GMR
The Original

FARM-TO-FORK MICROBIAL RISKS IN HYDROPONIC AND INDOOR MICROGREENS: A SCOPING REVIEW OF CONTAMINATION PATHWAYS, PREVENTIVE CONTROLS, AND PRIORITIES

Rizwan I[1], T. Samsai[2], C. Muralidharan[3], S. Angles[4], R. Gangai Selvi[5]

[1]Department of Agricultural and Rural Management, Tamil Nadu Agricultural University, Coimbatore 641003, Tamil Nadu, India, ORCID ID : 0009-0002-3851-0973
[2]Directorate of Planning and Monitoring, Tamil Nadu Agricultural University, Coimbatore 641003, Tamil Nadu, India, ORCID ID: 0000-0002-7912-1109 ,Email: tsamsai@tnau.ac.in, ,
[3]Directorate of Agribusiness Development, Tamil Nadu Agricultural University, Coimbatore 641003, Tamil Nadu, India, ORCID ID: 0000-0001-8602-0595
[4]Department of Agricultural Economics, Tamil Nadu Agricultural University, Coimbatore 641003, Tamil Nadu, India, ORCID ID: 0000-0001-6452-9745
[5]Department of Physical Science and IT, Tamil Nadu Agricultural University, Coimbatore 641003, Tamil Nadu, India, ORCID ID: 0009-0003-8689-5270

ABSTRACT

Microgreens are often eaten raw and are now more often grown using hydroponic, vertical and other controlled-environment technologies. While enclosures can decrease exposure to splashed soil, wildlife, and rain, they still do not eliminate microbial contamination risks from seeds, water, nutrient solutions, substrates, tools, personnel, packaging, and storage. Mapping the existing evidence on microbial contamination risks, indicators, foodborne pathogens, and any necessary controls and verification on the farm to fork continuum in India is the objective of this study. A scoping review, done and reported as per the PRISMA-ScR guidelines, was the chosen method. A reconstructed search log included Scopus, Web of Science, PubMed, ScienceDirect, Google Scholar, and citation analysis. Out of 1,028 research articles found, 742 remained after de-duplication, 130 were reviewed in full, and 50 research articles were included in the review. Evidence was organized by source, organism or indicator, stage of food production, control, verification, and limit. Irrigation water, nutrient water, and seed and soilless media were the most cited contamination entry routes. Total plate count and coliforms were the most cited indicators of contamination along the food production continuum. It is recommended the multi- hurdle model of contamination control be implemented along the food production continuum in India. Of all the recommendations made to improve food safety, many were focused on postharvest practices, and most of the recommended safety interventions lacked microbial baselines. Indoor growing of food should be considered controllable. Risk reduction relies on verified farm-to-fork controls and evidence specific to the system rather than production labels and end-product washing.

KEYWORDS: microgreens; microbial safety; hydroponics; indoor farming; PRISMA-ScR; India

1. INTRODUCTION

Microgreens are edible seedlings that, commercially, are ideally harvested just after the development of the seed leaves and the first true leaves. They have a fast growth cycle and have a stronger flavor compared to most greens [1]. This has caused a large shift in the market from the use of microgreens just as a garnish in restaurants, to the wholesale and retail markets [2], [3]. Urban farming has also helped this shift in growing and selling microgreens. Many studies from India also focus on the rapid growth of microgreens and the changing of the different methods of microgreen cultivation and processing [4], [5] as well as microgreens popularity among consumers [6], [7]. Since microgreens are ready to eat and are marketed as healthy, there is a significant need to focus on the safety of microgreens from pathogens, as well as their nutritional value.

Controlled-environment agriculture (CEA) offers some protections to the ususal cultivation threats of farming (pests and weather). CEA provides a high level of protection, but in a closed system, the same threats can be exacerbated. CEA systems use the same modular components (seeds, trays, tools, etc.) to repeat the same growth cycle [8], [9]. Hydroponic systems pose a unique threat, as they collect and redistribute pathogens in a closed water system [10]. High humidity can support the persistence of pathogens on surfaces [11]. For these reasons, indoor farming should be categorized as a production system with controllable, specific hazards, rather than an intrinsically sterile system.

Microgreens are in the middle range among sprouts and fully matured leafy greens. They are generally cultivated in the light and harvested above the roots. Like sprouts, microgreens share a seed origin and a warm and moist growing stage. Also, like sprouts, microgreens have no officially recognized kill step prior to consumption. Research has shown the transfer or persistence of Salmonella enterica, Shiga toxin-producing Escherichia coli, and Listeria monocytogenes to the edible portion of microgreens from contaminated seeds [12], [13], soilless growing media [14], [15], and contaminated

irrigation water [16], [17]. Studies using viral surrogates have shown that the sanitation of microgreens [18] is made even more difficult by the internalization and strong attachment of the microbes [19], [20].
This article is a scoping review and aims to showcase the range of existing data, provide clarification on contamination routes and controls, highlight gaps in research both in India and globally, and give an operational farm-to-fork verification system. The review question for this study was: what are the documented microbial hazards, process indicators, contamination routes, controls, and verification measures for hydroponic, indoor, and soilless microgreen production from seed to plate?

2. METHODS

2.1 Review design and reporting standard

A scoping-review design allows for the exploration of diverse concepts and gaps across a broad spectrum of evidence. This design also allows the authors to move away from estimating the effect of a single intervention. This review followed the JBI methodological instruction for scoping reviews and the PRISMA Extension for Scoping Reviews (PRISMA-ScR) [21], [22]. PRISMA 2020 was not the primary reporting framework for this review as it was not designed to address a specific intervention question and as this review did not include a meta-analysis and did not include a grading of the certainty of the evidence.

2.2 Eligibility framework

The Population–Concept–Context model was employed to define the eligibility criteria. Microgreen seeds, inputs and edible microgreens, production environments, food-contact surfaces, and growers made up the population. Microbial indicators, bacterial or viral hazards, the transfer of contaminating microorganisms, sanitation, and postharvest microbial quality, as well as food-safety practices, training, traceability, and the verification of practices, made up the concept. The context included hydroponics, aquaponics, vertical growing, indoor and greenhouse growing, and other soilless growing systems, as well as evidence from the sprout industry or Controlled Environment Agriculture (CEA) concerning leafy greens, when the evidence was directly applicable to the production of microgreens.
Studies that were peer-reviewed and published in English, either observational or experimental, surveys, qualitative studies, reviews and authoritative technical guidance, as well as grey literature, were included in the research. The main publication date was from January 2019 to June 2026. Studies that were older were only included if they were foundational studies in pathogen transfer, postharvest sanitation, or the interpretation of shelf-life. Studies and data were excluded if they only provided information related to the nutrient profile, plant physiology, or the lighting and yield of the plants, or if they provided information related to consumer preference and did not relate to food safety or some degree of control; focused on unrelated crops or field systems devoid of a transferable pathway; lacked sufficient methodological description; were duplicates of included data sets, or lacked a full text published in English.

2.3 Information sources and search strategy

Scopus, Web of Science, PubMed, ScienceDirect, Google Scholar, and backward and forward citation tracking were all used in the revised search. The search terms paired controlled-environment terms with microbial-safety terms, for example: (microgreen* OR ‘young edible seedling*’) AND (hydroponic* OR indoor OR vertical farm* OR soilless OR controlled environment) AND (microb* OR pathogen* OR Salmonella OR Listeria OR Escherichia coli OR coliform* OR ‘aerobic plate count’ OR virus OR sanitation OR shelf life). Other terms focused on seed decontamination, irrigation water and nutrient solution, substrates, grower practices, environmental monitoring, and cold chain and packaging, Indian microgreen production. The search will be updated to 30 June 2026. The source manuscript did not retain the original database exports; therefore, the screening log was reconstructed for this revision and hit counts may differ as a result of database indexing changes.

2.4 Study selection and PRISMA-ScR flow

The search identified 1,028 records: Manuscripts were identified in Scopus (326), Web of Science (241), PubMed (151), ScienceDirect (173), and Google Scholar with citation tracking (137). After removing 286 duplicates, 742 titles and abstracts were screened. 612 of these titles and abstracts were deemed not relevant and were removed, resulting in 130 full text articles. 80 of these full text articles were removed for the following reasons: 29 had no microbial or food-safety outcomes, 21 had an agronomic or nutrition-only focus, 12 had no evidence for microgreens or Controlled Environment Agriculture (CEA) that could be transferred, 9 had insufficient methodology, 5 had overlapping data sets, and 4 were in a language other than English. 50 studies were included in the qualitative synthesis. The flow diagram reflects the following math: 1,028 − 286 = 742; 742 − 612 = 130; and 130 − 80 = 50. All calculations in the flow diagram are consistent. The 50 included evidence sources correspond to references [1]-[20] and [23]-[52]; references [21] and [22] are methodological reporting sources and are not counted as included studies.

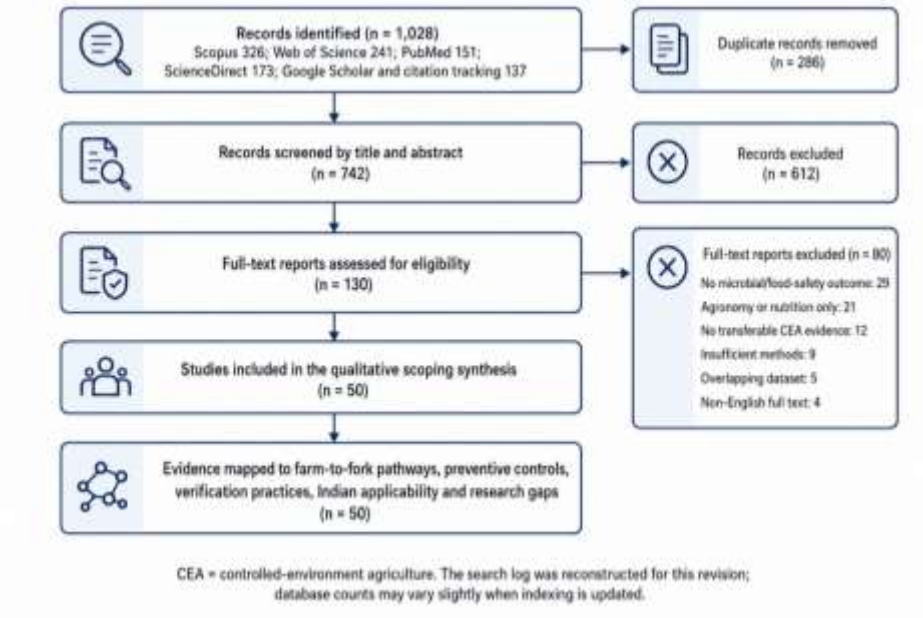

Figure 1. PRISMA-ScR study-selection flow for the revised scoping review. Counts report the reconstructed screening log used for this revision. Source: Author's own work; adapted from [22].

2.5 Data charting and synthesis

A systematic charting framework provided space to document citation (author, year), country/setting, production system, crop, sample type, organism/indicator, analysis, outcome, contamination pathway, control, verification, and limitation. Evidence was mapped to six interconnected domains: seed and planting material; water and nutrient solution; substrate and trays; the indoor environment, workers and equipment; harvest and packaging; and cold storage and distribution. Numeric values were used only if stated in the source. Due to the diversity in methods, no pooled microbial mean, cut-off, or meta-analytic effect was generated. The synthesis focuses on the direction and consistency of evidence and control signals and suggests plausible contamination pathways.

3. RESULTS

3.1 Characteristics and scope of the evidence

The included 50 studies published research on pathogen transfer and persistence, surveys of microorganisms and indicators, assessment of seeds and sanitizers, postharvest studies and studies assessing the shelf-life of products, surveys assessing the practices of growers, and integrative assessments pertaining to microgreens, sprouts, hydroponics, and indoor cultivation of leafy greens. Most of the experimentation focused on radish, broccoli, sunflower, pea shoots, and some other members of the Brassicaceae family. Most evidence of commercial practice was from North America and Europe. Studies by Indian authors recently published reviews [4], [5] and postharvest studies [23], [24] that added to the context of production and the discussion of potential interventions [6], [7], but the establishment of microbial baselines for hydroponic indoor microgreens in India is still largely unexplored.

The main evidence was integrated in order to reduce redundancy. Seed lots may have very high loads of aerobic microorganisms and coliforms [25]; matrices that are soil free exhibit different capabilities for the persistence of microorganisms [26]; pathogens may be transferred to the edible tissue of plants via contaminated seeds, matrices, and water [15], [16]; hydroponic products and systems may contain large and similar microbial communities [11]; and the quality of hydroponic products and the microorganisms after the harvest may be influenced by the temperature, moisture, and sanitization of the package, and the interventions during the handling of the product [3].

3.2 Seeds and pre-germination operations

Of all the inputs, seeds are the most problematic because contamination can happen prior to purchase, be concealed in irregularities on the surface of seeds, and get magnified during soaking and germination. Ocho Bernal et al. [25] noted that elevated aerobic counts coupled with frequent coliform detection prompted us to recommend supplier approval and lot-based verification. Contamination can happen during the entire seed to plant pathway for pathogens like E. coli O157:H7 [13], [27] and others, and to varying degrees, can be dependent on the plant species and the growing conditions [28], [29]. It was also shown in more recent studies that seeds used to grow microgreens can be a pathway for the contamination of the growing medium and the microbes in the soil or soilless growing medium to the microgreens themselves [12], [15].

Although seed treatment can reduce surface contamination, it does not work for all seeds and it may even impact germination negatively [4], [30]. Therefore, the literature supports validated and specific treatments for each crop. A generic treatment with time and concentration is not advisable [25], [31]. For each crop, treatment verification and supplier documentation is a must, along with treatment specifications, lot segregation, and assessment of germination of treated and untreated lots.

3.3 Water, nutrient solutions, and recirculation

Both hydroponics and aquaponics utilize water to transport and nourish crops. In these systems, the source of contamination may be in the reservoir and happen to affect many crops and surfaces in contact. Biofilms may limit the access of sanitizers and support persistence. Rao et al. [16] found that irrigation water pathogens introduced in the early stages of crop production may decline but will remain on edible plant tissues. Dong and Feng [11] found that there was a presence of the same kind of microorganisms on hydroponic crops and in their production environment, supporting the need for environmental and product sampling. The need for controls on the water quality in the production of hydroponic vegetables and indoor leafy greens is also supported by recent reviews [8], [10]. The recirculation system, the sanitation of the reservoir, and the practices of workers are critical controls [9].

The management of water in hydroponic systems should be risk-based and use-specific. Different systems and use of water should dictate the frequency of verification. Simply managing the reservoir is not adequate. Records should be kept for the water source and the treatment and any adjustments made to the pH and electrical conductivity of the water. System operation and microbial testing should be documented. Most recent studies of CEA systems support the approach of microbial profiling on a system-specific basis [32].

3.4 Substrates, trays, and facility reservoirs

Absence of soil does not equal absence of microbes. Various growth media contain different levels of organic material and have different structures. Some can hold water, and some can support microbial life [33], [34]. It was shown [26] that Salmonella Javiana and L. monocytogenes had different persistence behaviors depending on the media. Further, it was shown that many contaminated growth media can support the transfer of microbes to edible tissues [14], [15]. It can then be assumed that other components of the growth system (trays, junctions, drains, walls, fans, tables) can become contaminated, especially if they are not cleaned of dirt, sanitized, and allowed to dry.

To achieve separation of clean from dirty in a facility, especially during the harvest and packing processes, the area must be organized to enable efficient cleaning and sanitizing. A validation for the sanitizer must be in place for the removal of the cleaning and drying process. Environmental monitoring is most effective to substantiate a surveillance system, especially for the presence of Listeria in wet surfaces and for the presence of water-related organisms in closed channels or containers (reservoirs) [8], [9]. Responding to positive findings must be a documented root-cause analysis, especially in the absence of further testing of the end product [35], [36].

3.5 Workers, harvest, packaging, and cold chain

Human interaction increases during the seeding, moving, harvesting, and packing of trays. The indoor and microgreen growers' interviews and surveys [35], [37] exhibit a lack of consistency in the formal implementation of hazard analysis, sanitation verification, training, environmental monitoring, traceability, and recall preparedness [38]. Typically, training documentation and materials prioritize cultivation and control of the growth process, and yield, over control of the seeds, testing of water, and documentation of corrective action [39]. As a result, training, instructional materials, and training systems, if properly developed, can only be described as preventive control.

Moisture, microorganisms, and other contaminants are introduced to products via tools, packing materials, and gloves that touch cut surfaces and are in contact with packaging. The storage temperature and the type of package used can also affect the development of odor, moisture, and other unsatisfactory effects and promote the growth of microorganisms [40]. The fundamental principles of postharvest handling demonstrate the importance of the combination of temperature, packaging films, washing, and the use of sanitizing agents [41], [42]. The above-mentioned Indian Studies have shown similar work and evidence, with the addition of packaging and postharvest treatments, packing, storage, retention of quality [43], and microbial control of radish and broccoli microgreens [23], [24]. Oxidative treatments and UV-C can be used to control microorganisms but are crop and dosage specific and should not be used as a substitution for prevention [30], [44].

3.6 Interpretation of microbial indicators and pathogen tests

Total plate count measures cultured aerobic microorganisms, with living plant tissues having a high count due to the presence of seed microbiota, substrates, and water biofilms among other factors and not necessarily the presence of a specific pathogen. Coliform count measures are more process-oriented and are not indicative of fecal contamination. Both counts help assess suppliers and help during the optimization of sanitation cycles, and the evaluation of water systems [11] and the shelf life of produce [3]. However, both counts also fail to indicate the presence of pathogenic microorganisms such as Salmonella, L. monocytogenes, and pathogenic strains of E. coli as well as viruses [2], [25].

A process-hygiene indicator differentiation from food-safety criteria is essential for a credible verification program. The presence of generic E. coli indicates the control of fecal contamination and/or water is insufficient. Target pathogens can only be determined through presence/absence methods with validated enrichment, sample mass controls, detection limits, and quality controls. Negative results should be interpreted depending on the lot size and the number of samples collected. For Indian application, the methods and microbiological sampling plans for the assessment of fresh produce should be in alignment with the FSSAI microbiological manuals [45] and the guidelines for fruits and vegetables [46], [47].

3.7 Multi-hurdle preventive-control framework

No single intervention offers total protection. Seed treatment cannot address water contamination. Reservoir treatment cannot cover the unhygienic harvest. Refrigeration cannot eliminate pathogens that were introduced earlier. There is evidence to support a multi-hurdle system which comprises the qualification of inputs, validated treatments, the design of a hygienic facility [2], [8], environmental monitoring, controls of the workers, rapid cooling, traceability, and record of

correction actions [48]. Lighting and/or non-thermal technologies may have additional antimicrobial effects [49], [50], but the evidence is too limited to consider them as kill steps [51], [52].

Table 1. Concise farm-to-fork microbial risk-control matrix for indoor and hydroponic microgreens. Controls require local validation and should be linked to documented corrective actions.

Stage	Principal microbial concern	Preventive controls	Verification evidence
Seed procurement and storage	High background load; pathogen-contaminated lots; poor traceability	Approved suppliers; lot segregation; dry storage; crop-specific validated treatment	Supplier file; lot register; treatment and germination log
Soaking and pre-germination	Amplification in warm soak water; lot-to-lot cross-contamination	Fit-for-purpose water; single-lot containers; time–temperature control; clean equipment	Water record; soak log; sanitizer/heat validation
Substrate and tray preparation	Contaminated media; reusable tray and rack biofilms	Approved media; clean–sanitize–dry sequence; protected storage; zoning	Substrate batch record; sanitation checklist; swab results
Irrigation and nutrient solution	Contaminated source or recirculated water; reservoir biofilms	Water treatment; reservoir cleaning; controlled recirculation; filter/UV maintenance	Microbial report; pH/EC log; maintenance and corrective-action record
Indoor crop growth	Humidity, condensation, worker traffic, pests, shared surfaces	Microclimate control; access restriction; batch separation; environmental monitoring	Temperature–humidity record; pest log; environmental trend
Harvest and packaging	Cut-surface contamination; tools, hands, mixed lots, condensation	Sanitized tools and tables; hand/glove control; lot coding; moisture-managed packs	Pre-operational check; harvest record; lot code and packaging record
Cold storage and distribution	Temperature abuse, condensation, extended shelf life	Rapid cooling; cold-chain monitoring; first-in–first-out; shelf-life validation	Time–temperature log; dispatch traceability; shelf-life study

Source: Author's own work.

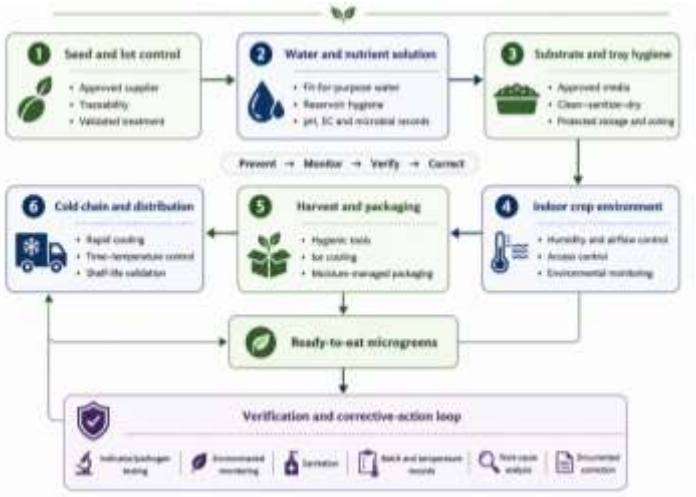

Figure 2. Integrated preventive-control and verification framework. The model treats microbial safety as a continuous system rather than an end-product testing exercise.

Source: Author's own work.

4. DISCUSSION

The main conclusion drawn is that indoor and hydroponic systems should be characterized as controllable rather than inherently safe. Enclosing a system diminishes a number of environmental risk factors, but increases reliance on the microbiological quality of all input materials and of shared surfaces. The principal upper-stage risk triad consists of the seeds, water or nutrient solution, and the substrate. The type of infrastructure and its reusability, as well as the type of handling, will determine whether a microorganism will be localized or will consider a facility as a new habitat. This understanding is equally valid for experiments on pathogen transfer [12], [16], CEA studies and surveys [11], studies on grower practice [36], and the most recent international recommendations [9].

The synthesis also explains what routine indicator testing means. Although TPC and coliforms can indicate failure of a given process, change of suppliers, sanitation failures or deterioration of the product, they cannot be classified as surrogate tests for pathogens. To support strong safety claims, sampling must be undertaken on a risk basis, and the methods of pathogen detection must be supported by evidence of the limits of detection. Moreover, the testing and the research must be supported by evidence of traceability for the given batch and the environmental factors. Experimental inoculation studies usually employ concentrations that are higher than concentrations that are normally found, and their purpose is to show possible routes of transfer and the control surfaces rather than to determine thresholds.

Evidence for India is disjointed. Based on existing publications, Indian authors have researched microgreen cultivation [5], [6], the seed-processing continuum [4], postharvest quality and packaging [23], [24], and emerging technologies [7]. However, the published microbial studies of Indian indoor and hydroponic microgreen systems remain few. The informal nature of the local economy, multiple sources for seeds and substrates, inconsistent access to accredited labs, warm conditions for distribution, and direct sales may influence the type of risks encountered and the feasibility of controls. Recommendations should be made in the context of the FSSAI hygiene and microbiological frameworks and include validation studies for microgreens.

The review is restricted because of the varied crops, inoculation strategies, analytic approaches, and measurement units, and is based on the limited, English-language literature and the search log that had to be built because the citing manuscript did not provide the export. These limitations stop a meta-analysis, but do not negate the evidence for the same pathways. The limitations require careful interpretation of the data. Reported microbial data should not be equated to limits of acceptance.

4.1. Practical Implications and Indian Research Priorities

Microgreens producers must have a written food-safety plan. It must assign responsibility for each production step, state how often the step will be checked, define what the step will look like, state how, and where, corrective action will be recorded. Required controls include: traceability of input materials; safe water; validated and documented cleaning and sanitation; separation of dirty and clean zones; sanitary harvesting and packaging; removal of field heat and temperature control; cold chain; and documentation. Small operations can start with auditable records for each control and sanitation and temperature control for field heat removal. Records of microgreen harvesting and soaking as well as water and sanitation records can be added later. Controls can be extended based on risk and laboratory capacity to include environmental and microbial testing and trending.

An Indian field study should focus on paired pathway sampling. finished product testing is insufficient. Sampling should be for seed and packaging materials, water and substrates, edible microgreens, product surfaces, and wet environmental sampling. Sampling should also be done while the product is held under refrigeration. At a minimum, total viable counts, coliforms, and E. coli should be tested. Limits of detection, sample size, and units should be reported for each method. Sampling should also include Salmonella and L. monocytogenes testing and should be done under better study designs. Multiple sampling and production systems should be documented to ensure that microbial testing can be correlated to sanitation, packaging, cold chain, and to the other practices and controls mentioned.

Research priorities are: (1) microbe baseline data for the various types of Indian hydroponic, vertical, cocopeat, mat and retail microgreens; (2) species-specific verification of seed treatments for the mucilaginous species and others; (3) thresholds for monitoring nutrient solutions and biofilms; (4) research combining microbial safety, germination, and yield and sensory shelf life; (5) studies on the persistence of viruses and their surrogates; (6) low-cost verification and training aids for small growers. This work should differentiate process indicators and pathogens and publish comprehensive sampling and quality control data.

5. CONCLUSION

Production labels do not provide coverage for hydroponic and indoor microgreen cultivation. Microbial contaminants can infiltrate the production process through any number of the aforementioned pathways and can survive the process of production and packaging, and can ultimately reach the consumer, via a product that is most commonly eaten raw. While TPC and coliforms can be used for monitoring the production processes, they do not ensure the absence of pathogens. An approach that is defensible to the greatest extent possible involves documented multi-hurdle, farm to fork systems, and includes verifiable and validated microbial and environmental assurances, sanitation, and hygiene throughout the production process, and safety and quality throughout the supply chain, and includes the provision for corrective actions and traceability. The scoping evidence provides support for the proposed framework and indicates that locally validated data from India is required. Future claims of "clean" indoor production should be replaced by claims of evidence of control performance.

REFERENCES

1. Choe, U., Yu, L. L., & Wang, T. T. Y. (2018). The science behind microgreens as an exciting new food for the 21st century. Journal of Agricultural and Food Chemistry, 66(44), 11519–11530. https://doi.org/10.1021/acs.jafc.8b03096
2. Riggio, G. M., Wang, Q., Kniel, K. E., & Gibson, K. E. (2019). Microgreens: A review of food safety considerations along the farm-to-fork continuum. International Journal of Food Microbiology, 290, 76–85. https://doi.org/10.1016/j.ijfoodmicro.2018.09.027
3. Turner, E. R., Luo, Y., & Buchanan, R. L. (2020). Microgreen nutrition, food safety, and shelf life: A review. Journal of Food Science, 85(4), 870–882. https://doi.org/10.1111/1750-3841.15049
4. Bhabani, M. G., Shams, R., & Dash, K. K. (2024). Microgreens and novel non-thermal seed germination techniques for sustainable food systems: A review. Food Science and Biotechnology, 33(7), 1541–1557.

https://doi.org/10.1007/s10068-024-01529-9
5. Gunjal, M., Singh, J., Kaur, J., Kaur, S., Nanda, V., Sharma, A., & Rasane, P. (2024). Microgreens: Cultivation practices, bioactive potential, health benefits, and opportunities for utilization as value-added food. Food Bioscience, 62, 105133. https://doi.org/10.1016/j.fbio.2024.105133
6. Partap, M., Sharma, D., HN, D., Thakur, M., Verma, V., Ujala, & Bhargava, B. (2023). Microgreen: A tiny plant with superfood potential. Journal of Functional Foods, 107, 105697. https://doi.org/10.1016/j.jff.2023.105697
7. Singh, A., Singh, J., Kaur, S., Gunjal, M., Kaur, J., Nanda, V., Ullah, R., Ercisli, S., & Rasane, P. (2024). Emergence of microgreens as a valuable food, current understanding of their market and consumer perception: A review. Food Chemistry: X, 23, 101527. https://doi.org/10.1016/j.fochx.2024.101527
8. 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. https://doi.org/10.1016/j.ijfoodmicro.2023.110546
9. Warriner, K., Hasani, M., Warriner, L., Farber, J., & Takeuchi, M. (2025). Modern indoor farming and food safety—A review of hazards, controls and regulatory consideration. Food and Agriculture Organization of the United Nations. https://doi.org/10.4060/cd6554en
10. Sela Saldinger, S., Rodov, V., Kenigsbuch, D., & Bar-Tal, A. (2023). Hydroponic agriculture and microbial safety of vegetables: Promises, challenges, and solutions. Horticulturae, 9(1), 51. https://doi.org/10.3390/horticulturae9010051
11. 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. https://doi.org/10.3389/fmicb.2022.879260
12. Rao, A. P., Pradhan, A. K., & Patel, J. (2025b). Transfer of Salmonella enterica, Escherichia coli O157:H7 and Listeria monocytogenes to microgreens and soil from contaminated seeds. Journal of Agriculture and Food Research, 21, 101761. https://doi.org/10.1016/j.jafr.2025.101761
13. Xiao, Z., Nou, X., Luo, Y., & Wang, Q. (2014b). Comparison of the growth of Escherichia coli O157:H7 and O104:H4 during sprouting and microgreen production from contaminated radish seeds. Food Microbiology, 44, 60–63. https://doi.org/10.1016/j.fm.2014.05.015
14. Deng, W., Misra, G. M., Baker, C. A., & Gibson, K. E. (2021). Persistence and transfer of foodborne pathogens to sunflower and pea shoot microgreens during production in soil-free cultivation matrix. Horticulturae, 7(11), 446. https://doi.org/10.3390/horticulturae7110446
15. Işık, S., Çetin, B., & Topalcengiz, Z. (2024). Transfer of Salmonella, Escherichia coli O157:H7 and Listeria monocytogenes from contaminated soilless substrate and seeds to microgreens. International Journal of Food Microbiology, 414, 110612. https://doi.org/10.1016/j.ijfoodmicro.2024.110612
16. Rao, A. P., Pradhan, A. K., & Patel, J. (2025a). Persistence of foodborne bacterial pathogens on microgreens and soil irrigated with contaminated water. Journal of Food Protection, 88(10), 100594. https://doi.org/10.1016/j.jfp.2025.100594
17. Xiao, Z., Bauchan, G., Nichols-Russell, L., Luo, Y., Wang, Q., & Nou, X. (2015). Proliferation of Escherichia coli O157:H7 in soil-substitute and hydroponic microgreen production systems. Journal of Food Protection, 78(10), 1785–1790. https://doi.org/10.4315/0362-028X.JFP-15-063
18. Fuzawa, M., Duan, J., Shisler, J. L., & Nguyen, T. H. (2021). Peracetic acid sanitation on arugula microgreens contaminated with surface-attached and internalized Tulane virus and rotavirus. Food and Environmental Virology, 13, 401–411. https://doi.org/10.1007/s12560-021-09473-1
19. Deng, W., & Gibson, K. E. (2023a). Persistence and transfer of Tulane virus in a microgreen cultivation system. International Journal of Food Microbiology, 387, 110063. https://doi.org/10.1016/j.ijfoodmicro.2022.110063
20. Deng, W., & Gibson, K. E. (2023b). Microgreen variety impacts leaf surface persistence of a human norovirus surrogate. Food and Environmental Virology, 15(1), 82–88. https://doi.org/10.1007/s12560-022-09536-x
21. Peters, M. D. J., Marnie, C., Tricco, A. C., Pollock, D., Munn, Z., Alexander, L., McInerney, P., Godfrey, C. M., & Khalil, H. (2020). Updated methodological guidance for the conduct of scoping reviews. JBI Evidence Synthesis, 18(10), 2119–2126. https://doi.org/10.11124/JBIES-20-00167
22. Tricco, A. C., Lillie, E., Zarin, W., O'Brien, K. K., Colquhoun, H., Levac, D., Moher, D., Peters, M. D. J., Horsley, T., Weeks, L., Hempel, S., Akl, E. A., Chang, C., McGowan, J., Stewart, L., Hartling, L., Aldcroft, A., Wilson, M. G., Garritty, C., ... Straus, S. E. (2018). PRISMA extension for scoping reviews (PRISMA-ScR): Checklist and explanation. Annals of Internal Medicine, 169(7), 467–473. https://doi.org/10.7326/M18-0850
23. Gunjal, M., Singh, J., Kaur, S., & Rasane, P. (2025). Postharvest technologies enhance quality, antioxidant activity, microbial control, and shelf-life of radish sango microgreens. Journal of Food Process Engineering, 48, e70209. https://doi.org/10.1111/jfpe.70209
24. Patil, M., Sharma, S., Sridhar, K., Anurag, R. K., Grover, K., Dharni, K., Mahajan, S., & Sharma, M. (2024). Effect of postharvest treatments and storage temperature on the physiological, nutritional, and shelf-life of broccoli (Brassica oleracea) microgreens. Scientia Horticulturae, 327, 112805. https://doi.org/10.1016/j.scienta.2023.112805
25. Ocho Bernal, T. G., Lyttle, N., & Jung, Y. (2023). Microbiological quality of microgreen seeds purchased from online vendors and evaluating seed decontamination techniques available online. Frontiers in Sustainable Food Systems, 7, 1264472. https://doi.org/10.3389/fsufs.2023.1264472
26. Misra, G., & Gibson, K. E. (2020). Survival of Salmonella enterica subsp. enterica serovar Javiana and Listeria monocytogenes is dependent on type of soil-free microgreen cultivation matrix. Journal of Applied Microbiology, 129(6), 1720–1732. https://doi.org/10.1111/jam.14696

27. Reed, E., Ferreira, C. M., Bell, R., Brown, E. W., & Zheng, J. (2018). Plant–microbe and abiotic factors influencing Salmonella survival and growth on alfalfa sprouts and Swiss chard microgreens. Applied and Environmental Microbiology, 84(6), e02814-17. https://doi.org/10.1128/AEM.02814-17
28. Wright, K. M., & Holden, N. J. (2018). Quantification and colonisation dynamics of Escherichia coli O157:H7 inoculation of microgreens species and plant growth substrates. International Journal of Food Microbiology, 273, 1–10. https://doi.org/10.1016/j.ijfoodmicro.2018.02.025
29. Wright, K. M., Wright, P. J., & Holden, N. J. (2022). Plant species-dependent transmission of Escherichia coli O157:H7 from the spermosphere to cotyledons and first leaves. Environmental Microbiology Reports, 14(6), 926–933. https://doi.org/10.1111/1758-2229.13115
30. Phornvillay, S., Yodsarn, S., Oonsrithong, J., Srilaong, V., & Pongprasert, N. (2022). A novel technique using an advanced oxidation process (UV-C/H2O2) combined with micro-nano bubbles on decontamination, seed viability, and enhancing phytonutrients of roselle microgreens. Horticulturae, 8(1), 53. https://doi.org/10.3390/horticulturae8010053
31. Fahey, J. W., Smilovitz Burak, J., & Evans, D. (2023). Sprout microbial safety: A reappraisal after a quarter-century. Food Frontiers, 4, 14–27. https://doi.org/10.1002/fft2.183
32. Gu, G., Zhou, B., Yang, Y., Nou, X., Millner, P. D., Zhang, B., & Luo, Y. (2025). Microbial profiles of baby spinach produced hydroponically in controlled environment agriculture and from soil-based open field production practice. Food Control, 175, 111198. https://doi.org/10.1016/j.foodcont.2025.111198
33. Işık, H., Topalcengiz, Z., Güner, S., & Aksoy, A. (2020). Generic and Shiga toxin-producing Escherichia coli (O157:H7) contamination of lettuce and radish microgreens grown in peat moss and perlite. Food Control, 111, 107079. https://doi.org/10.1016/j.foodcont.2019.107079
34. Chen, C.-H., Yin, H., & Patel, J. R. (2023). Influence of contamination source and cultivation matrix on survival of Escherichia coli O157:H7 and Salmonella enterica on daikon microgreens. LWT, 185, 115165. https://doi.org/10.1016/j.lwt.2023.115165
35. Hamilton, A. N., Topalcengiz, Z., & Gibson, K. E. (2023a). Growing safer greens: Exploring food safety practices and challenges in indoor, soilless production through thematic analysis of leafy greens grower interviews. Journal of Food Protection, 86(11), 100163. https://doi.org/10.1016/j.jfp.2023.100163
36. Hamilton, A. N., Gibson, K. E., Amalaradjou, M. A., Callahan, C. W., Millner, P. D., Ilic, S., Lewis Ivey, M. L., & Shaw, A. M. (2023b). Cultivating food safety together: Insights about the future of produce safety in the U.S. controlled environment agriculture sector. Journal of Food Protection, 86(12), 100190. https://doi.org/10.1016/j.jfp.2023.100190
37. Hamilton, A. N., Topalcengiz, Z., & Gibson, K. E. (2023c). Barriers to implementing risk management practices in microgreens growing operations in the United States: Thematic analysis of interviews and survey data. Food Control, 152, 109836. https://doi.org/10.1016/j.foodcont.2023.109836
38. Misra, G., & Gibson, K. E. (2021). Characterization of microgreen growing operations and associated food safety practices. Food Protection Trends, 41(1), 56–69. https://doi.org/10.4315/1541-9576-41.1.56
39. Hewage, S. C. N., Makawita, A., Chandran, S., Gibson, K. E., & Fraser, A. M. (2023). Evaluating the alignment and quality of microgreens training materials available on the internet: A content analysis. Journal of Food Protection, 86(1), 100021. https://doi.org/10.1016/j.jfp.2022.100021
40. Kou, L., Luo, Y., Yang, T., Xiao, Z., Turner, E. R., Lester, G. E., Wang, Q., & Camp, M. J. (2013). Postharvest biology, quality and shelf life of buckwheat microgreens. LWT—Food Science and Technology, 51(1), 73–78. https://doi.org/10.1016/j.lwt.2012.11.017
41. Chandra, D., Kim, J. G., & Kim, Y. P. (2012). Changes in microbial population and quality of microgreens treated with different sanitizers and packaging films. Horticulture, Environment, and Biotechnology, 53, 32–40. https://doi.org/10.1007/s13580-012-0075-6
42. Xiao, Z., Luo, Y., Lester, G. E., Kou, L., Yang, T., & Wang, Q. (2014a). Postharvest quality and shelf life of radish microgreens as impacted by storage temperature, packaging film, and chlorine wash treatment. LWT—Food Science and Technology, 55(2), 551–558. https://doi.org/10.1016/j.lwt.2013.09.009
43. Ghoora, M. D., & Srividya, N. (2020). Effect of packaging and coating technique on postharvest quality and shelf life of Raphanus sativus L. and Hibiscus sabdariffa L. microgreens. Foods, 9(5), 653. https://doi.org/10.3390/foods9050653
44. Işık, S., Çetin, B., Moreira, J., & Topalcengiz, Z. (2026). Post-harvest UV-C treatment of microgreens for inactivation of Salmonella enterica, Escherichia coli O157:H7 and Listeria monocytogenes. Foods, 15(6), 974. https://doi.org/10.3390/foods15060974
45. Food Safety and Standards Authority of India. (2024b). Manual on methods of analysis—Microbiological examination of food and water. FSSAI.
46. Food Safety and Standards Authority of India. (2020). Guidance document on clean and fresh fruit and vegetable market. FSSAI.
47. Food Safety and Standards Authority of India. (2024a). Appendix B: Microbiological standards for fruits and vegetables and their products (Version 2, 4 November 2024). FSSAI.
48. Abaajeh, A. R., Kingston, C. E., & Harty, M. (2023). Environmental factors influencing the growth and pathogenicity of microgreens bound for the market: A review. Renewable Agriculture and Food Systems, 38, e12. https://doi.org/10.1017/S174217052300008X
49. Alrifai, O., Hao, X., Marcone, M. F., & Tsao, R. (2019). Current review of the modulatory effects of LED lights on photosynthesis of secondary metabolites and future perspectives of microgreen vegetables. Journal of Agricultural and Food Chemistry, 67(22), 6075–6090. https://doi.org/10.1021/acs.jafc.9b00819

50. Budavári, N., Pék, Z., Helyes, L., Takács, S., & Nemeskéri, E. (2024). An overview on the use of artificial lighting for sustainable lettuce and microgreens production in an indoor vertical farming system. Horticulturae, 10(9), 938. https://doi.org/10.3390/horticulturae10090938
51. Dubey, S., Harbourne, N., Reilly, A., Hurley, D., & Elliott-Kingston, C. (2026). Microgreens: Optimising seed density and exploring the influence of white light and white light supplemented with UV-A radiation. Plants, 15(4), 635. https://doi.org/10.3390/plants15040635
52. Guragain, A., Topalcengiz, Z., & Moreira, J. (2026). Effects of LED lighting on the nutritional properties and microbial safety of microgreens. Frontiers in Nutrition, 13, 1869208. https://doi.org/10.3389/fnut.2026.1869208