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Review

Challenges and Solutions for Sustainable Food Systems: The Potential of Home Hydroponics

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Abstract: The global food system is currently facing significant challenges that make it unsustainable and environmentally harmful. These challenges not only threaten food security but also have severe negative impacts on the environment. Efforts have been made to reform agrifood systems and align them with the built environment, but emerging obstacles have revealed the weaknesses in these systems, particularly in less self-sufficient countries. This review outlines the primary environmental problems associated with global agrifood systems and the challenges in promoting food security. It emphasizes that the increasing global population and urbanization need rational and equitable changes in food systems, including production, distribution, storage, and consumption. These changes should aim to minimize environmental impacts by protecting and efficiently utilizing natural resources such as air, water, soil, and biodiversity, reducing food loss and waste, and mitigating pollution that contributes to ecosystem degradation and climate change. In this context, hydroponics emerges as a sustainable, plant-based food production technique that can be employed as a solution in urban areas. It can be implemented in domestic microproduction systems, serving as a complementary alternative to conventional food production methods. This study also provides insights into the challenges that need to be addressed in order to enhance home hydroponic systems. The integration of hydroponics into urban food production offers the potential to tackle both food security and environmental sustainability issues, providing a path toward more resilient and efficient food systems.

Keywords: environmental sustainability; food security; food systems; home hydroponics; urban agriculture; zero-acreage farming

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1. Introduction

The expansion of the world's population, increasingly concentrated in urban areas, and the pursuit of satisfying its needs have had detrimental effects on the planet and humanity. According to the United Nations, it is estimated that by 2050, the global population will reach 9.7 billion people, marking a 19% increase compared to the current population of 7.9 billion [1]. Projections for global urbanization also indicate that an increasing number of people will reside in cities, with the expected urban population rising from 55.3% (recorded in 2018) to 68.4% by 2050 [2].

Human nutrition is undeniably one of the key global priorities in achieving Sustainable Development Goal 2: Zero Hunger. The excessive utilization of natural resources in agriculture, livestock, and fisheries places considerable strain on their regenerative capacities. This strain is one of the primary reasons why we have already exceeded four of the nine planetary ecological boundaries: climate change, loss of biodiversity, alterations in land use, and geochemical cycles (nitrogen and phosphorus) [3]. Considering that food systems encompass the entire food supply chain, spanning from production to food preparation and consumption [4], it becomes evident that sustainable food systems are indispensable in ensuring food security and mitigating climate change [5].

Modern agriculture and food systems face multiple and complex risks that are intertwined and interconnected, making them difficult to address in isolation [6]. Global warming and changes in precipitation inevitably lead to adjustments in the management of natural resources, such as soil and water, which have an impact on agricultural productivity [5]. Rising temperatures result in droughts, heatwaves, erratic precipitation, floods, and other extreme events that impact the agricultural sector [7,8]. These changes in climate severely affect crop productivity [9,10], primarily due to their sensitivity to environmental parameters, especially temperature and relative humidity. This leads to reduced production, posing a direct threat to food and nutrition security [11]. If the current trajectory of global warming and climate change persists, increased crop losses in the future could contribute to reduced food production, affecting supply and potentially driving up prices, making it increasingly challenging to meet the global food demand [7].

Dietary choices are shaped by both individual preferences and food availability in the market. Conversely, consumer demand can stimulate production and influence the available food supply. Recognizing this dynamic is essential for continual improvement in diet quality and promoting healthy, sustainable food choices. Food systems must continue to provide sustenance, but they can be restructured and redistributed to yield positive outcomes for both nature and the climate. Transitioning to plant-based diets where appropriate is a logical first step, as nearly 80% of total agricultural land is devoted to feed and livestock production, providing less than 20% of the world's food calories [12]. Without adaptation strategies, climate change's growing vulnerability and severity will pose a significant challenge to ensuring global food security and sustainable agricultural development worldwide [4,13]. Efforts are being made to implement more sustainable technological solutions with targeted potential, such as hydroponics (see [14–23]). Urban agriculture (which may include hydroponic techniques) in the form of community and/or family gardens has also been examined [24–32].

This study aims to review more sustainable food systems, with a focus on the potential of home hydroponics. It seeks to describe the main environmental problems associated with global agrifood systems and the challenges in promoting food security, including the improvement of home hydroponic systems. Integrating hydroponics into residential buildings, tailored to individual cases, enables the incorporation of consumer-specific solutions, increased production control, and reduced environmental impact.

Figure 1 illustrates the goals of this research, focusing on the complexity of the global food system, its interconnected systems, and their environmental consequences, particularly in terms of climate change. It also explores the potential advantages of implementing home hydroponic systems in urban areas as a means to enhance food self-sustainability while minimizing environmental impacts. In the background, the various elements of the current global food system are depicted, as well as their connections and flows. This complex, interdependent system is susceptible to various factors that widen the gap between producers and consumers, leading to challenges in accessing food. In a central position, safeguarded from external factors, the intent is to represent the conceptual vision of home hydroponics, focusing on the consumer's role as an urban farmer.

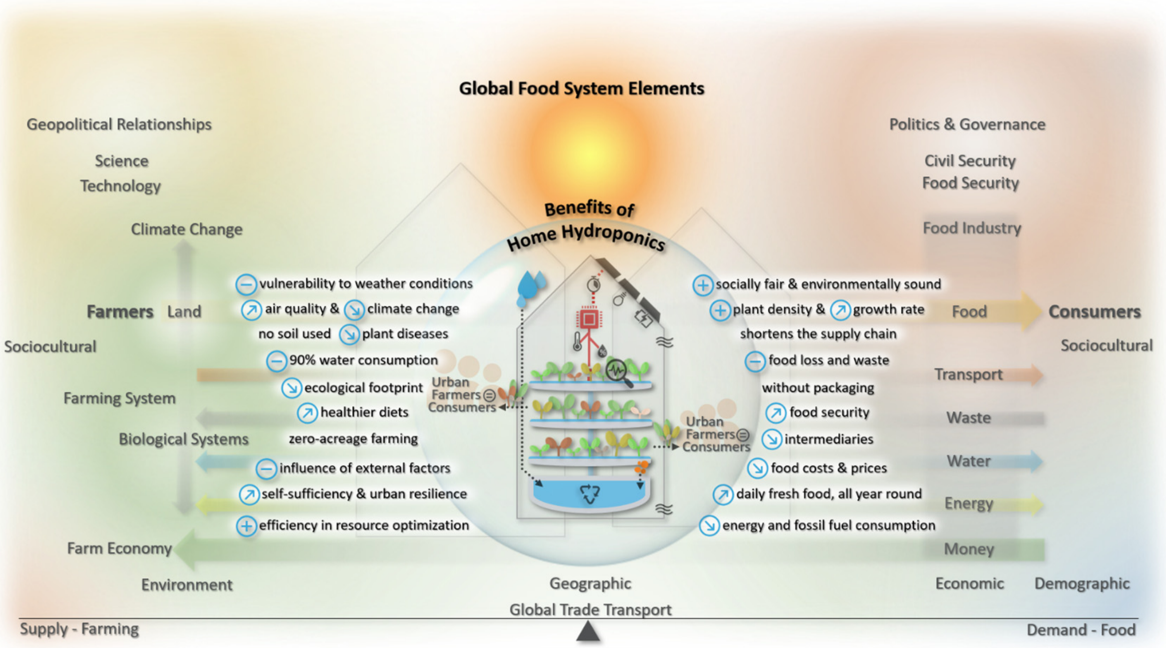

Figure 1. Conceptual approach to the benefits of home hydroponics in light of the current global food system. The background of the global food system was adapted from ShiftN CVBA [33–35].

The methodology employed for this review was anchored in the principles of currency and scientific relevance. Globally recognized scientific databases, including Scopus and Web of Science, were utilized alongside open-access repositories to gather information. Selection criteria prioritized contemporary and pertinent scientific articles on the targeted subjects published in English between 2013 and 2023. Exclusions encompassed articles from books, conference proceedings, and encyclopedias. Employing Boolean operators, general keywords were coupled with other pertinent terms. Additionally, credible documents from esteemed sources such as the Food and Agriculture Organization, World Health Organization, United Nations, European Commission, and World Resources Institute were incorporated, given their relevance to the study. Following a comprehensive analysis of numerous articles about the review's subject, 121 references were meticulously selected.

2. The Environmental Issue of Global Food Systems

As nations undergo urbanization and experience rising incomes above the poverty threshold, dietary habits tend to shift towards foods rich in sugar, fats, refined carbohydrates, meat, and dairy. Despite the relatively modest consumption of meat and dairy products in developing countries, the global surge in animal-based food consumption is both unnecessary and unhealthy [36]. Current consumption patterns, which lean towards more resource-intensive diets, primarily those based on animal products, have significant environmental repercussions. Such diets demand more land and water compared to plant-based diets [37,38], leading to a growing negative impact on the environment. This, in turn, contributes to climate change, the depletion of natural resources, and the loss of biodiversity [39].

It is worth noting that an astounding 94% of mammalian biomass (excluding humans) consists of livestock, meaning that the number of animals raised for food exceeds that of wild mammals by a ratio of 15 to 1 [40]. Nonetheless, despite exceeding more than a third of the average daily nutritional requirement for adults, the demand for animal-based proteins continues to rise significantly in people's diets at the expense of plant-based proteins [37]. Projections indicate that the consumption of animal-based foods will surge by 68% (considering the period from 2010 to 2050), with an 88% increase in the consumption of ruminant meats (beef, sheep, and goat) [4]. Given that a substantial portion of this production relies on crops for animal feed, the widening gap between plant-based and animal-based foods continues to expand [37]. In 2019, greenhouse gas emissions from agrifood systems, encompassing agricultural activities, land use changes, and pre- and post-food production processes, including energy consumption, packaging, fertilizers, and waste [41], accounted for 31% of global emissions [42] (FAO, 2021b). While emissions generated on farms have been well-documented in the literature, emissions stemming from the supply chain, transportation, transformation, as well as domestic consumption and waste, have been quantified more recently [41,43], accounting for 36% of agrifood system emissions in 2018 [41]. Approximately 30% of the world's energy is consumed by agrifood systems, with the majority being used in post-harvest stages, primarily in the form of fossil fuels [44]. In the primary production phase, energy is predominantly used to operate tractors, machinery, and irrigation systems, produce fertilizers and animal feed, and maintain greenhouses and other protected cultivation structures. Post-harvest processing and storage phases require energy for a variety of product transformation processes and often involve refrigeration to minimize losses. Energy for electricity, heating, cooling, and transportation plays a pivotal role in adding value and reducing food and income losses in agrifood systems. Energy consumption during the transportation and distribution phase varies significantly depending on supply chain structures and transportation modes. However, it predominantly relies on fossil fuels, making transportation costs susceptible to fluctuations in fuel prices. Lastly, energy consumption during the retail, preparation, and cooking phase is mainly linked to food storage, refrigeration, and the use of gas, electricity, or wood as cooking fuels [44].

The increased consumption of fresh food products in the past two decades has driven a growing demand for food packaging to prolong the shelf life of food [45]. In 2018, global plastics production nearly reached 360 million tons [46], with projections estimating this value to quadruple by 2050 [47]. It is important to note that approximately 42% of the world's plastic production is dedicated to packaging [48,49], and out of this, 60% (equivalent to 91 million tons) is specifically used for packaging food and beverages [50]. What is even more concerning is that nearly 95% of food packaging is discarded after just a single use, leading to an annual global accumulation of 86 million tons of non-recycled food packaging waste [47].

Globally, agriculture accounts for 72% of freshwater extraction, primarily for irrigation purposes [39], consuming between 80% and 90% of the total freshwater resources used in all human activities [51]. Water stress, which occurs when the ratio of freshwater abstraction exceeds 25% of the total available renewable freshwater resources, affects and is influenced by agriculture. On a global scale, water stress reached 18.6% in 2019, though this figure conceals significant regional variations. Notably, North Africa and West Asia recorded a critical water stress level of 84.1% that year, marking a 13% increase since 2015. This translates to over 733 million people (10% of the global population) living in countries with high or critical water stress levels, i.e., surpassing the 75% threshold [52]. The use of agrochemicals has profound negative effects on soil quality and contributes to freshwater pollution through runoff and drainage [39]. Synthetic reactive nitrogen fertilizers have seen increased usage, reaching 110 million tons in 2017. Industrial fertilizer production and biological nitrogen fixation in agriculture account for 80% of anthropogenic nitrogen fixation. Plants absorb less than half of the applied nitrogen, resulting in excess nitrogen causing harm to the environment [39,53]. The excessive use of nitrogen and phosphorus in fertilizers and the release of pesticides significantly contribute to one-third of the world's agricultural areas being classified as moderately to highly degraded [39]. There is limited room to expand productive land, as 98% of food is cultivated on land already occupying roughly half of the world's habitable areas (excluding deserts, polar regions, and inland water bodies) [39]. In 2009, animal-based food production was responsible for over three-quarters of global land use and approximately two-thirds of greenhouse gas emissions from agriculture [37]. Nearly 10 million ha of forest are lost annually, with agricultural expansion accounting for almost 90% of global deforestation (50% for plantations and 39% for cattle grazing) [52]. This impact becomes even more evident when considering that, despite using almost 80% of all agricultural land for livestock and feed production, it contributes to only 18% of the world's calorie production and 37% of total protein output [3,54].

Environmental factors, including pollution and climate change, have a detrimental impact on agricultural production, which relies on biogeochemical cycles that influence crop quantity and quality [39]. There is compelling evidence pointing to the breakdown of current agricultural systems, and these impacts resonate throughout the global food system. The current trends of agricultural intensification are proving unsustainable, placing immense pressure on land and water resources and affecting the productivity of farmers. Key agricultural systems are being compromised, posing a threat to people's livelihoods. Large commercial farms currently dominate agricultural land use, often exploiting economically poorer countries, while the fragmentation of smallholder farms concentrates subsistence agriculture on land vulnerable to degradation and water scarcity [39]. The environmental imbalances caused by human activity in the food sector result not only from soil and water overexploitation but also from conditions across the entire production, distribution, and consumption chain. These issues arise from excesses, wastage, and a lack of proportionality in supply, failing to align with the real nutritional needs of individuals. In addition to a lack of understanding of the cause-and-effect relationship with the environment, there is a lack of rationalization and efficiency in these processes. The food market, driven by growth, often prioritizes profit and consumerism, disregarding the side effects on the environment and vulnerable populations. The path to achieving Sustainable Development Goal 2: Zero Hunger by 2030 [39] is not solely about increasing food production but also ensuring equitable distribution and access for all. Despite the continuous growth of the global population, the amount of food currently produced (approximately 5 billion tons in 2021/2022) [55] is theoretically sufficient for the entire global population. However, a significant percentage of that production is lost or wasted, and a substantial portion of the world's population still lacks access to an adequate quantity and quality of food.

In the global context, where natural resources are becoming increasingly scarce and unpredictable, it is concerning to note that roughly one-third of the food produced goes unconsumed [56]. Food loss occurs after harvest, involving farmers and suppliers up to the point just before retail [56], due to factors such as inefficient transportation, bulk purchasing, and distribution lead time [57]. On the other hand, food waste takes place during distribution and consumption at retail and consumer levels, including stores, supermarkets, restaurants, and even at the consumer's home. This not only represents a missed opportunity to feed the world's population but also carries a double negative environmental impact: it exerts undue pressure on natural resources and ecosystem services, leading to pollution through discarded food [56]. According to the 2021 Food Waste Index Report from the United Nations Environment Program, in 2019, a staggering 931 million tons of food were wasted, which translates to about 121 kg per person per year. This waste is primarily attributed to household, food services (catering), and retail sectors, accounting for 17% of global food production [58]. In 2020, an estimated 13.3% of the world's food was lost shortly after harvesting and before reaching retail markets during activities such as transport, storage, processing, and full sale [52]. Distribution and sale to the final consumer also involve significant waste, ranging from 5% to 10%, particularly in the case of perishable products. Handling and packaging conditions, as well as storage and transport times with long journeys between producers and consumers, contribute to food quality loss and subsequent waste increase. The flow of food products is heavily influenced by market dynamics, the interplay between supply and demand, and purchasing power, which sometimes favors the availability of differentiated and remote products to consumers. However, this can lead to the spread of pests and diseases across borders, to the detriment of local products [53]. Although the 2021 Food Waste Index Report does not provide details about the percentage of food loss and waste by food type, the 2013 Summary Report—"Food Waste Footprint: Impacts on Natural Resources" prepared for FAO by BIO-Intelligence Service, France, mentions that plant-based foods, especially fruits, vegetables, and tubers, experienced the highest losses and waste, exceeding 40% of the total food produced in that category [56]. The same report also indicates that upstream losses, including production, handling, and post-harvest storage, accounted for 54% of the total waste, while downstream waste volumes, including processing, distribution, and consumption, contributed to the remaining 46% [56]. A mass flow analysis study conducted in the European Union found that over 40% of fruits and vegetables were wasted along the food supply chain [59].

Food loss and waste patterns are influenced by economic and technological differences, with food loss predominantly occurring closer to the consumer in developed regions and closer to the farmer in developing regions [37]. In developed regions, the abundance of food is attributed to robust markets and substantial purchasing power, while in developing regions, food shortages are more common, driven by limited economic resources or the inability to produce one's own food. This results in a greater emphasis on rationalization and efficient use of available products, reducing waste closer to the consumer [37]. Flaws in the food distribution and consumption systems have resulted in irrationality and inequity, leading to uneven access to food, hunger, malnutrition, and food insecurity. These challenges persist as pressing concerns, particularly in regions experiencing rapid population growth. On the other hand, unhealthy dietary habits, including overeating, are contributing to a surge in health problems such as obesity, diabetes, and cardiovascular issues in an increasing number of countries worldwide. These health challenges come with significant human and economic costs. Transformative changes are imperative within the world's food systems, including agricultural production systems, in order to feed the growing global population sustainably. Additionally, measures aimed at reducing inequalities are essential to ensure that safe, nutritious, sufficient, and accessible food is available for all [60].

Since 2014, the number of hungry and food-insecure individuals has been on the rise [39]. Various factors have contributed to this concerning trend, including the impacts of climate change, extreme weather events, the COVID-19 pandemic (which led to border closures, quarantines, and supply chain disruptions), conflicts, and growing inequalities among countries and populations. As a result, approximately 828 million people experienced hunger in 2021, which is around 150 million more individuals than in 2019. In other words, it is estimated that one in ten people worldwide is afflicted by hunger. Furthermore, nearly a third, approximately 2.3 billion people, were moderately or severely food insecure in 2021, signifying that they lacked consistent access to adequate food. This marks an increase of almost 350 million people since the onset of the pandemic [61]. The ongoing conflict in Eastern Europe poses an additional threat to food security, as the two involved countries are major producers and exporters of essential food products, fertilizers, minerals, and energy. Consequently, countries dependent on these imports are vulnerable to rising food costs and disruptions in the supply chain. In 2020, escalating food prices affected 47% of countries [52]. By March 2022, the FAO Food Price Index had reached its highest level since 1990, at 159.7 points [62]. With the surge in prices of basic commodities globally and the subsequent increase in agricultural product costs, the vulnerabilities of the food system are exposed. These include the dependence on imports of energy, fertilizers, and animal feed. This situation results in elevated costs for producers and has repercussions on food prices, raising concerns about consumer purchasing power and producer income [63]. It is noteworthy that around 3 billion people cannot afford healthy food [63]. Urgent joint, coordinated actions, and policy solutions are required to prevent food shortages for the world's most disadvantaged populations and to mitigate the impact of conflict and the lingering effects of the pandemic on global food insecurity [52].

3. Challenges of Agrifood Systems for Food Security and Environmental Sustainability

In light of the identified challenges to global food security, it is evident that current circumstances demand a different approach compared to the past. The future trajectory must align with evolving trends and adhere to the Principles for Responsible Investment in Agriculture and Food Systems as outlined by the Committee on World Food Security [64]

(CWFS, 2014). Furthermore, it should align with strategies defined in the United Nations Environment Program and the European Green Deal, including the Farm to Fork strategy.

Medium and long-term challenges for agrifood systems can be summarized as follows [51,63,65–67]: (a) reduce the ecological footprint, aiming for a neutral or positive environmental impact, with a focus on mitigating climate change, adapting to its impacts, and reversing the loss of biodiversity; (b) sustainably improve agricultural productivity and enhance crop production by achieving multiple harvests per year; (c) protect and restore natural ecosystems, ensuring a sustainable natural resource base, limiting land occupation, reducing water consumption, and rationalizing and enhancing the efficiency of agricultural processes; (d) reduce pollution, particularly stemming from waste production (including packaging) and the emission of atmospheric pollutants, including greenhouse gases contributing to global warming; (e) minimize food loss and waste; (f) reduce energy consumption and dependence, particularly on fossil fuels, and transition to clean, renewable energies; (g) shorten distribution chains and times, bringing producers closer to consumers and promoting the consumption of local products; (h) decrease the use of pesticides, antimicrobial agents, and excessive fertilization, and mitigate the associated risks; (i) foster the circular economy and organic agriculture; (j) minimize plant diseases, the proliferation of pests, cross-contamination, and the spread of diseases borne by food and their vectors; (k) promote seed security and diversity; (l) avoid competition between bioenergy and food crops and prevent the diversion of edible crops and land for bioenergy production; (m) ensure food security, nutrition, and public health, reduce inequality in food access, combat price speculation, and ensure that everyone has access to sufficient, safe, nutritious, and sustainable food, ultimately eradicating hunger and all forms of malnutrition; (n) promote healthier diets, reduce the consumption of ruminant meat, and encourage greater intake of plant-based protein to enhance nutrition; (o) decrease the cost and improve accessibility of food products and healthy diets; (p) enhance the efficiency, inclusivity, and resilience of food systems; (q) prevent cross-border and emerging threats to the food system, reduce dependence on external factors (economic, political, social, public health), and strengthen resilience to future challenges such as diseases, supply chain disruptions, transportation issues, societal crises (exacerbated by pandemics, contingencies, prolonged crises, catastrophes, and conflicts); (r) promote research, innovation, technology, and investment in food systems to develop and test solutions, overcome obstacles, and discover new market opportunities, (s) provide training to both producers and consumers; and (t) increase confidence, knowledge regarding the origin of consumed food, safety, and environmental awareness.

These challenges require a comprehensive and coordinated global effort to address the complex issues surrounding food security, environmental sustainability, and public health.

4. The Importance of Urban Agriculture

Innovative food production systems are essential to address past issues and adapt to current and future conditions. For investments in agriculture and food systems to yield positive outcomes, they must be responsible and oriented toward achieving social, economic, cultural, and environmental benefits while minimizing negative impacts. It is imperative to seek advanced technological solutions that not only meet present needs but also future requirements, with a focus on balance, social equity, and environmental sustainability. The goal extends beyond ensuring food security, nutrition, and public health; it pertains to the future of global food systems and the very survival of humanity.

Recent global events, notably the pandemic and the conflict in Eastern Europe, have underscored the vulnerability of large cities to global risks and crises. These unforeseen developments have heightened awareness regarding the critical importance of food availability for urban populations. Research from the Research Center for Agricultural Policies and Bioeconomy in Italy has revealed that the combined effects of border closures and movement restrictions have led to increased food losses and export costs, particularly for horticultural products and perishable goods. These challenges are more pronounced in countries that are not self-sufficient in food production. At the urban level, restrictions have influenced food consumption habits and diets, requiring quick adjustments [68]. In response, urban agriculture should be promoted and facilitated.

Urban agriculture can be defined as a practice that yields food and other outputs from agricultural production and related processes taking place on land and other spaces within cities. It involves urban actors, communities, places, policies, institutions, production systems, ecologies, and economies, largely using and regenerating local resources to meet the needs of local populations [69]. There are different types of urban agriculture: (a) home-based gardening; (b) community-based and other shared gardening; (c) commercial crop production; and (d) institutional food growing [69]. In home gardening, horticultural crops can be produced through conventional farming techniques, micro gardening, container growing, vertical farming, indoor farming, rooftop gardening, and hydroponic practices, making creative use of domestic spaces/surfaces, such as backyards, roofs, terraces, cellars, among others [69].

Urban agriculture serves as a nature-based solution, offering benefits that extend beyond food production to encompass important social and economic roles [70]. A recent study conducted in six cities around the world (Belgium, Ecuador, Honduras, Indonesia, Senegal, and Tanzania) states that urban agriculture is a vital strategy for building the resilience of cities' food supply, reducing poverty, and increasing employment, improving nutritional outcomes, and mitigating environmental degradation of urban spaces. It can efficiently meet the needs of various actors in urban areas [71].

To ensure positive outcomes for nature and the climate, food systems can be reimagined and redistributed. An initial step in this direction is the transition to plant-based diets, where feasible and appropriate [3]. Vertical urban agriculture, characterized by its efficient use of vertical space across multiple levels, relies on controlled environments with features such as light-emitting diode (LED) lighting, optimized atmospheres, and hydroponic systems for nutrient and water management. It is less vulnerable to the adverse effects of climate change or external factors that can impact production [15,22]. Urban agriculture, including hydroponics, is increasingly seen as a solution to enhance food production within cities, providing sustainable and resilient approaches to food supply in urban environments.

5. The Potential of Home Hydroponics

Hydroponics is an innovative agricultural method that enables plant growth without soil. It typically involves cultivating plants with their roots directly submerged in a nutrient solution or an artificial medium, such as mineral wool, rice husks, perlite, coconut peat, peat, expanded clay, or other substrates. Hydroponic systems allow precise control of key factors, including nutrient concentration, pH levels, electrical conductivity, dissolved oxygen, and temperature, to create optimal conditions for plant growth. This method utilizes a controllable mixture of water and nutrient solution that can be delivered to plants as needed [72]. When employed in indoor or outdoor domestic surfaces and spaces, it is designated by home hydroponics. Hydroponics is recognized as an eco-friendly, sustainable, reliable, and flexible approach to food production. It is considered by some experts to be the most advanced method for large-scale soil-less crop production and the most efficient strategy for vegetable cultivation. It typically results in faster growth (30 to 50% faster) and occupies less space compared to traditional soil-based agriculture. Additionally, it often requires less manual labor [19,73,74].

The application of domestic hydroponic systems can occur at any stage of construction and type of building, whether indoors or outdoors. It can be planned at the design stage of a new building or be integrated into an existing building. Buildings may need to be adapted with the inclusion of a new structure that houses the hydroponic system. If space is available, it can be partially or totally converted to receive a hydroponics unit. Mobile hydroponic systems or appliances that can be placed inside a building offer an additional solution. There is also the possibility of coupling hydroponic systems to the building structure. Examples of locations include a terrace (indoor or outdoor, with or without a roof/greenhouse), attic, wall (indoor or outdoor, inserted or attached to the wall), window, balcony, basement, room (with total or partial occupation), stairwell, among others (Figure 2).

Figure 2. Examples of locations for integrating home hydroponics into buildings. A, attic; B, terrace; C, inserted into a wall; D, mobile appliances; E, outdoor wall; F, greenhouse; and G, basement.

5.1. Types of Hydroponic Systems

There are several types of hydroponic systems, and the choice of system depends on various factors, including the specific plant under cultivation. The main and most commonly used hydroponic methods include: (a) Wick System; (b) Deep Water Culture (DWC) or Floating Root System; (c) Nutrient Film Technique (NFT); (d) Aeroponics; (e) Drip Irrigation System (DIS); (f) Aquaponics; and (g) Ebb and Flow or Flood and Drain System (Figure 3). Variations and combinations of these methods have also emerged. These systems can be categorized as either circulating/flowing culture systems or non-circulating/static culture systems. Most commercial growers prefer circulating culture systems, such as DIS, NFT, and aeroponics, as they allow for the recycling of nutrients and water within the system, reducing waste and increasing sustainability. In contrast, static systems require periodic replacement of the nutrient solution, which can increase costs and reduce sustainability. Key features common to most hydroponic systems include a reservoir for storing the nutrient solution and an aerator [75]. These methods offer innovative and resource-efficient ways to grow crops in controlled environments.

5.2. Types of Hydroponic Crops

Hydroponic production systems are versatile and capable of growing a wide variety of foods. Some of the main types of food that can be successfully cultivated in hydroponics include: (a) fruit: certain species like strawberries, tomatoes, and even small fruit trees like dwarf citrus trees; (b) leafy and stem vegetables are particularly suited for hydroponics (e.g., lettuce, spinach, cabbage, chicory, arugula, and peppers); (c) herbs that offer fresh and flavorful options (e.g., basil, cilantro, coriander, and mint); (d) microvegetables: hydroponic systems are excellent for growing microgreens and sprouts, which are tiny, nutrient-rich versions of plants like radishes, broccoli, and red beets; and (e) superfoods like wheatgrass plants and small aquatic plants from the genera *Lemna* and *Azolla*, known for their high protein content. This flexibility in the choice of hydroponic crops is particularly valuable for urban farming, controlled environment agriculture, and locations with limited access to arable land.

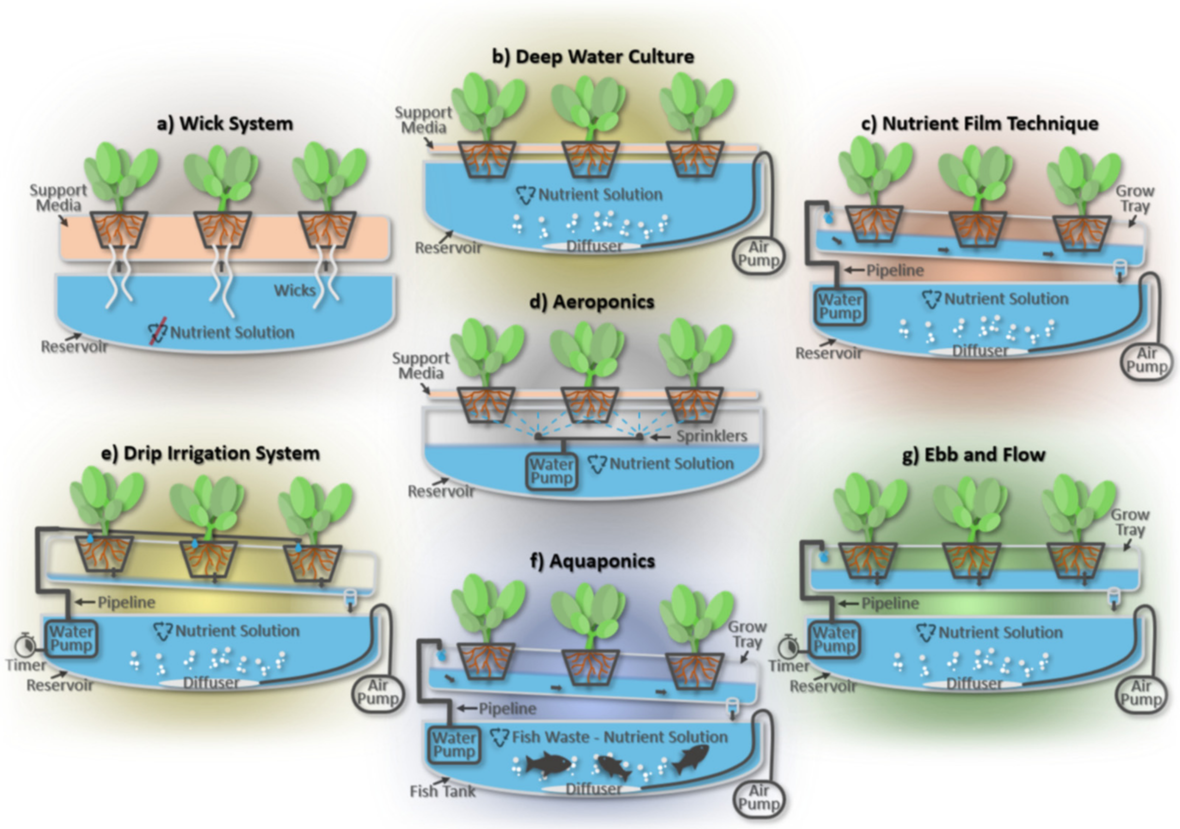

Figure 3. Different types of hydroponic systems. Adapted from Velazquez-Gonzalez et al. (2022) [75].

5.3. Advantages of Hydroponics

Hydroponics offer precise control over plant nutrition and efficient space utilization. It mitigates risks associated with exposure to pests and extreme weather conditions. Furthermore, it offers numerous benefits over conventional soil-based agriculture. This includes a diminished dependence on harmful chemicals like pesticides commonly employed in non-organic farming, coupled with a reduced reliance on synthetic chemical fertilizers, leading to decreased soil and water pollution. [72]. This method is gaining prominence in global agriculture and is particularly prevalent in regions where access to arable soil is limited, such as urban areas [76]. Often referred to as soilless cultivation, hydroponics focuses on efficient water usage, promoting self-sustainability in an environmentally friendly manner. In fact, it uses only about 10% of the water needed in conventional farming methods [14]. Table 1 presents a summary of how hydroponic systems, particularly domestic ones, can contribute to tackling several problems of the global food system, both from the perspective of food security and environmental sustainability.

Table 1. Summary of home hydroponics solutions to global food system sustainability problems.

Food System Sustainability Problem	Home Hydroponics Solution	Reference
Increase in world population and consequent demand for food	Optimized plant growing process and reduced maintenance, improves the efficiency, self-sufficiency, and resilience of food systems; high yields within limited space.	[22,68,71,77]
Market heavily influenced by external factors: political and socioeconomic	Small dependence on external factors since the consumer has control over the chain, from production, harvesting, and distribution, without intermediaries.	[15,22,72]
Increase in production costs, prices, and access to the final consumer	The elimination of distance and intermediaries is the basis for reducing production costs; access to the consumer is direct; decrease the cost and improve accessibility.	[68,74,78]
Inequity in access to food, increasing food insecurity	The premise of home hydroponics is that it is inclusive and accessible to everyone in any home; socially fair.	[68,70,71]
Increasing unhealthy consumption of meat-based diets	Increases the availability of plant-based foods and promotes the transition to sustainable and healthy diets.	[28,32,79]
Use of natural resources above their regenerative capacity	Environmentally sustainable, reducing the ecological footprint, removing CO_2 through plant photosynthesis; reduces the impacts of climate change; improves air quality.	[74,80–82]
Deforestation, destruction of ecosystems and biodiversity	No land occupation: zero-acreage farming; urban farming; vertical farming, with efficient use of built spaces.	[69,79,83]
Vulnerability to the negative impacts of climate change	Production under controlled environmental conditions reduces vulnerability to natural disasters and climate-related problems.	[15,22,84]
High consumption and waste of water, resulting in water stress and pollution	Efficient use of water, with its recirculation and direct absorption by plant roots, allows the consumption of only 10% of water compared to traditional agriculture.	[14,23]
Increase in pests and diseases associated with agriculture and food	Its location in a domestic environment protects crops from pests; soilless production minimizes susceptibility to pests and diseases.	[18,72]
Exaggerated use of agrochemicals and increased associated risks	Customized nutrient solutions; precise control over plant nutrition; symbiotic relationships with microorganisms reducing dependence on agrochemicals; bioponics.	[85–87]
High emission of greenhouse gases, with an effect on the ecological footprint	Largely reducing the use of fossil fuels, clearing land, allowing the restoration of natural habitats, among others, translates into a sharp decrease in CO_2 equivalent emissions.	[74,88]
Long production and supply chains, over time and distance	Production sites draw closer to end consumers; shortens distribution chains; eliminates the need for logistics and distribution; promotes local product consumption.	[69,74,81,89]
Huge amount of food loss and waste throughout the entire chain	Production, harvesting, and consumption according to consumer needs.	[68]
Growing production of food packaging and consequent waste	No need to use packaging, eliminating the impacts of its production and the generated waste.	[23,88]
Abuse of additives and preservatives to reduce food perishability	Products are fresh and healthy, without the need for the use of additives or food preservatives.	[68,74]
Decrease in the quality of food products and confidence in them	Enhanced flavor and nutrient-rich qualities; consumers produce their own food and know the origin of what they eat.	[23]
Impact on public health due to food insecurity and environmental pollution	Improve food safety and environmental sustainability, using more environmentally friendly practices and technologies that minimize risks and promote public health.	[72,90,91]

Comparative analyses of lettuce production demonstrate the superiority of vertical hydroponics over traditional methods. It not only yields higher production but also has an environmental footprint comparable to that of field cultivation and significantly lower than that of heated greenhouse farming, with reductions ranging from 2 to 12 times less [22]. Microvegetables, when grown hydroponically, offer a multitude of benefits. They are known for their enhanced taste, sustainability, cost-effectiveness, and nutrient-rich qualities. They require significantly less time to grow, with a reduced water consumption of 93 to 95%. Furthermore, they minimize the need for synthetic fertilizers and reduce food waste since both the stem and leaves are utilized in meal preparation. Their cultivation is uncomplicated, requiring minimal space and resources. As a result, there has been a surge in the domestic cultivation of microvegetables in urban settings attributed to the adoption of vertical agriculture techniques [23]. Despite the limitations of traditional urban agriculture practices, innovative and disruptive solutions, along with shorter supply chains for fresh agricultural products, can play a pivotal role in reducing the vulnerabilities associated with global systemic risks, food supply chains, shortages, and food transportation distances. This leads to increased accessibility and enhances the resilience of urban production [68]. As production sites draw closer to end consumers, there is a significant reduction in the need for long-haul supply chains, thus lowering fossil fuel consumption, which in turn has a positive impact on the environment [74]. Several studies have explored the potential of urban agriculture, not only in terms of food security, food diversity, poverty reduction, social inclusion, employment, income generation, and resource sustainability, but also as a source of motivation for healthy eating, physical exercise, and mental relaxation [90–92]. Consequently, in developed countries, there has been a surge in demand for urban plots for personal fruit and vegetable cultivation [93].

Field-scale studies and reviews suggest that various forms of innovative urban agriculture, including vertical indoor farming, greenhouses, and hydroponics, can yield as much as 140 $kg/m^2/year$ of vegetables [79]. Theoretically, the most advanced systems have the potential to meet the dietary needs of large population segments, primarily in terms of micronutrients and dietary fiber [28,79]. These cutting-edge urban farms are equipped with climate control systems that feature high-tech solutions such as precision automation for nutrient dosing, LED technology, and artificial intelligence. These technologies optimize the plant growing process and reduce maintenance and production costs [77]. Additionally, these advanced urban farming techniques are less vulnerable to natural disasters and weather-related problems [84], making it possible to repurpose abandoned buildings and empty spaces. A case study conducted in Uganda and Tanzania highlighted hydroponics as a climate-smart farming system. It showed that hydroponics offers high yields within limited space, is not susceptible to soil-borne pests and diseases, and provides farmers with control over environmental conditions. However, challenges such as high initial investment costs and limited technical knowledge about hydroponics have been reported. According to recommendations from farmers, hydroponics holds the potential to enhance food security in urban areas, provided there are concerted efforts to promote this agricultural system and to investigate ways to reduce the associated high costs [18].

Urban agriculture contributes to the self-sufficiency and resilience of cities while delivering positive environmental and social benefits. However, its effectiveness is contingent upon various factors, including the specific type of agriculture and the geographic location of the city. The sustainability of these practices is significantly influenced by the source of electricity production. In cases where carbon-neutral energy sources, like solar or wind power, are used, vertical hydroponic production can outperform traditional agricultural methods [22]. The adoption of renewable energy sources, particularly solar power, to meet electricity needs for heating and cooling and improve the overall environmental impact of the food sector has gained significant attention in various countries, showcasing its considerable benefits. Solar irrigation, a method that utilizes solar energy to power water pumps or other irrigation systems, is witnessing widespread adoption to enhance access to water resources. This has enabled multiple cropping cycles and significantly increased resilience to variable rainfall patterns. In India, for instance, solar-powered irrigation systems have contributed to yield increases of more than 50% compared to rain-fed irrigation. It is worth noting that life cycle emissions associated with solar-powered water pumping are estimated to be 95 to 98% lower than those of pumps powered by grid electricity or diesel [44].

From an environmental perspective, vertical farming in rooftop greenhouses has shown significantly enhanced sustainability when contrasted with traditional greenhouses, achieving reductions in environmental impacts ranging from 50 to 75%. For example, it results in emissions of just 0.58 kg of CO_2 per kg of tomatoes, whereas conventional greenhouses emit 1.7 kg of CO_2 per kg of tomatoes. The primary reasons behind this difference lie in reduced food packaging and transportation, which consequently diminish greenhouse gas emissions related to food transportation [88]. Several scientific studies have indicated that rooftop agriculture can bring substantial benefits to society as a whole. It has been observed that creating vegetable gardens on rooftops reduces carbon emissions and local temperatures. This helps mitigate the urban heat island effect, leading to improved air quality and reduced impacts of climate change. Additionally, rooftop agriculture can serve as a noise buffer, and it contributes to the local supply of fresh produce. These positive impacts have been documented in case studies from various countries, including Canada [89], Italy [94], Singapore [80], and the United States of America [81]. Further research has explored the application of vertical farming techniques within buildings, particularly in office spaces, concluding that it offers the advantage of increased carbon dioxide (CO_2) removal through plant photosynthesis. In fact, it can achieve removal rates up to 9.2 times higher than ornamental plants. Additionally, vertical farming within office spaces can lead to energy savings in building ventilation, with potential reductions ranging from 9 to 15% [82].

Concerning the possibility of implementing hydroponics at home, a study conducted in 2020 revealed that many individuals face challenges in terms of available space within their homes. However, there is a notable interest in participating in community gardens where space can be allocated for food cultivation and experimentation with new solutions. It is important to recognize that in order to sustain engagement in such community horticulture projects, a deeper motivation is required, as initial motivations tend to be somewhat fleeting [25]. On a global scale, while most empirical case studies support the notion that urban agriculture can be highly productive and effective in addressing some food security concerns [28,32], the scalability of these operations to achieve realistic, sustainable production with viable business models raises numerous open questions. These questions pertain to political, economic, technological, logistical, and distribution-related aspects [95]. Nevertheless, domestic production offers certain advantages by eliminating the necessity for logistics and distribution. Urban agriculture is not the sole solution to ensure food security, as it does have limitations related to space constraints for food self-sufficiency [29,78]. However, promoting the local production of fresh, highly perishable vegetables and fruits can serve as a resilient measure against food shortages. This not only helps maintain a balance with urban resources but also enhances food security, particularly for items susceptible to price volatility [78]. Local organic food production and consumption are one of the central parts of achieving sustainable development goals and promoting sustainability in agricultural-based urbanizing cities [96].

From an economic point of view, hydroponic vegetable cultivation has been studied essentially in large centralized systems, demonstrating favorable outcomes. For example, in Brazil, a study showed that a hydroponic farm with 2475 m^2 of greenhouses was economically viable [97]. On a smaller scale, a feasibility study of a domestic industrial-scale hydroponic business (as an alternative home business) indicated excellent profitability [98]. Other studies revealed that domestic vertical hydroponic production may be economically viable, with the potential to increase food security and the sustainability of urban areas [99,100].

Regarding acceptability, a study in Brazil revealed that hydroponics was regarded as an attractive alternative for producers [97]. Research conducted in Malaysia concluded that indoor hydroponics is gaining traction among urban residents, including in low-income housing complexes. However, for the latter, the available home space may restrict the design of the hydroponic system. As for user preferences, in terms of the types of plants to grow, price, and design, more studies are needed to allow researchers to develop a system that best suits the average citizen [101].

A study carried out in Syria focusing on strawberry production through the drip method concluded that growing vegetables on home balconies is a functional hydroponics technique. This method allows for the proximity of crops to consumers, resulting in time and cost savings in the acquisition and assurance of fresh vegetables [102].

5.4. Sustainable Synergies with Hydroponics

Urban agriculture is evolving with new areas of academic exploration, including the concept of zero-acreage farming (ZFarming) [24,103]. ZFarming extends beyond food production and has the potential to enhance a city's sustainability by promoting greener environments, reducing carbon footprints, encouraging the efficient utilization of organic waste, and raising consumer awareness [104–106]. ZFarming encompasses a broad spectrum of activities, ranging from small family food gardens to community-based shopping center projects that incorporate high-tech production methods [29–31]. Rooftop agriculture, for example, has been increasing throughout the world, most notably in North America, Europe, and Asia, with an increase of 44, 26, and 21%, respectively, in the last 30 years [107]. One of the primary benefits of ZFarming is the opportunity to integrate food production with urban structures, including repurposing abandoned or unused spaces. This concept explores potential synergies that can emerge from the combination of urban environments and food production. The fundamental idea is to establish resource-efficient, small-scale systems that link food production and consumption in both space and time, leading to energy savings in areas such as heating, transportation, cooling, packaging, and waste management [108]. Examples of such resource-efficient practices include the reuse of municipal wastewater and rainwater for irrigation, harnessing waste heat from local sources (e.g., buildings, swimming pools, or bakeries) to provide warmth for rooftop greenhouses, and recycling locally accumulated organic waste as plant nutrients [108,109]. These approaches and synergies are especially pertinent in densely populated cities with limited space for traditional agriculture or in large cities that lack sufficient surrounding agricultural land to establish comprehensive regional food systems [83].

Exploring symbiotic relationships between plants and microorganisms has become a promising approach to reduce the dependence on agrochemicals [86]. A study conducted in conventional hydroponic systems demonstrated that co-cultivating microalgae with plants, achieved through proper inoculation, significantly enhanced the growth of tomato plants, accelerating their growth by approximately 30 to 40%. Furthermore, this research highlighted that hydroponic production units have the potential to offer sustainable economic benefits, not only by enhancing plant nutrition but also through the treatment of process water [110].

An essential factor for the success of hydroponic systems is the utilization of customized nutrient solutions tailored to the specific requirements of each crop. These solutions consist of vital cations (e.g., Mg^{2+}, Ca^{2+}, and K^{+}) and anions (e.g., SO_4^{2-}, NO_3^{-}, and PO_4^{3-}) crucial for the growth of the cultivated plants. Traditionally, a surplus of nutrients is applied to common crops to mitigate the risk of nutrient deficiencies. However, plants absorb these nutrient ions at varying rates and generally take up more water than nutrient ions during their growth stages [85]. This can lead to an accumulation of excess nutrients in soils and in surface and groundwater. In precision farming techniques, like controlled hydroponics, dosing is tailored to the specific needs of the plants, with real-time monitoring of relevant parameters. Hydroponic crop fertilization primarily involves the use of nutrient solutions containing NPK (nitrogen, phosphorus, and potassium), along with other essential nutrients. These solutions are often commercially available and predominantly consist of synthetic products. Nevertheless, natural alternatives exist, such as those derived from food waste. In this process, the liquid fraction of food waste can undergo pasteurization, enabling the creation of a balanced nutrient solution for hydroponic systems while minimizing the risk of microbiological contamination. This offers a more sustainable and environmentally friendly approach to hydroponic fertilization.

The utilization of manure and sewage sludge in conventional soil-based agriculture is a common practice, but it poses a high biological risk if not adequately treated. In the realm of hydroponics, a promising innovation called bioponics is emerging and is considered the next revolution in soilless agriculture. Bioponics offers the possibility of cultivating crops using waste streams, including food waste rich in nutrients, without the need for chemical fertilizers. This is achieved by harnessing the symbiotic relationship between microorganisms and plants [87,111]. Aquaponics, a specific type of bioponics that utilizes aquaculture effluents as a nutrient source, has already found commercial applications. This was made possible through a well-established techno-economic analysis of the system [112,113]. In bioponics, microorganisms play a pivotal role in nutrient recovery, organic waste degradation to maintain water quality, and the transformation of nutrients for plant uptake [114,115]. Anaerobic digestion of agricultural residues, in particular, yields a substantial amount of nitrogen and phosphate, making it a valuable nutrient source when integrated with bioponics. However, it is essential to note that anaerobic digestion also generates residual volatile fatty acids, such as acetic acid, which can inhibit the growth of microorganisms and plants within bioponic systems [116,117].

Incorporating biological fertilizers, fostering the symbiosis between microorganisms and plants, and implementing co-cultivation are strategies aimed at bridging hydroponics with organic agriculture, with the goal of closing the nutrient cycle and promoting a circular economy.

5.5. Limitations and Challenges of Home Hydroponics

The hydroponics market is predicted to grow over the next two decades [75]. Nevertheless, despite the demonstrated capabilities and effectiveness of hydroponics, particularly on a large scale, there are limitations that hinder its implementation in small-scale systems, including domestic contexts in both urban environments and rural communities. These challenges are particularly pronounced in areas where access to technology is more restricted [75]. In fact, technological limitations are among the main constraints of implementing domestic hydroponics, making it necessary to embrace new paradigms, such as the Internet of Things (IoT). IoT-based hydroponic systems can facilitate control over variables—such as pH, electrical conductivity, temperature, lighting, and nutritional composition—thus augmenting production efficiency and resource conservation. [75,118]. In addition, IoT-based hydroponic systems can be user-friendly and do not require prior system expertise [119]. Optimizing nutritional needs for different leafy and fruit-bearing vegetable crops is one of the biggest difficulties in hydroponic systems [120]. Furthermore, scientific evidence reveals that misinformation about urban indoor hydroponics has been disseminated on social media platforms, accentuating the difficulties of the path forward [121].

Compared to traditional agriculture, the initial investment in home hydroponic systems is generally high [75,118], and technical knowledge is required [118,120], but the implementation of this technology on a small and medium scale can increase food security [18], and positively impact local economies, even promoting self-employment or profitable business activities [75].

Regarding the running costs of hydroponic systems, energy (electrical) continues to be a determining factor, but its impact can be minimized if it is carbon neutral (e.g., wind and solar energy) [22].

Additionally, the risk of waterborne diseases in home hydroponics cannot be ignored, as the same nutrient solution can circulate through all plants [118].

6. Conclusions and Future Perspectives

To achieve food security in harmony with environmental sustainability, it is imperative to promote changes not only in food systems but also in consumption habits, awareness, and environmental interventions in this domain. Encouraging healthier diets, transitioning from animal-based to plant-based proteins, and playing an active role in the food system, starting from production, are responsibilities that can largely depend on consumers. These actions will contribute not only to individual self-sufficiency and food security but also to global environmental sustainability. Vertical urban farming should be recognized as a sustainable solution to attain food security for urban populations. In light of the above, the implementation of hydroponic systems, with productivity ratios comparable to conventional systems, either within residential spaces or in close proximity, could provide food security with reduced reliance on external factors. These factors encompass economic, political, social, public health, and food supply chain issues, including the availability and pricing of food, raw materials, fuel, agrochemicals, and challenges like supply chain disruptions, transportation issues, societal standstills exacerbated by aspects such as lockdowns, pandemics, crises, strikes, and conflicts.

The benefits of this approach will also translate into global sustainability by reducing the impact on ecosystems, curbing pollution, and mitigating climate change. It will also decrease the influence of climate and pollution on food production, freeing up extensive areas currently under pressure from human activities, which can then be allowed to regenerate. This, in turn, will reduce the overall ecological footprint.

Hydroponics, despite its advantages, still faces several challenges, essentially at the technological level, that need to be addressed: (a) high energy consumption: One of the major drawbacks of hydroponics, particularly in vertical and indoor farming. Artificial lighting, ventilation, and heating or cooling are essential to maintain the precise environmental conditions required for plant growth. To mitigate this, the use of high-efficiency LED technology and better harnessing of solar energy can reduce energy consumption. Installing photovoltaic solar panels can also enable hydroponic systems to become more self-sufficient by supplying a significant portion or all of the required electrical energy; (b) water usage: While hydroponics is more water-efficient than traditional agriculture, capturing and storing rainwater for the production process can further reduce water consumption. This is especially important for regions facing water scarcity or looking to maximize resource efficiency; (c) limited crop variety: Hydroponics can produce a diverse range of plant species due to the ability to control environmental conditions. However, the variety is naturally smaller compared to what can be obtained through traditional supply chains. Depending on the type of hydroponic system installed, domestic hydroponic production can either serve as a source of subsistence or complement other food sources. It might even provide the sole source of family food, meeting nutritional and taste requirements, particularly when cultivating "superfoods" and alternatives like microalgae; (d) user-friendly systems: Not everyone has the expertise or time to become proficient farmers. Hydroponic systems must be further developed, simplified, and automated to make them accessible to a broader range of users. The synergistic relationship within the hydroponic ecosystem between microorganisms and plants can be harnessed to help balance and regenerate the system, making it more user-friendly and self-sustaining. Addressing these challenges is crucial to enhancing the efficiency and accessibility of hydroponics, making it a more sustainable and practical solution for urban food production.

Integration with building design can maximize the effectiveness of hydroponic systems, especially in urban environments. It is ideal to integrate them into the initial design phase of new buildings. This integration should consider all infrastructure, technical, engineering, and architectural aspects. Such an approach would enable the deployment of modular systems both inside and outside various types of structures, ensuring seamless installation and operation. Closed-loop hydroponics, which is a developing hydroponic system that functions as closed cycles, relying primarily on internal resources, is a significant challenge. This may involve self-sustaining processes such as nutrient production through the action of microorganisms and the use of food waste. The goal is to reduce dependence on external sources of fertilizers and resources, making the system more self-reliant. To promote the widespread adoption of hydroponics, raising awareness and inspiring changes in culture and dietary habits are essential. These include fostering a sense of commitment to nurturing the hydroponic "ecosystem" and producing one's own food. It is also important to reduce the influence of economic interests in the food sector to ensure benefits for the broader population rather than just a few.

Overcoming these challenges and limitations will be essential for making hydroponics a more accessible, sustainable, and integrated solution for urban food production. It involves a combination of technological innovation, architectural planning, and a shift in policies, economics, and societal attitudes toward food production and consumption.

It is advisable to engage stakeholders, including policymakers, researchers, and the general public, in the formulation and execution of policies aimed at enhancing food safety literacy. Additionally, efforts should be made to facilitate the public's access to domestic hydroponic systems economically and technologically. In this context, it is recommended that further studies on domestic hydroponics be conducted, coupled with endeavors to disseminate the research through open-access channels. This approach presents an opportunity to bridge gaps in scientific understanding and reach interested producers and consumers, ultimately contributing to the advancement of sustainable food systems.

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