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REVIEW PAPER

Fresh vegetables as a source of *Escherichia coli* bacteria and application methods limiting the occurrence of microbial contamination*

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Abstract

Growing consumer awareness of the health aspects of a diet has contributed to greater consumption of vegetables. However, vegetables, particularly leafy greens, are often consumed raw or undergo minimal processing, which may not adequately eliminate microbial contaminants. Therefore, vegetables can become a source of infection and transmit foodborne pathogens causing food poisoning in humans. Among these microorganisms, *Escherichia coli* is of particular concern because it possesses various mechanisms that enable it to colonize plant surfaces and tissues and persist in the vegetable production chain. To prevent microbial contamination, the microbiological quality of raw materials must be safeguarded during primary production. It is essential to maintain appropriate sanitary conditions and cultivation practices during the primary production of vegetables in order to avoid microbiological contamination and ensure high quality of raw material. The aim of this study was to review the current state of knowledge regarding the prevalence of *E. coli* in vegetables. Attention is paid to sources of the contamination during cultivation and also to mechanisms by which these bacteria adapt to colonize plants. Pre- and postharvest control methods are demonstrated, e.g. organic acid sanitation, lactic acid bacteria application or sonication. These methods are included in the One Health approach, which recognizes the interconnectedness of human, animal, plant, and environmental health and provides an integrated framework for addressing complex challenges such as climate change, food security, and infectious diseases. The scientific relevance and novelty of the work lie in its multifaceted approach to the survival of *E. coli* bacteria on vegetables, taking into account the influence of atmospheric, agronomic and environmental factors in the context of sustainable agriculture, where food safety is a priority.

Keywords: food safety, primary production, good agricultural practices, lactic acid bacteria, leafy vegetables

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INTRODUCTION

Vegetables make up a major portion of the human diet in many parts of the world and play a significant role in human nutrition, especially as sources of phytonutriceuticals: vitamins, minerals, dietary fiber and phytochemicals. Some phytochemicals of vegetables are strong antioxidants and are thought to reduce the risk of chronic disease by protecting against free-radical damage, modifying metabolic activation and detoxification of carcinogens, or even modulating processes involved in tumor cell growth. Vegetables in the daily diet have been strongly associated with overall good health, improvement of gastrointestinal health and vision, reduced risk of some forms of cancer, heart disease, stroke, diabetes, anemia, gastric ulcer, rheumatoid arthritis, and other chronic diseases. A vegetable-rich diet has been associated with lower risk of cardiovascular disease in humans (Ali et al. 2025).Vegetable industry, especially ready-to-eat fresh vegetables, has experienced considerable growing demand as consumer preferences are evolving toward more convenient and healthy food options. This increasing consumption is associated with a rise in foodborne outbreaks because microbial contamination may occur at any point along the fresh produce chain (production, harvesting, processing, etc.). Figure 1 demonstrates the main routes of *E. coli* transmission from environmental sources during primary production of vegetables.

During the past decade, foodborne outbreaks have been associated with fresh produce contaminated with *E. coli*. This is in part because of increased consumption of potentially more risky, fresh cut prepackaged products (Habib et al. 2023, Alhadlaq et al. 2024, Alegbeleye et al. 2025, Jaroni et al. 2025, Rood et al. 2025, Zahra et al. 2025).

The aim of this review is to present the current information about *E. coli* contamination of vegetables and show that vegetables can be colonized by the bacteria during primary production. Additionally, methods for reducing the contamination using environmentally friendly methods are presented. Major knowledge gaps to guide future research efforts were also identified.

METHODS

This review was based on scientific articles published between 2013 and 2026 and identified through searches of the ScienceDirect, Scopus, and Web of Science databases using the following keywords: microbial contamination of vegetables, food safety, and *Escherichia coli*.

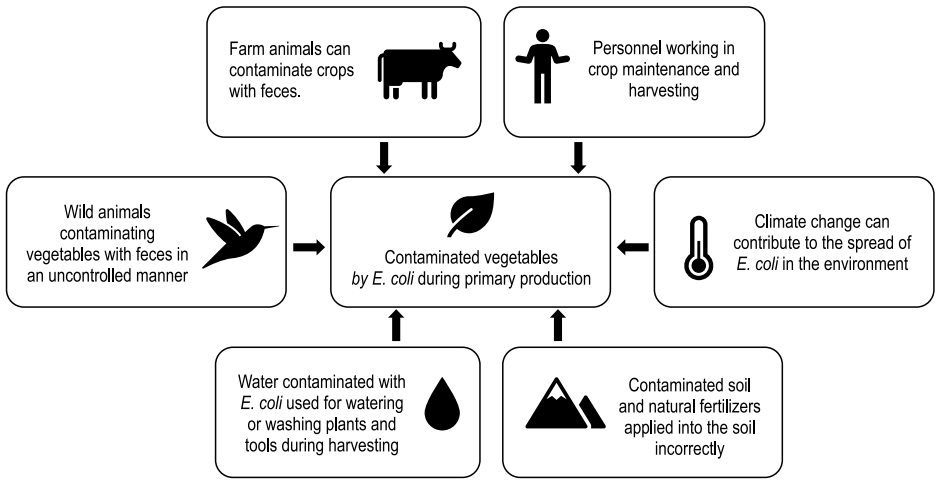


Fig. 1. Multiple routes of *E. coli* transmission from different environmental sources during primary production of vegetables

E. coli characteristics in the context of vegetable contamination

E. coli bacteria are classified as Gram-negative, facultatively anaerobic, non-spore-forming bacilli within the *Enterobacteriaceae* family. These microorganisms exhibit relatively low tolerance to adverse environmental conditions, with thermal inactivation occurring after 20 min of exposure to 60°C. Their optimal growth temperature is approximately 37°C, an evolutionary adaptation to their primary ecological niche – the gastrointestinal tracts of humans and animals. Although *E. coli* bacteria occur naturally in the digestive tract, certain strains possess pathogenic potential. Pathogenic strains have been frequently implicated in foodborne illness outbreaks. In 2011, Germany experienced the world's most extensive food poisoning outbreak caused by *E. coli* O104:H4, which involved 14 European nations, the United States, and Canada, resulting in 4,321 confirmed clinical cases and 54 recorded fatalities (Karch et al. 2012).

The emergence of drug-resistant *E. coli* represents a critical public health challenge, as such infections necessitate prolonged hospital stays and exert both direct and indirect economic strain on populations and healthcare infrastructures. Recent literature indicates that *E. coli* isolates recovered from vegetable produce demonstrate marked resistance to various antimicrobial agents (Ratshilingano et al. 2022, Habib et al. 2023, Zahra et al. 2025). Zahra et al. (2025) performed antibiotic susceptibility testing on 1,206 *E. coli* isolates sourced from vegetables, processing water, and vendor environments. The results revealed widespread resistance, particularly to ampicillin and erythromycin, while also identifying significant seasonal variations in the resistance profiles of vegetable samples. Similarly, Ratshilingano et al. (2022) documented that 33 out of 51 *E. coli* isolates obtained from leafy greens exhibited multidrug resistance to agents including neomycin, ampi-

cillin, amoxicillin, and tetracycline. The proliferation of antibiotic-resistant *E. coli* throughout the food chain may lead to clinical infections that are increasingly difficult to manage, thereby escalating treatment costs and burdening healthcare systems. Current research highlights the potential for the dissemination of antimicrobial resistance and associated resistance genes through the consumption of contaminated vegetables (Habib et al. 2023).

E. coli surviving in soil

While the presence of *E. coli* is primarily recognized as a fundamental parameter for assessing water quality, it is increasingly utilized as a critical indicator of soil sanitation. Detection of *E. coli* in soil samples serves as a marker of relatively recent contamination by human or animal waste, sewage, or biosolids. The environmental persistence of *E. coli* depends on several abiotic factors, including temperature, moisture content, pH, and nutrient availability. Under conditions of high humidity and temp. below 25°C, these bacteria can survive in the soil for up to 80 days and may persist on crops such as lettuce and radishes for over 20 days (Yao et al. 2015, Thomas et al. 2024, Wójcik-Fatla et al. 2024).

Soil can become heavily contaminated with bacterial pathogens introduced via irrigation water or the feces of wild fauna. The application of side-dressing, even when utilizing treated biological soil amendments, may extend the longevity of these introduced foodborne pathogens and consequently elevate the risk of crop contamination (Xiong et al. 2025). *E. coli* introduced through composted manure or poultry litter can remain detectable for up to 200 days post-application, with persistence in associated vegetable crops extending up to 177 days. Improper management of natural and organic fertilizers, as well as sewage sludge, can lead to significant soil contamination, thereby potentially exposing consumers to health risks through the ingestion of raw vegetables (Hartmann et al. 2017, Kłapeć et al. 2024, Wójcik-Fatla et al. 2024, Yang et al. 2025). Biological soil amendments provide niches for the survival of externally introduced pathogens. For instance, side-dressing with heat-treated poultry pellets, seabird guano, or corn steep liquor in organic romaine lettuce production has been shown to support the persistence of *E. coli* in the soil and its subsequent transfer to the plant tissues (Xiong et al. 2025).

Furthermore, vermicompost derived from various animal sources provides a conducive environment for *E. coli* persistence, allowing the pathogen to survive for at least 28 days. These pathogens can subsequently be transferred into plants. Investigations into baby greens and other leafy vegetables grown in vermicompost-supplemented substrates suggest these may serve as vectors for pathogen transfer, necessitating further inquiry. The increased risk associated with microgreen production underscores the need for stringent precautions when applying such fertilizers (Işik et al. 2025). Yao et al. (2015) demonstrated that *E. coli* survival fluctuates significantly following

the application of organic fertilizers. The time required to reach a detection limit of 100 cfu g^{-1} ranged from 12.57 days in soil amended with poultry manure to 25.65 days in soil amended with porcine manure.

In a comparative study of microbiological contamination between organic and conventional farming systems, Szczech et al. (2018) identified *E. coli* in crops of lettuce, radish, carrot, and beetroot. The prevalence of the bacteria was significantly higher in organic compared to conventional systems. This disparity is attributed to the frequent use of animal-based fertilizers in organic production, which act as a primary reservoir of pathogenic bacteria. These findings highlight the necessity for stringent sanitary protocols regarding the application of natural fertilizers of animal origin, particularly in organic agriculture, where the use of synthetic chemical agents is limited.

E. coli bacteria contaminating leafy vegetables

Leafy greens serve as a significant dietary source of fiber, essential vitamins, minerals, and natural antioxidants. Despite these nutritional benefits, leafy vegetables are consistently implicated in foodborne illness outbreaks and are categorized as high-risk commodities. This increased risk is primarily attributable to the frequent consumption of these products raw, which eliminates the opportunity to reduce microbiological hazards through thermal processing. Epidemiological data from 2010 to 2020 identify 132 foodborne outbreaks linked to vegetable consumption, with leafy greens accounting for 68.9% of these incidents. These 91 specific outbreaks resulted in 2,416 clinical cases, 380 hospitalizations, and 7 deaths (CDC 2022).

In open-field cultivation, leafy vegetables are highly susceptible to contamination from different sources, including soil, irrigation water, airborne pathogens, and wildlife. Their high surface-area-to-volume ratio provides extensive attachment sites for bacterial pathogens. Following initial contamination, *E. coli* can persist on the phyllosphere through the formation of protective biofilms and may proliferate rapidly in damaged or injured plant tissues (Thomas et al. 2024, Rood et al. 2025).

Research by George et al. (2024) indicates that lettuce cultivars exhibit differential susceptibility to *E. coli* colonization and surface survival. In an analysis of 31 cultivars, those possessing robust basal immunity against common phytopathogens and insect herbivores demonstrated significantly lower *E. coli* survival rates on wounded tissues under cold stress. Furthermore, specific defensive traits – such as elevated levels of phenolic compounds (including anthocyanins) coupled with high phenylalanine ammonia-lyase and peroxidase activity – were strongly correlated with the inhibition of *E. coli*. Despite these findings, plant breeding programs have not yet prioritized traits that limit the colonization of human enteric pathogens. Evidence further suggests that domesticated leafy vegetables may provide a more conducive environment for harmful bacteria than their wild relatives (Lenzi et al. 2022). Additionally, the translocation of *E. coli* from contaminated

seeds to the foliage has been confirmed over a 30-day growth period. Standard washing procedures have proven ineffective at reducing the pathogen load on leaf tissues, indicating that the bacteria are sequestered or tightly bound to the plant architecture (Samut et al. 2023, Mina, Deering 2026).

Transfer of bacteria

The transmission of foodborne pathogens to leafy vegetables can occur via contaminated soilless substrates, seeds, irrigation water, nutrient solutions, or agricultural equipment at any stage of the pre-harvest phase. Materials that support the survival or proliferation of these microorganisms pose a significant risk of contaminating the edible portions of the plant during production (Ratshilingano et al. 2022, Thomas et al. 2024, Mina, Deering 2026).

E. coli can be transferred from contaminated seeds to microgreens, persisting in the edible tissues until harvest. Contaminated seed lots are frequently identified as the primary vector in sprout-related outbreaks and microgreen-associated product recalls. Furthermore, pathogens originating from seeds can migrate to the growth media or soil, potentially compromising subsequent production cycles. A consistent trend was observed across daikon, red cabbage, mustard, and broccoli microgreens, where pathogen persistence generally declined by the 14th day of growth (Rao et al. 2025).

Research by Ratshilingano et al. (2022) further underscores the critical role of irrigation water in the potential transmission of human pathogens, including *E. coli*, to leafy vegetables intended for raw consumption. This transmission pathway represents a substantial health risk to the consumer. Consequently, the implementation of rigorous pre-harvest controls – specifically seed sanitation protocols and stringently managed irrigation water systems – is essential for mitigating the risk of microbial contamination during the cultivation process.

Internalization of *E. coli* bacteria in plant tissues

The internalization of *E. coli* into edible plant tissues has been documented in various crops, including spinach and lettuce, particularly when introduced via contaminated irrigation water. The initial attachment of *E. coli* to plant surfaces is governed by a combination of electrostatic interactions, hydrogen bonding, and surface wettability, alongside the specific hydrophobicity and surface charge of the bacteria. Generally, colonization occurs more frequently on the abaxial leaf surfaces. This preference is attributed to a higher density of stomata and trichomes, as well as a thinner epicuticular wax layer, all of which facilitate bacterial adhesion (Hartmann et al. 2017, Dong et al. 2024). Conversely, the periderm layer acts as a natural barrier to entry, highlighting the critical importance of minimizing physical damage during harvest and post-harvest handling to mitigate the risk of internal contamination.

The ability of certain *E. coli* strains to synthesize robust biofilms significantly enhances their environmental persistence. These biofilms serve as a primary mechanism for resistance against quaternary ammonium compounds and contribute to a high tolerance for gastric fluids. Biofilm formation is considered a decisive factor in the recurrence of specific outbreak strains. Strains characterized by elevated production of curli and cellulose develop denser biofilms, exhibiting prolonged resistance to chemical sanitizers compared to reference strains (Yang et al. 2025).

Vegetables harvested as baby leaves are particularly vulnerable to *E. coli* contamination. Attachment to the phyllosphere represents the initial stage of contamination, which may progress to internalization if decontamination measures are not applied promptly. Leaf morphology – specifically vein structure, stomatal density and size, trichome presence, and surface roughness – plays a key role in this process. Research indicates a positive correlation between *E. coli* persistence and both stomatal density and leaf roughness. Furthermore, increased leaf roughness has been shown to reduce the efficacy of UV treatments in neutralizing attached bacteria (Truschi et al. 2023).

Laboratory investigations using lettuce models demonstrated that *E. coli* progressively migrates toward and into the stomata over time, typically reaching peak occupation within 72 hours. This migratory process is significantly accelerated at a storage temp. of 25°C compared to 4°C, as evidenced by higher fluorescence intensity within stomatal cavities. At 4°C, the presence of *E. coli* induces an upregulation of antioxidant enzymes in the lettuce while accelerating the degradation of total phenols and soluble sugars. In contrast, samples inoculated and stored at 25°C exhibited rapid qualitative deterioration, characterized by visible yellowing and rot (Xie et al. 2025).

The chemical reaction of plant tissues to colonization by *E. coli*

When a plant detects pathogens via its pattern-recognition receptors, it undergoes an oxidative burst and synthesizes defensive chemical compounds to kill the bacteria. The plant rapidly generates Reactive Oxygen Species, that is chemical oxidants like hydrogen peroxide, superoxide radicals, and hydroxyl radicals to damage bacterial cell walls. In some cases, increased production of phenolic compounds, e.g. polyphenols, chlorogenic acid, caffeic acid, and salicylic acid, is recorded. Moreover, phytoalexins such as sulphur-rich compounds and terpenoids are upregulated to disrupt bacterial metabolic pathways (Kaur et al. 2022). The situation is similar when a plant detects *E. coli* contamination. A study conducted by Hudson et al. (2026) demonstrated that secondary metabolites in the lettuce plant can be significant components of the plant's response to *E. coli* contamination. The phenolic response is complex, closely linked to the plant immune response, and plays a direct or indirect role in modulating the bacterial population in lettuce. In model experiments, inoculation of pre-harvest leaves with *E. coli* caused

changes in phenolic levels, which in turn reduced the number of *E. coli* in the apoplast (Hudson et al. 2026).

Using spinach and rocket leaf lysates as a proxy for baby leaves, researchers obtained empirical evidence showing that it was possible to use volatile profiles to discriminate between sterile and *E. coli* contaminated samples. Emission of the volatile compounds: indole, phenylmethanol, 2-methoxyphenol, ethanol, propan-1-ol, decan-1-ol, tridecan-1-ol, nonan-2-one and tridecan-2-one, contributed most to the separation between *E. coli* contaminated and non-contaminated samples (Sousa et al. 2023).

Understanding molecular, chemical, and morphological traits that influence the differential survival of human pathogenic bacteria in the phyllosphere is critical for integrating plant-based approaches into food safety strategies. Resident phyllosphere microbiota can modulate chemical profiles during plant-microbe interactions. It was observed that the overall leaf surface and apoplast metabolite landscape varies substantially across lettuce types and cultivars, including differences in sugars, amino acids, pigments, and vitamins. *E coli* triggers lettuce immune responses, such as ROS burst and callose deposition, which may also reshape the chemical environment. The chemical environment of the phylloplane and leaf apoplast contributes to the differential persistence of *E. coli* among lettuce genotypes (Bridges et al. 2026).

The effect of temperature and humidity on the *E. coli* survival

Temperature serves as a primary determinant for the viability and proliferation of *E. coli* on plant surfaces. The species exhibits peak metabolic activity at 37°C, facilitating rapid multiplication and an increased risk of clinical infection. Conversely, lower temperatures induce deceleration of metabolic processes, thereby reducing survival rates. Consequently, refrigeration remains a highly effective intervention for suppressing the growth of *E. coli* on both processed foods and fresh produce (Samut et al. 2023, Awad et al. 2024).

The susceptibility of leafy greens to colonization by *E. coli* O157:H7 is significantly influenced by thermal conditions. At the optimal growth temperature of 37°C, population increases were most pronounced on kale, followed by spinach, romaine lettuce, and green leaf surfaces (Khalil, Frank 2010). On fresh-cut red cabbage, the dynamics of *E. coli* were strictly temperature-dependent; the pathogen exhibited no growth at 4°C or 8°C, yet increased by up to 2.2 log CFU g^{-1} within seven days when stored at 12°C. No significant differences were observed between sanitizing treatments, such as application of chlorine or peracetic acid and water washes, reinforcing the conclusion that temperature management is more critical than chemical disinfection in controlling microbial dynamics (Amarasekara et al. 2026).

Environmental humidity also affects the survival potential of *E. coli*. High humidity levels provide the needed moisture for bacterial maintenance,

whereas arid conditions induce cellular dehydration and eventual death. Controlling humidity during vegetable storage, particularly in areas susceptible to contamination, is a vital strategy for reducing pathogen persistence. Kwon et al. (2025) demonstrated that elevated humidity in potato storage facilities increases the risk of colonization, specifically in the presence of micro-fractures or bruising sustained during harvest or handling, which serve as entry points for internalization. Due to the bulk storage nature of potatoes and other crops like strawberries or berries, a single contaminated unit can facilitate widespread cross-contamination through physical contact, shared moisture, or airflow (Kwon et al. 2025). The integration of dehumidification, adequate ventilation, and temperature control is essential for establishing an environment inhospitable to *E. coli* (Moyne et al. 2020).

Furthermore, contemporary climate change has emerged as a global catalyst for the emergence and dissemination of foodborne pathogens. Flooding of agricultural land poses a particularly severe risk, as floodwaters frequently transport contaminants from septic systems, sewage treatment facilities, and livestock operations. *E. coli*, utilized as a proxy for fecal contamination, can persist in these flooded environments for extended periods, significantly compromising food safety (Liu et al. 2013, Furtak, Wolińska 2023, Awad et al. 2024, Kłapeć et al. 2024, Antonkiewicz et al. 2025).

Pre- and postharvest control of *E. coli* contamination on vegetables

The production of microbiologically safe vegetables necessitates the implementation of rigorous preventive strategies by producers to mitigate the risk of contamination in the final commodity. Consequently, an array of chemical and physical inactivation methodologies has been evaluated to enhance the safety profiles of fresh produce (Bautista-Baños et al. 2025). While initial washing with water remains a fundamental step for removing macroscopic debris and surface contaminants, traditional washing alone is generally inadequate for the total elimination of pathogens, driving the demand for advanced decontamination technologies.

The application of disinfectants to leafy greens offers a viable strategy for minimizing the presence of pathogenic bacteria on plant surfaces. Organic acids are generally recognized as safe (GRAS) and have been extensively studied for their broad-spectrum antimicrobial properties. Compounds such as acetic, lactic, butyric, citric, and malic acids are employed in food processing due to their efficacy and favourable safety profiles. The antimicrobial mechanism of these organic acids typically involves disrupting energy metabolism, altering cell membrane permeability, modifying intracellular osmotic pressure, and inhibiting the synthesis of essential biomolecules (Xu et al. 2025). The decontamination efficacy of organic acids is contingent upon several variables, including the specific microbial species and strain, the initial population density, concentration, exposure duration, temperature, and the delivery method such as spraying or immersion.

Recently, the integration of organic acids with physical technologies like ultrasonication has emerged as a promising "green" approach for produce sanitation. Turhan et al. (2025) demonstrated that combining thermosonication with organic acids significantly enhanced the removal of *E. coli* biofilms from spinach compared to thermosonication alone. Similarly, Mukhopadhyay et al. (2024) observed a synergistic inactivation effect using pulsed light in combination with nisin and organic acids, achieving a >5 log reduction in *E. coli* on romaine lettuce. These findings suggest that such multi-hurdle approaches can substantially improve the microbial safety and shelf life of leafy vegetables.

Innovative research by Canuel et al. (2026) explored the use of organic acid recovery solutions, specifically citric and malic acids derived from cranberry juice deacidification, as a natural disinfectant for fresh-cut lettuce. Their results indicated that *E. coli* inhibition was strongly concentration-dependent, with concentrations above 6.3 mg ml^{-1} showing significant bactericidal effects. On fresh-cut romaine, these organic acids achieved higher log reductions (0.9-1.1 log) than either water (0.4 log) or sodium hypochlorite (0.8 log) within minimal contact times. Furthermore, the natural alkaloid harmane has been shown to significantly reduce *E. coli* O157:H7 populations on fresh-cut lettuce over five days without compromising the vegetable's appearance. Harmane functions by decomposing mature biofilms, reducing exopolysaccharide content, and inducing cell death through multi-target synergies, including the impairment of ribosome function and the disruption of redox balance (Sui et al. 2025).

Besides chemical methods, biological control methods represent a sustainable and environmentally friendly alternative (Bautista-Baños et al. 2025). The use of lactic acid bacteria (LAB) is particularly notable due to their long history of safe use in food preservation (GRAS status) and their potential health benefits for consumers. LAB are increasingly utilized as biocontrol agents in minimally processed vegetables (Martins et al. 2013, Siroli et al. 2015, Pavli et al. 2018, Budryn et al. 2019, Uhlig et al. 2021, Kowalska et al. 2024, Kowalska and Wrzodak 2025). LAB isolates, particularly those recovered from fermented cabbage and cucumbers, possessed strong inhibitory effects against *E. coli* on spinach and lettuce. These isolates not only suppressed pathogens but also inhibited natural spoilage microflora, surviving effectively under refrigerated conditions. Furthermore, coating leafy greens with LAB creates a functional food matrix capable of delivering probiotic bacteria to the consumer (Kowalska et al. 2024).

Plant-derived essential oils (EOs) also serve as potent antimicrobial agents. Oils from oregano, cinnamon, and lemongrass, along with their primary constituents like carvacrol, cinnamaldehyde, and citral, have demonstrated significant growth inhibition of *E. coli* on vegetables (Xiao et al. 2024, Fan et al. 2025, Gomez-Llorente et al. 2025, Jaroni et al. 2025). In studies involving cherry tomatoes, the application of an oregano EO nanoemulsion

combined with ultrasound treatment resulted in a superior inactivation effect (5.06 log CFU ml^{-1}) compared to individual treatments (Fan et al. 2025). Similar synergistic effects were observed using *Zanthoxylum schinifolium* EO nanoemulsions and ultrasound on fresh-cut cucumbers, reaching an 8.91 log CFU ml^{-1} reduction. The mechanism of action involves increased cell membrane permeability, leading to the leakage of critical intracellular components such as proteins and ATP, alongside a significant reduction in bacterial mobility and biofilm formation (Jiang et al. 2025).

Good agricultural practices reduce risk of contamination

The adherence to Good Agricultural Practices (GAP) is the basic of pre-harvest safety, serving as a primary defence against the field-level contamination of crops. To address the complexities of pathogen persistence, the adoption of the One Health paradigm is increasingly recognized as vital. This holistic framework facilitates the prediction of human enteric pathogen prevalence by integrating environmental, animal, and human health data. Such models must comprehensively account for escalating climatic stressors, including thermal shifts, erratic precipitation patterns, prolonged droughts, and rising greenhouse gas concentrations, to develop resilient and scientifically grounded mitigation strategies.

The contamination of leafy vegetables represents a critical public health risk, as evidenced by its direct correlation with numerous large-scale foodborne outbreaks. Surface water sources, utilized frequently for irrigation, are inherently susceptible to fecal contamination via agricultural run-off and subterranean seepage (Rood et al. 2025). These vulnerabilities underscore the imperative for rigorous food safety protocols, specifically regarding the standardized storage and hygienic handling of fresh produce throughout the supply chain.

Furthermore, the implementation of climate-smart agriculture (CSA) is essential for bolstering food safety in an era of environmental instability. CSA focuses on sustainable practices that enhance agricultural productivity and systemic resilience while optimizing resource efficiency. By reducing the agricultural sector's vulnerability to climate-induced shifts, CSA provides a strategic barrier against the proliferation and transmission of foodborne pathogens, thereby safeguarding the integrity of the global food supply.

CONCLUSIONS

Developing robust mitigation strategies to ensure the microbial safety of vegetables during primary production remains a critical priority for future research. Advancements in food safety protocols are essential, with a particular emphasis on optimizing handling procedures from the initial cultiva-

tion stages through post-harvest processing. Furthermore, increasing the awareness of both consumers and regulatory authorities regarding the public health implications of contaminated produce, especially the emergence of antibiotic-resistant strains, is vital for limiting the dissemination of food-borne illnesses. Concurrently, there is an ongoing search for novel materials to be integrated into edible coating formulations. These materials must satisfy both industrial and consumer demands for preserving vegetable quality and extending shelf-life while effectively mitigating pathogen-related risks (Bautista-Baños et al. 2025). Plant-derived natural antimicrobials represent a significant area of investigation; future research should focus on optimizing extraction and purification techniques for their application as antimicrobial sprays, coatings, or sanitizers in both pre-harvest and post-harvest settings.

Looking forward, the identification of specific leaf morphological traits that correlate with reduced susceptibility to *E. coli* attachment and proliferation offers a strategic opportunity for selective breeding programs. By developing and adopting cultivars that are inherently less hospitable to human enteric pathogens, the vegetable industry can significantly enhance overall food safety (Truschi et al. 2023).

Additionally, pre-harvest sanitization emerges as a potential strategy to mitigate microbial risks associated with extreme weather events, such as dust storms or heavy precipitation, when applied immediately prior to harvest (Rood et al. 2025). However, further empirical studies are required to evaluate the efficacy of these interventions across various environmental scenarios and to determine their impact on product quality and ecosystem health. The development of a specialized risk assessment framework for specific crops and cultivation conditions is necessary to provide a scientific justification for the implementation of such pre-harvest sanitization protocols.

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Conflicts of interest

The author ensures that she has neither professional nor financial connections related to the manuscript sent to the Editorial Board. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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