The Potential of Home Hydroponics

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The global food system is 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. 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.

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

1. 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 [1] (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 [2][3][4][5][6]: (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.

2. 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 [7]. 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 [8]. 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 [8]. 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 [8].

Urban agriculture serves as a nature-based solution, offering benefits that extend beyond food production to encompass important social and economic roles [9]. 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 [10].

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 [11]. 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 [12][13]. 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.

3. 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 [14]. 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 [15][16][17].

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 1**).

Figure 1. 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.

3.1. 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. 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 [18]. These methods offer innovative and resource-efficient ways to grow crops in controlled environments.

3.2. 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.

3.3. 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. [14]. 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 [19]. 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 [20]. **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.	[7][10][13][21]
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.	[12][13][14]
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.	[7][17][22]
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.	[7][9][10]
Increasing unhealthy consumption of meat-based diets	Increases the availability of plant-based foods and promotes the transition to sustainable and healthy diets.	[23][24][25]
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.	[17][26][27][28]
Deforestation, destruction of ecosystems and biodiversity	No land occupation: zero-acreage farming; urban farming; vertical farming, with efficient use of built spaces.	[8][25][29]
Vulnerability to the negative impacts of climate change	Production under controlled environmental conditions reduces vulnerability to natural disasters and climate-related problems.	[12][13][30]
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.	[20][31]
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.	[14][32]
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.	[33][34][35]
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.	[17][36]
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.	[8][17][27][37]
Huge amount of food loss and waste throughout the entire chain	Production, harvesting, and consumption according to consumer needs.	[7]
Growing production of food packaging and consequent waste	No need to use packaging, eliminating the impacts of its production and the generated waste.	[31][36]
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.	[7][17]
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.	[31]
Impact on public health due to food insecurity and environmental	Improve food safety and environmental sustainability, using more environmentally friendly practices and technologies that minimize	[14][38][39]

Food System Sustainability Problem	Home Hydroponics Solution	Reference
pollution	risks and promote public health.	

…ods. 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 [13]. 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 [31]. 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 [7]. 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 [17]. 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 [38][39][40]. Consequently, in developed countries, there has been a surge in demand for urban plots for personal fruit and vegetable cultivation [41].

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 [25]. 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 [23][25]. 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 [21]. Additionally, these advanced urban farming techniques are less vulnerable to natural disasters and weather-related problems [30], 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 [32].

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 [13]. 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 [42].

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 [36]. 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 [37], Italy [43], Singapore [26], and the United States of America [27]. 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% [28].

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 [44]. 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 [23][24], 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 [45]. 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 [22][46]. 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 [22]. 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 [47].

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 [48]. On a smaller scale, a feasibility study of a domestic industrial-scale hydroponic business (as an alternative home business) indicated excellent profitability [49]. 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 [50][51].

Regarding acceptability, a study in Brazil revealed that hydroponics was regarded as an attractive alternative for producers [48]. 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 [52].

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 [53].

3.4. Sustainable Synergies with Hydroponics

Urban agriculture is evolving with new areas of academic exploration, including the concept of zero-acreage farming (ZFarming) [54][55]. 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 [56][57][58]. 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 [46][59][60]. 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 [61]. 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 [62]. 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 [62][63]. 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 [29].

Exploring symbiotic relationships between plants and microorganisms has become a promising approach to reduce the dependence on agrochemicals [34]. 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 [64].

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 [33]. 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 [35][65]. 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 [66][67]. 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 [68][69]. 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 [70][71].

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.

3.5. Limitations and Challenges of Home Hydroponics

The hydroponics market is predicted to grow over the next two decades [18]. 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 [18]. 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. [18][72]. In addition, IoT-based hydroponic systems can be user-friendly and do not require prior system expertise [73]. Optimizing nutritional needs for different leafy and fruit-bearing vegetable crops is one of the biggest difficulties in hydroponic systems [74]. Furthermore, scientific evidence reveals that misinformation about urban indoor hydroponics has been disseminated on social media platforms, accentuating the difficulties of the path forward [75].

Compared to traditional agriculture, the initial investment in home hydroponic systems is generally high [18][72], and technical knowledge is required [72][74], but the implementation of this technology on a small and medium scale can increase food security [32], and positively impact local economies, even promoting self-employment or profitable business activities [18].

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) [13].

Additionally, the risk of waterborne diseases in home hydroponics cannot be ignored, as the same nutrient solution can circulate through all plants [72].

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