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Socio-Economic Influences on Soilless Agriculture

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***Abstract*—**In urban farming, research and innovation are taking place at an unprecedented pace, and soilless growing technologies are emerging at different rates motivated by different objectives in various parts of the world. Local food production is ultimately a main objective everywhere, but adoption rates and expressions vary with socio-economic drivers. Herein, the status of hydroponics and aquaponics is summarized for four countries with diverse socio-economic settings: Europe (Denmark), Asia (Japan and Nepal) and North America (US). In Denmark, with a strong environmental ethic, soilless growing is increasing in urban agriculture because it is considered environmentally friendly. In Japan, soil-based farming is being replaced with commercial plant factories using advanced technology such as complete environmental control and computer monitoring. In Nepal, where rapid loss of agricultural land is occurring near cities, dozens of hydroponics and aquaponics systems have been built in the past decade, particularly in "non-traditional" sites such as roof tops to supplement family food. In the US, where there is also strong interest in locally grown fresh food, backyard and commercial systems have proliferated. Nevertheless, soilless growing is still in the research and development and early adopter stages, and the broad contribution of hydroponics and aquaponics to food security is yet to be fully determined. Nevertheless, current adoption of these technologies in diverse environments in different socio-economic settings highlights the potential contribution to food security with social and environmental benefits which contribute to several Sustainable Development Goals.

***Keywords*—**Aquaponics, hydroponics, soilless agriculture, urban agriculture.

I. Introduction

FOOD production for a growing human population is a major news topic. Concerns about conventional industrial food production systems are topics of discussion internationally [1]. According to a United Nations report "it is time to rethink how we grow, share, and consume food" [2].

Several recent reviews have addressed agricultural practices in terms of the capacity to meet Sustainable Development Goals (SDGs) including feeding increasing human populations, environmental impacts, and food distribution systems (e.g., [1], [3]-[5]. Increased urbanization with associated loss of affordable agricultural land near cities [6]-[8] and the impacts of climate change on agriculture [9]-[11] contribute to the challenges of addressing SDG #2 relating to reducing hunger and improving nutrition with sustainable agriculture practices [12].

Clearly, humans will need more food in the future, and as more people concentrate in urban areas, dependence on smoothly functioning and economically affordable supply systems is critical. Shortening supply chains with locally grown produce can help increase availability of fresh vegetables and fruits with their associated health benefits [13]-[17]. While production of less perishable staples such as rice (*Oryza sativa*), maize (*Zea mays*), and barley (*Hordeum vulgare*) will continue to require large areas of hinterland, vegetables and fruit can be grown in smaller spaces such as those available in cities.

Vacant lots, roof tops, and repurposed buildings are being used in urban agriculture with approaches varying from growing food in containers such as used sacks to plant factories/ vertical farms [18]-[21]. The use of LED lighting [22] and artificial intelligence to regulate growing conditions in controlled environments [23]-[25] is increasing. Environmentally friendly approaches include use of renewable energy [26] and reuse of "waste" heat, water, and nutrients [27], [28]. Soilless food production, using fertigation of plants growing in media other than soil, includes a suite of methods that offer some advantages for urban agriculture [29]. Closed loop soilless growing is expanding [30], [31], especially in urban agriculture [32]-[36] because it addresses some of the negative issues of soil-based agriculture and offers opportunities in situations where there are no good alternatives.

Aquaponics and hydroponics are being promoted as appropriate technologies in urban agriculture because they offer the opportunity to grow food (particularly vegetables and herbs) at high densities in limited space with minimal use of water [37]-[39]. These technologies lend themselves well particularly to controlled environment agriculture where space is at a premium. Context is recognized as important in sustainable production systems [39], [40].

The objective here is to evaluate how aquaponics and hydroponics are being adopted in different areas. The advantages and disadvantages of these technologies are reviewed, and their status is addressed in four countries (Denmark, Japan, Nepal, and United States) with different socio-economic settings to get a sense of the differences and commonalities. Information like this contributes to the body of knowledge needed by individuals, businesses, policy makers, and educators about these relatively new technologies.

II. Methods

A partial review of the primary literature was conducted using Google Scholar, Academia, ResearchGate, and Semantic Scholar to locate appropriate references to provide an overview of the advantages and disadvantages of aquaponics and hydroponics for urban agriculture. Selection criteria included

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relevance for urban agriculture, and, with a few exceptions, articles published within the last 10 years.

III. Results

Overview of Aquaponics and Hydroponics

Hydroponics and aquaculture have been practiced historically [41]-[42], but aquaponics, a combination of recirculating aquaculture [43] and hydroponics [44] is relatively new [45]-[49]. The basics of system design and operation of aquaponics and hydroponics have been described in many publications [45], [47], [48], [50]-[53]. Recent overviews by Maucieri et al. [54] and Palm et al. [55] list the main system designs based on the type of hydroponic plant growing bed components illustrating a range of methods for implementing the technologies in an urban context.

Interest in aquaponics and hydroponics has proliferated in the past 10-15 years [31], [56]. Most aquaponics units are small, home-based systems used by families to grow some of their own food [57], and "hobby" hydroponics has also become popular in the last few decades [44]. Scaling up to large commercial operations in aquaponics is only recently beginning to occur [58], and there is not yet enough information to fully assess the sustainability of widespread large commercial operations [37], [53], [59]-[60]. In contrast, commercial hydroponics is well established [45], [61].

Advantages and Disadvantages of Aquaponics and Hydroponics

Aquaponics Compared to Hydroponics

In both production methods, nutrients are provided to plant roots through water fertilized with dissolved nutrients [32], but aquaponics produces fish as well as plants. Conventional hydroponics uses carefully formulated inorganic nutrient solutions to fertilize plant roots [44], [62]-[64], whereas in aquaponics, most nutrients are derived from fish wastes through bioconversion by microorganisms [48]. Nutrients are more carefully controlled in hydroponics than in aquaponics, and in hydroponics nutrient solutions can be more precisely matched to the needs of different types of plants [55]. Nevertheless, nutrient solutions can be expensive and/or difficult to get in some areas, and they need to be monitored [65] to evaluate concentrations to determine replacement frequency. Aquaponics mimics a more "natural" ecosystem, and there is less precise control of nutrients.

Aquaponics and Hydroponics Compared to Soil-Based Growing in Comparable Settings

Besides producing fish and plants, one of the primary advantages of aquaponics and hydroponics over soil production is the use of less water [45], [66]-[68] and the capacity to grow plants in higher densities [47], [69]-[71] and with higher growth rates [72]-[75]. This combination of higher density and increased yield makes soilless growing an attractive approach by reducing the land footprint needed for production [39], thus maximizing use of small unused spaces such as those available in cities. An example would be flat roofs of buildings. The primary disadvantages are higher initial costs and the need for electricity to operate the system.

Aquaponics Compared to Recirculating Aquaculture

Aquaponics is more environmentally friendly than recirculating aquaculture because it has little or no discharge to the environment and it uses less water. However, aquaponics takes more space because of the plant growing areas, and typically fish are stocked at lower densities than in recirculating aquaculture [52], [75].

Types of Plants and Fish Grown in Aquaponics and Hydroponics

In 2015, the UN Food and Agriculture Organization indicated they had documented more than 150 species of "vegetables, herbs, flowers, and small trees that have been grown successfully in aquaponic systems, including research, domestic and commercial units." [76], and Lennard [52] indicates that he has grown over 60 species of plants in aquaponics. The list of plants would vary according to region of the world, whether indoor or outdoor, the type of aquaponics system, and family preferences or markets. Nevertheless, leafy greens, tomato (*Solanum lycopersicum*), and various culinary herbs are frequently grown [43], [53], [77]. A similar high diversity of vegetables and herbs is grown in hydroponics [45] [62]. Hydroponics is also used widely to grow flowers [78].

Many types of fish have been used in aquaponics [48], [53], [56] [79}. Criteria for selection are based on temperature range, availability of fish species, water quality tolerance of fish, regulations, and objectives for the system (commercial or personal consumption only). In some areas, local native species are primarily used for aquaponics [53], [80], but in many parts of the world tilapia (*Cinclidae*), catfish (*Clariidae, Ictaluridae*, *Pangasiidae*), carp (*Cyprinidae*), trout (*Salmo idae*), and/or ornamental fish are commonly used [43], [48], [80].

Potential of Aquaponics and Hydroponics in Urban Agriculture in Selected Countries

The advantages and disadvantages of soilless growing in recirculating systems for urban agriculture have differing implications depending on the geographic and socio-economic setting. Denmark, the United States, and Japan are developed, highly urbanized countries where urban agriculture is being practiced to differing degrees. Nepal is a developing country with a currently lower proportion of the population living in cities but a high rate of increasing urbanization where discussions about urban agriculture are beginning. Here, we summarize the current status of hydroponics and aquaponics in these counties and discuss potential future expansion.

Denmark

Denmark is highly urbanized with nearly nine of 10 people in the country living in cities, and urbanization is still increasing but at only about 4% per year [81]. Over 60% of its land is under agriculture, but over 80% of the total agriculture area is used for growing feed for livestock and only about 10% for growing food for humans. Also, the number of farms is declining as larger farms become more prevalent [82]. Denmark is affluent and is recognized as having high values for protection of the environment and sustainable approaches to living [83], [84]. Examples are the green roof requirement in Copenhagen for new buildings without steep roofs [85], and nitrogen impact mitigation measures [86]-[89]. Denmark has a goal to cut down CO_2 emissions by 70% in 2030 and be carbon neutral by 2050 [90]. According to the Organization for Economic Co-operation and Development, Denmark is "a leader in eco-innovation" [91], and the country has made progress in managing waste streams and moving toward their goal of pursuing a circular economy. Apparently, interest is increasing in local food production [91], and there are policies that encourage this [92]. All this points to a national priority on green technologies, potentially including closed loop soilless growing, particularly for fruit and vegetables. Denmark currently grows primarily cucumber, tomato, lettuce and strawberries, [84], but it also imports large amounts of fruits and vegetables from the US and elsewhere [94].

Soilless growing is not new to Denmark where flower production in greenhouses is particularly common [94]-[95], often incorporating innovative computer monitoring [96]. Aquaponics is uncommon in Denmark and a recent review of the status of aquaponics in Scandinavia [97] suggested aquaponics, with a few exceptions, is not yet sufficiently incorporated into value chains to be commercially profitable. These authors [97] however point out the perception of value from aquaponics to a sustainable food movement in the European Union, and they state the need for increased awareness about aquaponics within civil society and among policy makers. The need for a certification mechanism and policy specific to aquaponics was mentioned. The policy and regulation challenges for this relatively new technology which does not cleanly fit into hydroponics are similar elsewhere in the European Union [97], [98]. Expertise in aquaculture is available in Denmark, which has a history of rearing fish in ponds, and experience in production of commercial fish food has resulted in a substantial industry [99]. Therefore fish, fish food and technical assistance in rearing fish (e.g. pike perch, *Stizostedion lucioperca* or rainbow trout, *Oncorhynchus mykiss*) would be readily available to those interested in starting aquaponics.

Apparently, there are numbers of "hobby" hydroponics operators in Denmark [100], and some larger commercial farms. Recently, NORDIC HARVEST [101] started a large indoor commercial hydroponics business, with a growing area of 7000 m^2, arranged in 14 vertical shelves, equivalent to one football pitch [102]. The facility produces 1000 tons of salads and herbs in 15 harvests during one year of production cycle. The same production quantity would require 100 times the space if produced in conventional soil-based production. Currently only 30% of the local consumption is produced locally and installation of 20 such production facilities, can meet the total local demand of 20,000 tons of salads and herbs in Denmark [102]. With this scenario, Denmark can significantly reduce the food miles in terms of production, transport and logistics for salads and herbs and can spare the land equivalent to 7000 x 100 x 20 = 1400 hectare, which can be used to produce grains and cereals crops for local consumption or export.

NEXTFOOD is another innovative Danish technology company with hydroponics as the core business model for production of salads and herbs [103]. NEXTFOOD is an advocate for plant-based food supply chain from farm to fork with a decentralized partner network of local indoor farms. The company provides partners with hardware infrastructure and software for managing their farms, enabling them to grow delicious, fresh, flavorful, nutritious, and pesticide-free vegetables all year-round. There are also a number of microgreen producers using hydroponic system for production of herbs and microgreens. Some of the prominent producers are NABOFARM [104] and MICROGREEN [105]. NABOFARM is located in the city of Copenhagen and produces shoots, herbs and leafy greens and sells to restaurants and cafes or directly to the individual customers. MICROGREENS is located in the outskirts of the city, around 50 km from Copenhagen and produces microgreens for the local market. Both producers use LED light as precursor for growth and control temperature, humidity and pH to enhance growth and improve the quality of the produce for sale.

There is some focus on aquaponics in Denmark. For example, the Institute of Global Food and Farming [106] has a stated objective of connecting urban agriculture and aquaponics in Denmark, and some research has been done as part of Aquaponics NOMA [107]. Skar et al. [107] indicate that there are some small, home-based "hobby" aquaponics systems in Denmark (as of 2015).

Denmark's affluence, desire for fresh vegetables (particularly in winter), and concern for the environment are reasons to expand use of closed loop soilless growing there. Constraints on expansion include the lack of a pressing current need, and lack of widespread awareness of the quality of food grown without soil. Expansion of aquaponics will, in part, depend on the demand for freshwater fish as an added value to the vegetables produced.

Japan

More than 90% of people in Japan live in cities and the rate of urbanization is slightly negative, with a net movement out of cities [81]. Although farm acres have declined, in part due to urban sprawl [108], urban agriculture is appreciated and encouraged through planning, policies, and incentives resulting in interspersion of farming areas within urban and peri urban zones [109]-[111]. There has been a shift in crop focus recently to increased production of fresh vegetables [109], which are in high demand in this affluent country.

Although Japan imports about 60% of its food based on caloric value, most of the vegetables are grown in the country [111]. Nevertheless, the average age of existing farmers is over 65 years [112] and promoting traditional farming to younger generations is a challenge. Growing food with soilless methods [113] in controlled environments (e.g., "Plant Factories") has rapidly expanded [114]. Concerns have been raised for the future of traditional agriculture and contamination of soil and crops [115] after the 2011 tsunami and the related nuclear power plant accident. At that time (2011), neither aquaponics or hydroponics was widely practiced in Japan [115], but the increased use of hydroponics in greenhouses in the future was suggested [116], and Japan Aquaponics was formed for the stated purpose of encouraging the use of aquaponics due to contamination of soil [117].

Takeuchi and Endo [118] advocated for aquaponics in Japan for fish production in the future. Salt water capture fisheries and marine aquaculture have been the main source of fish for Japan historically, and inland freshwater fish farming is not widespread in Japan [119], [120]. Nevertheless, there is some aquaculture with Japanese eel (*Anguilla japonica*), and common carp *Cyprinus carpio* which could be used for aquaponics.

Japan is advanced in application of technical approaches and soilless growing is no exception. For example, Japan has one of the first farms in the world using robots [121], and the use of biotechnology has achieved exceptional successes in some cases [111], [121]. Internet of Things [122], [123], is being used in controlled environment growing routinely, and feedback systems for self-learning has is used in some plant factories [124]. Japan is now one of the leaders in plant factories with artificial lighting (PFAL). According to [114], in 2015 there were about 200 PFALs in commercial operations in Japan. Hydroponics (often delivered aeroponically) is frequently used in plant factories to deliver the nutrients. Aquaponics is less well known, and apparently not yet widely practiced in Japan [125]. However, some aquaponics research is beginning to be published from Japan [126], and at least one company, Shonan Akponi Farm, is selling aquaponics units and offering training [127].

As a country rich in tradition, perspectives on food not grown in soil may be a constraint to broad acceptance of soilless grown vegetables, but Yano et al. [128] found that of consumers in Japan that had a negative impression of hydroponically produced food, many changed their minds once they understood the process better. Also, Japan's affluence and interest in fresh food could provide a combination which supports premium prices often needed for soilless growing to be economically viable.

Nepal

Only about 20% of the population of Nepal lives in cities currently, but the rate of urbanization is one of the highest in south Asia at nearly 4% annually [129], [130]. The majority of people are moving to the Kathmandu and Pokhara valleys [131] where agricultural land is disappearing rapidly [132]. Several municipalities are beginning to encourage urban agriculture including rooftop farming [133]. Subsistence agriculture is still a main profession for many families in Nepal [134] and it has long been a cultural norm. Most people moving to the cities would likely feel most secure if they are able to grow at least some of their own food [135], Most buildings in cities like Kathmandu have flat roofs, and these are beginning to be used for growing food and ornamental plants as space even for small "kitchen" gardens is disappearing [136]-[138]. While fresh fruit and vegetables are usually available in cities, particularly through street side vendors, supply disruption can be significant. Recent examples beside lockdowns due to COVID-19 include the large earthquake in 2015 followed the same year by a border blockade, frequent monsoon related flooding and earth slides blocking roads, and political unrest resulting in general strikes [138].

Soilless growing started in Nepal within the past 12 years, but currently there are at least 50 aquaponics operations and over 35 hydroponics units [138]. Most are growing leafy greens, and aquaponics operators are using primarily common carp and tilapia (*Oreochromis niloticus*). The majority of soilless growing is for personal use of families or children's homes, but several larger commercial systems are operating and the number of new units has increased recently [138]. Reported constraints to soilless growing include initial costs, awareness about the technologies, and availability of training [138].

United States

Urbanization was at about 84% in 2020. Nearly 90% of the people will be living in cities by 2045 [139]. Agriculture is big business in the United States. For example, in 2020 exports of fruit and vegetables totaled about 7 billion USD [140], but the value of imported fresh fruit and vegetables exceeded that [141]. Urban agriculture is a common topic of conversation, planning, and research [142], with expressions in many cities [143]. A 2013 survey of urban farms in the US (which produced at least 1,000 USD of produce annually) indicated that vegetables were by far the most frequent crop produced [144]. Only 3% of the urban farms were on rooftops. They also found that the average urban farmer surveyed had been in operation for 10 years, and urban farmers tended to be relatively young (average age 44 years). Approximately 8% and 5% of those surveyed were using aquaponics and hydroponics, respectively.

Hydroponic commercial production in greenhouses has been happening in the US since at least the 1970s [145], but after some ups and downs, commercial hydroponics, particularly in covered environments, have been steadily increasing since about 1988 with a focus on vegetable production [146]. This includes vertical farms in buildings, shipping containers, and greenhouses [19]. A survey in 2017 of the status of indoor commercial farming in the US indicated about 25% were soil based but the rest involved hydroponics (about half) or aquaponics [147]. The primary plants grown were leafy greens, microgreens, tomatoes, and flowers. There were over 2,800 hydroponics businesses in the US in 2021 [147], and commercial aquaponics units and equipment and supplies for aquaponics is also expanding. North America has the largest market share for aquaponics [148], and apparently the largest aquaponics system in the world (Superior Fresh LLC) is in the US [148]. Also, home ("hobby") systems are abundant in the US as indicated by the number of Facebook sites and YouTube channels devoted to the subject. Both hydroponics and aquaponics are being widely used in STEM education in the US and elsewhere [149] ,[150].

As indicated above, aquaponics is a newer approach than hydroponics. Stemming largely from research in the U.S. Virgin Islands by James Rakocy and his team [46]; which built on earlier work by McMurtry et al. [45], it has expanded rapidly in the past 20 years.

A survey of aquaponics operations, conducted by Love et al. [42] was meant to be of international scope but 80% of the responses were from the US and therefore characterize the status of aquaponics there. Although there are a number of commercial aquaponics operations in the US, most of the respondents from the survey were not commercial operators but were using the technology to grow some of their own food and had a sense they were producing healthier food in an environmentally friendly manner. Many of the home or hobby-based aquaponics systems in the US are owner built [57], and there is large diversity in designs. Also, many species of fish are used ranging from ornamental species to edible fish.

Advocacy for expansion of aquaponics both commercially and for home use is building as indicated by the emergence of organizations like the Aquaponics Association [150].

Soilless growing has been practiced longer in the United States than in Japan or Nepal, but only recently has it begun to expand substantially. Like Denmark, there is not yet a pressing need, but awareness and interest in food quality, local growing, and sustainability are some of the reasons for the increasing use of soilless methods. Awareness of hydroponics and aquaponics is increasing through social media and use of these methods in STEM education programs in schools [150]. Hobby aquaponics has grown particularly as more people, with discretionary time and finances, are finding pleasure (and pride based on social media posts) in building and operating their own systems. Constraints for commercial systems include uncertainty about return on investment because of the paucity of extended track records and the realization that produce grown with these methods must find a niche market to sell at a premium.

IV. Discussion

Aquaponics, Hydroponics, and Food Security

Plant factories [22], vertical farming [19], and other expressions of controlled environment agriculture are increasing in urban agriculture, and innovation approaches are emerging [151]. Closed loop soilless growing is a frequent part of this expansion, but like other new technologies, these new approaches are going through the early stages of development [152], [153]. Although research in soilless growing has increased substantially in the past 10 years [154]-[158] and is becoming more sophisticated [154], it is still not yet a mature field of study, particularly with respect to fully understanding precisely how sustainable and environmentally friendly these technologies can be [159]. Nevertheless, soilless growing is widely proclaimed as a good idea with a range of benefits, some of which are listed above, but many have pointed out that challenges remain before these methods can reach their full potential to help with urban food security [40], [160]. Innovation and improvement in efficiencies will probably come as different expressions are used, thus, early adopters in different cultures will likely contribute to breakthroughs which can be applied appropriately in other regional contexts. Although space, water, and nutrient efficient characteristic of hydroponics and aquaponics would be included in the motives for trying these technologies in many situations, adoption rates, sizes and types of systems, and specific objectives of owners of systems vary.

Europe

Like in Denmark, many countries in western Europe are actively addressing SDGs including those emphasizing food and conservation of resources [161], and this is an important motivating factor for considering soilless growing methods in this region. Previous advances in using controlled environment agriculture, like in the Netherlands [162], provide valuable contributing experience and knowledge. In 2016, a survey of aquaponics in Europe confirmed food sustainability and the potential to decrease the negative effects of climate change were among the common reasons for using aquaponics, but growing their own food was not a major objective [80]. Government grants and funds for university research contributed to most of the operations reported by responders to this survey [80].

Asia

Japan has very recently increased their focus on SDGs [164], but like Singapore [165] and China [166] for example, the major motivating factor for considering soilless agriculture is lack of affordable land for traditional agriculture. Known for expertise in technology, Japan, Singapore, and China (and other developed countries in Asia) are employing soilless growing using innovative “high tech” approaches to hydroponics (and potentially aquaponics). In Japan and some other Asian countries, perspectives on food not grown in soil may be a constraint to broad acceptance of soilless grown vegetables. Nevertheless, the need to produce more food with limited space may encourage further expansion of soilless methods, particularly in cities.

Nepal and other developing countries in Asia have a rich tradition for subsistence agriculture. As people are moving to cities, they bring with them a knowledge base about growing plants, but many have no opportunity to use that knowledge due to lack of access to land. Soilless growing has only recently been introduced to Nepal [138] and other developing countries in Asia (e.g., [167]-[169]) and there is very little broad awareness of the technologies. The early adopters who are pioneering these techniques in several cities in Nepal are enthusiastic about their operations, even though they are constrained by costs, unreliable power, difficulty in getting supplies, and little technical assistance [170]. Nevertheless, the growing awareness of the need to begin growing food on rooftops as urbanization continues is resulting in government encouragement in several countries [167], [171] and these incentives could help expand soilless growing which lends itself well to this setting and offers the added advantage in countries like Nepal of providing water during the dry season, protection from flooding during monsoon, and immunity to supply chain disruptions which occur periodically. In many Asian cities there is a growing middle class [172] and the hope of tourists returning after pandemic shutdowns [173], both groups are willing to pay more for fresh vegetables grown locally with limited (hydroponics) or no (aquaponics) use of chemical pesticides.

North America

In the US, where soilless growing is relatively common, frequently stated motivations for aquaponics were growing food for personal use and a sense of using an environmentally friendly approach [42]. The availability of materials for home-built systems has caused family sized units to proliferate and commercial systems are increasing, but Love et al. [30] point out that more research and development is needed to improve profitability. Soilless growing is much less common elsewhere in North America. Nevertheless, the desire to grow food locally year around has generated interest in soilless growing in controlled environments in Canada where a few large commercial operations have recently been built [174] and where a research program for aquaponics has been underway for more than a decade [49], [175], [176]. In Mexico, irrigation water is a limiting factor for agriculture, particularly during the dry season, and this is reported as a motivation for considering soilless recirculating growing [177]-[179].

Common Issues and Comparisons

In both developed and developing countries, initial investment costs of soilless growing relative to soil-based growing are a constraint, particularly for businesses. Also, the willingness of customers to pay more for vegetables grown in hydroponics or aquaponics depends on perceptions about the quality of food not grown in soil [180]. Expanded awareness can increase consumer preference for soilless grown food [181]. Since recirculating soilless growing, particularly in cities, is relatively new, track records are typically relatively short therefore there is uncertainty among lenders and investors. Policies regulating or providing incentives for soilless growing are not yet well developed, particularly for aquaponics which includes horticulture and aquaculture, often regulated by different agencies. It is confusing for government agencies or certifying bodies to know how best to regulate, certify or permit soilless growing [182]. Energy costs of controlled environment agriculture, including recirculating soilless methods, are a concern, but use of renewable energy sources and advances in energy efficient lights and other equipment are occurring.

Advantages of hydroponics and aquaponics in all the countries include efficient use of water and nutrients, and the capacity to produce high densities of food in limited space, often near where it will be consumed. Research is continuing to try to evaluate more fully the environmental benefits of growing food locally, but there is evidence of multiple benefits.

Direct and Indirect Benefits of Aquaponics and Hydroponics in Relation to SDGs

Aquaponics and hydroponic practices are adopted at an increasing rate, especially in the urban settings, for production of microgreens, leafy greens, fruits, and vegetables. With the advent of COVID-19, local food production has gained more importance and aquaponics and hydroponics has seen unprecedented increase in adoption by food entrepreneurs. Local food production has multiple benefits for the local consumers, community and for the planet. The local consumers can get fresh produce with longer shelf-life as the time lag between the harvest and the consumption is shorter due to short distance to market and direct connection between the producer and the consumers. Due to the short supply chain, the produced food crops reach the end-consumer in a shorter time compared to traditional practice of importing from long distances and short supply chains reduce food loss and food waste along the supply chain, contributing to more food available to the end-consumers. The local community will benefit in terms of employment and creation of new jobs as food entrepreneurs, and formation of community networks will encourage more entrepreneurs to produce food and therefore kicks-off a positive spiral of knowledge exchange and entrepreneurship culture. The benefits to the environment include improved nutrient use efficiency with no leakage into the environment, no use of pesticides or fungicides, no off-site impacts in terms of eutrophication or contamination of water bodies and indirectly substitutes soil-based production reducing the pressure on the land-based production to release the land for rewilding and enhanced ecosystem health.

Aquaponics and hydroponics contribute to the different SDGs [164] as follows:

- SDG 2: End hunger, achieve food security and improved nutrition and promote sustainable agriculture: Aquaponics and hydroponics can produce nutritious microgreens, leafy greens, fruits, and vegetables, which on consumption can provide multiple health benefits for consumers. Local production of food crops contributes to food security of the local population when disruptions occur to the supply chain of food crops (e.g., COVID-19).
- SDG 6: Ensure availability and sustainable management of water and sanitation for all: Water use is reduced significantly in aquaponics and hydroponics as the same water is recycled for several rounds in the growing system or the same water is used for aquatic species and crop production enhancing the water use efficiency in contrast to conventional water use.
- SDG 9: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation: As the aquaponics and hydroponics production systems are enclosed in green houses or located in unused spaces in buildings, the food production is not exposed to the natural environment characterized with droughts or floods. Hence, such production system is resilient and climate-smart to produce food for local population in case of natural unforeseen events.
- SDG 12: Ensure sustainable consumption and production patterns: Aquaponics and hydroponics are closed systems in terms of water and nutrient use facilitating reuse of the same water for several irrigation regimes. Such production systems discharge minimum waste to the environment due to cascading use of the water and nutrients and hence these practices are sustainable.
- SDG 14: Conserve and sustainably use the oceans, seas and marine resources for sustainable development: As the

water use is minimum due to recycling of water, aquaponics and hydroponics contribute to increasing the water productivity compared to the soil-based agriculture. As water is a scarce resource, these practices release the pressure on the competing demands for water.

- SDG 15: Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss: As the escape of nutrients and contamination of water to the outside environment is negligible in aquaponics and hydroponics, less inputs of nutrients and water are required to produce the same outputs in conventional agriculture. In this way, the carbon footprint of such production systems is less than soil-based agriculture.

V. Conclusions

Soilless growing is still in its early stages in urban agriculture. Much remains to be learned to more fully understand its potential to contribute substantially to urban food production. As indicated above, some of the advantages apply across cultures and socio-economic conditions, but if predictions are accurate, urban agriculture will have to play a major role in food security in the future, and soilless growing likely will be the main process used. Critics play a valuable role in rooting out false claims about the wonders of soilless growing, and much more research is needed to evaluate claims of benefits more fully, and to clarify various aspects of how efficiency in production can be optimized. Affluent countries like, but certainly not limited to, Denmark, Japan, and the United States will almost certainly continue to expand research and use of soilless growing, but the technology also will likely find its way to developing countries like Nepal, particularly for use in urban areas.

References

[1] United Nations Food Systems Summit 2021 Available online: https://www.un.org/en/food-systems-summit (accessed on 22 January 2022).

[2] United Nations Sustainable Development Goals. Goal 2. Zero Hunger Available online: https://www.un.org/sustainabedevelopment/hunger/ (accessed on 20 January 2022).

[3] Committee on World Food Security Urbanization, Rural Transformation and Implications for Food Security and Nutrition: Key Areas for Policy Attention and Possible Roles for CFS. In Proceedings of the Making a Difference in Food Security and Nutrition; Committee on World Food Security: Rome, October 17, 2016; pp. 1–18.

[4] FAO Food and Agriculture Organization of the United Nations *The Future of Food and Agriculture: Trends and Challenges.*; Food and Agriculture Organization: Rome, 2017; ISBN 9789251095515.

[5] Ramankutty, N.; Mehrabi, Z.; Waha, K.; Jarvis, L.; Kremen, C.; Herrero, M.; Rieseberg, L.H. Trends in Global Agricultural Land Use: Implications for Environmental Health and Food Security. *Annual Review of Plant Biology* 2018, *69*, 789–815.

[6] Lovatelli, A.; Stankus, A. Report of the FAO Technical Workshop on Advancing Aquaponics: An Efficient Use of Limited Resources. *FAO Fisheries and Aquaculture Report No. 1133* 2016, 1–71.

[7] D'Amour, C.B.; Reitsma, F.; Baiocchi, G.; Barthel, S.; Güneralp, B.; Erb, K.H.; Haberl, H.; Creutzig, F.; Seto, K.C. Future Urban Land Expansion and Implications for Global Croplands. *Proceedings of the National Academy of Sciences of the United States of America* 2017, *114*, 8939–8944, doi:10.1073/pnas.1606036114.

[8] Benke, K.; Tomkins, B. Future Food-Production Systems: Vertical Farming and Controlled-Environment Agriculture. *Sustainability: Science, Practice, and Policy* 2017, *13*, 13–26, doi:10.1080/15487733.2017.1394054.

[9] Adams, R.; Hurd, B.; Lenhart, S.; Leary, N. Effects of Climate Change on Agriculture. *Climate Research* 1998, *11*, 19–30.

[10] Kulshreshtha, S.; Wheaton, E. *Sustainable Agriculture and Climate Change*; MDPI AG - Multidisciplinary Digital Publishing Institute, 2018; ISBN 9783038427254.

[11] Arora, N.K. Impact of Climate Change on Agriculture Production, and Its Sustainable Solutions. *Environmental Sustainability* 2019, *2*, 95–96, doi:10.1007/s42398-019-00078-w.

[12] Sustainable Development Goals Available online: https://www.fao.org/sustainable-development-goals/goals/goal-2/en/ (accessed on 22 January 2022).

[13] Dias, J.S. Nutritional Quality and Health Benefits of Vegetables: A Review. *Food and Nutrition Sciences* 2012, *03*, 1354–1374, doi:10.4236/fns.2012.310179.

[14] Aires, A. Hydroponic Production Systems: Impact on Nutritional Status and Bioactive Compounds of Fresh Vegetables. In *Vegetables - Importance of Quality Vegetables to Human Health*; Asaduzziman, M., Asao, T., Eds.; InTechOpen, 2018; pp. 2–13.

[15] Ülger, T.G.; Songur, A.N.; Çırak, O.; Çakıroğlu, F.P. Role of Vegetables in Human Nutrition and Disease Prevention. In *Vegetables - Importance of Quality Vegetables to Human Health*; InTech, 2018.

[16] Slavin, J.L.; Lloyd, B. Health Benefits of Fruits and Vegetables. *Advances in Nutrition* 2012, *3*, 506–516, doi:10.3945/an.112.002154.

[17] Yahia, E.M.; García-Solís, P.; Maldonado Celis, M.E. Contribution of Fruits and Vegetables to Human Nutrition and Health. *Postharvest Physiology and Biochemistry of Fruits and Vegetables* 2019, 19–45, doi:10.1016/B978-0-12-813278-4.00002-6.

[18] Despommier, D. *The Vertical Farm Feeding the World in the 21st Century*; St. Martin's Press: New York, 2010.

[19] Birkby, J. Vertical Farming. *ATTRA Sustainable Agriculture* 2016, *IP516*, 1–12.

[20] Beacham, A.M.; Vickers, L.H.; Monaghan, J.M. Vertical Farming: A Summary of Approaches to Growing Skywards. *Journal of Horticultural Science and Biotechnology* 2019, *94*, 277–283.

[21] Butturini, M.; Marcelis, L.F.M. Vertical Farming in Europe: Present Status and Outlook. In *Plant Factory (Second Edition): An Indoor Vertical Farming System for Efficient Quality Food Production*; Kozai, T., Nui, G., Takagaki, M., Eds.; Elsevier Inc., 2020; pp. 77–91 ISBN 9780128166918.

[22] Kozai, T.; Niu, G.; Takagaki, M. *Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production*; 2016.

[23] Yanes, A.R.; Martinez, P.; Ahmad, R. Towards Automated Aquaponics: A Review on Monitoring, IoT, and Smart Systems. *Journal of Cleaner Production* 2020, *263*.

[24] Cohen, A.R.; Chen, G.; Berger, E.M.; Warrier, S.; Lan, G.; Grubert, E.; Dellaert, F.; Chen, Y. Dynamically Controlled Environment Agriculture: Integrating Machine Learning and Mechanistic and Physiological Models for Sustainable Food Cultivation. *ACS ES&T Engineering* 2021, doi:10.1021/acsestengg.1c00269.

[25] Ragaveena, S.; Shirly, E.; Surendran, U. Smart Controlled Environment Agriculture Methods: A Holistic Review. *Reviews in Environmental Science and Bio/technology* 2021, *20*, 887–913, doi:10.1007/s11157-021-09591.

[26] Karimanzira, D.; Rauschenbach, T. Enhancing Aquaponics Management with IoT-Based Predictive Analytics for Efficient Information Utilization. *Information Processing in Agriculture* 2019, *6*, 375–385, doi:10.1016/j.inpa.2018.12.003.

[27] Denzer A; Wang, L.; Thomas, Y.; McMorrow, G. Greenhouse Design with Waste Heat: Principles and Practices. *AEI* 2017, *2017*, 440–455.

[28] Weidner, T.; Yang, A. The Potential of Urban Agriculture in Combination with Organic Waste Valorization: Assessment of Resource Flows and Emissions for Two European Cities. *Journal of Cleaner Production* 2020, *244*, doi:10.1016/j.jclepro.2019.118490.

[29] Raviv, M.; Lieth, J.H.; Bar-Tal, A. *Soilless Culture Theory and Practice Second Edition*.

[30] Love, D.C.; Fry, J.P.; Li, X.; Hill, E.S.; Genello, L.; Semmens, K.; Thompson, R.E. Commercial Aquaponics Production and Profitability: Findings from an International Survey. *Aquaculture* 2015, *435*, 67–74, doi:10.1016/j.aquaculture.2014.09.023.

[31] dos Santos, M.J.P.L. Smart Cities and Urban Areas—Aquaponics as Innovative Urban Agriculture. *Urban Forestry and Urban Greening* 2016, *20*, 402–406, doi:10.1016/j.ufug.2016.10.004.

[32] Savvas, D.; Gianquinto, G.; Tuzel, Y.; Gruda, N. Soilless Culture. In *Good Agricultural Practices for Greenhouse Plant Production and Protection*; FAO Food and Agriculture Organization of the United Nations: Rome, 2013; pp. 303–354 ISBN 9789251076491.
[33] Putra, P.A.; Yuliando, H. Soilless Culture System to Support Water Use Efficiency and Product Quality: A Review. *Agriculture and Agricultural Science Procedia* 2015, *3*, 283–288, doi:10.1016/j.aaspro.2015.01.054.
[34] Chatterjee, A.; Debnath, S.; Pal, H. Implication of Urban Agriculture and Vertical Farming for Future Sustainability. In *Urban Horticulture - Necessity of the Future*; Solankey, S., Akhtar, S., Maldonado, A., Rodriguez-Fuertes, H., Cointreras, J., Reyes, J., Eds.; IntechOpen, 2020; pp. 157–167.
[35] Dsouza, A.; Price, G.W.; Dixon, M.; Graham, T. A Conceptual Framework for Incorporation of Composting in Closed-Loop Urban Controlled Environment Agriculture. *Sustainability* 2021, *13*, 1–28.
[36] de Wever, V. Thinking Urban and Peri-Urban Agriculture. *Aquaponics Association Website*.
[37] Goddek, S.; Delaide, B.; Mankasingh, U.; Ragnarsdottir, K.V.; Jijakli, H.; Thorarinsdottir, R. Challenges of Sustainable and Commercial Aquaponics. *Sustainability (Switzerland)* 2015, *7*, 4199–4224, doi:10.3390/su7044199.
[38] Silva, L.; Gasca-Leyva, E.; Escalante, E.; Fitzsimmons, K.M.; Lozano, D.V. Evaluation of Biomass Yield and Water Treatment in Two Aquaponic Systems Using the Dynamic Root Floating Technique (DRF). *Sustainability (Switzerland)* 2015, *7*, 15384–15399, doi:10.3390/su71115384.
[39] Joyce, A.; Goddek, S.; Kotzen, B.; Wuertz, S. Aquaponics: Closing the Cycle on Limited Water, Land and Nutrient Resources. In *Aquaponic Food Production Systems*; Goddek, S., Joyce, A., Kotzen, B., Burnell, G., Eds.; Springer: Chem, Switzerland, 2019; pp. 19–34.
[40] Diver, S. Aquaponics-Integration of Hydroponics with Aquaculture. *NCAT* 2006, 1–28.
[41] Hambrey, J.; Evans, S.; Pantanella, E. *The Relevance of Aquaponics to the New Zealand Aid Programme, Particularly in the Pacific*; 2013;
[42] Love, D.C.; Fry, J.P.; Genello, L.; Hill, E.S.; Frederick, J.A.; Li, X.; Semmens, K. An International Survey of Aquaponics Practitioners. *PLoS ONE* 2014, *9*, e102662, doi:10.1371/journal.pone.0102662.
[43] *Recirculating Aquaculture*; Timmons, M., Eberling, J., Eds.; Third.; Ithaca Publishing Company: Ithaca, 2013.
[44] Resh, H. *Hydroponic Food Production: A Definitive Guidebook for the Advanced Home Gardener and the Commercial Hydroponic Grower*; Resh, H., Ed.; Seventh.; CRC Press, 2013; ISBN 13.978-1-4398-7869-9.
[45] McMurtry, M.; Nelson, P.; Sanders, D.; Hodges, L. Sand Culture of Vegetables Using Aquaculture Effluents. *Applied Agricultural Research* 1990, *5*, 280–284.
[46] Rakocy, J.E.; Masser, M.P.; Losordo, T.M. Recirculating Aquaculture Tank Production Systems: Aquaponics-Integrating Fish and Plant Culture. *SRAC-454* 2006, 1–16.
[47] Somerville, C.; Cohen, M.; Pantanella, E.; Stankus, A.; Lovatelli, A. Small-Scale Aquaponic Food Production. Integrated Fish and Plant Farming. *FAO Fisheries and Agriculture Technical Paper* 2014.
[48] Lennard, W.; Goddek, S. Aquaponics: The Basics. In *Aquaponics Food Production Systems*; Springer International Publishing, 2019; pp. 113–143.
[49] Nichols, M.; Savidov, N. Aquaponics: A Nutrient and Water Efficient Production System. *Acta Horticulturae* 2012, *947*, 129–132.
[50] Sardare, M.D.; Admane, S. v A Review of Plant without Soil-Hydroponics. *IJRET: International Journal of Research in Engineering and Technology* 2013, *2*, 941–946.
[51] Rakocy, J.; Eberling, J. Aquaponics: Integrating Fish and Plant Culture. In *Recirculating Aquaculture*; Timmons, M., Eberling, J., Eds.; Ithaca Publishing Co. LLC: Ithaca, 2013; pp. 663–710 ISBN 13 978-0971264656.
[52] Lennard, W. *Commercial Aquaponics Systems: Integrating Recirculating Fish Culture with Hydroponic Plant Production*; Wilson Lennard, 2017; ISBN 1642048372, 9781642048377.
[53] Goddek, S.; Joyce, A.; Kotzen, B.; Burnell Editors, G.M. *Aquaponics Food Production Systems Combined Aquaculture and Hydroponic Production Technologies for the Future*; Goddek, S., Joyce, A., Kotzen, B., Burnell, G., Eds.; Springer: Cham, Switzerland, 2019; ISBN ISBN 978-3-030-15942-9.
[54] Maucieri, C.; Nicoletto, C.; Os, E. van; Anseeuw, D.; Havermaet, R. van; Junge, R. Hydroponic Technologies. In *Aquaponics Food Production Systems*; Springer International Publishing, 2019; pp. 77–110.
[55] Palm, H.W.; Knaus, U.; Appelbaum, S.; Strauch, S.M.; Kotzen, B. Coupled Aquaponics Systems. In *Aquaponics Food Production Systems*; Goddek S, Joyce, A., Kotzen, B., Burnell, G., Eds.; Springer International Publishing, 2019; pp. 163–199.
[56] Love, D.; Genello, L.; Li, X.; Thompson, R.; Fry, J. Production and Consumption of Homegrown Produce and Fish by Noncommercial Aquaponics Gardeners. *Journal of Agriculture, Food Systems, and Community Development* 2015, *6*, 161–173, doi:10.5304/jafscd.2015.061.013.
[57] Proksch, G.; Ianchenko, A.; Kotzen, B. Aquaponics in the Built Environment. In *Aquaponics Food Production Systems*; Springer International Publishing, 2019; pp. 523–558.
[58] Konig, B.; Junge, R.; Bittsanszky, A.; Villarroel, M.; Komives, T. On the Sustainability of Aquaponics. *Ecocycles* 2016, *2*, 26–32, doi:10.19040/ecocycles.v2i1.50.
[59] Palm, H.W.; Knaus, U.; Appelbaum, S.; Goddek, S.; Strauch, S.M.; Vermeulen, T.; Haïssam Jijakli, M.; Kotzen, B. Towards Commercial Aquaponics: A Review of Systems, Designs, Scales and Nomenclature. *Aquaculture International* 2018, *26*, 813–842.
[60] Turnsek, M.; Morgenstern, R.; Schroter, R.; Mergenthaler, M.; Huttel, S.; Leyer, M. Commercial Aquaponics: A Long Road Ahead. In *Aquaponics Food Production Systems*; Goddek, S., Joyce, A., Kotzen, B., Burnell, G., Eds.; Springer: Cham, 2019; pp. 453–486.
[61] Sharma, N.; Acharya, S.; Kumar, K.; Singh, N.; Chaurasia, O.P. Hydroponics as an Advanced Technique for Vegetable Production: An Overview. *Journal of Soil and Water Conservation* 2018, *17*, 364, doi:10.5958/2455-7145.2018.00056.5.
[62] Savvas, D. Hydroponics: A Modern Technology Supporting the Application of Integrated Crop Management in Greenhouse. *Food, Agriculture, and Environment* 2003, *1*, 80–86.
[63] Nguyen, N.T.; Mcinturf, S.A.; Mendoza-Cózatl, D.G. Hydropoics: A Versatile System to Study Nutrient Allocation and Plant Responses to Nutrient Availability and Exposure to Toxic Elements. *Journal of Visualized Experiments* 2016, e54317, doi:10.3791/54317.
[64] van Os, E. Dutch Developments in Soilless Culture. *Outlook on Agriculture* 1982, *11*, 165–171, doi:10.1177/003072708201100404.
[65] Voogt, W.; Bar-Yosef, B. Water and Nutrient Management and Crops Response to Nutrient Solution Recycling in Soilless Growing Systems in Greenhouses. In *Soilless Culture Theory and Practice*; Reviv, M., Lieth, J., Bar-Tal, A., Eds.; Elsevier, 2019; pp. 425–508 ISBN 9780444636966.
[66] Lennard, W. Aquaponics Integration of Murray Cod (*Maccullochella peelii peelii*) Aquaculture and Lettuce (*Lactuca sativa*) Hydroponics, 2005.
[67] Al shrouf, A. Hydroponics, Aeroponic and Aquaponic as Compared with Conventional Farming. *American Scientific Research Journal for Engineering, Technology, and Sciences* 2017, *27*, 247–255.
[68] Kawser, R.; Sheikh, B.; Rahman, M.; Hossain, A.; Hossain, M.; Fahamida Yeasmin, M. Optimizing Planting Density of Lettuce (*Lactuca sativa*) with Tilapia (*Oreochromis niloticus*). *American Journal of Agricultural Science, Engineering and Technology* 2016, *3*, 1–11.
[69] Maboko, M.M.; du Plooy, C.P. Effect of Plant Spacing on Growth and Yield of Lettuce (*Lactuca sativa* L.) in a Soilless Production System. *South African Journal of Plant and Soil* 2009, *26*, 195–198, doi:10.1080/02571862.2009.10639954.
[70] Bailey, D.S.; Ferrarezi, R.S. Valuation of Vegetable Crops Produced in the UVI Commercial Aquaponic System. *Aquaculture Reports* 2017, *7*, 77–82, doi:10.1016/j.aqrep.2017.06.002.
[71] Grillas, S.; Lucas, M.; Bardopoulou, M.; Saaopoulos, E.; Voulgari, M. Perlite Based Soilless Culture Systems: Current Commercial Applications and Prospets. *Acta Hortic* 2007, *548*, 105–114, doi:10.17660/ActaHortic.2001.548.10.
[72] Rakocy, J.E.; Bailey, D.S.; Shultz, R.C.; Thoman, E.S. Update on Tilapia and Vegetable Production in the UVI Aquaponic System. In Proceedings of the New Dimensions on Farmed Tilapia: Proceedings of the Sixth International Symposium on Tilapia Aquaculture; Boliver, R., Ed.; Manila, Phillippines, 2004; pp. 676–690.
[73] Salam, M.A.; Prodhan, M.Y.; Sayem, S.M.; Islam, M.A. *Comparative Growth of Taro Plant in Aquaponics vs Other Systems*; 2014; Vol. 7.
[74] de Souza, P.F.; Borghezan, M.; Zappelini, J.; de Carvalho, L.R.; Ree, J.; Barcelos-Oliveira, J.L.; Pescador, R. Physiological Differences of 'Crocantela' Lettuce Cultivated in Conventional and Hydroponic Systems. *Horticultura Brasileira* 2019, *37*, 101–105, doi:10.1590/s0102-053620190116.
[75] Timmons, M.; Eberling, J. Culture Units. In *Recirculating Aquaculture*; Timmons, M., Eberling, J., Eds.; Ithaca Publishing Company: Ithaca, 2013; pp. 93–138.

[76] FAO Food and Agriculture Organization of the United Nations *Management of the Aquaponic Systems*; 2015;
[77] Thorarinsdottir, R. *Aquaponics Guildlines 2015.*; Reykjavik, Iceland, 2015.
[78] Winterbourne, J. *Hydroponics Indoor Horticulture*; Pukka Press Ltd: London, 2005.
[79] Miličić, V.; Thorarinsdottir, R.; dos Santos, M.; Hančič, M.T. Commercial Aquaponics Approaching the European Market: To Consumers' Perceptions of Aquaponics Products in Europe. *Water (Switzerland)* 2017, *9*, doi:10.3390/w9020080.
[80] Villarroel, M.; Junge, R.; Komives, T.; König, B.; Plaza, I.; Bittsánszky, A.; Joly, A. Survey of Aquaponics in Europe. *Water (Switzerland)* 2016, *8*, doi:10.3390/w8100468.
[81] The World Bank Urban Population Growth (Annual %) 2018.
[82] The Danish Agrifish Agency *Denmark's Report for the State of the World's Biodiversity for Food and Agriculture the State of the World's Biodiversity for Food and Agriculture in Denmark*; 2016;
[83] Andersen, M.S.; Liefferink, D. *European Environmental Policy: The Pioneers*; Andersen, M., Liefferink, D., Eds.; Manchester University Press, 1997.
[84] The Danish Government *A Green and Sustainable World*; 2020;
[85] Berardi, U.; Ghaffarian Hoseini, A.; Ghaffarian Hoseini, A. State-of-the-Art Analysis of the Environmental Benefits of Green Roofs. *Applied Energy* 2014, *115*, 411–428.
[86] Dalgaard, T.; Hansen, B.; Hasler, B.; Hertel, O.; Hutchings, N.J.; Jacobsen, B.H.; Jensen, L.S.; Kronvang, B.; Olesen, J.E.; Schjørring, J.K.; et al. Policies for Agricultural Nitrogen Management-Trends, Challenges and Prospects for Improved Efficiency in Denmark. *Environmental Research Letters* 2014, *9*, doi:10.1088/1748-9326/9/11/115002.
[87] Andersen, B.; Sørensen, J. Agriculture in Denmark 2015.
[88] Hoffmann, C.C.; Zak, D.; Kronvang, B.; Kjaergaard, C.; Carstensen, M.V.; Audet, J. An Overview of Nutrient Transport Mitigation Measures for Improvement of Water Quality in Denmark. *Ecological Engineering* 2020, *155*, 105863, doi:10.1016/J.ECOLENG.2020.105863.
[89] CBI Ministry of Foreign Affairs Which Trends Offer Opportunities or Pose Threats on the European Fresh Fruit and Vegetables Market? 2021.
[90] OECD Organization for Economic Co-operation and Development OECD Environmental Performance Reviews: Denmark 2019 Available online: https://www.oecd.org/greengrowth/oecd-environmental-performance-reviews-denmark-2019-1eeec492-en.htm (accessed on 19 January 2022).
[91] Liverino, G. *Wonderful Copenhagen*. Copenhagen January 4, 2021.
[92] Christensen, L.S. *Some Structural Aspects of Food Production, Food Retail Markets and Procurement in Denmark-Implications for National Strategies of the REFRAME Approach*; 2019.
[93] Denmark-Agriculture Sector Available online: https://www.export.gov/apex/article2?id=Denmark-Agricultural-Sector (accessed on 22 January 2022).
[94] Andersen, A. Danish ornamental horticulture in greenhouses and the quest for new crops. *Acta Horticulturae* 1989, *252*, 13–52, doi:10.17660/ActaHortic.1989.252.1.
[95] Gadtke, L. Sustainable Horticultural Production in Denmark, Saint Paul, 2010.
[96] Howard, D.A.; Ma, Z.; Veje, C.; Clausen, A.; Aaslyng, J.M.; Jørgensen, B.N. Greenhouse Industry 4.0 – Digital Twin Technology for Commercial Greenhouses. *Energy Informatics* 2021, *4*, 37, doi:10.1186/s42162-021-00161-9.
[97] Gregg, J.; Jürgens, J. The Emerging Regulatory Landscape for Aquaponics in Scandinavia-a Case Study for the Transition to a Circular Economy. *14th Nordi Environmental Social Sciences Conference* 2019, 1–12.
[98] Hoevenaars, K.; Junge, R.; Bardocz, T.; Leskovec, M. EU Policies: New Opportunities for Aquaponics. *Ecocycles* 2018, *4*, 10–15, doi:10.19040/ecocycles.v4i1.87.
[99] Skov, C.; Berg, S.; Eigaard, O.; Jessen, T.; Skov, P. Danish Fisheries and Aquaculture: Past, Present, and Future. *Fisheries* 2019, *45*, 33–41, doi:10.1002/fsh.10330.
[100] Rasmus; Katie Can We Make Hydroponics Popular in Demark? Available online: https://sustainableraskat.wordpress.com/2016/05/02/the-definitive-plan-for-making-hydroponics-popular-in-denmark/ (accessed on 19 January 2022).
[101] We Will Do That Obvious to Eat Sustainable Available online: https://www.nordicharvest.com/ (accessed on 22 January 2022).
[102] Peters, A. 2020 This Vertical Farm in Denmark Will Grow 1000 Tons of Local Greens a Year Available online: https://www.agritecture.com/blog/2020/12/14/this-vertical-farm-in-denmark-will-grow-1000-tons-of-local-greens-a-year (accessed on 19 January 2022).
[103] Building and Operating Your Vertical Farm Available online: https://nextfood.co/ (accessed on 22 January 2022).
[104] Cultivated Locally Available online: https://nabofarm.com/ (accessed on 22 January 2022).
[105] Micro-Greens Denmark Available online: https://micro-greens.dk/ (accessed on 22 January 2022).
[106] Aquaponic Food Production Available online: https://www.igff.dk/ (accessed on 22 January 2022).
[107] Skar, S.; Liltved, H.; Kledal, N.; Høgberget, R.; Björnsdottir, R.; Homme, J.; Oddsson, S.; Paulsen, H.; Drengstig, A.; Savidov, N.; et al. New Innovations for Sustainable Aquaculture in the Nordic Countries. *Nordic Innovations Publication* 2015, *6*, 1–108.
[108] Tsubota, K. *Urban Agriculture in Asia: Lessons from Japanese Experience*.
[109] Sioen, G.B.; Terada, T.; Sekiyama, M.; Yokohari, M. Resilience with Mixed Agricultural and Urban Land Uses in Tokyo, Japan. *Sustainability (Switzerland)* 2018, *10*, doi:10.3390/su10020435.
[110] Harada, K.; Hino, K.; Iida, A.; Yamazaki, T.; Usui, H.; Asami, Y.; Yokohari, M. How Does Urban Farming Benefit Participants' Health? A Case Study of Allotments and Experience Farms in Tokyo. *International Journal of Environmental Research and Public Health* 2021, *18*, 1–13, doi:10.3390/ijerph18020542.
[111] Hayes, J. Agriculture in Japan Available online: https://factsanddetails.com/japan/cat24/sub159/item941.html (accessed on 16 January 2022).
[112] Cao, W.; Kimiami, L.; Kiminami A Analysis on the Attitude of Employed Japanese Farmers from the Viewpoint of Human Resource Management. *J Rural Econ* 2012, 53–60.
[113] Westhead, R. Japan Embraces the Grow-Up. *Toronto Star* 2014.
[114] Hayashi, E. Current Status of Commercial Plant Factories with LED Lighting. In *LED Lighting for Urban Agriculture*; Kozai, T., Fujiwara, K., Runkle, E., Eds.; Springer, 2016; pp. 289–294.
[115] Yamaguchi, N.; Taniyama, I.; Kimura, T.; Yoshioka, K.; Saito, M. Contamination of Agricultural Products and Soils with Radiocesium Derived from the Accident at TEPCO Fukushima Daiichi Nuclear Power Station: Monitoring, Case Studies and Countermeasures. *Soil Science and Plant Nutrition* 2016, *62*, 303–314.
[116] Asao, T.; Asaduzzaman, M.; Mondal, F. *Horticultural Research in Japan. Production of Vegetables and Ornamentals in Hydroponics, Constraints and Control Measures*; *Horticulture Science* 2014, 28, 167-178.
[117] Sawyer, T. Aquaponics in Japan. *The Aquaponics Source* 2012.
[118] Takeuchi, T.; Endo, M. Aquaponics. In *Applications of recirculating aquaculture systems in Japan*; Takeuchi, T., Ed.; Springer, 2017; pp. 257–266.
[119] Katano, O.; Hakoyama, H.; Matsuzaki, S. Japanese Inland Fisheries and Aquaculture: Status and Trends. In *Freshwater Fish Ecology*; Craig, J., Ed.; Wiley Blackwell, 2015; pp. 231–240.
[120] Brown-Paul, C. Robo Farming. *Practical Hydroponics and Greenhouses* 2016, *165*, 17–22.
[121] Kajiura, I. Biotechnology Contributes to Agriculture and Environment in Japan. In Proceedings of the Fifth Conference, Science Council of Asia; 2005; pp. 1–8.
[122] Lee, C.; Jhang, J. System Design for Internet of Things Assisted Urban Aquaponics Farming. In Proceedings of the IEEE 8th Global Conference on Consumer Electronics (GCCE); Osaka, 2019; pp. 986–987.
[123] Gnanasagar, V.; Vivek, M. Design and Implementation of a Controller for a Recirculating Aquaponics System Using IoT. *International Research Journal of Engineering and Technology (IRJET)* 2020, *7*, 6347–6351.
[124] Kozai, T.; Fujiwara, K. Moving toward Self-Learning Closed Plant Production Systems. In *LED Lighting for Urban Agriculture*; Kozai, T., Fujiwara, K., Runkle, E., Eds.; Springer, 2016; pp. 445–448 ISBN 978-0-12-801775-3.
[125] Boekhout, R. Bringing Aquaponics Closer to Japanese Society.
[126] Yamane, K.; Kimura, Y.; Takahashi, K.; Maeda, I.; Iigo, M.; Ikeguchi, A.; Kim, H.J. The Growth of Leaf Lettuce and Bacterial Communities in a Closed Aquaponics System with Catfish. *Horticulturae* 2021, *7*, doi:10.3390/horticulturae7080222.
[127] Shonan Akponi Farm Available online: https://aquaponics.co.jp/shonan-aquponi-farm/ (accessed on 22 January 2022).
[128] Yano, Y.; Nakamura, T.; Maruyama, A. Consumer Perceptions and Understanding of Vegetables Produced at Plant Factories with Artificial Lighting. In *LED lighting for urban agriculture*; Kozai, T., Fujiwara, K.,

Runkle, E., Eds.; Springer, Singapore: Singapore, 2016; pp. 347–363.

[129] The World Bank Urban Population-Nepal Available online: https://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS?locations=NP (accessed on 22 January 2022).

[130] Bakrania, S. Urbanisation and Urban Growth in Nepal Available online: www.gsdrc.org.

[131] Thapa, R.B.; Murayama, Y.; Ale, S. City Profile Kathmandu. *Cities* 2008, *25*, 45–57, doi:10.1016/j.cities.2007.10.001.

[132] Thapa, R.; Murayama, Y. Examining Spatiotemporal Urbanization Patterns in Kathmandu Valley, Nepal: Remote Sensing and Spatial Metrics Approaches. *Remote Sensing* 2009, *1*, 534–556, doi:10.3390/rs1030534.

[133] Thapa, S.; Nainabasti, A.; Bharati, S. Assessment of the Linkage of Urban Green Roofs, Nutritional Supply, and Diversity Status in Nepal. *Cogent Food and Agriculture* 2021, *7*, doi:10.1080/23311932.2021.1911908.

[134] Holmelin, N.B. National Specialization Policy versus Farmers' Priorities: Balancing Subsistence Farming and Cash Cropping in Nepal. *Journal of Rural Studies* 2021, *83*, 71–80, doi:10.1016/j.jrurstud.2021.02.009.

[135] Jha, R.; Bhattarai, N.; KC, S.; Shrestha, a; Kadariya, M. Rooftop Farming: An Alternative to Conventional Farming for Urban Sustainability. *Malaysian Journal of Sustainable Agriculture* 2019, *3*, 39–43, doi:10.26480/mjsa.01.2019.39.43.

[136] Thapa, S.; Nainabasti, A.; Acharya, S.; Rai, N.; Bhandari, R. Rooftop Gardening as A Need for Sustainable Urban Farming: A Case of Kathmandu, Nepal. *International Journal of Applied Sciences and Biotechnology* 2020, *8*, 241–246, doi:10.3126/ijasbt.v8i2.29592.

[137] Thapa, S.; Bhandari, R.; Nainabasti, A. Survey on People's Attitudes and Constraints of Rooftop Gardening in Dhulikhel. *Ecofeminism and Climate Change* 2020, *1*, 89–96, doi:10.1108/efcc-04-2020-0008.

[138] Byrd, G.; Maharjan, S.; Jha, B.; Gurung, S. A Review of Soilless Agriculture in Nepal. *World Applied Science Journal* 2021, 39,69-83, doi: 10.5829/idosi.wasj.2021.69.83.

[139] Forecast of the Degree of Urbanization in the United States 2000-2050 Available online: https://www.statista.com/statistics/678561/urbanization-in-the-united-states/ (accessed on 22 January 2022).

[140] US Department of Agriculture Foreign Agriculture Service Fruits and Vegetables Available online: https://www.fas.usda.gov/commodities/fruits-and-vegetables (accessed on 20 January 2022).

[141] Kenner, B. U.S. Fruit Imports Grew by $8.9 Billion over the Last Decade to Meet Rising Demand Available online: https://www.ers.usda.gov/amber-waves/2020/september/us-fruit-imports-grew-by-89-billion-over-the-last-decade-to-meet-rising-demand/ (accessed on 17 January 2022).

[142] Oberholtzer, L.; Dimitri, C. Urban Agruiculture in the United States: Characteristics, Challenges, and Technical Assistance Needs 2016, 1–12.

[143] Amirthamasebi, R. The North American Urban Agriculture Experience.

[144] Dalrymple, D. *Controlled Environment Agriculture: A Global Review of Greenhouse Food Production*; Washington DC, 1973.

[145] Walters, K.J.; Behe, B.K.; Currey, C.J.; Lopez, R.G. Historical, Current, and Future Perspectives for Controlled Environment Hydroponic Food Crop Production in the United States. *HortScience* 2020, *55*, 758–767, doi:10.21273/HORTSCI14901-20.

[146] Agrilyst *State of Indoor Farming*; 2017.

[147] IBISWorld Hydroponic Crop Farmin Industry in the US-Market Research Report Available online: https://www.ibisworld.com/united-states/market-research-reports/hydroponic-crop-farming-industry/ (accessed on 17 January 2022).

[148] North America Aquapnonics System Market Available online: https://www.marketdataforecast.com/market-reports/north-america-aquaponics-system-market (accessed on 22 January 2022).

[149] Junge, R.; Bulc, T.; Anseeuw, D.; Yildiz, H.; Milliken, S. Aquaponics as an Educational Tool. In *Aquaponics Food Production Systems*; Goddek, S., Joyce, A., Kotzen, B., Burnell, G., Eds.; Springer Open: Cham, Switzerland, 2019; pp. 561–596 ISBN 978-3-030-15942-9.

[150] Expanding the Practice of Aquaponics through Education, Advocacy, and Connection Available online: https://aquaponicsassociation.org/ (accessed on 22 January 2022).

[151] Shamshiri, R.R.; Kalantari, F.; Ting, K.C.; Thorp, K.R.; Hameed, I.A.; Weltzien, C.; Ahmad, D.; Shad, Z. Advances in Greenhouse Automation and Controlled Environment Agriculture: A Transition to Plant Factories and Urban Agriculture. *International Journal of Agricultural and Biological Engineering* 2018, *11*, 1–22, doi:10.25165/j.ijabe.20181101.3210.

[152] Rogers, E. *Diffusion of Innovations*; First.; The Free Press of Glencoe: New York, 1962.

[153] Beck, D.F. *SANDIA REPORT Technology Development Life Cycle Processes*; Albuquerque, 2013.

[154] Goddek, S.; Joyce, A.; Kotzen, B.; Dos-Santos, M. Aquaponics and Global Food Challenges. In *Aquaponics Food Production Systems*; Goddek, S., Joyce, A., Benz, K., Burnell, G., Eds.; Springer Open: Che, 2019; pp. 3–17.

[155] Junge, R.; König, B.; Villarroel, M.; Komives, T.; Jijakli, M.H. Strategic Points in Aquaponics. *Water (Switzerland)* 2017, *9*.

[156] Yep, B.; Zheng, Y. Aquaponic Trends and Challenges – A Review. *Journal of Cleaner Production* 2019, *228*, 1586–1599.

[157] Wirza, R.; Nazir, S. Urban Aquaponics Farming and Cities-a Systematic Literature Review. *Rev Environ Health* 2021, *36*, 47–61, doi:10.1515/reveh-2020-0064.

[158] Wu, F.; Ghamkhar, R.; Ashton, W.; Hicks, A.L. Sustainable Seafood and Vegetable Production: Aquaponics as a Potential Opportunity in Urban Areas. *Integrated Environmental Assessment and Management* 2019, *15*, 832–843.

[159] Gonnella, M.; Renna, M. The Evolution of Soilless Systems towards Ecological Sustainability in the Perspective of a Circular Economy. Is It Really the Opposite of Organic Agriculture? *Agronomy* 2021, *11*, doi:10.3390/agronomy11050950.

[160] Viviano, F. *National Geographic Magazine*. September 2017.

[161] Schnitzler, W.H. Urban Hydroponics for Green and Clean Cities and for Food Security. *Acta Horticulturae* 2013, *1004*, 13–26, doi:10.17660/ActaHortic.2013.1004.1.

[162] Greenfeld, A.; Becker, N.; Bornman, J.F.; Angel, D.L. Identifying Knowledge Levels of Aquaponics Adopters. *Environmental Science and Pollution Research* 2020, *27*, 4536–4540, doi:10.1007/s11356-019-06758-8/Published.

[163] Joly, A.; Junge, R.; Bardocz, T. Aquaponics Business in Europe: Some Legal Obstacles and Solutions. *Ecocycles* 2015, *1*, 3–5, doi:10.19040/ecocycles.v1i2.30.

[164] United Nations. Make the SDGS a Reality. https://sdgs.un.org/ (accessed February 13, 20226

[165] Mok, W.; Tan, Y.; Chen, W. Technology innovations for food security in Singapore: A case study of future food systems for an increasingly natural resource-scarce world. *Trends in Food Science and Technology* 102, 155-168. doi/10.1016/j.tifs.2020.06.013.

[166] Piechowiak, M. Countries using vertical farming. *Vertical Farming Planet.* Available online: https://verticalfarmingplanet.com/countries-using-vertical-farming/ (accessed on 19 August 2022).

[167] Azad, Ka.; Salam, M.; Azad, Kh. Aquaponics in Bangladesh: current status and future prospects. *Journal of Bioscience and Agriculture Research* 2016, 07(2), 669-677. doi 10.18801/jbar.070216.79.

[168] Khanh, N. Growing power: The Saigon aquaponics movement. *Oi Vietnam*. Available online: https://oivietnam.com/2015/05/growing-power-the-saigon-aquaponics-movement/#:~:text=A%20growing%20group%20of%20enthusiasts,food%20in%20your%20own%20home.&text=the%20purpose%20of%20rooftops%20as,for%20a%20rooftop%20aquaponics%20movement (assessed on 19 August 2022).

[169] Tarigan, N.; Goddek, S.; Keesman, K. Explorative study of aquaponics systems in Indonesia. *Sustainability* 2021, 13, 12685. doi.org/10.3390/su132212685.

[170] Maharjan, S. Hydroponics systems in Nepal: status and nutrient solution assessment. MS thesis. Kathmandu University 2022. Dulikhel, Nepal.

[171] Rawal, S.; Thapa, S. Assessment of the status of rooftop garden: its diversity, and determinants of urban green roofs in Nepal. *Hindawi Scientifica* 2022, 1-13. doi.org/10.1155/2022/6744042.

[172] Bonnet, A.; Kolev, A. The middle class in emerging Asia: Champions for more inclusive societies? OECD Working Paper No. 347. Available online: www.oecd.org/dev/wp (assessed on 19 August 2022).

[173] Wayne, S.; Jordon, P. Covid-19 and the future of tourism in Asia and the Pacific. Asian Development Bank and World Tourism Association. 2022. Available online: https://www.adb.org/sites/default/files/publication/784186/covid-19-future-tourism-asia-pacific.pdf (accessed on 19 August 2022).

[174] Good Leaf Farms. Canada's largest vertical farm setting up operations in Calgary. *AgriTech Tomorrow* 2021. Available online: https://www.agritechtomorrow.com/story/2021/11/canadas-largest-commercial-vertical-farm-setting-up-operations-in-calgary/13336/ (assessed on August 19, 2022).

[175] Savidof, N.; Hutchings, E.; Rakocy, J. Fish and plant production in a recirculating aquaponic system: A new approach to sustainable

agriculture in Canada. *Acta Horticulturae* 2007, 742. doi 10.17660/actahortic.2007.742.28.
[176] Nichols, M.; Savidov, N. Aquaponics: A nutrient and water efficient production system. Acta Horticulturae 2012, 947, 129-132. doi 10.17660/ActaHortic.2012.947.14.
[177] de Ande, J.; Shear, H. Potential of vertical hydroponic agriculture in Mexico. *Sustainability* 2017, 9, 140. doi 10.3390/su9010140.
[178] Johnson, T. Urban gardening on the rise in Mexico City. *The Christian Science Monitor* 2012. Available online: https://www.csmonitor.com/World/Americas/2012/1030/Urban-gardening-on-the-rise-in-Mexico-City. (Accessed on August 20, 2022).
[179] Balquiah, T.; Pandyanto, H.; Astuti, R.; Makhtar, S. Understanding how to increase hydroponic attractiveness: economic and ecological benefit. E3S Web of Conferences 2020, 211, 01015. doi.org/10.1051/e3sconf/202021101015.
[180] Greenfeld, A.; Becker, N.; Bornman, J.; dos Santos, M.; Angel, D. Consumer preferences for aquaponics: a comparative analysis of Australia and Israel. *Journal of Environmental Management* 2019, 257, 1, 921-934. doi 10.1016/j.jenvman.2019.109979.
[181] Joly, A.; Junge, R.; Bardocz,T. Aquaponics business in Europe: some legal obstacles and solutions. *Ecocycles* 2015, 1, 2, 3-5. doi 10.19040/ecocycles.v1i2.30.