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Review

Beyond Efficiency: The Social and Ecological Costs of Plant Factories in Urban Farming—A Review

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Abstract: Ever-growing cities constantly increase the distance between suburban regions and semi-urban areas on the perimeter of the cities, where traditional crop production can take place with relatively fewer restrictions. The implementation of ultra-short supply chains implies moving the means of crop production as close to inhabitants as possible. Two main directions can be identified as effective for increasing the food resilience of densely populated suburban areas; these are soil-based traditional urban agriculture and high-tech plant factories. Both approaches to crop production offer a certain level of integration with the built environment; however, these alternatives differ in terms of their contributions to environment modulation, agrobiodiversity, social well-being, and food resilience. Vertical farms can produce a high amount of nutritionally rich crops for direct use, although the involvement of inhabitants is minimal; therefore, they can be considered a service function without social advantages. Open-field plant production can contribute to the well-being of locals, but the yields are considered rather supplementary. The combination of both production approaches to strengthen common advantages is less likely; automated production technologies require a low number of highly qualified personnel; therefore, community plant factories cannot be considered possible contributors to urban social well-being in the future.

Keywords: agrobiodiversity; living soil; microbial diversity; controlled-environment agriculture (CEA); organic farming

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1. Introduction

1.1. Definitions and General Comparison

By 2018, the world's human population living in urban areas exceeded 55 percent, and it is further expected to reach 70% by 2050 globally [1]. Although this percentage varies highly, according to geographical locations (e.g., compared to North America (82%), Hungary has over 70% of its inhabitants living in urban environments, while Ethiopia has only 23% [2]), it illustrates well that more and more people live in an environment where nature is closed out and vital ecological processes are hidden from view [3]. A possible bridge reconnecting urban societies with nature is urban agriculture (UA), which is the re-exploration of food production [4] activities within cities and in densely populated built environments.

UA covers all activities related to plant/animal-based food production, processing, and distribution performed in or around cities [5–7]. Other definitions also mention the environmental and social functions of UA that support local economies [8–10].

Urban farming can provide several benefits for the environment and society. Being multifunctional, UA supports food security and reduces environmental pollution, but it also has implications at the societal level by promoting healthy lifestyles, serving educational purposes, and creating and sustaining local communities [10,11]. Water conservation, energy savings, reduced air pollution, strengthened community ties, improved economic well-being, and the revitalization of low-income neighborhoods have all been attributed to urban farming as well [12,13]. At the same time, special limitations and threats apply to open-field urban forms of food production, such as land/space constraints, air and soil contaminants, water scarcity, pest and disease pressure, engagement of practitioners, lack of knowledge, and seasonality [13–20].

Challenges and harms jeopardizing the qualitative and quantitative traits of UA production have led to innovative solutions in both science and technology [21]. This has led to a division of UA into the categories of uncontrolled-environment agriculture (UEA) and controlled-environment agriculture (CEA) [7,22]. UEA, often referred to as traditional urban agriculture (TUA) [23], includes all food production in open spaces, such as rooftop gardens, community gardens, and private gardens, while CEA is generally isolated from the natural environment. A slightly overlapping category of innovative urban agriculture (IUA) was defined by Armanda et al. [21], including all urban food production activities, irrespective of the space being open or closed, which applies any kind of recent agricultural technological innovation, such as soilless production, vertical alignment, remote control, digital sensors, or grow-light recipes.

The functions of UA are generally different in certain parts of the world. Studies show that UA has a considerable contribution to the daily food demands of urban citizens in developing countries [24], while in developed countries, UA rather serves to fulfill social functions [21]. On the other hand, in developed countries like the USA and Canada, UA can contribute significantly to the food security of marginalized communities [25]. Typically, low-income social groups, but not the poorest, participate in UA practices [5].

1.2. Background

1.2.1. Present and Future Prospects of Traditional Urban Gardens

The history of urban gardens goes back thousands of years [26]. These gardens were basically created to produce food, herbs, and medicinal plants, but over time, they have also served cultural, social, climatic, and aesthetic functions [27–31].

The narrow, open spaces of medieval towns and cities, surrounded by walls, provided few possibilities for gardens of ornamental value, and even gardens for food production were usually pushed behind the city walls because of a lack of space [32].

Renaissance gardens and the evolution of cities, especially their breaking out of tight walls, allowed gardens to expand and become larger and more decorative. The tradition of urban gardens in Russia is closely linked to the food supply, especially in harsher climatic, economic, and political conditions. Dacha gardens were particularly important in the Soviet era, as backyard food production and self-sufficiency allowed families to grow fresh vegetables, fruit, and herbs even in economically difficult times [33]. Victory gardens played a somewhat similarly important role in the development of the idea of modern urban gardens during the Second World War in the USA, as they ensured food supplies during the war [34]. Urban gardening, as the descendant of victory gardens [35], is still present today in the form of community gardens, which serve for both food production and, now, the additional function of the sustainability of community life, and perhaps surprisingly, ornamental function is hardly ever a feature. Some community gardens promote social relations among residents, while others focus on the cultivation of food, primarily vegetables and spices, but the amount of produce is by no means a complete supply; rather, such gardens were created for the purpose of maintaining a lifestyle [36].

The demand of maintaining community gardens is persistently increasing, especially in the post-COVID era, when social and ecological functions have been re-evaluated [37,38]. Their outstanding role in urban climate mitigation and biodiversity enhancement is now well recognized, as these factors are also involved in education and in promoting social awareness [39]. The constant development of analytical science, especially in terms of urban pollutant sources, highlights the actual extent of threats impacting human health through TUA; incentives for reducing environmental pressure are, therefore, of high priority [40]. At the same time, limitations in terms of available space underline the need for supportive policies for green spaces among stakeholders [41].

1.2.2. Present and Future Prospects of Plant Factories

Today's modern vertical farms, or plant factories, are often seen as the successors to earlier urban gardens. However, their purpose is different from that of historical gardens and today's community gardens. Food production in a concentrated, artificial environment does not fulfill community but, rather, market goals; it serves to replace shrinking agricultural areas and convert modern technologies into food [42].

The very first step in the evolution of plant production in controlled environments was taken by, among others, W.F. Gericke [43] with the suggestion to produce plants in nutrient solutions. By the end of the 1980s, hydroponic technology was completely developed and utilized for year-round plant production [44]. The next significant step towards mass production was the suggestion to stack plant production shelves on top of each other, creating the term "vertical farming" [45]. With Agriculture 3.0, the 2000s brought novel technological solutions, such as LED grow-lights, sensors, and automated climate control [46]. By 2010, professional, profit-oriented companies started to invest in plant factories in several parts of the world [47].

Plant factories have been recognized as a viable contributor to urban agriculture, especially in regions with limited arable land. CEA systems vary significantly across different regions, influenced by local needs, technological advancements, and market dynamics. The U.S. and Canada emphasize local production, and Europe focuses on optimizing yield and quality, while Japan prioritizes food safety and advancing production technology, reflecting distinct regional food trends and supply-chain dynamics [48].

Europe is witnessing a rapid increase in vertical farms, including various types, such as PFALs (plant factories with artificial light), container farms, and in-store farms, although the overall number remains limited [49].

In Asia, vertical farming has been embraced as a solution for land-scarce regions. [50]. For example, China is witnessing a mixed reception of these systems, primarily due to high operational costs and low market penetration, despite increasing consumer acceptance [51]. Countries like China and Japan are leading in the implementation of PFALs, primarily producing herbs and leafy vegetables in urban settings [52].

Indoor vertical farming seems to be a viable solution in Africa, highlighting countries like South Africa, Seychelles, and Egypt for their sustainability potential while addressing challenges such as high initial investments and resource availability for successful implementation [53]. However, climate change and resource shortages are still challenges [54], similar to maintenance and sociocultural perceptions [55], advocating for policy initiatives to support urban vertical gardens for food production.

While vertical farming offers numerous benefits, challenges such as high energy costs and the need for technological investment may hinder its widespread adoption in South America [56].

In Australia, despite its sparse population density and abundant sunlight, factors like labor shortages, water scarcity, and increasingly unpredictable weather patterns make traditional farming challenging. Vertical farming is relatively underdeveloped, but annually, it is rapidly growing. According to the 2023 Protected Cropping Australia (PCA) conference, vertical farming is not intended to replace existing methods but to work alongside them, enhancing food resilience by offering year-round production and efficient resource use [57].

The challenges can also be grouped by climatic conditions. The system may face high energy demand in warm climates due to the energy demand for cooling, while in temperate or cold regions, such demand applies to heating. Higher water demand may occur in arid climates, but high humidity can be problematic in humid areas [58].

These challenges suggest that vertical farms need tailored solutions that consider regional energy infrastructure, crop demands, and economic conditions to sustainably scale across diverse regions.

Research continues to focus on optimizing growth conditions, energy efficiency, and crop yield [59]. The most recent topics cover grow-light settings, technological innovations towards automation, the daily life integration of CEA systems, and the specialized application of advantages provided by total independence from environmental factors [60,61]. Now, detailed scientific data are available concerning the applicability of grow-light programs targeting enhanced vegetative development or phytonutrient synthesis, as well as increased post-harvest characteristics [54,62,63]. Continuous innovation in the monitoring and automatization of CEA systems is experienced [64,65], which reduces human interaction but requires highly skilled personnel at the same time. The modularity and network connection of CEA units enable highly tailored design according to urban environments and consumers [66,67]. Speed breeding and bioproduction are only two of the many applications that support plant-related scientific innovation in CEA systems [68,69].

1.3. Aims of the Study and Hypothesis

High-tech solutions, such as plant factories, are becoming more and more popular, and research directions benefiting from all controlled environments generally envision that open-field urban production forms will be overridden by CEA in the future [51,64,70–72]. Although the advantages of urban community gardening are well explored, their fragility concerning innovation is less researched. Therefore, the aim of this narrative review is to shed light on those aspects that are under threat when open-field UA is intended to be replaced by plant factories.

The hypothesis of the study is that the losses caused by breaking the direct link between urban agriculture and the natural, uncontrolled environment results in serious losses in terms of both productivity and societal functions.

2. Materials and Methods

2.1. Methodological Criteria

Bibliographical databases (ScienceDirect, Scopus, Web of Science, Google Scholar) were used for the preparation of this narrative review. In the last three decades, a significant technological advancement in CEA and a notable reposition in the functions of TUA were experienced; therefore, publications published preferably in the period of 1990–2024 with relevance to at least one discussed topic were considered for inclusion. The definition of this timeframe also ensured high-quality and recent findings as the foundation of this review. The applied keywords covered the selected topics of the research in connection with urban gardening and controlled-environment agriculture.

Topics were selected as representing the key areas where UA likely contributes to a higher extent to human health, nutrition, and well-being, as well as to maintaining a natural living environment, in contrast with CEA systems. Fundamental goals and underlying theories create substantial differences between urban agriculture and plant factories; the holistic approach leads to significant variations in factor analysis. The selected topics are agrobiodiversity, links to living soil, abiotic, and biotic stress impacts, plant protection challenges, and sociological functions.

This narrative review aims to provide a scientific summary of the above-mentioned aspects based on the available literature, together with the authors' own interpretation [73]. Unlike systematic or comprehensive reviews, this study did not follow a strict methodology or structure to minimize bias [74], with the aim of encouraging peers to comment on the suggested issues.

2.2. Limitations

The main limitation that arose from the aim of this article was to elucidate the aspects that are less discussed on a scientific level and that are non-transferable features of open-field urban farming practices. Therefore, well-researched topics such as technological innovations, resource (energy, water, and nutrient) use efficiency, or financial profitability are not discussed in detail here. The genre of this paper also does not necessitate a balanced and in-depth analysis of all aspects of a given situation to generate discussion; this fact can be interpreted as a limitation for the sake of constructive debate. However, according to the intentions of the authors, a high number of references, including research papers, case studies, and review, were included in this study.

Throughout the synthesis of the available literature, a shortcoming of the topic is the non-consistent use of terms and concepts related to both CEA and TUG, especially in terms of abbreviation use and uncategorizable forms of urban farming.

3. Results

UA is undoubtedly capable of contributing to the supply of urban dwellers as a supplementary source of food produce in addition to peri-urban agricultural facilities [75]. Numerous locations, both free, open spaces and building-integrated ones, provide countless possibilities for plant production, revitalizing empty urban lots, brownfields, or unused building structures [76]. Urban forms of plant production can be categorized in many ways, such as by scale size, plot size, investment demands, social–ecological scale, level of building integration, or business model [77]. A possible categorization of urban farming models is provided in Table 1.

Table 1. Different forms of urban farming categorized according to the level of utilization and investment costs.

Level of Utilization	Investment Costs/Technological Level		
	Low	**Medium**	**High**
Individual	Backyard gardening Window boxes Container gardens	DIY hydroponics Walipini	Mini-plant factory
Interpersonal	Raised bed gardening Guerrilla gardening	Rooftop gardening Community gardens Indoor gardens	Vertical gardening Skyfarming Hydroponics Digeponics Aquaponics
Collective	Urban orchards Pocket gardens	Miyawaki forests	

Basic aspects of the comparison of TUA and CEA systems, highlighting their main differences based on scientific references, are provided in Table 2.

Table 2. Basic aspects of the comparison of traditional urban agriculture and controlled-environment agriculture.

	Traditional Urban Farming	**Controlled-Environment Agriculture**	**References**
Economic aspects			
Investment costs	Low	High	[78]
Area needed for same amount of product	30 times higher	Lower due to continuous production and climatic independence	[79]
Facility and initial resources needed	Simple tools and abundantly available resources, relatively easy design	High-tech tools and devices, special facility	[80]
Labor demands: professional skills, work hours, costs, etc.	Low (non-professionals), skills easy to learn, voluntary work	Specially skilled, highly experienced personnel needed	[3,81–87]
Level of crop production intensification, expected yields	Extensive production	Highly intensified yield maximization due to high costs	
Vulnerability of the system	Vulnerable to environmental challenges	Highly regulated, heavy reliance on technology	[88,89]
Primary objective	Self-sufficiency, social aspects	Profit	[42,90–92]
Food produced			
Product value	Product utilized by plot owners	High productivity per unit area	[93]
Trust in the produced food	High (self-grown)	High or low (artificial conditions)	[94,95]
Nutritional value	Higher levels of antioxidants due to environmental stress, provides diverse diet	Can be manipulated by fine-tuning the environment	[90,95]
Food waste	Low due to emotional connection to the food	Possibly slightly higher	[89,96,97]
Social aspects			
Power in local communities	Common aims contribute to strengthening local communities	Service-like production, low involvement of locals	[4]
Employment	Seasonal production, free work	Providing permanent employment, salary	[98]

Table 2. *Cont.*

	Traditional Urban Farming	Controlled-Environment Agriculture	References
Economic aspects			
Participants in production	Large number of often lay participants, conflicts may arise	Skilled workers specialize in different roles, aim to reduce human labor to minimize costs	[99–101]
Characteristics of cultivation			
Growing media	Natural compound-based media or genuine soil	Soilless cultivation (-ponics)	[102–107]
Plant protection	Challenging, weeds less threatening due to small-scale, highly labor-intensive methods	Sterile environment required, infections and weeds excluded,	[93,108–110]
Optimal growing conditions	Difficult to achieve (urban environment, exposure to weather)	Difficult to achieve (differences among growing levels, artificial conditions)	[111,112]
Environmental impacts			
Energy demand	Low	High, aims to minimize with renewables	[12,13,59,113]
Water usage	Weather-dependent	Usually uses 70–95% less water	[79,89]
Species and varieties, biodiversity	Less limited in space, fruits, grapes, no arables	Highly limited	[42,82,109,114–116]
Waste/by-products from cultivation	Low waste (less synthetic material, organic material recycling)	High amount of waste (plastic, electronics, growing media, hydroponic fluid), tends to minimize	[90,96]

3.1. Comparison of TUA and CEA Based on Their Contribution to Agrobiodiversity

When biodiversity is discussed, agrobiodiversity is a very important aspect from this point of view, which spans four levels: (i) food and crop biodiversity per se, like many different crop varieties and animal breeds; (ii) associated biodiversity, like pollinators, soil organisms, and wild relatives of crops and livestock; (iii) sociocultural and economic diversity, including skills, resource management, foodways, etc.; and (iv) institutional diversity, like agricultural organizations and community-based solutions [117].

3.1.1. Food and Crop Biodiversity

Based on past experiences [28–30,33,34], open-space UA potentially offers several ways to maximize species, as well as variety-level richness in various scales and spaces [118–120]. Vegetables, combined with fruits, herbs, and ornamental species creating highly diverse habitats, can dramatically increase the attraction of various pollinators and beneficial insects [114,116]. Being basically non-commercial facilities, open-field UA spaces are suitable for experimenting with species and varieties optimal for the cultivation environment [82]. In 2021, 61 big cities of the world with populations over one million were identified as using agrobiodiversity as a climate adaptation action, but only 6 of these actions were reported as related to urban food-supply chains, 15 to food choices and 14 to the food environment [121]; however, urban landscape design is becoming more and more aware of the importance of agrobiodiversity [122].

In contrast, closed environment facilities, such as plant factories, typically focus on the high-yield production of a limited number of species, often single-crop systems like lettuce or herbs. Although such systems are highly effective in terms of resource utilization and profit maximization [42], diversity is typically very low within the facility. This limited biodiversity can have implications for pest management and resilience against diseases, as diverse systems are often better at resisting unfavorable environmental conditions [123]. An example of the issues facing such mono- or bicultures is that they fail to benefit from advantages provided by crop combinations, i.e., beneficial effects that different plant species grown together express to each other, such as nitrogen fixing, repellence or luring, or synergistic allelopathic effects [124–126].

Both systems offer unique advantages and challenges regarding species richness. Open-space urban farming promotes biodiversity and supports ecological interactions, while plant factories prioritize efficiency and resource management.

3.1.2. Associated Biodiversity

Urban agricultural areas can provide more than lessening the environmental pressure of food transportation [127] from agricultural areas outside cities or, in many cases, even from higher distances by enabling food produced closer to urban residents. These urban food-producing areas are highly managed plant communities [128] that could provide many ecosystem services [75]. One of the sources of these services [129] could be the increased biodiversity compared to green-free city areas; in some cases, their species richness exceeds those of city parks with closely mown lawns, traditional urban ornamental gardens, and vacant lots that became green spaces [6] or semi-natural habitats [130]. Generally, the overall species richness negatively correlates with the intensity of urbanization [131] and the high ratio of impervious surfaces [132,133]. On the other hand, biodiversity could be enhanced through the so-called "luxury effect" in more affluent parts of big cities [134], and its benefits are not evenly distributed throughout neighborhoods [135].

Many studies suggest that animal-species richness (vertebrates and invertebrates) is connected to plant-species richness [136–139], which could be high where the variety in land use is the highest, so basically in the transition zones between city centers and outskirts with extensive habitat diversity [140], which could be lower where agricultural management is intensive with lower plant-species diversity [132]. However, this diversity is frequently based on geological and geographical diversity, and usually, cities have been established in areas where different soil types and different natural landscape types (e.g., coasts, valleys, plains, loess landscapes, low mountains, and high mountains) meet, and thus, pre-existing biodiversity has been high [140,141]. This original biodiversity of urbanized places could be preserved or even enhanced by planning and creating as many green spaces as possible.

Bee and butterfly species' richness, e.g., had a close positive connection to the size of floral areas and sunlight availability of 18 community gardens of heavily populated districts of New York where ground-level habitats are shaded by tall buildings [142]. Therefore, implementing floral patches in rooftop gardens or on sunlit terraces could serve as a network of habitats for pollinators throughout the whole city—even in the heavily built-up areas—thus connecting it with peri-urban species-rich habitats [111]. The diversity of these above-mentioned floral patches will determine the diversity of not only pollinators [143] but also parasitoid species [144], beneficial living organisms with a plant-protection effect. Semi-wild, unmanaged areas in urban gardens are also helping pollinator species [111]. Therefore, a positive tendency in the spreading of urban vertical farming facilities, that they can decrease the need to turn more natural areas into agricultural land around cities [79] with the utilization of vacant lots and buildings, could supply produce to cover the ever-growing food need of urban residents [6].

The category of a weed [145] or an unwanted plant is a human-defined term. Among weeds, there are common characteristics, like the ability to outcompete crops and disturb any human activities [146], or sometimes they are only considered unattractive [145]. In a biodiversity survey of 60 domestic gardens in the UK [147], 18 of the 20 most frequently found plant species were natives, mostly common weeds. These weeds, besides being harmful when interacting with agricultural activities or interfering with human well-being, could also provide ecosystem services [148], which should not be neglected, especially because they are growing everywhere for free. In urban areas, any kind of green plant prevents the heating up of different surfaces and, therefore, mitigates the urban heat island (UHI) effect [149]. With evaporation, these green surfaces provide a more livable microclimate for the inhabitants of cities during the warmer and dryer periods of the year [150]. Weeds better accommodate extreme circumstances and generally can grow from a very low amount of poor soil as well; thus, they are suitable for growth in urban environments and fulfill these tasks. Moreover, in an urban garden, they could be used as resources, as weeds accumulate different nutrients from the soil quite effectively and, therefore, could be used as nutrient sources after composting [80]. With the increased biodiversity of plants including weed species [151], the number of flowering plants could be increased; therefore, pollinators are safer in finding a reliable nectar and pollen source [152] and helping with fertilizing crop flowers. On the other hand, possible human health issues related to urban weeds cannot be denied, such as pollen allergy or contact dermatitis [153]; the first has a strong positive correlation with the level of urbanization due to the increased amount of other air pollutants in urban areas [154]. These negative effects [155], as well as the ecosystem services provided by weed species, are obviously lacking in CEA systems, which are separated from the natural environment.

3.1.3. Sociocultural and Economic Diversity

Community gardeners contribute to UA biodiversity by producing special vegetable species or varieties that are generally not available in local grocery stores [156]; in addition to increasing the genetic diversity of plants in cities, cultural diversity is also enhanced, with urban farmers learning about new species and cultivars and their ways of growing.

In community gardens, people with different social and economic statuses and cultures from different nations could work together along a common agreement and towards common goals in engaging with semi-natural environments [157]. These urban green spaces provide a safe environment against daily stresses [158] and grant relief from extreme climatic conditions, and they serve as meeting places and possibilities for democratic, intracultural interactions, especially for cities with a lot of immigrants from a great diversity of different nations. On the other hand, these urban gardens have to be inclusive and available for all to fulfill this purpose [159].

In community gardens, as several people work in the same area, conflicts and clashes of interest are common. For example, there are often disputes over weeds [160], even though weeds can be useful and can play an important role in increasing diversity and in covering and improving soil quality. The use of pesticides and fertilizers (in terms of quantity and quality) can also cause conflicts. Food safety and the safety of those working in and around a garden can be improved if it is agreed in advance and specified in the garden's constitution that the garden will be managed in a chemical-free manner or organically [161,162]. In this latter case, it is specified that only products approved for organic farming will be used. Otherwise, these products should only be used as a last resort, when prevention is not effective. This does not necessarily eliminate conflicts completely because it is not easy to define what is allowed and what is not. It always depends on the situation at hand, whether they can agree on rules that are acceptable to all, and whether they can stick to these rules. In contrast, plant factories employ a low number of laborers due to the high level of automation and for financial purposes as well [101]. They typically work in a corporate manner; therefore, individual opinions are not necessarily expressed.

3.1.4. Institutional Diversity

A community garden takes up space in a city while providing a green area, making the environment more livable and having positive social effects [163]. In urban gardens, vegetation, especially woody plants, plays a key role in mitigating climate change. Therefore, its support from the institutional side is generally high. Local governments, community organizations, and informal networks provide legal, financial, or physical support, as well as providing knowledge and experience [157]. Community gardens are cultivated with a group of people among whom only their motivation to produce food is common; obviously, the coordination of a professional or an NGO is useful, although democratic decision-making also works in several cases in such decentralized structures. Gardeners often share local food traditions and farming practices, contributing to community knowledge and maintaining agricultural heritage.

Plant factories operate on different foundations; these facilities are built up by private-sector investments or by technology-related research/educational institutions. Subsidies or grants are possibly available according to the local policy priorities of governments [164]. These profit-oriented firms are led in a centralized manner whose focus is on maximizing profitability through high-tech solutions, which enable high levels of standardization. Compared to traditional urban farms, plant factories often involve less direct community engagement or cultural connections, as they are primarily driven by efficiency, scalability, and technological solutions.

3.2. Link to the Living Soil

3.2.1. General Introduction, Comparison of TUA vs. CEA Based on Growing Medium Use

The main functions of a growing medium are to support roots and provide optimal conditions for the continuous uptake of water and nutrients. A medium has chemical and physical properties that allow roots to develop, has neutral chemistry, has a good water and air capacity, has a durable structure, and is free from pests, pathogens, and substances that can be harmful to plants and humans [165,166]. Generally, in plant-factory systems, the dual function of media is not fulfilled; inorganic media typically have low nutrient content, and due to their low colloidal content, they have a low adsorption and buffering capacity [104,105].

The mediums that can be used in various forms of organic farming are as follows: (this list also includes mediums that can be used with limitations): sand, gravel, volcanic tuff/lava rocks, perlite, vermiculite, pumice, silt, peat moss, coconut coir, biochar, dried digestate residual after the production of biomethane gas, composted plant minerals/leaf mold, Posidonia compost, spent mushroom compost, municipal solid waste compost, food processing waste compost, animal manure compost, sheep's wool manure compost/manure, sewage sludge, paper waste, shells or hulls, dry plant residues, pressed fruit residues, wood fiber, and vermicompost [167]. These mediums can be considered natural or natural-based materials, and they are typically used in open-field UA systems as well. In the case of plant factories, theoretically, other mediums can be also used: fish fertilizer derived from aquaponics, mineral wool, expanded clay granules, polystyrene, polyurethane sponge/foam, phenolic resin/phenolic foam, foamed glass, water-absorbing crystals/polymers, polyester fleece, or expanded shale [107]. The mentioned mediums have to be adjusted to the strict rules of sterility in a plant factory. Therefore, several mediums are essentially excluded from CEA production due to their inability to fulfill sterility expectations. Additionally, inorganic materials face deposit and recyclability challenges, as well as threats of microplastic pollution [168,169].

3.2.2. Contaminants of Urban Living Soil

Along with the growing popularity of urban gardening, there is also a concern about the potential health risks associated with crops grown in urban soils due to the presence of pollutants [170,171]. The availability of healthy, living soil, which is a fundamental requirement for a healthy plant, is frequently limited in urban areas. The majority of community gardens and plant factories are established in brownfields or empty lots. When growing outdoors, the built environment is characterized by higher temperatures and lower humidity. Non-optimal conditions impede the protection of crops, as plants are weakened in unfavorable environmental conditions. These include degraded soil or heat reflection and the shade of houses [111]. Urban agriculture requires special precautions, as the areas used for cultivation are typically small, often characterized by poor or contaminated soils, and surrounded by busy roads and buildings that limit light the supply [112].

The expansion of agriculture into urban environments raises concerns about the impact of pollutants on plants and, thus, on human health. This is linked to the absorption and accumulation of heavy metals in plants [172]. The relationship between the presence of heavy metals in the air and soil and their accumulation in horticultural crops has been the subject of investigations by researchers worldwide [112,173,174]. Urbanization has a significant impact on soil composition, leading to low organic matter content, and soil properties can become unfavorable for crop production [175]. Consequently, it is essential to conduct a comprehensive evaluation prior to the establishment of community gardens in urban ecosystems [25]. It is mandatory to investigate whether the soil is suitable for crop production by evaluating factors such as soil texture, erosion potential, nutrient availability, and overall fertility. Additionally, it is crucial to consider the historical context of the area, including past local pollution incidents, such as previous industrial activities or waste-disposal practices [176]. Some studies have demonstrated that the highest concentrations of heavy metals are present within a 10 m distance from the street, subsequently declining with an increasing distance up to 60 m, which is considered a safe threshold [112,177].

The presence of hydrocarbons and Pb in paints and other sources has been identified as a potential concern [178,179]. The most significant threats in garden soils are likely to be Pb, Cd, Hg, As, and polycyclic aromatic hydrocarbons (PAHs) [180]. However, for the majority of urban gardeners, the risks associated with exposure to metals are minimal [181]. Three studies of community gardens in Boston have demonstrated that arsenic can leach into garden soil from pressure-treated wood and that PAHs can leach from old railroad tracks [102]. Additionally, garden soil may contain elevated levels of lead-based paint, asbestos, coal ash, and automotive oil. The presence of cadmium is a common issue, particularly in acidic soils, as it is readily absorbed by vegetables [182]. The presence of lead is almost ubiquitous in urban areas. It would be advisable to research the history of the site under consideration, as this may provide information regarding the potential presence of contaminants in the soil. Leafy vegetables are particularly capable of accumulating these substances [183]. Transportation is a significant source of pollution. Vegetation can play a crucial role in reducing particulate matter (PM) concentrations as deposited pollutants are washed off from leaves into the soil or absorbed through leaves into plant matter, thereby improving the quality of life for urban residents and the environment [184]. In community gardens, garden users are often unaware of how dangerous the contamination may be or how to mitigate its effects [185]. For these reasons, soil replacement can be a solution, but it is a very costly and complex operation. It is more advisable to build raised beds and use compost, which also has a positive effect on plant protection. However, care should be taken because contaminated compost is not as rare as one might think; therefore, the testing of both soil and compost is important [102]. The bioavailability of heavy metals and organic pollutants can be reduced by introducing soil amendments, including compost, mulch, and mineral fertilizers, which improve soil health and promote soil life activity and species diversity [186,187]. Recycling organic waste through composting or mulching not only reduces methane emissions from disposal sites but also improves garden soil and helps capture carbon [96]. Synthetic nitrogen fertilizers are also energy-intensive to produce and use, and they release significant amounts of greenhouse gases, adding to the problem in cities with already polluted air. Covering the soil with plants also helps absorb carbon (using grasses, cereals, or legumes) [188].

An additional potential solution to the issue of polluted urban soils is the complete avoidance of soil and the utilization of alternative growing media. The concept of vertical farming, which is based on the principles of the circular economy and encompasses techniques such as aquaponics and hydroponics, represents a pioneering approach [106]. The concept of sky farming, which is a novel form of urban agriculture, also warrants consideration [187], as well as digeponics, which is the combination of aquaculture with anaerobic digestion, where organic matter is broken down by anaerobic microorganisms to produce biogas [189,190]. The food-to-waste-to-food project is considered the first efficient method to integrate food-waste treatment with biogas production, while the digested material is used as biofertilizer in crop production and heated in a bubble-insulated greenhouse with the biogas produced [191].

3.2.3. Contact with Microbiota, Microbiological Diversity

More than 60% of the Earth's biomass is represented by microorganisms [192]. Due to their numerous functions, they play essential roles in sustainability and biogeochemical cycling [193]. Scientists are advised to utilize the potential underlying the functions of microbiomes to mitigate natural and anthropogenic activities, which lead to the evolution of new strains of pests and pathogens, to climate change, and to the overuse of chemical fertilizers, as these activities are continuously menacing stable agricultural production [194,195]. Soil is essential in the evolution of the human gut microbiome, and it provides beneficial gut microorganisms. In particular, there are functional similarities between soil bacteria and human gut bacteria [196]. In recent decades, global comparisons have revealed a decrease in gut microbial diversity attributed to missing natural soil contacts, Western diets, high hygiene levels, biodiversity loss, and lifestyle and healthcare practices such as caesarean section, antibiotic use, and formula feeding [197]. More than 100 different immune-mediated diseases have been diagnosed; this is the second-highest cause of chronic illnesses, and therefore, preventive approaches must be implemented. Accumulating evidence supports the biodiversity hypothesis of immune-mediated diseases; the benefits and trade-offs of consuming soil microbiota have become a scientifically important research direction [198,199]. The available literature suggests that geophagy and the consumption of safe soil mixtures can provide immunological resilience [197]. Large clinical trials are necessary before soil microorganisms can be considered beneficial contributors to the planetary health plate.

An association was shown between gardening and health and well-being in many studies [200–202]. Urban soils provide ecosystem and health benefits, but they are understudied compared to agricultural and wildland soils [203]. Healthy soils host diverse microbiota, exposure to which may be critical for immune development and protection against chronic disorders, such as allergies and asthma [110]. Gardening represents a key pathway for microbiota exposure, yet little is known about the microbial community structure of urban garden soils [203], the degree of soil-to-skin transfer during gardening, and the ability of soil microbes to persist on human skin. In a study, 40 volunteers were asked to collect soil samples from their gardens and skin swab samples before and after gardening [201]. Soil and skin bacterial communities were characterized using amplicon (16S) sequencing, and soil samples were analyzed for chemical/physical characteristics. Soil bacterial communities had more alpha diversity and less beta diversity than skin communities, which varied greatly across individuals and within the same individual across time. The number of bacterial taxa shared between skin and garden soil increased immediately after gardening for most study participants, but the imprint of garden soil disappeared within 12 h. A daily gardening routine with repeated and extended contact with soil likely reinoculates the skin such that soil microbes are often present, holding the potential to impact health [186,201,204]. A biodiversity-focused trial demonstrated that urban indoor gardening has the potential to diversify the microbiota on human skin and to increase anti-inflammatory cytokine levels in plasma. The experimental setting i.e., the beneficial microbial exposure, can be obtained indoors and year-round through an activity that is both meaningful and satisfying. Urban gardening offers year-round exposure to environmental microbiota, which might help prevent immune-mediated diseases [201].

The soil also has harmful effects, depending on the immune status of an individual; it can cause serial diseases via pathogen microbes [205].

A study found that, during peak harvesting season, families that garden regularly and consume a substantial portion of their diet directly from their gardens have more soil-associated bacteria in their feces than non-gardening families [186]. These exposures are generally benevolent with regard to human health. For the vast majority of human evolution, exposure to soil- and plant-associated microbiota has been unavoidable, and it might have been important for maintaining health [206]. Emerging evidence suggests that exposure to diverse microorganisms (e.g., to those associated with traditional farm environments) trains the immune system and reduces inflammation [201,207]. Many rural societies have higher fecal bacteria richness when compared to Western populations, and different environmental exposures take part in these microbial differences. A study found more intestinal bacteria with a higher capacity to ferment complex carbohydrates when modernized Italians were compared to non-industrialized communities with traditional lifestyles. The dietary variations between these groups probably play a role in these differences, as traditional communities tend to consume more fiber compared to urban residents [186]. Community gardeners and their household members eat fruits and vegetables more frequently than nongardeners. Contact with soil in a garden and eating chemical-free grown vegetables and fruits with intact microbiota can potentially alter the human microbiome composition and enhance human microbial diversity [208]; e.g., a greater diversity in the types of vegetables and fruits consumed resulted in a greater α-diversity of the gut microbiome. Through immunomodulation, the microbiota influences human health as well (Figure 1) [209–213].

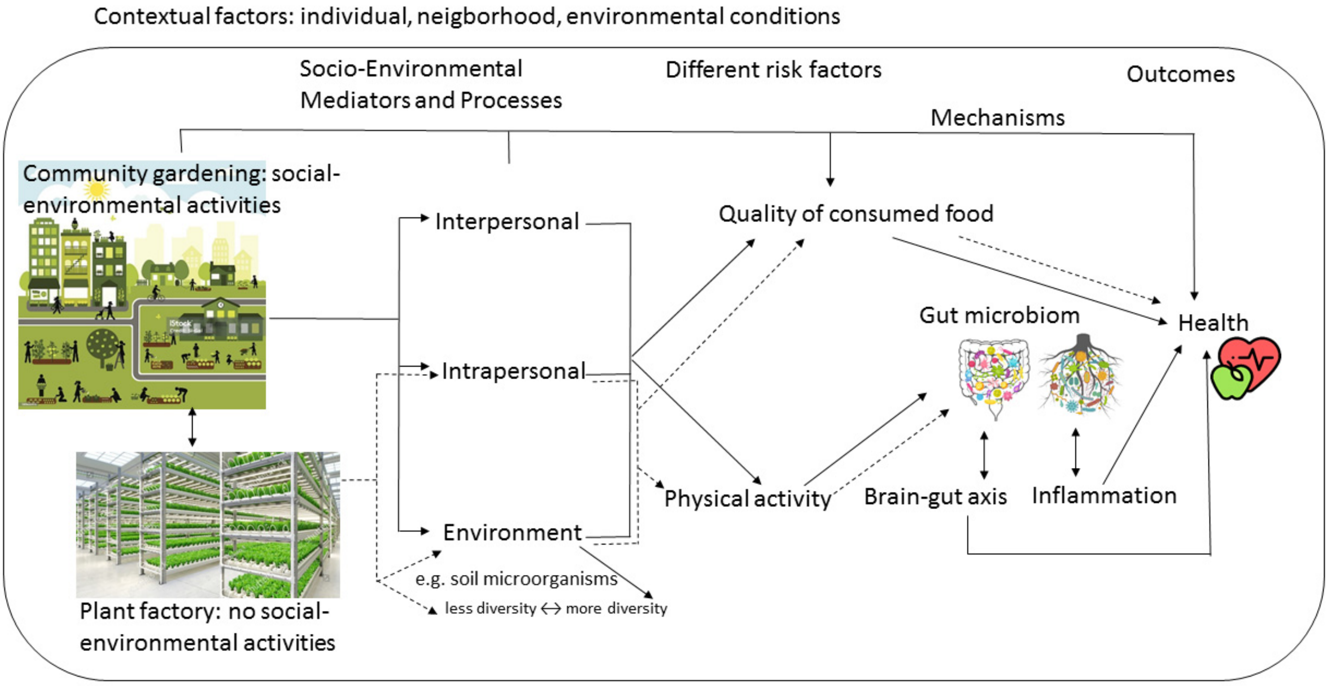

Figure 1. Connection between community gardening and a plant factory in terms of socio-environmental mediators, risk factors, and direct impacts on human health through changes in microbial diversity [214]. Continuous lines indicate community gardening, while dotted lines indicate plant factory-related factors.

Gut microbiota is a key regulator of immune functions and inflammatory responses [110]. A Denver Garden Environment and Microbiome Study Disease (DGEM) study evaluated whether community gardening can be a preventive intervention to reduce risk factors for chronic diseases such as cancer and heart diseases, as well as mental health conditions such as mood and psychiatric disorders [215–217]; due to a small sample size (16 participants), no microbial effects were statistically significant [200]. According to relevant studies, the microbiomes of direct gardening vs. supermarket produce are quite different in diversity consideration. Microorganisms have effects on both humans and circumstances. Garden-fresh foods are typically less washed and sanitized than supermarket products; therefore, they could contain indigenous plant- and soil-associated microbiota at the point of consumption. Supermarket products have lower microorganism diversity, although the number of microorganisms is not less than that from direct gardening [218]. Another technological step with a high risk of losing microbiology is the processing of food before consumption. The “Ready-to-eat”-market shows that the constant increase and consumption of these processed vegetables increases the risk of food-borne diseases. The washing of produced leafy vegetables is standard in commercial processing to avoid contamination. Research has examined the bacterial communities of spinach (*Spinacia oleracea*) and rockets (*Diplotaxis tenuifolia*) to identify potential contamination possibilities and investigate effects on the bacterial load through commercial processing [218]. Samples originated from different places: fresh from a field, after washing, and at the end of their shelf life. The results showed that the bacterial-community composition and diversity significantly changed from the harvest to the end of the shelf life. Huge changes in microbial composition were documented: less than 2% of the original microbial taxa were detected at the point of sale. A substantial shift from indigenous communities to other microbes acquired from the processing environment was experienced [218].

In a plant-factory environment, the basic aim is to exclude or eliminate microorganisms to simplify the system from a plant-protection view. However, with this, a possible niche is created, which is easily reachable for surviving or newly entering microorganisms. The long handling chain is also a potential source to use this niche for both human pathogenic and non-pathogenic microorganisms. Initiations have, therefore, been made to enrich the artificial environment of plant factories with targeted microbiota, especially with the aim of ensuring optimal plant development [219]. The function of the microbiome in plant protection is also indisputable; most animals and plants have associated microorganisms, which can provide essential functions. Host-associated microbiomes have the potential to fundamentally contribute to the adaptation of the host-microbiome assemblage. Microbiomes may be important for rapid adaptation to novel environments, as microbiomes can change more rapidly than host genomes [202]. A relationship was found between host and microorganisms adaptation [202] that could be missing because of the lower microbial diversity in plant factories. A good example of the function of garden microbes is a study where bacterial communities in urban garden soils were characterized [220]; it was found that the boxwood blight pathogen (*Calonectria pseudonaviculata*) population declined rapidly. According to the study, Rhizobiales and Burkholderiales were the dominant bacterial orders across all five states/gardens and the two sampling times, and 66 bacterial species known to have strains with antagonistic activities against plant pathogens (BCA candidates) were also identified. These results highlight the importance of microbiome components in garden-soil health and provide a new perspective on ornamental-plant disease management in gardens and other public spaces in the future [220].

Due to the lack of living soil in plant factories, maintaining the healthy microbial balance of the medium is challenging. For certain plants, such as soybeans, the presence of microbes for successful agricultural production is necessary. Science should find ways to substitute the missing microbes with artificially prepared microbe products [219]. Generally speaking, PF systems aim to model natural processes to produce plants without harmful ingredients; however, as to whether microbes should be considered necessary or unnecessary harmful ingredients of nature, future scientific knowledge must provide the foundation for answering such questions.

3.3. Impact of Stress Factors

3.3.1. Abiotic Stress Factors Influencing Plant Life

TUA systems and CEA facilities significantly differ in the range and severity of abiotic and biotic stress factors that plants experience. Although simple yet functional measures can be applied in modulating the exposure of plants to environmental stress in urban open-field systems, such as windbreaks, shading nets, mulching, or optimized planting schedules [221], this is not comparable with the highly optimized environment the CEA can provide. Avoiding stress factors has a notable impact on the nutritional content of products [222,223]. Plants typically adapt to stress conditions by altering the gene expression of proteins that regulate the production of certain metabolites related to environmental interactions, such as polyphenols; these play vital roles throughout the plant's life cycle, particularly in stress-response mechanisms [224,225].

Phytonutrients with antioxidant properties in plants are synthesized to respond to abiotic (heat, water, or nutrients) and biotic (pests and pathogens) stress factors as parts of the plants' defensive mechanisms [226–228]; having an antimicrobial effect, polyphenolic compounds are part of the constitutive and salicylic acid (SA)-inducible systemic resistance mechanism as well [229]. The human health-related importance of polyphenols is derived from their antioxidant properties, pharmacological functions, and nutritional role [230]. It seems evident that, due to the higher stress impact of open-field conditions, as well as fundamental differences in plant nutrition, the polyphenolic content of organic products is generally higher [231] when compared with intensive production; the same assumption might be applied when open-field TUA is compared with CEA products due to the optimized, stress-less environment of the latter.

Although the direct link between organic farming and higher pest and disease impact is scientifically not proven, it seems evident due to the non-use of pesticides; the interlinkages between the applied fertilization system and the polyphenol levels are well founded. Several studies support the fact that, with the use of synthetic fertilizers, polyphenolic [232] and phenolic acid and flavonoids content [233] remain lower, while the exclusion of synthetic fertilizers and pesticides does not influence the polyphenolic content at all. Further data show that there is a direct and scalable reverse correlation between the availability of nitrogen sources and the polyphenolic content of products [234,235]. The above results lead to the assumption that CEA products show possibly lower phytonutrient levels in comparison with open-field fruits and vegetables exposed to a wide variety of environmental stress factors. However, it was also recognized that mild stress, i.e., a slightly unfavorable environmental modulation, that does not cause irreversible damage or growth inhibition can be beneficial in terms of producing quantitative and qualitative traits [63,236,237]. This latter can easily be managed in a CEA facility and can be considered an advantage over TUA.

Among all environmental factors, light is the primary factor that defines plant vegetative and generative growth; therefore, light parameters are key factors in facilities where natural light is not provided [238,239]. The future role of LED appliances in CEA is inevitable, as these are highly adjustable in terms of spectral composition, light intensity (PPFD), and light duration either on a daily basis or through the whole vegetation period. Additionally, LEDs consume less electrical energy and do not generate a significant amount of heat. Specific produce requirements for shape, flavor, and secondary metabolites can be achieved by inducing mild stress through targeted CEA environmental settings [46]. Studies on the vegetative development and metabolomic mechanisms of CEA crops show that certain light settings are capable of changing these traits [239,240]. It is now widely recognized that the growth, sensory aspects, and nutritional parameters of crops can be modulated via proper light quality, quantity, and timing settings called light recipes [63]. These recipes have to be tightly tailored to the demands of the cultivated plant; a high number of recent LED-related research results showed that plant responses differ at the species and variety level as well in terms of both development and metabolite synthesis. Regarding wavelengths, the effect and the ratio of red and blue light is the most commonly researched topic. General rules are applicable: red light supports plant growth and inhibits secondary metabolites, while blue light is responsible for the management of different metabolic pathways, such as the synthesis of polyphenols, vitamins, and carotenoids [241], and deteriorative for plant development [239]. The ratio of red and blue wavelengths is under continuous research [242–244]. However, other wavelengths have additional functions in terms of plant development and phytonutrient synthesis, but blue and red wavelengths are the most commonly used light-spectral setting, and they have proven to be more effective in terms of production efficiency than fluorescent lamps [245,246]. Based on the above, it seems evident that the targeted modulation of the environment, especially of light parameters, can directly influence the nutritional quality of produce, which encourages the use of CEA solutions to provide urban dwellers with high-value, nutritious crops. At the same time, TUA solutions can benefit from metabolomic synthetases with relevance to human health due to unpredictably occurring unfavorable environmental conditions (mild or severe stress) and the use of organic nutrient forms. Additionally, targeted light settings can contribute to the value of produce even after harvest. The shelf life of lettuce grown in CEA environments is expected to be two times longer than those from an open field [247]. The storability and glucosinolate content of pak choi [248], as well as the phytonutrient levels of kale [249], are elevated with special-light irradiance settings. An extensive review is provided, by D'Souza et al. [250], among others, about the effect of different light spectra on certain traits of post-harvest product quality.

Urban environments can generally be characterized as having a higher CO_2 concentration in comparison with rural areas [251,252]. Elevated CO_2 levels in cities are caused by intensive anthropogenic activity, especially energy production and transport facilitation through burning fossil fuels [253,254]. The transformation of rural land into urban areas results in the loss and alteration of vegetation and soils, consequently affecting the local and regional carbon cycle [255]. A prospective approach to carbon capture is provided by natural processes [256]. Plants in cities can play a valuable role in mitigating CO_2 levels by acting as local carbon banks [257]. Urban forests, as well as other plant patches, can fulfill the same function to different extents, such as UA plots [258]. Extensive research was done with the application of seagrass and seaweed to sequester more carbon from the environment [259] as part of an assisted biological process. Additionally, nature uses its own mechanism to reduce CO_2 levels, as plants grow faster in such environments, although it has only a limited impact on the global system [4,260]. In CEA systems, CO_2 levels, similar to other environmental factors, can be adjusted to the optimal needs of plants, or mild stress conditions can even be employed easily. However, in contrast with open-field urban green plots, this has no beneficial effect on local or global climates, as CEA spaces are totally isolated from natural environments since CO_2 demands are not covered from urban air.

TUA and CEA systems differ in terms of their exposure to abiotic stress; while mild stress can be induced and fine-tuned easily according to consumer demands in CEA systems, this effect is rather unpredictable in open-field TUA. At the same time, beneficial metabolomic changes are expected from the use of organic nutrient sources and from the higher pathogen and pest pressure in urban gardening.

3.3.2. Biotic Stress Factors—Plant Protection

Biotic stress factors, such as pests, pathogens, and weeds, pose significant threats to plant health, making effective plant protection strategies essential for mitigating these biological challenges and ensuring sustainable crop production. The unique characteristics of open-field UA and CEA imply that the emphasis on plant protection strategies is fundamentally different among systems.

The primary objective of plant protection in agroecological management, which is commonly applied in open-field urban farming, is the prevention of damage. The implementation of strategies such as increasing diversity, cultivating a wide range of species and varieties, attracting and retaining beneficial organisms in the field, plant and crop rotation, and the use of compost can help minimize damage [109,115].

The most common in plant factories is monoculture or growing very few species in one place at one time. In particular, as community gardens are divided into plots, most people prefer to grow a few popular species (e.g., everyone wants tomatoes, cucumbers, peppers, etc.). The predominance of some species makes them more exposed to pests and pathogens [109]. It is easier to develop a self-sustaining, biodiversity-based system in private gardens than in community gardens or in plant factories, though no effort is made to do so.

The difficulty in convincing skeptics is that increasing diversity does not seem to have an immediate effect. Often, it takes years to develop a more stable system, with less need for plant-protection interventions. An experiment also confirmed that habitat heterogeneity reduces crop damage at both the local and landscape scales [109]. It was shown that urban agroecosystems are vulnerable to insect and disease pests but that there are local agroecological diversification strategies that cause lower plant damage, such as increasing the proportion of flowering species, incorporating agroforestry, and using mulches. Susceptibility to insect and disease pests is largely determined by a combination of factors beyond our control, including garden size, the size of surrounding natural habitats, and temperature fluctuations. Thus, dense urbanization and climate change will increasingly challenge the sustainability of urban gardens in the future. Increasing species richness is not an impossible mission. It can be achieved partly by planting flowering mixes in communal areas, e.g., along fences; insect hotels (habitat for natural enemies) and bird boxes both contribute to biodiversity. Plant beds should be enriched with more species and varieties of vegetables, fruits, and herbs. Mixed cultivation or companion planting is advised, and more levels can be created in a garden with trees, shrubs, and climbing plants, but this requires the cooperation of garden users.

To solve plant protection challenges arising from the unwanted presence of pests, diseases, and weeds, agriculture generally uses chemical agents, such as fungicides, insecticides, and herbicides. The impact of these chemicals on human health is an ever-intensively researched topic, which is exacerbated by profit interests and sometimes by excess skepticism. However, long-term trials clearly show the unfavorable consequences of agrochemical overuse. Additionally, plants and humans may face an increased risk of newly emerging pathogens and diseases due to the widespread use of pesticides [110]. While the use of pesticides in agriculture is strictly regulated and controlled for food for sale, it is a gray area in the private sector with no controls; the correct use of pesticides depends on the amateur gardener's sense of responsibility. In many European countries, legislation differentiates between pesticides based on their hazard, dividing agrochemicals into professional and amateur use groups [83]. Although nature is of great importance to the amateur gardener, environmentally friendly practices are not yet widespread [87]. It is not uncommon for garden soils to be over-fertilized or for pesticides to be used inappropriately with unsuitable plant species selected, which can ultimately lead to feelings of frustration, rather than the enjoyment associated with gardening. Regarding the use of herbicides in uncultivated zones, including paved surfaces, roads, pavements, and driveways, it is a common misbelief that they will not cause problems there. Protective clothing is not usually used either. The average age of gardeners is decreasing, and in parallel, the knowledge base is also eroding. Some surveys show a growing rejection of pesticides, while others report a steadily high rate of pesticide use. A number of labeling and food scandals have also led to a general distrust in commercially available food [95,261], with more and more people starting to grow their own food in urban gardens. At the same time, there is an increased ecological awareness and a rejection of chemical pesticides. The advantage of community gardens is that practitioners have a high level of confidence in the food they grow, as it is chemical-free and respectful of the environment, and because it is grown outdoors, one can expect better nutritional value due to stress effects. Urban food gardens can also help improve the nutritional quality of gardeners' diets by diversifying them [94,95]. It can help reduce food waste because it provides a deeper appreciation of the food that is grown. Defects in appearance are increasingly tolerated [96,97].

Methods of integrated pest management (IPM) that are also applicable in the urban sector include agrotechnical methods (e.g., planting dates, fertilization, and tillage), the selection of cultivars adapted to the growing site), mechanical, physical, and biological control (e.g., mulching, hoeing, the use of insect traps, lawns that are rarely cut and left long, the use of antagonists, and pheromone traps) and chemical pest management [83]. Synthetic versions of semiochemicals (pheromones) can be used in IPM to monitor, trap, or disrupt the reproduction of pests. A constant indoor climate and less air movement in CEA facilities improve the applicability of these agents [262].

The response of plant factories to adverse urban conditions is to isolate cultivation; climatic conditions are aimed to be adjusted to the needs in a completely artificial and precise way [263,264]. This can be difficult because some growing parameters, such as temperature, humidity, and light intensity, vary between different growing levels in a vertical growing system [265]. Different conditions for crops and for pests and diseases also occur at different levels. Air circulation is used to balance the climate, which can also facilitate the spread of pests and pathogens [78]. Dripping water due to condensation causes too-dense plant populations, and loosened plant fibers develop as a consequence of shortages of light and nutrient availability; both contribute to the spread of diseases.

Despite increased environmental control, heterogeneity in growth conditions cannot be completely eliminated; some plant layers may be exposed to sub-optimal environmental conditions. This can lead to abiotic stress, which enables the easier infection of the plant. Plant cultures need to be set up very carefully [266]. The wavelength of LED illumination can also influence the behavior of pathogens and insects [267–269].

Supporters of plant-factory systems claim that these growing systems completely prevent the introduction of insect pests and plant diseases, making pest control completely unnecessary by creating a sterile environment [93,108]. Although greenhouses and especially CEA systems limit the entry of pests and diseases, it is unrealistic to expect to completely prevent the introduction of pests and diseases [113,270]. They can enter, for example, with employees or through seeds, or via ventilation systems and doors, as large entry and exit openings are required when harvesting and selling crops. It is, therefore, necessary to use plant protection because the much-emphasized sterility cannot be maintained. Additionally, in the case of chemical crop protection, spray droplets of insecticides and fungicides move downwards via gravity and can accumulate at lower levels, potentially exceeding health limits [266]. Additionally, a CEA system is essentially characterized by a complete absence of microbes. The natural soil ecosystems are missing, and this can lead to particular vulnerabilities to pests and diseases. The involvement of synthetic microbial communities has been found to replicate the beneficial microbes typically found in soil. These communities can help suppress disease and support plant growth in soilless systems such as hydroponics, which are common in vertical farming. These microbe communities can provide functional redundancy and disease resistance similar to natural soil ecosystems [271].

In biological control, flightless natural enemies, such as the predatory mite *Phytoseiulus persimilis*, cannot move easily among levels [266]. However, for natural enemies that can fly, there is a great advantage in having a protected environment, as the released insects remain inside the equipment and cannot fly elsewhere. For example, in the Almeria region of Spain, chemicals are almost completely replaced with biologicals [272].

The chemical usage in vertical farming varies significantly across different regions, influenced by local agricultural practices, technological advancements, and environmental regulations. Vertical farming generally promotes reduced reliance on chemical fertilizers and pesticides due to its controlled environments [273], while vertical farming techniques, particularly in North America and Asia-Pacific, focus on producing pesticide-free crops [274]. In developing countries, excessive chemical use remains a challenge, but vertical farming offers a pathway to organic practices, addressing consumer demand for chemical-free products [273].

Diseases can also be spread through the hydroponic culture medium, and beneficial microorganisms may be unable to compete with pathogenic species [275]. Disinfectants such as hydrogen peroxide, UV radiation, ozone, ultrafiltration, or heat treatment can be used to purify the hydroponic medium [276,277]. In addition to nutrients, pesticides or biostimulants can be added to the hydroponic liquid to promote pest and disease control. The potential exists to enhance crop protection by adopting IPM-based strategies that include the artificial light-based manipulation of pest and disease behavior, combined with sophisticated nutrient management, control, and isolation systems, as well as semiochemical applications. These methods should be individually customized for each vertical farm type and each growth stage to maximize efficiency and minimize pest and disease risk [266]. A comparative summary of the factors affecting plant protection in TUA and urban CEA systems is provided in Table 3.

Table 3. Main factors affecting plant protection in two forms of urban agriculture: traditional urban agriculture and urban controlled-environment agriculture.

Affecting Factor	**Traditional Urban Agriculture**	**Urban Controlled-Environment Agriculture**	**References**
Contaminated soil	Cultivation in soil: soil replacement, raised beds filled with controlled-quality soil or compost	Soil abandonment, artificial growing media	[102,103,176,178–180,182,183]
Soil life	Possibly active, supplemented with compost	None; artificial imitation	[25,175,176,271]
Light	Natural, buildings may shade	Artificial, adjustable LED lighting	[111,112]
Temperature	Weather-dependent, heat extremities	Adjustable, fine-tuning	[111]
Humidity	Weather-dependent, atmospheric drought	High humidity issues	[111]
Biodiversity	Possibly high	Usually low (monoculture)	[109]
Pesticide use	Uncontrolled	Controlled, pesticides may accumulate at lower growing levels, potential in biological control	[83,162,266,272]

3.4. Human-Related Aspects of Urban Agriculture

3.4.1. Agricultural Knowledge

Farmers, especially younger ones, have to develop new skills with new technological innovations in UA [278], while community gardening requires soft skills like engaging with the community or the ability to work in teams, as well as learning about plant protection and nutrient management [279]. Expectations concerning the economic development and job-creating potential of UA are greatly surpassed by its social benefits [280].

Community gardening is now playing an increasingly important role in cities in terms of "environmental education", as it is a valuable tool for raising awareness of biodiversity issues, especially involving young people, and allowing them to develop a direct relationship with nature [3,81,82]. As it is cultivated by non-professionals [161], training is a particularly important aspect. A lack of skills, or a lack of receptivity to learning among non-professional gardeners, can lead to challenges [99]. In plant factories, highly skilled labor is required, and employees might specialize in different roles, such as crop monitoring, technical maintenance, logistics, and quality control. In more advanced plant factories, fewer employees may be required due to automation, robotics, and AI-controlled systems, while less automated facilities need more labor-intensive roles.

Urban gardens help restore the connection between urbanites and the soil [281], and the practice of agroecological gardening in community gardens brings soil back into the city; additionally, it calls for the attention of urban people, who often have limited knowledge of the ecosystem services provided via these systems [84–86]. This can even result in a change in identity [87]. The Internet can be very helpful in spreading environmental awareness, but unfortunately, it also has its drawbacks. A survey in Germany [83] showed that members of community gardens have better knowledge of plant protection than home gardeners, as they required more information through training. Leisure gardeners get most of their information from gardening books, magazines, neighbors, family, and friends, whom they also trust a lot. Online sources often provide dangerous misinformation. There is also a problem with gardeners' willingness to experiment (e.g., with nicotinoids). It was found that the proportion of those who have used biological/microbiological measures is very low (5-7%) and that the age group over 60 is the most likely to use chemical pesticides. Community gardens are much more cooperative in an organized setting than individual home gardeners. The use of chemical pesticides in community gardens is relatively low due to prohibitions in the garden regulations and social control.

3.4.2. Therapeutic Effects and Social Functions

The innate, biologically driven need for humans to interact and observe life and lifelike processes was described as biophilia [282]. Dunnett and Qasim [283] identify two types of home garden users: those who prefer active gardening and those who prefer passive experiences of relaxation and non-action. In these stressful times, an increasing number of people have some kind of mental disability [284] or social anxiety [285]. An urban garden represents a place where urbanites can escape from increased stress, like noise and health-damaging effects, being exposed to and having direct contact with nature at the same time [286]. Primary healthcare could be completed with programs supported by community gardening with promising results [287] and even provide fresh, organically produced food [288] for patients and their families if they are attached to healthcare institutions [289]. In community or private gardens, gardeners improve their physical and physiological health simply through an increased level of physical activity during gardening [290]. Many psychological issues, like losing purpose in life and autonomy, could be tackled via urban food production [291]. Horticultural therapy is a more focused, prescheduled program designed to tackle the special needs of a certain target group using plants and gardens in a passive or active way [292]. Health issues often go hand in hand with societal problems like isolation, feelings of brokenness, and uselessness, especially when not only physical illness but also mental health issues are considered.

3.4.3. Societal Benefits

Social aspects of person-driven recovery based on strengths and responsibility were examined with good results when occupational therapists were able to use horticultural therapy [293]. In addition to all the positive effects on human health, an urban garden, especially a community garden, which is open to community members, instead of being a private urban garden, can direct attention to environmental issues in food production and improve the respect for farmers in society [285]. An urban community garden can serve as glue in creating a healthy community. All the participating actors, like the volunteers working in the garden, the organizer, and the populations served, benefit through community collaborations [294]. The societal benefits of being involved in an urban gardening program can be observed in all age groups of participants. In a Texan study [295], youths residing in low-socioeconomic communities were found to be able to be prevented from engaging in antisocial behaviors not only during and shortly after the timespan of the gardening program but in the long term as well. This way, the so-called luxury effect [296] (the uneven distribution of benefits of higher biodiversity in cities according to the average income in different neighborhoods) could be mitigated. In a midlife crisis, targeted horticultural therapy [297,298], or simply engagement in the maintenance of a community garden, could make a difference. Lessening the isolation of elderly urbanites is again an important purpose for urban planning to create common places where old people can meet and work together toward a common goal with younger generations [299], above the health benefits of gardening activity [300].

On the other hand, traditionally [29–32], the garden is a way of self-expression: with the design, the quality of maintenance, the way it looks, the plants that are selected, it could become a source of pride. Sometimes, even private urban gardens can provide a possibility for social interactions with passers-by or neighbors. Gardening topics can link family members to each other; several plants in the garden can recall memories of family occasions when they were gifted to the garden owner [301]. Cameron et al. [302] identified two types of garden use. First, the garden offers the opportunity for self-expression in contact with nature, while for others, the garden represents extra effort, with the advantage of a parking space for cars. Educational activity in an urban garden is a relevant aim not only in the case of school or preschool gardens but also in many community gardens, where there are educational programs [303] that are, in many cases, initiated by urban gardeners themselves [279]. Obviously, these beneficial impacts cannot be provided via industrialized plant factories, although certain CEA facilities can be visited through guided tours; therefore, the educational function of these facilities can be granted. Due to sterility, special skill requirements, and a high level of automatization, the community-based operation of PFs is unrealistic in the near future.

It could be concluded that TUA can not only contribute food sovereignty for developed countries' urban inhabitants, therefore increasing their resilience to changes, but also provide possibilities for social inclusion [304] and community dynamics promoting cohesion. Moreover, especially in low-income communities, initiating and organizing urban agriculture can contribute to the social capital of a community, as it requires complex knowledge to manage all actors and stakeholders [35]. Plant factories could enhance food quality, health benefits, and food security with reduced resource use, though their economic viability requires a careful evaluation against traditional horticulture systems [305].

4. Discussion

4.1. Evaluation of the Differences Between Open-Field and Indoor Urban Plant Production

The fundamental difference between urban gardens and plant factories is their purpose. Today's urban gardens play a social role; their food production function is less prominent, and they typically do not produce for the market. However, the plant-factory system is primarily an artificial and closed form created according to market needs, where communities only appear as buyers of the products on the market. Its food production serves the urban supply, but only based on market mechanisms, not according to the expectations of the people living there. Both TUA and CEA, however, are expected to contribute to supplementing urban food demands in the future.

With the rise of urban gardening, concerns have been raised about the health risk of crops grown on urban soils due to the presence of contaminants, as gardens are mostly established in former industrial sites or on the grounds of demolished buildings, so the issue of the decontamination of all forms of urban gardens should be considered, taken seriously, and supported via soil testing in all cases [106,170,171]. In outdoor urban gardens, rather than replacing the soil, it is suggested to build raised beds and use excess amounts of organic matter and compost, which also helps with plant protection [102,103]. The response of plant factories to this problem is to eliminate soil altogether and switch to artificial media. The question is what we lose with the complete absence of soil and microorganisms beneficial to human health [271].

Open-field urban gardens and plant factories exhibit fundamental differences in microbiological diversity. A system that operates in isolation from nature, in which natural processes are solved using precision methods, may be simpler and more profitable in the short term from a human point of view, but these systems, such as the ever-increasing demand for chemicals in agriculture or possibly developing antibiotic resistance, do not prove that this will not create new problems in the future. Every day, humankind is describing new species of microbes that are yet unknown. There is still a lot of knowledge missing, even about the function of already described species/taxa or their role in an ecosystem. Nature is a system with many factors, in which a small change can trigger other large changes. Perhaps the biggest difference is that TUA tailors or reinvents [4] well-proven systems for urban reality that have been in place for centuries and are now backed by science or better understood, while the plant factory tries to mimic the way nature works in a simplified way, experimenting with the knowledge currently available, and is therefore forced into endless experimenting and refinement.

In open-field urban agriculture, the built environment [111], and in indoor cultivation, the lack of natural soil and outdoor ecosystems, can increase the susceptibility to certain pests and diseases [266]. Additionally, plant factories tend to grow monocultures or very few species in one place at one time. Similarly, in community gardens that are divided into plots, the predominance of a few species makes plants more exposed to pests and pathogens [109]. Prevention is the most important pillar of plant protection in agroecological farming systems. Increasing diversity, cultivating as many species and varieties as possible, attracting and maintaining beneficial organisms in the field, crop rotation, and the use of compost have been shown to help minimize damage. The use of chemical pesticides in community gardens is relatively low due to regulations and social control. Overuse and misuse due to a lack of control are more common in home gardens [83]. Food safety and the safety of those working in the community garden can be improved by agreeing in advance and including in the garden constitution that the garden will be cultivated using an organic approach, but as such gardens are cultivated by lay people, training is a paramount consideration.

There is a high level of trust in the food that is produced by people themselves, unlike food produced at plant factories, where the process is hidden from the consumer. Supporters of the system claim that the sterile environment eliminates the need for pesticides, but in fact, it has been shown that it is impossible to exclude pest- and pathogen-breeding colonies from growing facilities [270]. A real advantage, however, is that biological control is easier to implement indoors [306], allowing for the possibility of switching [272].

4.2. Investigation of the Possibility of Integrating the Advantages of TUA into CEA

The majority of papers dealing with the innovative role of CEA in urban agriculture emphasize the possibility of integrating open-space crop production into CEA systems. The isolated environment provides several benefits, such as a reduction in resource use, especially water, a reduction in contaminants, or the utilization of automatization to reduce labor costs [307–309]. With this, the sustainability, resilience, and food safety of the urban food supply can be improved. Less or no research deals in depth, however, with crop production-related indirect impacts on humankind in terms of transitioning from TUA to CEA, such as urban agrobiodiversity, societal benefits, or the consequences of giving up the connection to living soil. Bridging these losses requires further research; beyond the recognition of these threats, no complete solution has been outlined to our understanding.

The most probable scenario outlines the co-existence of these systems, with partial solutions for minimizing functional losses. These might include the following directions, included in Table 4.

Table 4. Scenarios to mediate functional losses in transitioning from traditional urban farming to controlled-environment agriculture.

Function	Scenario
Societal functions	Inclusion of labor by handicapped or mentally challenged people
	CEA facilitation in prisons, hospitals, psychiatric institutions, or nursing homes
	Inclusion of unskilled labor in less knowledge-demanding roles
	Sharing maintenance of CEA facilities among residential of workplace community
Agrobiodiversity	Inclusion of recent breeding results to widen crop species and variety use
	Enrichment of soil-based growing media with soil-bacterial communities
Various	Blurring the sharp isolation between built and natural environments by designing light-transmitting surfaces
	Exploiting co-existence by providing support for TUA in seedling production
	Exploiting dead spaces on rooftops or PFs with the operation of open rooftop gardens

4.3. Future Trends

Global future prospects and trends anticipate certain changes that could influence or threaten the present form of urban agriculture, and the task of stakeholders and food-chain actors is to prepare for the expected future trends. Based on the scientific resources reviewed, the following trends can be outlined:

- The emphasis will be laid on induced mild stress in controlled-environment plant production facilities to model natural multifactorial environments. Stress-condition treatments can be tailored to the specific aim of production, such as yield, appearance, or phytonutrient content.
- Great innovation potential within CEA systems makes digital technological improvements widely usable, similar to disruptive technologies in space science or army applications in the past. Open-field plant production will benefit from these processes as well through the simplified adaptation of advancements.
- Energy demands can become a limitation for the spreading of CEA facilities, which requires solutions from a technological side, such as the diversification of production activities or the application of renewable energy sources to optimize production as standalone units with island operation capabilities.
- Climate change suggests the prospect of more frequent and more serious future weather extremities, which will influence urban farming possibilities as well. Open-field UA might benefit from the climate modulation potential of the built environment in terms of mediating heat extremities and frosts.
- Consequently, the group of cultivable crop species will change within urban open spaces; therefore, a re-evaluation of traditional knowledge will become necessary, and certain species might be produced only within CEA frameworks. The adaptation of urban agricultural practice to climate reality should be continuous.

5. Conclusions

Controlled-environment facilities have a relatively short history within urban frameworks; although their integration into built environments is relatively smooth, it requires investment. In contrast, open-field urban plant production has a long history and unlimited forms, as well as numerous benefits on the environmental, economic, social, and human nutritional levels. It seems clear that, due to pollution in urban environments, open-field agricultural forms are under threat, and in most cases, a certain level of isolation from natural ecosystems—especially from contaminated soils and air pollutants—is already unavoidable. However, several important functions of open-field farming cannot be implemented or interpreted within the framework of plant factories, such as social and therapeutic functions, as well as functions the natural environment can benefit from, i.e., carbon sequestration, agrobiodiversity, and climate mitigation. Therefore, it is impossible to equate open-field UA with CEA, and plant factories cannot be interpreted as the innovative or modernized version of urban plant production that is capable of replacing all the advantages of TUA: fundamental functions would be lost with the complete abandonment of TUA. At the same time, a carefully engineered co-existence of TUA and CEA systems can be envisioned for the food supply of urban dwellers in the future, especially when adverse environmental changes escalate.

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