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Review

Food Safety Hazards and Mitigation Strategies in Controlled Environment Agriculture: A Review

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Abstract

Controlled environment agriculture (CEA) is emerging as a viable system for producing fresh food in areas with reduced water and land usage and year-round production. However, growing crops in a controlled environment does not completely eliminate food safety risks. This narrative review summarizes the most important food safety threats of CEA and the methods available for mitigating those risks. Biological hazards (*Listeria monocytogenes*, *Salmonella*, *Escherichia coli*, and noroviruses) can be introduced into CEA systems via water, seeds, growing substrates, equipment, workers, and pests. Chemical hazards can also be caused by pesticides, heavy metals, nutrient solutions, and sanitizer residues, as well as by damaged equipment, plastic, metal, glass, and other foreign materials, which are known as physical hazards. This review also addresses mitigation methods, such as seed treatment, water disinfection, sanitation, worker hygiene, waste management, pest control, and Good Agricultural Practices (GAPs). Moreover, advancements in technology like sensors, biosensors, artificial intelligence and digital monitoring could aid in better early detection and food safety management. In general, CEA can contribute to sustainable food production, but issues of food safety must be addressed in the process. Further studies are required to develop and validate novel food safety practices for each of the various CEA systems and to assess the viability of new technologies for use in commercial food production.

Keywords: controlled environment agriculture; food safety; food safety management; good agricultural practices; microbial hazards

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1. Introduction

Food safety is one of the most critical issues in public health worldwide, especially in the 21st century. Foodborne illnesses are causing significant public health and economic problems in the world despite significant technological and regulatory developments [1]. According to the Centers for Disease Control and Prevention [2], about 48 million people, representing approximately 1 in 6 Americans, fall ill each year from contaminated food, with approximately 128,000 hospitalizations and 3000 deaths annually. The increased rate of population growth is putting more pressure on food supplies, which intensifies the challenge of ensuring food safety.

The global population has been rising in recent decades. According to the United Nations [3], the global population is estimated to be approximately 10 billion by 2050, and 6.2 billion people are expected to be living in cities. This trend is expected to substantially

increase demand for a wide range of human necessities, particularly food, both in terms of quantity and quality. To meet these requirements, global food production will need to increase by approximately 60–70% [4]. In past decades, climate change has been impacting agriculture production through extreme weather which reduces crop yield and quality and impacts food security [5]. In addition to climate change, scarcity of arable land, water management, soil degradation, and pest infestations are all main factors that limit the ability of conventional outdoor farming to meet future food demand [6]. Controlled environment agriculture (CEA) has been regarded as a solution to deal with many of these challenges, thereby helping to increase crop yield and meet nutritional demand, especially for people living in cities.

Controlled environment agriculture (CEA) refers to the indoor production of crops where environmental factors such as light, temperature, humidity, water, nutrients and carbon dioxide are precisely controlled to maximize crop growth and yield [7–9]. This allows for year-round production and overcoming external climatic changes. CEA encompasses systems including greenhouses, vertical farming, hydroponics, aeroponics, aquaponics and other systems [9]. These systems have gained attention in recent decades due to their efficient use of land and water, ability to optimize crop yield and improve crop quality, and reduced risks compared to conventional agriculture [10]. According to Regmi et al. [11], water usage can be reduced by more than 90% in hydroponic/aeroponic CEA systems compared to traditional agriculture. Despite all the advantages of CEA, it also faces its own technical, economic and environmental challenges, including high energy requirements, substantial initial investment and operating costs, dependence on sophisticated infrastructure, and the need for effective management of water and nutrient recirculation [12]. While these systems offer greater control over crop production, their reliance on recirculating water, enclosed environments, and high humidity can also introduce unique food safety considerations that require careful management.

Food safety is a fundamental aspect of modern food production systems. Food safety risks can be triggered by physical, chemical, microbial or other external contaminants. Microbial contamination within CEA can enter through various sources, including water and nutrient solutions, growth substrate, seeds, or human contact [13,14]. Due to the enclosed and recirculating nature of most protected culture production systems, biofilms can form in pipes and reservoirs, serving as persistent reservoirs for microbial contamination [15]. Microbial contamination in fresh food products is the most concerning issue because it can cause outbreaks within a short time and affect many people. This leads to multiple food recalls and foodborne illness. In controlled environments, conditions favorable for plant growth, such as warm temperatures and high humidity, can also be favorable for the growth of microorganisms [16].

Chemical hazards also pose safety risks in CEA systems which can originate from inputs and materials used throughout the production process. Compared to conventional agriculture, CEA reduces pesticide usage, thus lowering the risk of chemical hazards. However, other chemical-related risks may arise from nutrient formulations, water treatment agents, or materials used in system construction [17,18]. For instance, improper mixing or monitoring of nutrient solutions can lead to the accumulation of heavy metals or imbalances that may affect both plant health and food safety. Physical hazards, while not often discussed, are also important in controlled environments. Examples of physical hazards include foreign materials such as plastic, metal and/or glass that may enter the controlled environment from the infrastructure, equipment, and packaging materials of the finished product [18].

CEA operations in the United States may be regulated under the Food Safety Modernization Act (FSMA) Produce Safety Rule, which provides science-based minimum standards to prevent food meant for human consumption from being contaminated during growing,

harvesting, packing and holding [19]. Protective culture operations (such as greenhouses and indoor growing facilities producing fresh leafy greens) may be subject to these requirements depending on the nature of the operation, produce type and the applicable exemptions and modified requirements based on the farm size and marketing practices. Secondly, Good Agricultural Practices (GAPs) offer clear guidelines on how to reduce food safety hazards during the farming process by managing water resources correctly, maintaining good hygiene among farmworkers, sanitizing, controlling pests and disease, and handling food safely [20]. These guidelines are a starting point for food safety management but may need to be adapted to the characteristics of CEA production, including recirculating nutrient solutions, soilless growing substrates, controlled irrigation systems, and enclosed growing environments.

Food safety risks should be mitigated before they occur, using a comprehensive approach covering both preventive measures and monitoring systems. Techniques such as ultraviolet (UV) treatment, ozonation, and filtration are commonly employed to reduce microbial loads in recirculating systems [21]. Additionally, environmental controls including air filtration, humidity regulation, temperature management and sanitation protocols play a crucial role in limiting pathogen introduction and persistence. Worker hygiene and training are equally important, as human handling remains a significant source of contamination in fresh produce systems.

Technological advancements offer promising tools for enhancing food safety in CEA. Sensors, automation, and data analytics enable real-time monitoring of environmental conditions and system performance which facilitate early detection of anomalies that may indicate contamination risks [22]. Furthermore, the integration of traceability systems can improve transparency and accountability across the supply chain, enabling rapid response in the event of a food safety incident. However, the effectiveness of these technologies depends on proper implementation, maintenance, and interpretation of data.

The objectives of this review are to synthesize the current understanding of food safety risks associated with CEA systems and to assess current mitigation approaches. More specifically, this review aims to (i) identify and categorize the major biological, chemical, and physical food safety hazards of food safety associated with CEA production systems; (ii) examine the sources and pathways of contamination specific to CEA systems; and (iii) explore new technologies that may help improve food safety through prevention, monitoring, and control of contamination. Moreover, this review aims to identify current research gaps to help create food safety management strategies specifically for CEA systems. As CEA continues to expand as a way to produce fresh food to closer meet consumer demands, ensuring the safety of these systems is essential for protecting public health and maintaining consumer trust. Addressing food safety hazards will play an important role in supporting the wider adoption of CEA and its contribution to future food security.

This review was done based on the relevant scientific literature and institutional publications. The literature search was performed in the Web of Science Core Collection, Scopus, PubMed and Google Scholar databases from the years 2015 to 2026. The search terms were categorized into three concept groups: (a) production systems: “controlled environment agriculture”, “hydroponic”, “vertical farm”, “indoor farm”, and “greenhouse”; (b) food safety hazards: “food safety”, “Salmonella”, “Listeria”, “Escherichia coli”, “pathogen”, “pesticide residue”, “physical hazard”, “chemical hazard”, and “biological hazard”; and (c) control and mitigation measures: “mitigation”, “intervention”, “sanitization”, “disinfection”, and “good agricultural practice”. Only publications published in the English language were taken into account. The sources were peer-reviewed original research articles, review papers, institutional publications and technical reports. Particular consideration was given to publications that involved biological, chemical and physical hazards related

to controlled environment agriculture (CEA) and related soilless and greenhouse crops. Studies and publications on crop productivity, plant growth, or food safety that did not relate to CEA were not considered.

2. Overview of Controlled Environment Agriculture (CEA)

2.1. History of CEA

The history of controlled environment agriculture dates back to ancient Rome (14–37 CE). This was the earliest form of protected agriculture, which was implemented during the reign of Emperor Tiberius. In this system, cucumber plants were grown throughout the year through artificial means in specularia, which is similar to a greenhouse [23]. This system was implemented to ensure food was grown throughout the year despite adverse weather. However, due to the growing problems with climate change and an increasing population, a major paradigm shift has been made towards indoor farming, and this has led to major innovations. This has, in turn, led to the evolution of greenhouse structures to ensure maximum growth and quality while minimizing the adverse impacts of weather, pests, and diseases and maintaining a controlled environment for growing crops. This has been made possible through the development of climate-specific designs, temperature control mechanisms, artificial lighting, and hydroponic farming.

2.2. Types of Protected Culture Systems

CEA includes various types of production systems that involve managing conditions in the environment to be conducive to plant growth. These include high tunnels, screen houses, greenhouses, shade houses and indoor vertical farms, all of which have varying levels of enclosure, environmental control, and technological complexity. Production techniques involve soil production, substrate systems and soilless systems such as hydroponics and aquaponics (Figure 1) [22,24,25]. Environmental controls can include light intensity and photoperiod, irrigation, nutrient supply, temperature, and relative humidity. For basic structures, it is possible to use fans for natural ventilation and passive protection, whereas more sophisticated greenhouses and indoor farms incorporate automatic climate control, artificial lighting and controlled irrigation systems to ensure crop production is optimized.

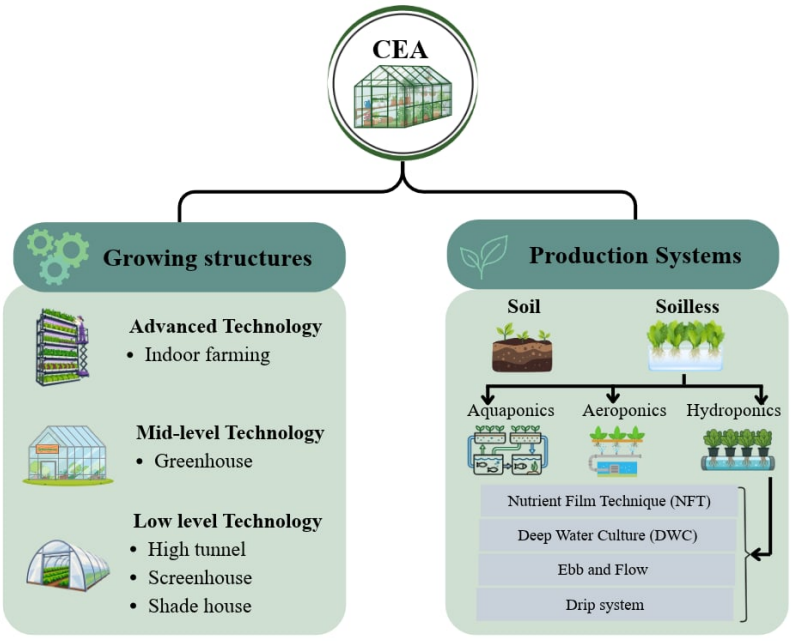

Figure 1. Classification of CEA based on growing structure and production systems [25].

Environmental control systems are the operational heart of any CEA facility, managing the physical variables that most directly influence plant physiology. The lighting system is configured to emit a light spectrum that is optimized for plant growth, mainly through red and blue wavelength lights [26]. Temperature, carbon dioxide, oxygen levels in the root zone, and humidity, among other environmental factors, should be considered [24]. Environmental management has implications for food safety through creation of favorable conditions for microorganisms to thrive. High humidity and condensation may facilitate microbial persistence or transfer through droplets, while aerosols and ventilation can introduce or redistribute airborne particles.

3. Contamination Routes

3.1. Water

One of the most significant vectors of contamination in CEA is water. In recirculating hydroponic systems, all the plants in the production unit are connected by the nutrient solution. This creates a big risk of cross-contamination of the system in case a pathogen is introduced to the supply [27]. Through means of a failed source, ineffective treatment or environmental penetration, the pathogen can spread quickly across the entire production system once it is introduced in the system. Gurtler and Gibson [28] affirmed that fresh produce outbreaks have been recurrently caused by contaminated irrigation water, and water quality must be a priority management concern.

3.2. Seeds and Planting Materials

Another route of entry that has been well documented is contaminated planting materials. Contaminated soilless substrates and seeds have been reported to transfer *Salmonella*, *E. coli* O157:H7, and *L. monocytogenes* to the edible portions of microgreens in several studies [29,30]. Seeds can contain pathogens which may survive during germination and throughout the whole growing period until harvesting, when they can contaminate the product before the harvest is handled. Wright and Holden [31] showed that Shiga toxin-producing *E. coli* strains, which had been inoculated onto seeds, grew on microgreens, confirming seed surface contamination as a viable and serious pathway.

3.3. Employees

Human workers are another common contamination source that is underestimated in CEA. A study by Dong and Feng [27] revealed that employees who failed to change their shoes and clothes when transitioning between indoor and outdoor farms brought outside microbes indoors, and shoe swabs had microbial sequence variants consistent with samples of *E. coli* taken from produce; this indicates active foot-traffic-mediated contamination. This risk is increased by poor hand hygiene, the use of the wrong personal protective equipment, and insufficient training of the workers. Hamilton et al. [20] identified training and education as essential factors in achieving good food safety culture in the operations of CEA.

3.4. Equipment and Tools

Unsanitary equipment and tools can harbor and transfer pathogens between plants and production cycles. A case study of an FDA (Food and Drug Administration) inspection of a hydroponic CEA facility reported the absence of cross-contamination control between leaf harvesting activities and production water and the inability to properly record routine cleaning and sanitization of equipment, tools, and buildings [32]. The growth of biofilms on the surfaces of grow channels, pumps, and harvesting tools is especially hard to remove and could act as long-term reservoirs of pathogens like *Listeria monocy-*

togenes [33]. Hamilton et al. [20] highlighted the importance of implementing standard operating procedures and taking into account the design of hygienic equipment to ensure a safe production environment.

3.5. Pests

Pests like insects, rodents, and birds also serve as meaningful contamination vectors, even within enclosed structures. Aphids are examples of insects that typically feed on plants, and they have been known to pick up *Salmonella enterica* on contaminated lettuce surfaces and transmit it to other plants when they move and feed [34]. Insects like flies and birds can access CEA facilities through ventilation holes or when workers enter the facility. Dong and Feng [27] reported the presence of *Salmonella* and *E. coli* in a hydroponic tomato facility and concluded that entry of wild birds into the facility was a contributing factor to the presence of these bacterial species, which supports the importance of physical exclusion strategies in an otherwise controlled environment. A research project by Orozco and Iturriaga [35] examined a commercial greenhouse with a fully closed hydroponic tomato production system, which used chlorinated well water. They found that tomatoes were frequently contaminated with *Salmonella* and *E.coli* but did not contain *Listeria monocytogenes*. Importantly, they showed that floodwater intrusion allowed wild animals (such as opossums, mice, and sparrows) to enter the greenhouses, which were likely sources of transmission to the tomatoes. The table below (Table 1) summarizes the general characteristics of different CEA production systems and their potential exposure to external contamination sources [36].

Table 1. Comparison of major controlled environment agriculture systems.

System	Enclosure	Water and Nutrients	Growing Medium	Potential for Pest, Wildlife, and Human Contact Contamination
Indoor farm (vertical farm, plant factory)	Fully enclosed, with managed environmental conditions	Often recirculating (hydroponic or aeroponic)	Soilless	Lowest exposure to pests and wildlife. Contact concentrated in workers, equipment, and inputs
Greenhouse	Enclosed but vented	Open or recirculating	Soil or soilless	Moderate; pests can enter through vents and openings
High tunnel	Partly open and plastic-covered	Usually open (drip or overhead)	Soil	Greater exposure due to open sides and ends
Screen or shade house	Partially enclosed with insect screens or shade materials	Open irrigation systems	Soil or soilless	Limited physical barrier and exposure depends on the type of mesh size

The contamination chain in CEA starts with the contamination of the production system by pathogens via sources like water, growing substrates, workers, pests, and contaminated equipment as discussed above. Once introduced, pathogens may persist in the system, particularly in recirculating nutrient solutions, growing substrates, roots, and on equipment surfaces. The presence of pathogens can lead to the formation of biofilms [37], which are communities of microorganisms attached to surfaces and surrounded by a protective layer. These structures can support microbial survival and make microorganisms more difficult to remove through routine cleaning and disinfection [38]. A study by Ilic et al. [39] revealed that inoculated *Salmonella Typhimurium* and *Listeria monocytogenes* persisted in the nutrient solution and increased in rockwool and lettuce roots. Their results also indicated the possibility of pathogens being transmitted to the edible parts of lettuce. This poses a

potential risk to consumers, especially if they eat leafy vegetables without washing and sanitizing them (Figure 2).

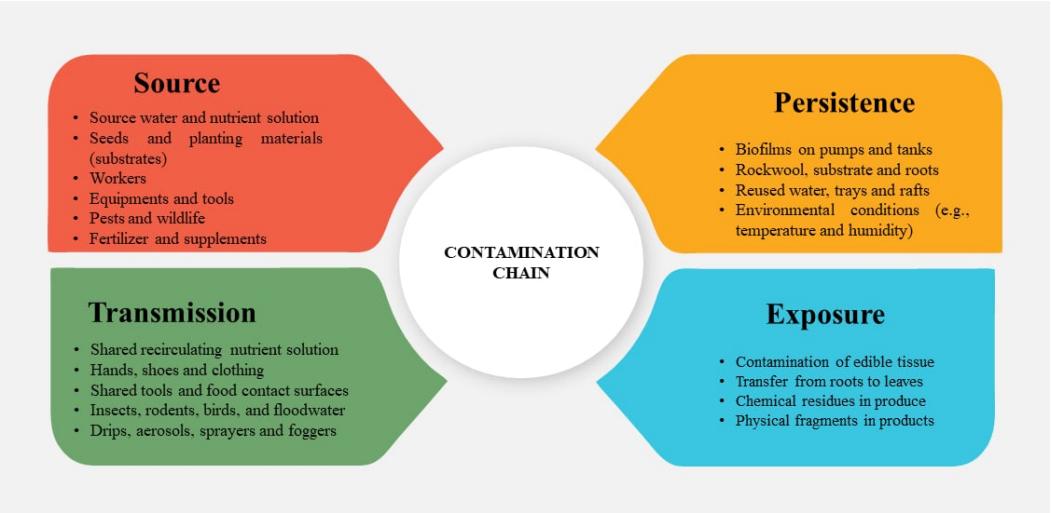

Figure 2. Overview of the contamination chain in hydroponic production systems (the sources, transmission pathways, persistence, and potential exposure routes of contaminant).

4. Food Safety Hazards

4.1. Biological Hazards

Biological hazards are disease-causing microorganisms such as bacteria, viruses, and fungi which can be passed to humans via contaminated food, water, or surfaces [40]. They are of particular concern in food production systems since they cause most of the foodborne illnesses worldwide. The greatest biological hazards in CEA are microorganisms that are capable of living and reproducing in water, with bacteria being the most widespread group of concern.

4.2. Biological Contamination

- *Listeria monocytogenes*

Listeria monocytogenes is an important foodborne pathogen in CEA production. It is a psychrotrophic bacterium capable of surviving and growing at refrigeration temperatures, including approximately 0 °C, allowing it to persist in the cool, moist environments commonly found in indoor growing, packing, and storage facilities. Its growth is not inhibited by normal refrigeration [41,42]. Besides temperature, *L. monocytogenes* can grow and survive in a pH range of 4.3–9.4 under otherwise ideal conditions [18]. The most significant issue is that this bacterium may stick to surfaces and create biofilms, which are thin protective coatings. Such biofilms have the potential to grow on objects frequently utilized in a CEA system, including stainless steel, plastic irrigation pipes, and concrete floors. The bacteria that were once on a biofilm are far more difficult to dislodge due to the layer that protects the bacteria against cleaning chemicals, drying, and disinfectants [18,37].

- *Salmonella* spp.

Salmonella spp. is a type of Gram-negative, non-spore-forming bacteria that are rod-shaped and belong to the Enterobacteriaceae family. They are one of the most significant causes of gastroenteritis in human food-borne illness worldwide, with *Salmonella enterica* subsp. *enterica* being especially significant. The reported lower growth temperature for Salmonella is about 5.2 °C, but most serotypes will not grow below 7 °C; this is affected by strain-specific factors and by environmental conditions [41]. Salmonella can multiply under

conditions with a wide pH range, namely 3.8–9.5, with the highest multiplication occurring around a pH of 7.0–7.5 [18]. Many hydroponic CEA systems use nutrient solutions with a pH of 5.5–7.0 [17] which may allow the survival and growth of *Salmonella*, if environmental conditions are favorable. *Salmonella* have been shown to colonize the surfaces of roots in experimental hydroponic systems and to spread to edible leaf tissues of hydroponically grown lettuce, indicating possible dissemination of the pathogen by contaminated production water [39].

- *Escherichia coli*

Escherichia coli is a type of Gram-negative, non-sporing member of the Enterobacteriaceae family. Genera of the Escherichia family are often referred to as coliforms. All *E. coli* strains are not harmful as the organisms are inherently found in the human gut and in the environment. Due to this fact, *E. coli* detection in foods may indicate the presence of fecal contamination, which is why it is an indicator organism [18]. Shiga toxin-producing *Escherichia coli* (STEC), especially O157:H7, has a very low infectious dose and an epidemiological link with leafy greens that are not cooked [43]. In CEA systems, contamination most commonly arises from fecally contaminated source water or organic amendments, with STEC capable of colonizing the rhizosphere and internalizing within plant tissue [44].

- Norovirus

The human norovirus is the most common nonbacterial gastroenteritis-causing agent worldwide, resulting in 58 percent of all reported food-borne illnesses annually. It causes approximately 900 cases of death a year in the United States alone, mostly in adults aged 65 and above. The virus is extremely infectious and can be transmitted by contaminated food, water, surfaces, and direct contact with ill persons, with outbreaks occurring throughout the year, but with a peak during the months between November and April [45]. DiCaprio et al. [46] studied the internalization and dissemination of human norovirus in hydroponically grown lettuce and spinach. They found that human norovirus RNA could infect the root system and be found in the upper parts of the plants (shoots and leaves) for the duration of the experiments. These results provide evidence of internalization and persistence of viral genetic material in plant tissues but do not establish on their own that the virus remained infectious in them. However, these studies emphasize the possibility of human norovirus contamination of the hydroponic water used to grow leafy vegetables.

4.3. Chemical Hazards

Field crops are exposed to chemical hazards via pesticides, industrial chemicals, pollutants, or even soil, where they may accumulate heavy metals [36]. In indoor farming, the majority of chemical hazards are monitored which minimizes their risks, though they are not completely removed. Chen et al. [47] conducted a study to evaluate the level of pesticides or heavy metal contamination of lettuce, celery, tomatoes, and cucumbers produced using hydroponic and conventional systems. The findings revealed that, despite lower contamination levels of hydroponic produce, pesticides were found to have residual traces in 30 percent of samples, and heavy metals, particularly lead, continued to be present in all crops. An unusual chemical contamination incident in CEA detected mercury concentrations of up to 10.0 ppm in curly kale cultivated in a commercial vertical indoor hydroponic farm in Singapore, exceeding the applicable Singapore regulatory limit of 0.05 ppm. Through chemical analysis of vegetables, farm inputs, and environmental samples, the researchers identified the polyurethane encapsulant of the LED lighting equipment used in the facility as the source of mercury contamination. Further characterization of the encapsulant revealed the presence of mercury, which the authors associated with the

use of mercury-based catalysts during polyurethane manufacturing. This means that this type of chemical risk is still possible in produce that is cultivated using CEA systems [48].

4.4. Physical Hazards

Physical hazards are foreign bodies which can cause injury when ingested, and most physical hazards lead to choking, lacerations, or broken teeth. Foreign objects are the most easily noticeable sign of product contamination and are therefore most often identified through production checks. Nevertheless, they are likely to affect fewer people compared to chemical or biological risks due to the fact that the incidents are often isolated and not systemic [49]. Physical hazards in CEA can include glass, metal, plastics, or wires which can come from the equipment used or infrastructures [36].

5. Mitigation Strategies

For effective food safety management in CEA, mitigation measures at various stages of the production process need to be implemented. The mitigation measures in this case include pre-germination seed treatments, water and irrigation treatments, growing substrate management, sanitation procedures, waste disposal, water hygiene, and pest management. Microbiological testing and validation are important in all of the above aspects in order to ensure compliance with food safety standards, as stipulated by regulations such as the FSMA Produce Safety Rule [50]. Several chemical and physical methods have been evaluated to reduce microbial contamination of agricultural production. However, the efficacy and potential toxicity of these methods vary with the crop species, seed characteristics, microorganisms being targeted, organic matter, pH, water quality, treatment concentration and treatment duration. Hence, the treatment conditions mentioned in the individual studies are not meant to be considered as recommendations for CEA operations.

5.1. Biological Hazards

5.1.1. Seeds

- Chemical Treatments

Studies related to chemical treatments, especially chlorinated agents, hydrogen peroxide, peroxyacetic acid, and chlorine dioxide, have been conducted more widely to reduce microbial contamination on seeds intended for sprout production. A treatment involving calcium hypochlorite solution at 20,000 ppm (2% Weight/Volume) for 20 min has been found to reduce *Salmonella* and *E. coli* O157:H7 by 2–5 log CFU/g (Colony-Forming Units) in alfalfa and other sprout seeds in many studies [51,52]. There are limitations such as inefficiency against certain seeds due to their surface structure, organic material content, and pathogen internalization, as well as residual chlorine which affects seedling development at high concentrations [51]. Hydrogen peroxide (H_2O_2) treatments have been evaluated as an alternative method to microbial decontamination of alfalfa and radish seeds. The combined treatment of warm water (50 °C) followed by 2% hydrogen peroxide with 0.1% acetic acid resulted in reductions of at least 3 log in *E. coli* O157:H7, *Listeria monocytogenes* and *Salmonella enterica* without seed quality loss [53]. Apart from chemical treatment, seeds can be treated using physical methods to remove microbial contaminants.

- Physical Treatments

Hot water treatment (HWT) is a physical decontamination process for seeds that uses elevated temperatures for microbial decontamination. For small-seeded vegetable crops including tomato, pepper, cabbage, broccoli, cauliflower, carrot, celery, and lettuce, exposure to temperatures between 48 and 50 °C for 20–30 min has been shown to effectively inhibit bacterial and fungal pathogens without impacting germination rates [54]. Physical

treatments can also be combined with chemical treatments to enhance microbial inactivation. For example, Bari et al. evaluated a combined treatment in which mung bean seeds were exposed to hot water at a temperature of 85 °C for 40 s, followed by chlorine treatment, and reported effective inactivation of *E. coli* O157:H7 and *Salmonella Enteritidis* without significantly affecting seed germination [51]. Nevertheless, although such results appear promising, the technology needs to be tailored to each crop to avoid seed damage that would impact germination.

- Biological Treatment

Bacteriophages (or phages) are naturally occurring viruses that selectively lyse and kill bacteria without impacting plant and animal cells. In seed production, bacteriophages have been explored as an alternative to chemical sanitizers to control seed contamination with bacteria that may be able to quickly multiply during seed germination used for sprouting. For instance, a commercial six-phage cocktail (SalmoFresh) at 10^8 PFU/mL (Plaque-Forming Units) was tested on romaine lettuce, mung bean sprouts and mung bean seeds contaminated with 10^5 CFU/mL of *Salmonella*. The study showed that *Salmonella* on lettuce and sprouts was reduced by about 2.4 and 2.2 log CFU/g, respectively, by immersion in phage solution [55]. However, the phage treatment was ineffective in controlling Salmonella contamination on mung bean seeds and in sprouts subsequently produced from those seeds. These reductions reflect surface decontamination of treated produce rather than control of seedborne contamination. Similarly, Fong et al. [56] reported that the *Salmonella Enteritidis* count on artificially contaminated alfalfa seeds decreased by approximately 2.51 log CFU/g after treatment with the phages. The pathogen reduction, however, was not statistically significant during the germination period, indicating that reducing the pathogen levels through this treatment might not be enough to maintain pathogen control. While seed treatments are important for reducing the initial introduction of pathogens, maintaining the cleanliness of the growth substrate is equally important.

5.1.2. Growth Substrates

Growth substrates such as rockwool, expanded clay, coco coir, perlite, and organic media used in hydroponic systems can be a source of pathogen contamination within the growing process [38]. Evidence of the efficacy of chemical treatment of substrates against human pathogens is limited. A study conducted by Mensah et al. [57] on plastic surfaces of nutrient film technique systems using chlorine-based sanitizers (bleach at a concentration of up to 200 ppm and chlorine dioxide) showed that they did not eliminate *Salmonella Typhimurium* and were mostly statistically similar to water, whereas peroxyacetic acid-based products (SaniDate 12.0 at 200 ppm and Zerotol at 5%) eliminated it. These tests were conducted on inanimate surfaces, not porous substrates, and adding the sanitizers to the nutrient solution reduced lettuce and basil yields. Sodium hypochlorite has also been evaluated for sanitation of peat-based substrates, although organic matter in the substrate can reduce the availability and efficacy of chlorine-based sanitizers [58].

5.1.3. Water

- Chemical treatment

Chemical oxidants are commonly used to disinfect irrigation water and nutrient solutions in hydroponic systems. The most common disinfectants used in recirculating hydroponic crops are chlorine compounds such as sodium hypochlorite (bleach) and calcium hypochlorite, that effectively control a wide spectrum of bacteria, viruses, and fungi at free chlorine concentrations ranging from 1 to 5 ppm [59]. Chlorine-based disinfectants are effective against a broad range of microorganisms, although their efficacy varies among

pathogen species. Ozone is a highly reactive oxidizing compound which has been studied as an antimicrobial seed and sprout treatment. Mohammad et al. [60] tested ozonated water with acidic electrolyzed water (AEW) against *Salmonella* and STEC on inoculated alfalfa seeds and sprouts. Seeds were soaked in ozonated water (5 mg/L) for 15 or 20 min, then soaked in AEW for 15 min. The combined treatment effectively ($p < 0.05$) reduced *Salmonella* and STEC by 3.6 and 2.9 log CFU/g on seeds, and by 3.1 and 3.0 log CFU/g on sprouts, respectively, without causing any quality alteration in the sprouts. These results come from artificially inoculated alfalfa under laboratory conditions and concern surface treatment of seeds and sprouts, so they cannot be extended to pathogen control in irrigation water or nutrient solutions.

- Physical treatment

Ultraviolet-C (UV-C) irradiation is a physical method used to disinfect recirculating irrigation water. It can effectively inactivate bacteria, viruses, and some protozoa without introducing chemical residues or substantially altering the composition of the nutrient solution. Studies have been conducted to determine the effectiveness of UV-C in reducing microbial loads. Moore et al. [61] reported *E. coli* reductions of about 1.4–1.5 log CFU/mL using UV-C radiation at 254 nm. Likewise, Correa et al. [62] showed that a reduction of about 1.7 log CFU/mL was obtained after treatment with UV-C radiation at 254 nm in static mode. Suspended particles and dissolved organic matter in the water absorb UV radiation and serve as a physical shelter for microorganisms; these are the main factors that limit UV disinfection of recirculating nutrient solution [59]. Implementing Good Agricultural Practices is important for maintaining water quality and supporting the effectiveness of water disinfection measures such as UV-C irradiation.

5.2. Chemical Hazard Management

Controlled environment agriculture relies on a range of chemical inputs, including fertilizers, nutrient solutions, sanitizers, and pesticides. Although these inputs are important for crop production and sanitation, their improper use can introduce chemical hazards to edible crops. The possible hazards include nutrient accumulation, residue of pesticides, residue of sanitizer/by-products of sanitizer, contamination of water and contamination of other production input [47]. Rocha et al. [63], for instance, showed that the form of nitrogen supplied in hydroponically grown lettuce affected the nitrate content of the leaves, with higher nitrate levels observed when nitrate was the only nitrogen source. This highlights the need to properly manage nutrient inputs to control nitrate build-up in lettuce. In the same way, Chen et al. [47] found pesticide in vegetables both in hydroponic and conventional systems, so there is not an absolute hydroponic production system that eliminates the chance of pesticide contamination. Chemical hazards can also be caused by water and nutrient sources. Additionally, sanitation practices can also create chemical hazards. Tham et al. [64] reported that hydroponic systems must be properly flushed after the use of sodium hypochlorite to prevent the accumulation of chlorate in the nutrient solution and in plants. These results suggest the need to use suitable chemical inputs, to apply these inputs at recommended rates, to monitor water and nutrient solution quality, to keep records of chemical input use, and to minimize chemical hazards through proper storage and handling methods in CEA systems.

5.3. Physical Hazard Management

Physical hazards have been identified as food safety concerns within CEA systems, although documented cases involving physical contaminated produce remain limited. In hydroponic greenhouse production, identified physical hazards include broken trellis wires, springs from damaged equipment, loose nuts and bolts, and broken glass from greenhouse

structures [65]. Similarly, Buscaroli et al. [66] identified infrastructure-associated materials, including plastics, as potential hazards in vertical farming, while Tan et al. [67] highlighted the possibility of materials such as microplastics and asbestos being deposited onto crops from overhead structures and equipment. These findings indicate that equipment deterioration, structural damage, and inadequate facility maintenance represent plausible physical contamination pathways in CEA. Practices for prevention include regular inspections and maintenance of growing systems, as well as correct handling and storage of tools and equipment, with appropriate use of protective covers to keep production and packing areas clean. Appropriate monitoring and corrective actions assist in minimizing the likelihood of physical contamination [50].

5.4. Good Agricultural Practices

Good Agricultural Practices (GAPs) are a fundamental food safety risk management control strategy in CEA systems to reduce biological, chemical and physical risks throughout the production process. These practices include water quality management, worker health and hygiene, cleaning and sanitation of equipment and facilities, proper handling and storage of production inputs and environmental monitoring. These practices are critical in preventing pathogen introduction and dissemination [20]. Evidence from commercial hydroponic systems suggests these practices are important. A Salmonella outbreak investigation in leafy greens from an indoor hydroponic CEA facility in 2021 revealed several possible deficiencies in food safety practices, such as failing to recognize hydroponic water as agricultural water, condensate dripping from equipment, and improper storage of growing media and pallets. Poor employee practices, equipment maintenance, and cleaning and sanitation were also identified as potential risk factors [32]. Practices highlighted in GAPs are consistent with the principles of risk-based preventive principles, as outlined in the FSMA Produce Safety Rule, designed to reduce the risk for contamination in fresh produce production and ensure the production of safe fresh produce [50].

The implementation of FSMA and GAPs in controlled environment agriculture (CEA) presents distinct adaptation challenges. For FSMA, a major challenge involves determining how existing regulatory requirements apply to the specific infrastructure and production activities of CEA operations. Although the Produce Safety Rule establishes requirements for covered produce farms, existing food safety guidance may not adequately address all the specific characteristics of hydroponic production systems [68]. Similarly, the challenge with GAPs lies in translating general agricultural food safety recommendations into practical procedures suitable for different CEA production systems. Although hydroponic-specific GAPs guidelines are available, their implementation requires consideration of the particular production practices and operational characteristics of these systems [69]. Furthermore, the limited availability of validated food safety interventions under commercial hydroponic production conditions highlights the need for further research and the development of more CEA-specific food safety guidance [68].

- Personal Hygiene

Maintaining good personal hygiene by workers is a good practice to mitigate pathogens in CEA systems. Basic hygiene measures, including frequent hand washing, wearing clean protective clothing and gloves, covering cuts and wounds, and avoiding working when ill, can significantly decrease the chance of contamination of fresh produce [36]. Evidence from the food safety literature demonstrates that inadequate hand hygiene can facilitate pathogen transfer and contribute to food contamination. A review of 816 foodborne outbreaks involving food workers identified failure to properly wash hands as one of the most frequently reported factors associated with worker-related outbreaks, following bare-hand contact with food [70]. Experimental research further demonstrated that inadequate

hand hygiene can facilitate the transfer of Escherichia coli from workers' hands to fresh produce, including hand-harvested carrots, highlighting the potential for contaminated hands to directly introduce pathogens during produce handling. Similarly, a quantitative microbial risk assessment of produce harvesting and packing showed that inadequate handwashing by workers potentially infected with norovirus could result in contamination of lettuce, tomatoes, and raspberries, whereas high handwashing compliance substantially reduced predicted produce contamination and consumer infection risk [71].

- Waste Management

Effective waste management is an important component of food safety management in CEA systems. Plant residues, discarded or spoiled produce, spent growing media, and other organic waste can serve as reservoirs or vehicles for microorganisms and contribute to cross-contamination [36]. Findings from previous studies in a commercial hydroponic production demonstrates the potential importance of growing media as a microbial reservoir. Dankwa et al. [38] found that postharvest peat-moss substrate had high populations of aerobic bacteria, coliforms, yeasts, and molds, while harvested lettuce had substantially higher aerobic plate counts than preharvest lettuce, suggesting microbial transfer from the root ball and substrate to edible leaves during harvesting and/or packaging. Similarly, Huang et al. [72] demonstrated that contaminated organic matter enhanced bacterial transfer to fresh-produce surfaces by approximately 1 log unit compared with bacterial cells suspended in wash water alone, highlighting the potential role of organic residues in facilitating cross-contamination. Effective waste management combined with good cleaning and sanitation practices can improve the quality of crops grown in a CEA.

- Sanitation

Regular cleaning and sanitation of production equipment, water distribution systems, and food-contact surfaces are important preventive measures for controlling microbial contamination in CEA systems. This is particularly important in hydroponic systems, where biofilms can develop on system surfaces and provide opportunities for pathogen persistence and colonization. Tham et al. [64] identified biofilm-producing bacteria in commercial indoor NFT (Nutrient Film Technique) hydroponic farms that promoted the binding and colonization of Salmonella on PVC surfaces. The research also revealed that under the conditions tested, sodium hypochlorite was more effective at removing biofilms than hydrogen peroxide and sodium percarbonate. Likewise, Zhu et al. [73] demonstrated the synergistic effect of sodium dodecyl sulfate and citric acid was found to be very effective in eliminating Salmonella biofilms on PVC (Polyvinyl Chloride) pipes in hydroponic systems, with a reduction of over 5.6 log CFU, compared with substantially lower reductions when either compound was used individually. These findings underscore the need for periodic cleaning in CEA systems to manage biofilms and limit pathogen persistence and cross-contamination. Warriner et al. [36] has identified five steps for an effective sanitation process. First, use brushes and shovels to remove the plant debris and unwanted material, use a proper detergent to remove any leftover dirt and organic material, rinse to remove detergent residue, apply sanitizer at the proper concentration with the proper contact time, and then rinse with potable water if needed. These steps, along with regular sanitation schedules and employee training, can help to reduce cross-contamination and ensure safe production.

5.5. Emerging Technologies for Food Safety

As technology advances, new tools are being utilized in CEA to enhance monitoring and food safety management. Continuous monitoring of environmental and production parameters can be achieved using sensor-based systems. Internet of Things (IoT) technologies,

artificial intelligence (AI), machine learning, and data analysis can help process these data to detect deviations and assist with early intervention [74,75]. In CEA, the large amount of data generated can be leveraged by AI for risk-based monitoring and adaptive sampling to support timely food safety interventions [74]. Sensor-based systems can also provide rapid detection of foodborne pathogens in hydroponic production environments. For example, Qian et al. [76] combined an impedimetric electrochemical aptasensor with machine learning to improve detection of pathogenic E. coli O157:H7 in water used for hydroponic lettuce irrigation. Similarly, Cavallaro et al. [77] developed a laser-induced graphene aptasensor for detecting Listeria monocytogenes in hydroponic water, achieving approximately 86% accuracy and a detection limit of 10 CFU/10 mL. These studies demonstrate the potential of integrating biosensors with advanced data-analysis approaches for more rapid pathogen monitoring in CEA. Despite these benefits, cost barriers, skill requirements, data management, and integration issues may limit adoption. Integrating these technologies with preventive food safety systems has the potential to enhance hazard monitoring and improve the consistency and responsiveness of food safety management in CEA [20,36].

6. Conclusions

CEA can enhance land and water productivity and allow for all-season production of fresh produce. But food safety hazards cannot be eliminated by controlled production conditions. Biological hazards may be introduced and spread by recirculating water and nutrient solutions, seed, growing substrates, workers and pests. Chemical hazards, such as heavy metals, residues of pesticides, nitrate buildup, and by-products of sanitizers also need to be controlled, along with physical hazards like plastic, metal, glass and damaged equipment. All of these risks can be reduced during the production process by implementing Good Agricultural Practices (GAPs), as well as water treatment, appropriate seed and substrate handling, cleaning and sanitation, health and training of workers, pest control, and environmental monitoring. However, the effectiveness of individual control measures may vary depending on the characteristics of each CEA system, highlighting the importance of combining multiple preventive measures to minimize contamination risks throughout production. New technologies like sensors, biosensors, artificial intelligence and digital traceability could also help in food safety monitoring and early detection, but still need to be validated for use in commercial CEA systems. Several research gaps remain in CEA food safety. Guidelines on food safety must be tailored and validated for various CEA systems such as hydroponic, vertical, aquaponic and greenhouse production. Although the various food safety frameworks already in place for traditional agricultural production offer a useful starting point, they might not necessarily be representative of the unique challenges of CEA, especially the recirculation of water and nutrient solutions and the potential for spreading contamination across separate yet interconnected production systems. Chemical and physical hazards have not been given the same focus as microbial hazards and are worthy of further investigation. In addition, emerging technologies need further evaluation to determine their accuracy, reliability, and practicality for commercial food safety management. Further studies under commercial production conditions are also required to evaluate the effectiveness and repeatability of the integrated preventive measures and to provide evidence-based food safety recommendations for CEA systems. Addressing these gaps will support the development of effective food safety practices and the production of safe fresh produce in CEA systems. As a foundation for food safety management, CEA producers are encouraged to follow existing FDA guidance, including the Guide to Minimize Microbial Food Safety Hazards for Fresh Fruits and Vegetables [40] and applicable requirements under the FSMA [50], while adapting these practices to the specific characteristics of CEA systems.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
AEW	Acidic Electrolyzed Water
CEA	Controlled Environment Agriculture
CFU	Colony-Forming Units
FDA	Food and Drug Administration
FSMA	Food Safety Modernization Act
GAPs	Good Agricultural Practices
HWT	Hot Water Treatment
IoT	Internet of Things
LED	Light-Emitting Diode
NFT	Nutrient Film Technique
PFU	Plaque-Forming Units
PVC	Polyvinyl Chloride
STEC	Shiga Toxin-Producing *Escherichia coli*
UV	Ultraviolet
UV-C	Ultraviolet-C

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