigations confirmed that leafy greens were the source of the outbreak, the specific crop could not be identified (FDA 2022b).

Comparable trends have been reported in other regions. For example, between 2008 and 2018, Canada reported 11 outbreaks of *E. coli* O157:H7 associated with leafy greens, including romaine lettuce and iceberg lettuce (Coulombe et al. 2020). In addition, several recalls and outbreaks associated with leafy greens and microgreens produced in controlled environment agriculture (CEA) have been caused by pathogens such as *L. monocytogenes* and *Salmonella* (Topalcengiz et al. 2024). Studies indicate that *Pseudomonas* species are among the most frequently detected bacterial genera in hydroponically grown fresh produce, while predominant bacterial phyla include Proteobacteria, Actinobacteria, Cyanobacteria, Bacteroidetes, and Firmicutes (Dong, Feng 2022). Additionally, a range of spoilage bacteria and pathogenic species, including *Pseudomonas* and *Clostridium*, have been reported during microgreen production in hydroponic farms (Dong, Feng 2022). Human pathogens, such as *Salmonella* Typhimurium and *Listeria monocytogenes,* can persist in a hydroponic system throughout the lettuce production cycle, facilitating cross-contamination of edible tissues and resulting in economic losses and public health risks (Ilic et al. 2022). These findings indicate that shared water sources, continuous nutrient solution recirculation, and biofilm formation can create favourable conditions for microbial persistence. Once pathogens are introduced into the system, the risk of widespread contamination during a single production cycle is high. Although controlled envi-

https://doi.org/10.17221/132/2025-HORTSCI

Table 1. Types of hydroponic systems, their characteristics, advantages, disadvantages, and suitable plants

Types of hydroponic systems	Description
Deep water culture (DWC)	DWC is a hydroponic method in which plant roots are suspended in a nutrient-rich solution contained within a reservoir. Oxygen is supplied to the root zone through aeration devices, such as air stones or diffusers, to maintain adequate dissolved oxygen levels (Aires et al. 2023). *Advantage*: DWC systems are relatively simple to construct and can be implemented at different production scales. The large volume of nutrient solution surrounding the roots helps to maintain stable nutrient concentrations, temperature, and pH. These characteristics simplify system management, particularly for small-scale growers (Niu, Masabni 2022). DWC systems are also suitable for crops with extensive root systems, such as cucumbers and tomatoes (Ballabh et al. 2022). *Disadvantage:* Plants are susceptible to root diseases under poor management conditions. Excessive root growth may obstruct irrigation pathways and reduce system efficiency (Grigas et al. 2020). *Suitable plants:* Leafy greens, herbs, tomatoes, cucumbers, and peppers (Singh et al. 2019; Niu, Masabni 2022).
Nutrient film technique (NFT)	The NFT is one of the most widely used hydroponic systems in controlled environment agriculture. In NFT, a thin film of nutrient solution continuously flows through slightly sloped channels containing plant roots. The solution passes along the root surface and then returns to the reservoir for recirculation (Domingues et al. 2012; Ballabh et al. 2022). *Advantage:* NFT systems allow efficient circulation of nutrient solutions with a relatively low risk of clogging. Continuous recirculation reduces nutrient solution costs (Grigas et al. 2020), making it suitable for vertical farming and high-density production of leafy vegetables. *Disadvantage:* NFT systems are sensitive to environmental fluctuations and system failure (Rajaseger et al. 2023). This system is generally limited to crops with small root systems, such as leafy greens (Jan et al. 2020; Macwan et al. 2020). *Suitable plants:* Leafy greens, herbs, strawberries, beans, radishes, and cucumbers (Warrington 2019; Rajaseger et al. 2023).
Drip system	In drip hydroponic systems, nutrient solutions are delivered directly to individual plants through a network of tubes and emitters connected to a pump and controlled by an automated timer (Rouphael, Colla 2005). The nutrient solution is applied gradually near the root zone, ensuring a consistent supply of water, nutrients, and oxygen. *Advantage:* Drip systems provide precise control over irrigation and nutrient delivery, allowing growers to adjust nutrient supply to meet crop requirements (Khan et al. 2020; Kumar, Singh 2023). *Disadvantage:* Emitter clogging is a common operational challenge in drip systems (Adelmann 2023). *Suitable plants:* Vegetables, fruits, herbs, and flowering plants (Rajaseger et al. 2023).
Ebb-and-flow system	The ebb-and-flow system operates through automated, periodic flooding and draining cycles that supply nutrient-rich solutions to plant roots (Buwalda et al. 1993; Jan et al. 2020). During irrigation, a timer-controlled pump delivers nutrient solutions to the growing tray, temporarily submerging the root zone before the solution drains back into the reservoir (Dong et al. 2020). *Advantage:* This irrigation strategy promotes root development and improves water-use efficiency while reducing labour requirements associated with manual watering. Maintaining dry foliage during irrigation can also reduce the risk of certain foliar diseases (Dong et al. 2020). *Disadvantage:* Inadequate or poor water quality management may increase the risk of root diseases (Miyake et al. 2014). *Suitable plants:* Lettuce, spinach, tomatoes, cucumbers, peppers, strawberries, and radishes (Rajaseger et al. 2023).
Wick system	The wick system is a passive hydroponic method that operates without electricity, pumps, or aerators, making it the only non-mechanical hydroponic system (Shrestha, Dunn 2017; Ballabh et al. 2022). Plants are typically grown in substrates such as coco coir, vermiculite, or perlite, with a wick connecting the growing medium to a nutrient reservoir. *Advantage:* Due to its simple design and low installation cost, the wick system is suitable for small-scale hydroponic production (Lee, Lee 2015; Ferrarezi, Testezlaf 2016).

https://doi.org/10.17221/132/2025-HORTSCI

Table 1 to be continued

Types of hydroponic systems	Description
Wick system	*Disadvantage:* Passive nutrient delivery limits their suitability for crops with high nutrient and water demands or extended growth cycles (Lee, Lee 2015). *Suitable plants:* Leafy greens, herbs, and strawberries.
Aeroponics	In aeroponics systems, plant roots are suspended within a closed chamber and nourished with a fine mist of nutrient-rich solution (Lee, Lee 2015; Li et al. 2018). This configuration provides an oxygen-rich root atmosphere with adjustable root-zone conditions, promoting rapid plant growth (Kratsch et al. 2006). Although used in research applications, aeroponics is less common in large-scale commercial production (Lee, Lee 2015; Resh 2022). *Advantage:* Aeroponic systems allow precise control of root-zone conditions and can improve nutrient use efficiency by maximising oxygen availability and nutrient absorption (Rajaseger et al. 2023). *Disadvantage:* Installation and maintenance costs are relatively higher, and system failure can rapidly damage crops (Lee, Lee 2015). Root desiccation is also a potential risk (Rajaseger et al. 2023). *Suitable plants:* Leafy greens, cucumbers, tomatoes, herbs, strawberries, potatoes, and flowers (Li et al. 2018; Rajaseger et al. 2023).

ronment agriculture reduces exposure to external contaminants, such as stormwater, soil, dust, and animals, microbial contamination within the system can still occur (Orozco et al. 2008). Potential contamination pathways include irrigation water, equipment surfaces, growth media, and human handling practices (FDA 2022a).

Among all potential contamination routes in a hydroponic system, water quality represents the most critical control point, as nutrient solutions directly contact plant roots. Treated municipal or desalinated tap water generally poses a lower risk of pathogen contamination. In contrast, untreated surface water, groundwater, and moderately treated reclaimed water can introduce contamination and increase public health risks (Park et al. 2012; Uyttendaele et al. 2015; Allende, Monaghan 2015; Gurtler, Gibson 2022). Therefore, hydroponic enterprises should prioritise water treatment and verification, comply with applicable rules and regulations, implement proper handling and sanitation procedures, and conduct continuous monitoring to safeguard consumer health (Llamas 2015).

POTENTIAL SOLUTIONS TO ENHANCE FOOD SAFETY IN HYDROPONICS

Ensuring microbial safety in hydroponic systems requires the adoption of multiple preventive and control strategies. One fundamental strategy involves implementing GAPs. These practices include training growers in effective sanitation, temperature control, and routine microbial monitoring (Schmit et al. 2020). Maintaining strict hygiene in hydroponic facilities helps mitigate pathogen risks to a manageable level (Vallance et al. 2009; Alsanius, Wohanka 2019). In addition to sanitation practices, biological approaches have been investigated as potential tools for mitigating microbial risk. For example, plant growth-promoting bacteria (PGPR) can suppress plant pathogens by competing for nutrients, producing antimicrobial compounds, and stimulating plant defence responses (Compant et al. 2005; Beneduzi et al. 2012; Velivelli et al. 2014). Although these biocontrol strategies have shown promise, their effectiveness may vary depending on environmental conditions and microbial community dynamics within the hydroponic system.

Water disinfection technologies represent another critical component of food safety management in hydroponic production. In hydroponics, nutrient solutions directly contact plant roots, necessitating water treatment to prevent the introduction and spread of pathogens. Heat treatment disinfects irrigation water by denaturing proteins and enzymes essential for microbial survival (Nastouli et al. 2022). The most common method for water disinfection is chlorine treatment (Rozman et al. 2022). The application of SaniDate 12.0 (200 ppm) in nutrient solutions effectively disinfects *Salmonella* Typhimurium in a hydroponic system (Mensah et al. 2024). Several additional water treatment methods are available, including peracetic acid

https://doi.org/10.17221/132/2025-HORTSCI

(CH_3CO_3H), electrolysed water, ozone, membrane filtration (MF/UF/RO), advanced oxidation (UV/H_2O_2, O_3/H_2O_2), and bio-, slow-sand, or GAC filters. However, recent research has shifted toward non-chemical, low-cost alternatives, such as ultraviolet (UV-C) irradiation, for safer water treatment in hydroponic systems.

UV-C provides rapid, broad-spectrum disinfection without introducing chemical residues. It also allows scalable, on-demand operation with relatively low operating and maintenance costs. Ultraviolet (UV) radiation is widely used to disinfect waterborne pathogens. Irradiation at 254 nm effectively inactivates a wide range of pathogens (Saguti et al. 2022). Studies have shown that UV radiation reduces *Salmonella enterica* contamination in lettuce (Lippman et al. 2020). Additionally, another study found that UV-C can prevent the attachment and growth of *L. monocytogenes* on lettuce leaves, making it a potential tool for enhancing food safety in the fresh produce industry (Kyere et al. 2021). Lee et al. (2015) reported that a UV-C dose of 1 440 mJ/cm^2 reduced algae and biofilm growth, ultimately extending the lifespan of hydroponic systems. However, Lehtola et al. (2003) reported that UV-C (254 nm) irradiation doses greater than 204 mJ per cm^2 can convert organic phosphate into a form readily available to microbes, potentially leading to regrowth. Nutrient solutions treated with UV-C at a dose of 1.32 mJ/cm^2 for a longer time significantly reduced *L. monocytogenes* (Mendoza et al. 2025). Nevertheless, the effectiveness of UV-C treatment in a hydroponic system is influenced by water quality during crop production. Moore et al. (2025) reported that as nutrients and microorganisms accumulated over time in the hydroponic system, water turbidity increased, reducing UV-C transmission and disinfection effectiveness. Collectively, the evidence indicates that although UV-C is effective, its performance is strongly influenced by turbidity and applied dose.

CONCLUSION

Hydroponic production systems offer significant advantages in resource efficiency and controlled cultivation; however, they are not inherently free from microbiological risks. Contamination may arise from multiple sources within recirculating hydroponic systems, emphasising the need for targeted risk management strategies. Among available mitigation approaches, UV-C irradiation represents a promising non-chemical intervention for reducing microbial loads in nutrient solutions. Nevertheless, treatment efficacy depends on operational parameters such as turbidity and applied dose. Despite increasing research attention, many intervention studies have been conducted under controlled laboratory or pilot-scale conditions, which may not fully reflect the variability and operational complexity of commercial hydroponic systems. Future research should focus on optimising disinfection protocols under commercial-scale conditions and on integrating multi-barrier safety strategies to ensure safe and sustainable hydroponic production.

Acknowledgement: This review is based on a literature synthesis conducted as part of the author's MS Report (Adhikari 2025).

REFERENCES

Adelmann T. (2023): The hydroponic drip system – Structure, components, advantages and disadvantages. Available at: https://hydroplanner.com/blog/hydroponics-drip-system-EN

Adhikari S. (2025): Evaluate the Postharvest Quality of Romaine Lettuce Grown in a UV-treated Hydroponic System. [MS Report.] Olathe, Kansas State University.

Aires L., Ispolnov K., Luz T.R., Pala H., Vieira J.S. (2023): Optimization of an indoor DWC hydroponic lettuce production system to generate a low N and P content wastewater. Processes, 11: 365.

Allende A., Monaghan J. (2015): Irrigation water quality for leafy crops: A perspective of risks and potential solutions. International Journal of Environmental Research and Public Health, 12: 7457–7477.

Alsanius B.W., Wohanka W. (2019): Root zone microbiology of soilless cropping systems. In: Soilless Culture : Theory and Practice. 2nd Ed. Academic Press: 149–194.

Ballabh J., Nautiyal M., Joshi R., Singh M., Jain G., Saini N. (2022): Hydroponics: An overview of advanced growing approaches. Journal of Survey in Fisheries Sciences, 8: 306–310.

Beneduzi A., Ambrosini A., Passaglia L.M.P. (2012): Plant growth-promoting rhizobacteria (PGPR): Their potential as antagonists and biocontrol agents. Genetics and Molecular Biology, 35: 1044–1051.

Bennett S.D., Sodha S.V., Ayers T.L., Lynch M.F., Gould L.H., Tauxe R.V. (2018): Produce-associated foodborne

disease outbreaks, USA, 1998–2013. Epidemiology and Infection, 146: 1397–1406.

Buwalda F., Baas R., Van Weel P.A. (1993): A soilless ebb-and-flow system for all-year-round chrysanthemums. International Symposium on New Cultivation Systems in Greenhouse, ISHS Acta Horticulturae, 361: 123–132.

Coelho F.C., Coelho E.M., Egerer M. (2018): Local food: Benefits and failings due to modern agriculture. Scientia Agricola, 75: 84–94.

Compant S., Duffy B., Nowak J., Clément C., Barka E.A. (2005): Use of plant growth-promoting bacteria for biocontrol of plant diseases: Principles, mechanisms of action, and future prospects. Applied and Environmental Microbiology, 71: 4951–4959.

Coulombe G., Catford A., Martinez-Perez A., Buenaventura E. (2020): Outbreaks of *Escherichia coli* O157:H7 infections linked to romaine lettuce in Canada from 2008 to 2018: An analysis of food safety context. Journal of Food Protection, 83: 1444–1462.

Domingues D.S., Takahashi H.W., Camara C.A.P., Nixdorf S.L. (2012): Automated system developed to control pH and concentration of nutrient solution evaluated in hydroponic lettuce production. Computers and Electronics in Agriculture, 84: 53–61.

Dong C.Y., Li Q., Wang L., Shang Q. (2020): Dynamic changes in bacterial communities in the recirculating nutrient solution of cucumber plug seedlings cultivated in an ebb-and-flow subirrigation system. PLoS ONE, 15: e0232446.

Dong M., Feng H. (2022): Microbial community analysis and food safety practice survey-based hazard identification and risk assessment for controlled environment hydroponic/aquaponic farming systems. Frontiers in Microbiology, 13: 879260.

Dorick J., Kumar G.D., Macarisin D., Widmer J.A., Stivers T., Dunn L.L. (2024): Longitudinal survey of aeromonas hydrophila and foodborne pathogens in a commercial aquaponics system. Journal of Food Protection, 87: 100230.

Douglas J.S. (1975): Hydroponics. Bombay, Oxford: 1–3.

Ferrarezi R.S., Testezlaf R. (2016): Performance of wick irrigation system using self-compensating troughs with substrates for lettuce production. Journal of Plant Nutrition, 39: 147–161.

FDA (2022a): Investigation Report: Factors Potentially Contributing to the Contamination of Packaged Leafy Greens Implicated in the Outbreak of *Salmonella* Typhimurium During the Summer of 2021. Available at https://www.fda.gov/media/155402/download

FDA (2022b): Outbreak Investigation of *E. coli* - Leafy Greens. Available at https://www.fda.gov/food/outbreaks-foodborne-illness/outbreak-investigation-e-coli-leafy-greens-december-2020

Forster T., Santini G., Edwards D., Flanagan K., Taguchi M. (2015): Strengthening urban rural linkages through city region food systems. Regional Development Dialogue, 35: 1–19.

Goldstein B., Hauschild M., Fernández J., Birkved M. (2016): Urban versus conventional agriculture, taxonomy of resource profiles: A review. Agronomy for Sustainable Development, 36: 1–19.

Goto N., Bazar G., Kovacs Z., Kunisada M., Morita H., Kizaki S., Sugiyama H., Tsenkova R., Nishigori C. (2015): Detection of UV-induced cyclobutane pyrimidine dimers by near-infrared spectroscopy and aquaphotomics. Scientific Reports, 5: 11808.

Grigas A., Kemzūraitė A., Steponavičius D. (2020): Hydroponic devices for green fodder production: A Review. Rural Development, 2019: 21–27.

Gulyas B.Z., Edmondson J.L. (2021): Increasing city resilience through urban agriculture: Challenges and solutions in the global north. Sustainability, 13: 1465.

Gurtler J.B., Gibson K.E. (2022): Irrigation water and contamination of fresh produce with bacterial foodborne pathogens. Current Opinion in Food Science, 47: 100889.

Huang R., de Vries D., Chen H. (2018): Strategies to enhance fresh produce decontamination using combined treatments of ultraviolet, washing and disinfectants. International Journal of Food Microbiology, 283: 37–44.

Hunter M.C., Smith R.G., Schipanski M.E., Atwood L.W., Mortensen D.A. (2017): Agriculture in 2050: Recalibrating targets for sustainable intensification. BioScience, 67: 386–391.

Ilic S., Moodispaw M.R., Madden L.V., Lewis Ivey M.L. (2022): Lettuce contamination and survival of *Salmonella* Typhimurium and *Listeria monocytogenes* in hydroponic nutrient film technique systems. Foods, 11: 3508.

Ivey M.L.L., Mensah A.A., Diekmann F., Ilic S. (2025): Food safety in hydroponic food crop production: A review of intervention studies to control human pathogens. Foods, 14: 2308.

Jan S., Rashid Z., Ahngar T.A., Iqbal S., Naikoo M.A., Majeed S., Bhat T.A., Gul R., Nazir I. (2020): Hydroponics – A review. International Journal of Current Microbiology and Applied Sciences, 9: 1779–1787.

Jaramillo F., Destouni G. (2015): Comment on "Planetary boundaries: Guiding human development on a changing planet." Science, 348: 1217.

Jones A. (2002): An environmental assessment of food supply chains: a case study on dessert apples. Environmental Management, 30: 560–576.

Kamarasu P., McLandsborough L., Moore M.D., Kinchla A.J. (2025): Evaluating the potential for contamination of leafy greens with *Listeria* when using retrofitted washing machines. Npj Science of Food, 9: 126.

https://doi.org/10.17221/132/2025-HORTSCI

Khan S., Purohit A., Vadsaria N. (2020): Hydroponics: Current and future state of the art in farming. Journal of Plant Nutrition, 44: 1515–1538.

Kratsch H.A., Graves W.R., Gladon R.J. (2006): Aeroponic system for control of root-zone atmosphere. Environmental and Experimental Botany, 55: 70–76.

Kumar V., Singh J. (2023): Trends in hydroponics practice/technology in horticultural crops: A review. International Journal of Plant and Soil Science, 35: 57–65.

Kyere E.O., Popovich D.G., Palmer J., Wargent J.J., Fletcher G.C., Flint S. (2021): Reduction of the attachment, survival and growth of *L. monocytogenes* on lettuce leaves by UV-C stress. LWT, 145: 111528.

Lee S., Lee J. (2015): Beneficial bacteria and fungi in hydroponic systems: Types and characteristics of hydroponic food production methods. Scientia Horticulturae, 195: 206–215.

Lee S., Ge C., Bohrerova Z., Grewal P.S., Lee J. (2015): Enhancing plant productivity while suppressing biofilm growth in a windowfarm system using beneficial bacteria and ultraviolet irradiation. Canadian Journal of Microbiology, 61: 457–466.

Lehtola M.J., Miettinen I.T., Vartiainen T., Rantakokko P., Hirvonen A., Martikainen P.J. (2003): Impact of UV disinfection on microbially available phosphorus, organic carbon, and microbial growth in drinking water. Water Research, 37: 1064–1070.

Lenka S., Lenka N.K., Sejian V., Mohanty M. (2015): Contribution of agriculture sector to climate change. In: Climate Change Impact on Livestock: Adaptation and Mitigation. Springer: 37–48.

Li Q., Li X., Tang B., Gu M. (2018): Growth responses and root characteristics of lettuce grown in aeroponics, hydroponics, and substrate culture. Horticulturae, 4: 35.

Lippman B., Yao S., Huang R., Chen H. (2020): Evaluation of the combined treatment of ultraviolet light and peracetic acid as an alternative to chlorine washing for lettuce decontamination. International Journal of Food Microbiology, 323: 108590.

Llamas K. (2015): Bacterial assessment on leaves of green vegetable grown on hydroponics and its possible health risks. Journal of Agriculture and Environmental Sciences, 4: 1–7.

Macwan J., Pandya D., Pandya H., Mankad A. (2020): Review on soilless method of cultivation: Hydroponics. International Journal of Recent Scientific Research, 11: 37122–37127.

Matacena R. (2016): Linking alternative food networks and urban food policy: A step forward in the transition towards a sustainable and equitable food system. International Review of Social Research, 6: 49–58.

Mendoza J., Lituma I., Fontenot K., Adhikari A. (2025): Effect of pH, nutrient composition, and UV-C light treatment on *Listeria monocytogenes* in hydroponic nutrient solutions. Journal of Food Protection, 88: 100632.

Mensah A.A., Ivey M.L.L., Moodispaw M.R., Ilić S. (2024): Effectiveness of chemical sanitizers against *Salmonella* Typhimurium in Nutrient Film Technique (NFT) hydroponic systems: Implications for food safety, crop quality, and nutrient content in leafy greens. Foods, 13: 1929.

Miyake N., Nagai H., Kageyama K. (2014): Wilt and root rot of poinsettia caused by three high-temperature-tolerant *Pythium* species in ebb-and-flow irrigation systems. Journal of General Plant Pathology, 80: 479–489.

Moore M., Yang T., Douraki M.J., Rivard C., Pliakoni E., Nwadike L., Bhullar M. (2025): Effect of ultraviolet water treatment on survival and growth of *Escherichia coli* in recirculating hydroponic systems. Journal of Food Protection, 88: 100575.

Murali M.R., Soundaria M., Maheswari V., Santhakumari P., Gopal V. (2011): Hydroponics. A novel alternative for geoponic cultivation of medicinal plants and food crops. International Journal of Pharmacology and Biology Sciences, 2: 286–296.

Nastouli A., Tsirigka A., Harasek M., Karabelas A.J., Patsios S.I. (2022): The effect of heat sterilization on key filtration performance parameters of a commercial polymeric (PVDF) hollow-fiber ultrafiltration membrane. Membranes, 12: 725.

Niu G., Masabni J. (2022): Hydroponics. Chapter 9. In: Kozai T., Niu G., Masabni J. (eds.): Plant Factory Basics, Applications and Advances. Academic Press: 153–166.

Orozco L., Rico-Romero L., Escartín E.F. (2008): Microbiological profile of greenhouses in a farm producing hydroponic tomatoes. Journal of Food Protection, 71: 60–65.

Park S., Szonyi B., Gautam R., Nightingale K., Anciso J., Ivanek R. (2012): Risk factors for microbial contamination in fruits and vegetables at the preharvest level: A systematic review. Journal of Food Protection, 75: 2055–2081.

Prosekov A.Y., Ivanova S.A. (2018): Food security: The challenge of the present. Geoforum, 91: 73–77.

Rajaseger G., Chan K.L., Tan K.Y., Ramasamy S., Khin M.C., Amaladoss A., Haribhai P.K. (2023): Hydroponics: Current trends in sustainable crop production. Bioinformation, 19: 925.

Resh H. M. (2022): Hydroponic Food Production: A Definitive Guidebook for the Advanced Home Gardener and the Commercial Hydroponic Grower. 8th Ed. Boca Raton, CRC Press.

Rouphael Y., Colla G. (2005): Growth, yield, fruit quality and nutrient uptake of hydroponically cultivated zucchini squash as affected by irrigation systems and growing seasons. Scientia Horticulturae, 105: 177–195.

Rozman U., Uranjek N., Turk S.Š. (2022): Optimisation of chlorine disinfection in drinkingwater supply network. Sanitarno Inženirstvo International Journal of Sanitary Engineering Research, 15: 19–30.

Saguti F., Churqui M.P., Kjellberg I., Wang H., Ottoson J., Paul C.J., Bergstedt O., Nordér H., Nyström K. (2022): The UV dose used for disinfection of drinking water in Sweden inadequately inactivates enteric virus with double-stranded genomes. International Journal of Environmental Research and Public Health, 19: 8669.

Sardare M.D., Admane S.V. (2013): A review on plant without soil-hydroponics. International Journal of Research in Engineering and Technology, 2: 299–304.

Savvas D. (2003): Hydroponics: A modern technology supporting the application of integrated crop management in greenhouse. Journal of Food, Agriculture & Environment, 1: 80–86.

Schmit T.M., Wall G.L., Newbold E.J., Bihn E.A. (2020): Assessing the costs and returns of on-farm food safety improvements: A survey of Good Agricultural Practices (GAPs) training participants. PLoS ONE, 15: e0235507.

Sela Saldinger S., Rodov V., Kenigsbuch D., Bar-Tal A. (2023): Hydroponic agriculture and microbial safety of vegetables: Promises, challenges, and solutions. Horticulturae, 9: 51.

Shrestha A., Dunn B. (2017): Hydroponics. Stillwater, Oklahoma State University.

Singh H., Dunn B.L., Payton M., Brandenberger L. (2019): Selection of fertilizer and cultivar of sweet pepper and eggplant for hydroponic production. Agronomy, 9: 433.

Taban B.M., Halkman A.K. (2011): Do leafy green vegetables and their ready-to-eat [RTE] salads carry a risk of foodborne pathogens? Anaerobe, 17: 286–287.

Talib M.H., Rahman K.A.A.A., Dollah M.S. (2018): Analyzing hydroponic rack design for apartment house. International Journal of Engineering and Technology, 7: 128.

Topalcengiz Z., Chandran S., Gibson K.E. (2024): A comprehensive examination of microbial hazards and risks during indoor soilless leafy green production. International Journal of Food Microbiology, 411: 110546.

UN DESA (2018): 68% of the world population projected to live in urban areas by 2050, says UN. Department of Economic and Social Affairs. Available at https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html

United Nations Department of Economic and Social Affairs (2024): World Population Prospects 2024: Summary of Results. UN.

Uyttendaele M., Jaykus L.A., Amoah P., Chiodini A., Cunliffe D., Jacxsens L., Holvoet K., Korsten L., Lau M., McClure P., Medema G., Sampers I., Rao Jasti P. (2015): Microbial hazards in irrigation water: Standards, norms, and testing to manage use of water in fresh produce primary production. Comprehensive Reviews in Food Science and Food Safety, 14: 336–356.

Vallance J., Déniel F., Floch G., Le Guérin-Dubrana L., Blancard D., Rey P. (2009): Pathogenic and beneficial microorganisms in soilless cultures. In: Lichtfouse E., Hamelin M., Navarrete M., Debaeke P. (eds): Sustainable Agriculture. Vol. 2, Dordrecht, Springer: 711–726.

Velivelli S.L. S., Sessitsch A., Prestwich B.D. (2014): The role of microbial inoculants in integrated crop management systems. Potato Research, 57: 291–309.

Viazis S., Bazaco M.C., Blessington T., Seelman Federman S.L., Lindsay M., Minor T., Nork B., Mattioli M.C., Marshall K.E., Wise M.E., Weed B., Haendiges J., Gieraltowski L., Nolte K. (2025): An overview of farm investigation findings associated with outbreaks of shiga toxin-producing *Escherichia coli* infections linked to leafy greens: 2009–2021. Journal of Food Protection, 88: 100542.

Vieira L.C., Serrao-Neumann S., Howes M., Mackey B. (2018): Unpacking components of sustainable and resilient urban food systems. Journal of Cleaner Production, 200: 318–330.

Wang L., Anna H., Zhang L., Xiao Y., Wang Y., Xiao Y., Liu J., Ouyang Z. (2019): Spatial and temporal changes of arable land driven by urbanization and ecological restoration in China. Chinese Geographical Science, 29: 809–819.

Warrington I. (2019): Horticultural Reviews. John Wiley & Sons, Inc.

Webb N.P., Marshall N., Stringer L.C., Reed M.S., Chappell A., Herrick J.E. (2017): Land degradation and climate change: Building climate resilience in agriculture. Frontiers in Ecology and the Environment, 15: 450–459.

Weidner T., Yang A., Hamm M.W. (2019): Consolidating the current knowledge on urban agriculture in productive urban food systems: Learnings, gaps and outlook. Journal of Cleaner Production, 209: 1637–1655.

Yuan G.N., Marquez G.P.B., Deng H., Iu A., Fabella M., Salonga R.B., Ashardiono F., Cartagena J.A. (2022): A review on urban agriculture: Technology, socio-economy, and policy. Heliyon, 8: e11583.

Received: December 1, 2025
Accepted: May 12, 2026
Published online: October 16, 2026