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Potential of Vertical Hydroponic Agriculture in Mexico

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Abstract: In 2050, Mexico's population will reach 150 million people, about 80% of whom will likely live in urban centers. This increase in population will necessitate increased food production in the country. The lands classified as drylands in Mexico occupy approximately 101.5 million hectares, or just over half the territory, limiting the potential for agricultural expansion. In addition to the problem of arid conditions in Mexico, there are conditions in other parts of the country related to low to very low water availability, resulting in pressure on the water resources in almost two-thirds of the country. Currently, agriculture uses 77% of the water withdrawn, primarily for food production. This sector contributes 12% of the total greenhouse gas emission (GHG) production in the country. Given the conditions of pressure on water and land resources in Mexico and the need to reduce the carbon footprint, vertical farming technology could offer the possibility for sustainable food production in the urban areas of the country in the coming years.

Keywords: sustainable agriculture; food security; drylands; greenhouse horticulture; protected agriculture; vertical farming; Mexico

1. Introduction

In 2010, the population of Mexico was 114.3 million inhabitants, 77.8% of whom were in urban areas. Urban areas in Mexico are considered those where the population is higher than 2500 inhabitants [1]. According to recent estimates, the population of Mexico will reach 150.8 million inhabitants in 2050 [2,3]. Therefore, the country will require more land to produce primary food products, which will need to be transported to urban areas. To cover the projected food needs, more land for cultivation will be required, leading to changes in land use and vegetation cover, increased deforestation and increased pressure on natural resources and ecosystems. Additionally, according to the National Council for Evaluation of Social Development Policy (Consejo Nacional de Evaluación de la Política de Desarrollo Social, CONEVAL) [4], in 2014, Mexico had 55.3 million poor people in the country, representing 46.2% of the total population. Among the total number of poor people, 28.0 million (representing 23.4% of the total population) suffered a lack of access to adequate food. Paradoxically, Mexico presents an index of food availability equivalent to 3145 kcal per person per day, one of the highest indices in the world, including both food production and imports, compared with the average daily dietary energy consumption per capita in Mexico of about 2362 kcal recommended by FAO [5]. The food security and nutrition in Mexico present a picture of contrasts. While dietary energy supply available in Mexico exceeds requirements to meet demand, high variability in access to food presents a mixed picture of large gaps that require focus on large population groups and in certain regions [5]. The poor access to food for a large sector of the population, chronic child malnutrition and the high prevalence of overweight and obese children, adolescents and adults are issues that illustrate the problem of access to nutritious food. Malnutrition prevents proper physical and intellectual development, at the same time increasing the risk of chronic non-transmissible diseases, such as diabetes, with large direct and indirect costs for families and society [6].

In the last ten years, hydroponic culture technology started to gain favor in the developing world because the population growth in urban areas represented an opportunity to grow food near consumers [7]. The 100–200 million urban farmers worldwide providing the city markets with fresh agricultural products are the evidence of how food security can be achieved by urban agriculture [8].

This paper briefly discusses the state of land, water and agriculture in Mexico and the evolution of protected agriculture in the country. In this work, protected agriculture is defined as a system of production under various artificial structures to protect crops by minimizing the restrictions and effects imposed by climate and weather [9]. We analyzed the development of hydroponic culture as a potential way to produce food products in the regions having high water scarcity problems. We also investigated the potential opportunities and benefits representing the possibilities to advance the existing hydroponic technology on vertical farming technology in Mexico for both rural and urban environments, taking into account the actual social, economic and government conditions that could successfully promote this technology in the country. In this paper, vertical farming is referred to as those facilities being only a few meters above the ground, where it is still possible to use natural sunlight to produce vegetables, thus avoiding the use of LEDs to supply artificial light; these facilities do not require sophisticated designs as do much higher facilities frequently cited as green skyscrapers in the literature [10–13].

In researching this subject in the Mexican context, we required official information from the Ministry of Agriculture in Mexico (Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación, SAGARPA), National Institute of Statistics and Geography (INEGI, Instituto Nacional de Estadística y Geografía, INEGI) and the National Commission of Water (Comisión Nacional del Agua, CONAGUA) among other official and scientific sources. The official data that we collected allowed us to analyze the future limitations of agricultural productivity in Mexico due to environmental factors, such as climate conditions, available arable land and the increase of water scarcity due to the increase of population and the concentration of people in urban areas located in arid or semiarid regions of the country. Based on the available socio-economic and environmental information, we explained how the recent increase in protected agriculture and the introduction of hydroponic culture in Mexico, driven by internal and external food demands, such as the large market of the United States, represent an opportunity to increase the productivity of the land by introducing the concept of vertical farming. The fact that this technology does not use agricultural land and that it significantly increases agricultural productivity allows a significant reduction in the national ecological footprint of agriculture and also increases the income derived from agricultural exports. The discussion of the possibilities of introducing this technology in Mexico was supported by the principles of vertical farming technology [14–16] and by the experiences in developed and developing countries, which now have successful initiatives using protected agriculture.

1.1. State of Land, Water and Agriculture in Mexico

Drylands are defined by their scarcity of water. They are zones where precipitation is counterbalanced by evaporation from surfaces and transpiration by plants (evapotranspiration) [17]. The United Nations Convention to Combat Desertification (UNCTAD) ranks drylands according to an aridity index into three categories: arid, semi-arid and dry subhumid [18]. Using these criteria, the estimated drylands in Mexico are approximately 101.5 million hectares or just over half the total territory (see Figure 1). Of this area, arid lands account for 15.7%, semi-arid lands 58% and dry subhumid lands 26.3% [19]. In Mexico, 77% of the available water is used for agriculture; water availability in most of the central and northern regions of the country is already scarce [20]. Paradoxically, in the regions of the country classified as water stressed, the economy has developed more extensively than the rest of the country [20]. This is because of the proximity to the United States markets; consequently, the population in these areas has also grown faster, further increasing the water demand [21]. Mexico is now considered as a water-scarce country, facing several technical and administrative challenges. For example, there is a need to optimize water use, particularly in agricultural areas such as the "El Bajío" (located in the middle central portion of the country) and "Valle del Yaqui" (located in the northwestern portion of the country). In these two areas, the competition for water between municipal and industrial demand is increasing with population growth and urbanization [22].

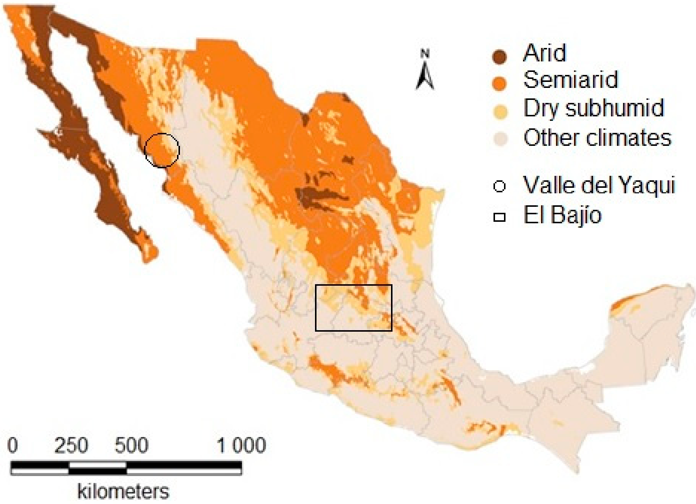

Figure 1. Distribution of drylands in Mexico [19].

According to the 2007 agricultural census, agricultural areas in Mexico occupied 29.9 million hectares (15.2% of the country), of which 5.3 million hectares were irrigated and 24.6 million hectares were rain-fed [23]. The average productivity of irrigated areas is 3.7-times higher than the rain-fed areas [24]; despite its substantially smaller area, irrigated agriculture generates more than half of the national agricultural production (see Figure 2). Mexico's agricultural productivity growth in the last 10 years has been less than 1.1 percent, thus falling below the 2.5 percent average for all of Latin America [24,25]. The very high use of water in agriculture in much of the country has prompted improvements in water conservation, but environmental issues, such as surface and groundwater pollution and groundwater overdraft, are threatening the resource base mainly in the central and northern regions of the country [22]. Additionally, drainage problems and resultant salinization are important considerations in irrigated areas, while flood control is a concern in the southern regions of the country [20]. In addition, because of the arid conditions prevailing in most of the country and the increasing needs of water for agriculture, most of the aquifers located in the central and northern part of the country are classified as overexploited [20]. In these areas, there are now conditions of low to very low water availability, and the degree of pressure on the water resource has increased markedly in recent years, reaching almost two-thirds of the national territory [20]. The current problems in Mexico regarding water availability have old historical roots, derived from the country's socio-economic evolution and from water abuses, over-exploitation of aquifers, scarcity of surface waters, pollution and, especially, the low value that society attributes to this resource [22].

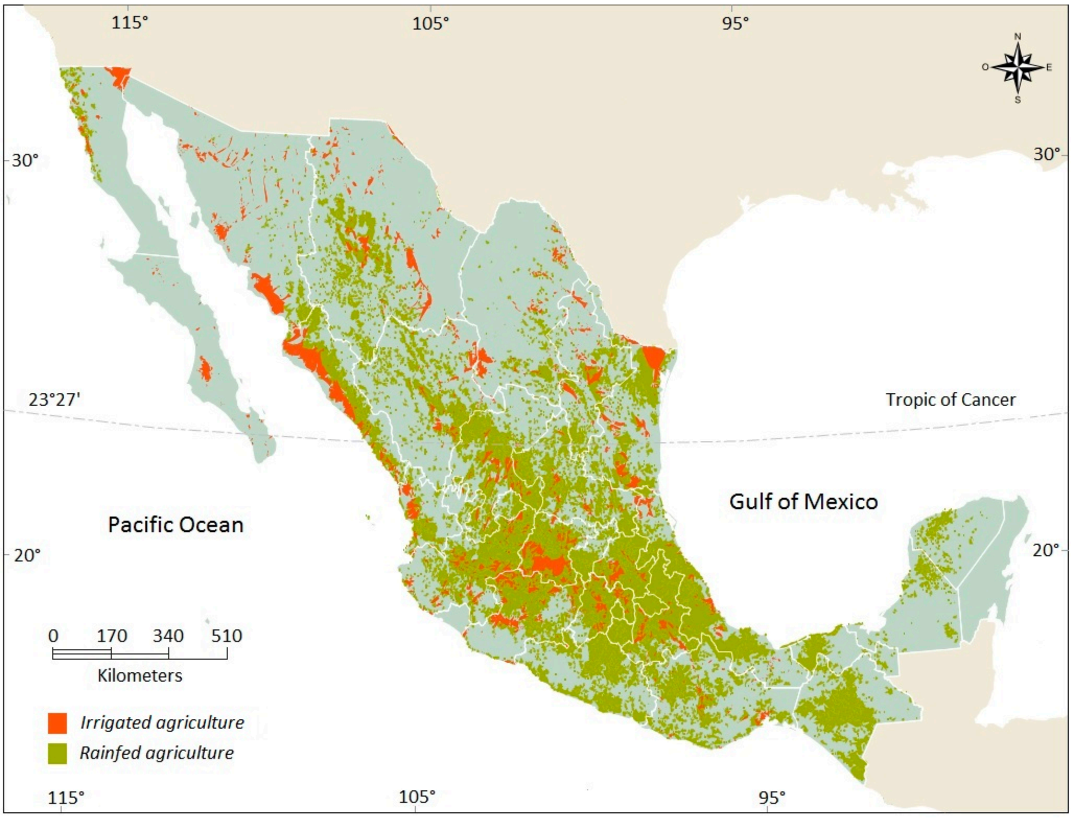

Figure 2. Land area of Mexico covered with irrigated and rainfed agriculture [26].

1.2. Protected Agriculture in Mexico

Protected agriculture, as noted above, is a system of production under various structures to protect crops by minimizing the restrictions and effects imposed by climate phenomena [9]. Among other advantages, it allows the development of agricultural crops outside of their natural cycle and in a shorter time. It is more successful when faced with pests and diseases and has better yields in less space, and better quality crops demand a higher price in the market, generating a better income for producers [9,27]. As a response to the pressure of increasing the agricultural productivity in Mexico, the decrease in water availability and the significant food export opportunities to the United Sates, horticultural production in Mexico has begun to focus on greenhouse/shade house technology throughout the northern and central parts of the country [28]. In Mexico, protected hectares have expanded from 1998 to 2008 at an average annual growth rate of 34.5%, with different grades of technology used [9] (see Table 1). The policy of the Ministry Agriculture, Livestock, Fishery and Food (SAGARPA, its acronym in Spanish) has a program to support sustainable agriculture projects, whose specific goal is to promote the production of healthy food, meeting national and international quality standards [14]. While there are slight differences between greenhouses and shade houses, many producers throughout Mexico believe that both technologies can provide similar productivity and thus refer to this technique for marketing purposes as protected agriculture [15].

Protected agriculture is one that is carried out under production methods that help to exercise a certain degree of control over the various factors of the environment. This allows minimizing the restrictions caused by adverse climatic conditions on crops [14]. Protected agricultural facilities are built in modular or in battery structures that can be in soil with drip irrigation or can use hydroponic or aeroponic technologies. Because of the advantages of using less water and gaining increased productivity in greenhouse/shade house technology compared with traditional irrigated land technology, producers started using these technologies at the end of the 1990s [15].

In 1980, 300 hectares (ha) were reported with this production system and in 2008, around 9000 ha. Recent statistics from 2011 and 2014 reported by SAGARPA show that there are about 23,000 ha under protected agriculture, distributed in about 40,000 facilities [16]. According to Table 1, most of the facilities are greenhouses, shade houses or macrotunnels [16]. About 86% of the production units are smaller than 0.5 ha; 11.5%, from 0.51 ha to 5 ha and 2.5% have more than 5 ha under production. This indicates that most of the farmers have very small production units, which limits their access to technology, training and technical assistance, as well as increased penetration into the most demanding markets [16].

Table 1. Type of facilities in Mexico dedicated to protected agriculture [16].

Type of Facility	Number of Units	Percentage (%)	Surface (ha)	Percentage (%)
Greenhouse	25,055	62.67	11,100.25	47.27
Shade houses	5032	12.59	6366.66	27.11
Macrotunnels	5001	12.51	3705.61	15.78
Mesh shade	1362	3.41	1550.33	6.60
Microtunnels	2693	6.74	575.95	2.45
Pavilion	605	1.51	133.34	0.57
Nursery	229	0.57	50.77	0.22
	39,977	100.00	23,482.92	100.00

Table 2 shows the states of Mexico that have significant protected agriculture facilities and the percentage of area planted in 2008 and in 2011 to 2014. The increase in the planted surface during this period was 263%, making Mexico one of the fastest growing countries in this sector worldwide. This trend is likely to continue for the next several years, especially for producers of tomatoes (70%), sweet and bell peppers (16%) and cucumbers (10%) [9,27,28]. It is noteworthy that some of the states growing fastest with this technology are located in the central and northern areas of the country, where semiarid climates and a water deficit prevail, but with the advantage that they are located close to the United States border, the main market for these products.

Table 2. Evolution of protected agriculture facilities in Mexico [16,29].

State	2008		2011 to 2014	
	Surface (ha)	Percentage (%)	Surface (ha)	Percentage (%)
Sinaloa	2500.00	27.98	4744.22	20.20
Jalisco	900.00	10.07	3310.09	14.10
Baja California	1220.00	13.66	2689.91	11.45
Estado de México	100.00	1.12	1517.39	6.46
Chihuahua	80.00	0.90	1497.74	6.38
Sonora	990.00	11.08	1196.43	5.09
Others	3144.00	35.19	8527.14	36.31
	8934.00	**100.00**	**23,482.92**	**100.00**

Table 3 shows the states of Mexico having low- to high-tech facilities using protected agriculture. The lower the ratio between the number of installed facilities using protected agriculture and the covered surface in hectares, the higher is the grade of technology used in the facility, since large facilities require more technology to control the variables for the growth and productivity of plants. Once again, the states located in the north, closer to the United States border, are those having facilities using medium-high technologies. If we assume that medium-high technology should have less than two units per hectare, medium technology from three to five units per hectare and low technology facilities more than five units per hectare, from Table 3, we find that 78% of protected agricultural systems are medium-high technology, 16% medium technology and 6% low technology.

Table 3. Relationship between numbers of installed facilities in Mexico using protected agriculture and the covered surface in hectares from 2011 to 2014 [16].

State	Number of Units	Surface (ha)	Number of Units/Covered Surface (ha)
Chihuahua	275	1497.74	0.18
Sinaloa	1074	4744.22	0.23
Baja California Sur	364	803.2	0.45
Baja California	1339	2689.91	0.50
Sonora	724	1196.43	0.61
Michoacán	870	1004.06	0.87
Jalisco	3004	3310.09	0.91
Coahuila	327	353.99	0.92
Tamaulipas	286	295.19	0.97
Colima	439	425.38	1.03
Guanajuato	811	655.34	1.24
San Luis Potosí	1129	901.41	1.25
Zacatecas	729	410.54	1.78
Querétaro	573	244.77	2.34
Nuevo León	282	106.64	2.64
Quintana Roo	151	56.48	2.67
Aguascalientes	238	87.96	2.71
Puebla	3021	1071.25	2.82
Campeche	199	69.51	2.86
Veracruz	367	112.38	3.27
Estado de México	5564	1517.39	3.67
Morelos	1038	237.53	4.37
Nayarit	555	121.08	4.58
Durango	365	75.02	4.87
Yucatán	360	67.89	5.30
Guerrero	907	151.28	6.00
Tabasco	89	13.61	6.54
Hidalgo	2556	272.47	9.38
Oaxaca	4671	482.91	9.67
Chiapas	3651	273.74	13.34
Tlaxcala	1163	81.05	14.35
Distrito Federal	2856	152.45	18.73
Country	39,977	23,482.92	1.70

Data in Table 3 show that protected agriculture technology in Mexico varies from low technology to medium and mid-range to high technology. Low technology is 100% environment dependent, using simple technologies similar to those used in outdoor cultivation. Medium technology corresponds to modular or battery structures that are semi-heated, with programmed irrigation, and can be in soil or hydroponics. Usually, the productivity and quality are higher than in low technology facilities. High technology includes facilities that have automated climate control (greater independence of the external climate), irrigation, computerized and precision injections of CO_2, all requiring sensors and devices that operate the irrigation systems and ventilation, thermal screens for the control of the illumination and cultivation of plants on substrates [15]. The level of technology depends on the amount of labor required and on the yields achieved for installation [16].

A low technology greenhouse has an average cost in Mexico of about \$5 USD/m^2 and consists of simple elements, such as light metal structures, plastic, mesh shades made of synthetic fiber, etc.; the medium technology greenhouse has a cost of about \$19 USD/m^2 and uses semiautomatic processes; a high technology greenhouse is fully automated and has an average cost of \$115 USD/m^2 [9,15]. Annual yields of tomatoes in field-grown agriculture are about 40 to 60 t/ha; in low technology greenhouses, about 120 to 150 tonnes per hectare (t/ha); in medium technology greenhouses, about 200 to 250 t/ha; and in high technology greenhouses, about 600 t/ha [9,30]. In 2014, Mexico produced about 2.8 million of tonnes of tomatoes, generating revenues of about $1.35 billion USD. The domestic consumption was only 37%, the rest being exported to the United States (95%) and Canada (5%), meaning that the Mexican tomato crop depends mainly on the exports to one market [31].

Canada and the U.S. have slowed the growth in greenhouses, so horticulture in Mexico tends to increase exports to the United States since production prices in Mexico are cheaper. The 2007 census of agriculture in the USA showed a decline in the area planted in horticultural crops. The area of crops in fields decreased in all categories, except flower seeds and sod. Additionally, the area of crops under greenhouse or other protected agriculture technologies dropped in all categories except nursery stock [32]. For example, the area dedicated to cut flowers and cut florist greens decreased 24.3% in the period of 2002 to 2007; indoor foliage plants decreased 23.7%; and greenhouse vegetables decreased 4% in the same period [32].

Large-scale production facilities in Mexico dominate the export markets, in contrast to small and medium-sized facilities that are more focussed on the needs of domestic markets. Finally, one must consider the factors that can boost or inhibit the growth of protected agriculture in Mexico. These are: (1) the low level of education among the farmers; (2) the need to fulfil phytosanitary regulations; (3) investments required for greenhouses of medium and high technology level; (4) the operating costs to control temperature and relative humidity in the extreme climates in the northern regions of the country; (5) effective facilities' design; and (6) the production scale to achieve a profit. Additionally, one must keep in mind that the problems arising from design failures may increase the preoperative expenditures and time, and the expected annual production yields may be lower [9].

1.3. The Development of Hydroponic Culture in Mexico

The soilless culture of plants was popularized in the 1930s in a series of publications [33], but the growing of plants in nutrient-rich water has been practiced for centuries in Mexico [34]. Chinampas have long been regarded as one of the most productive forms of agriculture in pre-Hispanic Mesoamerica [35,36]. Hydroponics is a technology that facilitates plant growth in the presence of water enriched with nutrients, without the presence of soil. Another form of soilless plant cultivation, aeroponics, uses hydroponic principles, but the plants are grown leaving the roots exposed to a moist environment enriched with nutrients [7,8,37].

As already noted, hydroponic agriculture has grown relatively rapidly in Mexico in recent years. The presence of pests, such as arthropods and nematodes, and diseases are the main problems that face many medium and low-tech greenhouse growers in Mexico [28]. On the other hand, the savings in water and the use of degraded lands unsuitable for traditional agriculture make hydroponic agriculture attractive [38].

In the official statistics in Mexico, hydroponic facilities are combined with protected agriculture, so we could not find separate growth trends for this segment. Fifty percent of the area with protected agriculture is concentrated mainly in four states: Sinaloa (22%), Baja California Norte (14%), Baja California Sur (12%) and Jalisco (10%). The main crops grown under protected agriculture are tomato (70%), pepper (16%) and cucumber (10%). In recent years, there has been a diversification of crops, such as papaya, strawberry, habanero chili, flowers, medicinal and aromatic plants (see Figure 3). Nevertheless, we found that the states where most hydroponic greenhouse production is located are Jalisco, Sinaloa, Sonora, Baja California, Oaxaca, Puebla, State of Mexico, Morelos and Michoacán where mainly tomatoes, cucumber, bell pepper and strawberries are grown, as well as chrysanthemums, roses, carnations and alstroemeria (Peruvian lily or lily of the Incas) [14,39].

Figure 3. Stevia production in a greenhouse by using a hydroponic system in Mexico [40].

1.4. From Hydroponics to Low Height Vertical Farming

Vertical farming as a component of urban agriculture is the practice of producing food in vertically-stacked layers, vertically-inclined surfaces and/or integrated into other structures. Vertical farming is not a new idea. In 1915, Bailey coined the term "vertical farming" [41]. Since then, architects and scientists, especially towards the end of the twentieth century, have repeatedly looked into the idea of producing food in urban environments because of constant human population growth and the pressures exerted on resources for food production [42]. Denmark was the first country to attempt to implement the concept of agricultural integration in a built environment in a house in the 1950s; they tried to grow watercress (*Nasturtium officinale*) on a large scale [43]. Today a more evolved urban agriculture, where the product is grown in a totally controlled urban environment, in closed vertical structures, is attracting more attention in several countries. In the past two decades, scientists in the United States, Europe and several Asian countries have been conducting research and development to bring this concept into reality [44].

Several countries, such as South Korea, Japan, China, Singapore, Italy, Holland, United Kingdom, Jordan, Saudi Arabia, United Arab Emirates and Canada, are moving ahead in the development of vertical farming projects [45]. Vertical farming technology has been seen as a solution to the problems of limited land area suitable for agriculture, as well as a more rational use of water resources, thus providing better opportunities for a sustainable food supply in both developed and developing countries [45,46]. Because of advances in hydroponic and aeroponic technology, lighting through LEDs and energy provided using solar cells, it is now possible to have agriculture in cities and possibly even in individual households to create centers of production and consumption integrated with urban and suburban communities [44]. One can grow crops inside multi-story city buildings, using very little land to produce food that would not need to be shipped far to the end consumer [47].

1.5. Impact of Vertical Farming in the Ecological Footprint

Currently, the ecological footprint arising from global agricultural activities is the size of South America (17,840,000 square kilometers) [48]. The Association for Vertical Farming (AVF) is an internationally active non-profit organization focusing on advancing urban and vertical farming technologies, designs and businesses. AVF, among other authors, has noted that through vertical agriculture, environmental, economic and social benefits are possible [42,44–46]. This is particularly relevant for those regions of the planet where dryland conditions are present (including the very dry areas). These regions occupy 41.3% of the planet, equivalent to 6090 million hectares distributed mainly in Mediterranean Europe, Asia, North Africa, Americas and most of Australia [17,49–51]. The main issues that this technology could help to solve are [42,44,45,48]:

(1) Fertilizer use leading to agriculture runoff causing eutrophication of lakes and reservoirs and ocean acidification;
(2) Global water use; globally, 80% of freshwater is used in agriculture;
(3) Food transport leading to significant food waste and greenhouse gas emissions; and
(4) The growing demand for food; by 2050, the global population is expected to be 10 billion people, 80% of whom will live in urban areas, thus increasing demand for food in cities.

In Mexico, the total GHG emissions reported in 2013 were 633 $MtCO_2e$ with agriculture contributing 80 $MtCO_2e$. This amount represents about 12.6% of the total GHG emissions of the country and about 0.74% of the total GHG emissions due to global agriculture [52]. In this sense, the impacts of the ecological footprint due to the production and transportation of agriculture products could be reduced compared to conventional agriculture [46,47]. As well, in countries located in tropical and subtropical climates, the energy consumption required by protected agriculture facilities could be supplied by solar power [27,28].

2. Discussion

As explained before, the benefits of vertical farming are very broad; however, one must take into account some problems that may arise in the food production projects based on vertical farming [13]. In large-scale units, vertical farming should produce food at a lower cost to the final consumer than does conventionally-grown food; but to meet this goal, a careful selection of technology for environmental control within these buildings with regard to lighting, temperature, flow, recirculation, pollination and the provision of plants is among the important factors needed for success. It is also essential to take into account the financing issues including the cost of land. However, using soilless culture systems does not automatically result in the production of high-quality vegetables, since the perception of some consumers is that these products are of inferior quality compared to products grown in soil; nevertheless, numerous studies confirm that soilless culture systems enable growers to increase vegetable yields, to achieve better water use efficiency without quality losses compared to soil cultivation [53,54]. In addition, one must consider that the prices of the products in the grocery or convenience stores today do not consider externalities or shadow costs (pollution, soil degradation, loss of biodiversity, loss of habitat, invasive species, intensive use of pesticides, etc.) related to unsustainable production that prevail in all countries [55–57].

According to the above-mentioned facts, protected agriculture and its evolution to vertical farming technology could contribute to a reduction in some of the following social, economic and environmental issues faced in the country (Table 4). Additionally, Table 5 explains some issues of concern in food production using vertical farming technology in Mexico.

Table 4. Potential benefits of vertical farming in Mexico.

Current Situation in Mexico	Potential Benefits of Vertical Farming Referred to in the Literature
The rate of deforestation of forests and rain forest in Mexico from 2005 to 2010 was 155,000 ha per year [58,59].	Decrease in land use changes driven by traditional soil cultivation systems, allowing restoration of the damaged forests and rainforest ecosystems [42,43].
There are 2583 species in Mexico classified at risk [60].	Reducing the risk to endangered species in several damaged ecosystems by reducing deforestation and better land use [61].

Table 4. *Cont.*

Current Situation in Mexico	Potential Benefits of Vertical Farming Referred to in the Literature
In Mexico, as in many other countries, 77% of the available water is used for agriculture; water availability in most of the central and northern regions of the country is already scarce [20,62]. Moreover, 115 aquifers are classified as overexploited in the country (19.3% of the total), and most of the rivers have been fragmented due to the construction of embankments or dams for agriculture [20].	Important reduction of water use for agriculture, allowing for the recovery of aquifers and the flows in streams in rivers necessary for ecological goods and services [42,44,63]. Potential reuse of treated waste water in hydroponic culture production [64].
More than 70% of the water bodies have some degree of contamination. Lakes, rivers, mangroves and coasts are polluted, affecting humans, animals and plants that inhabit these ecosystems [65].	Substantial reduction in the overuse of fertilizers and pesticides with a resultant decrease in air, soil and water pollution [7,42–48].
There are 4462 dams, 667 of which are classified as large dams. These cause habitat fragmentation, reduction of environmental flows in rivers and other environmental-related issues [20].	Reversal in the trend in the construction of small and large dams to store water for irrigation, thus permitting the restoration of natural ecological flows of rivers and the recovery of disturbed ecosystems.
The total GHG emissions reported in 2013 were 742.2 $MtCO_2e$, where agriculture contributed 89.1 $MtCO_2e$. This amount represents about 12% of the total GHG emission of the country and about 0.74% of the total GHG emissions due to global agriculture [52].	Reduction in the national carbon footprint, because of substantial savings in energy from reductions in the use of agricultural machinery, as well as vehicles for transporting farm products to cities, and reduced transport in the supply chain to supermarkets and consumers [42,44–48].
Agricultural productivity has only increased by about 1.1% in Mexico in recent years [24,25].	Substantial increase in the agriculture productivity throughout the year, as the photoperiod can be extended with the use of LEDs for lighting; energy can be ensured with solar cells or other low ecological impact forms of energy production, such as low impact small hydropower plants where water flow is available [66,67].
The transformation of agriculture in Mexico City from a conventional rural form to a new urbanized model, as a reaction to urban development and the availability of waste products from the city, as well as a response to the demands of recreation and tourism. From this has emerged a new concept of the rural producer or urban farmer who now has access to an urban infrastructure, to education and research [68].	Potential improvement of the quality of life and in the environment in the most populated metropolitan areas of the country, such as the Valley of Mexico (20.1 million inhabitants), Guadalajara (4.4 million inhabitants) and Monterrey (4.1 million inhabitants), and eight more cities having more than one million inhabitants [1]. Access of the urban consumers to fresh, safe and locally-produced products [48].
Mexican cities have the lowest rates of emigration; the rural places that are spatially proximate to cities have the highest emigration rates. These findings suggest that while urban development retains emigrants within city borders, it may generate emigration out of neighbouring rural places [69,70].	Creation of new permanent jobs in low height vertical farm mainly in urban areas and in areas near the cities. Creation of a national culture of food production and settlement of rural families near the cities based on the application of sustainable-based technologies. Introduction of this technologies in small and medium-sized cities could avoid emigration of the population by creating jobs and profitable export activities.

Table 5. Issues of concern on food production using vertical farming technology [13].

Disadvantages	Advantages in the Mexican Context
Cost of production:	
A skyscraper-sized vertical farm would cost hundreds of millions of dollars to build and equip for agricultural needs.	The hydroponic agriculture is in fact a growth business in Mexico and can be even more profitable in a medium scale of production by using vertical farming, given the opportunities of the USA market [9,16,27–29]. Thus, in the country, it is not necessarily required to build costly skyscrapers to have a profitable business. Improvements in the design of the existing high-tech and medium high-tech facilities could increase the productivity even more (see Figure 4).
Cost of maintenance:	
The cost to run thousands of LED lights, keep the growing temperature suitable for the crop and supply water to plants will outweigh the cost to run a traditional farm unless operators can find a way to make the energy renewable and self-sustaining.	It is possible to design greenhouses being only some meters high to generate a vertical farming concept without introducing artificial light or complex control systems. In fact, Mexico is growing faster in the field of protected agriculture due to favourable climate conditions [28]. Additionally, Mexico is one of the countries with major opportunities to use solar energy to supply the energy needs of the population [71]. Therefore, photovoltaic energy is one of the growth sectors, mainly in the central and northern regions of the country. Therefore, several Mexican companies now produce LEDs for several applications by using their own technology.
Cost of urban land:	
Vertical farming must be profitable to investors, but the cost of land in urban areas is usually higher than farmland, so profit margins could be smaller.	In Mexico, urban and peri-urban agriculture can be a profitable business and can be further improved using technologically-advanced facilities similar to ones in developing countries [68,72].
Limited variety of products:	
Vertical farming technology is not yet capable of producing different varieties of fruits and vegetables. Today, there are only a few varieties of fruits and vegetables that can be produced in a controlled environment generating attractive profits for investors.	Greenhouse crop production and hydroponic production systems located in Mexico produce a variety of vegetables and flowers. Today, there are more than 15,000 ha in production using intensive agriculture technologies in the country, and most of these producers have export activities [14].
Intensive hand work:	
Pollination is something that needs serious consideration because insects are crucial in the process of the production of seeds and fruits. Therefore, given that the technology is an insect-free environment, pollination has to be done by hand, which is labour intensive and could affect production costs and diminish profits.	Mexico has a developing economy and still needs to create jobs for that part of the population having a low level of education. Vertical farming could create many job opportunities for families living in peri-urban areas where the emigration rates are high [70].
Processing problems:	
Vertical farming does not take into account the fact that much of the vegetation produced there will still need to be processed. Fruits like tomatoes will need to be transported to another facility to be processed into products, such as ketchup, sauce and juice. If the cost of production is already high, sending the crops to another facility for processing will drive it up even more.	Since the small and medium enterprises (SMEs) boost an important part of the GDP and employment in Mexico [73], production in vertical farming units located close to cities has the potential to create small food processing facilities next to the farms. The actual strategy based on low and medium-tech protected agriculture has been resulting in Mexico in the last few years in an increase in the value of production, developing local and foreign markets and creating jobs [9,16,27–29].

Table 5. *Cont.*

Disadvantages	Advantages in the Mexican Context
Dependence on technology:	
Loss of power to the facility for even a day could be catastrophic to production. The plants are reliant on the perfect temperature, air quality and lights that the artificial environment supplies; if these failed, those crops could die.	Mexico has a new energy reform that encourages the investment in renewable electricity production [74]. On the other hand, the excellent geographic location of the country permits the use of natural solar energy instead of using electricity for lighting and heating vertical farming projects in winter.
Sophisticated control systems required:	
Vertical farms must also take into account the costs of controlling LED lighting, environment control systems, flow control and water circulation and temperature controls.	The fast growth of protected agriculture in Mexico indicates that farmers in Mexico have access to training and technical assistance and that they are able to solve the technical problems involved in this production system.
High dependence on technology:	
Cell phones, laptops and tablets will control these farms. This technology depends on dependable, functioning networks. If the technology needed to run these structures were to fail, the farm would be at stake.	There is expertise in Mexico to develop structures based on information technologies (IT), Internet of Things (IoT) and mobile apps. Only some protected agriculture facilities based on advanced technology would require the control systems based on this kind of sophisticated remote control system. In most of the existing facilities, the production uses locally-controlled systems.
Skilled labour:	
The workers in a vertical farm facility have to be highly trained in best management practices to deal with the production of food in an isolated and controlled environment.	In the country, there are technological development centres oriented to build capabilities in management of hydroponic or aeroponic cultures by using some meters high vertical farming technologies as already proven and validated in R&D centres in Mexico [75].
Putting traditional farmers out of work:	
Due to the use of technology for plant needs, vertical farms need far fewer employees than traditional farms need. Their efficiency and location within the city, where the customers live, would put many traditional farmers out of work.	The policy of the Ministry of Agriculture (SAGARPA) is to foster projects in Mexico of low to medium levels of technology that would employ 8 persons per hectare [14]. Additionally, this technology could create new indirect jobs for services required by the greenhouse vertical-farm producers.
Currently not an all-encompassing system:	
Not all crops are suitable for indoor cultivation, such as grains and livestock.	Undoubtedly, the production of wheat, maize and sorghum in Mexico will have to be carried out in accordance with conventional farming methods currently used in the country. However, low height vertical farming technology opens the possibility that a variety of vegetables and other hydroponic or aeroponic crops may migrate to this technology.

Considering that Mexico is able to solve most of the problems pertaining to protected agriculture and its evolution to vertical farming, this technology requires attention to other issues in order to have successful application. As explained before, in Mexico, protected horticulture is growing and has demonstrated good management of the technology among high technology and medium-high technology producers. Nevertheless, knowledge about the setup and operation of hydroponics systems needs to be improved, since 60% of the installed hydroponic greenhouses have failed to date because of deficient training of the producers, the lack of technicians and poor location of markets [39]. This situation can also arise in low height vertical farming facilities, since the bases of operation are similar (see Figure 4). To be successful in applying this technology, it is necessary to strengthen the technical knowledge of crop production in hydroponic greenhouses, as well as technical training for the producers [39,76]. In order to reduce the risk of failure and to develop more sustainable agriculture in the country, SAGARPA and the trusts instituted in relation to agriculture (Fideicomisos Instituidos en Relación con la Agricultura, FIRA) have offered financial and technical support for those producers looking to start up protected agriculture projects by using greenhouse and shade technology, including hydroponic technology [14,38,75].

Figure 4. Lettuce production using a vertical hydroponic arrangement in Yucatan, Mexico [77].

3. Conclusions

Protected agriculture has started to develop in several countries in recent years. The implementation of this technology is progressing slowly because people around the world still believe there is enough cropland (and water) to feed the population in most countries. However, the concept of protected agriculture enhanced by vertical hydroponic agriculture could help resolve a looming food shortage attributable to a lack of arable land and water, which climate change will exacerbate. Additionally, the governments of developing countries have become conscious of the importance of improving the preservation and protection of natural resources.

A population of 150 million inhabitants in Mexico by 2050, of whom 80% will be concentrated in urban areas, is forecast. To feed this population, government and industry will have to solve the various technical problems outlined above with regard to protected agriculture and to foster the R&D activities to advance the concept to vertical farming. These solutions will involve the control of the costs of production to reduce the ultimate cost of produce to the end consumer. It is worth developing vertical farming since this concept may revolutionize traditional agriculture, reducing the existing pressures on natural resources in the country. If vertical farming becomes a reality in the near future in Mexico, it could lead to traditional farmers focusing their efforts on suppling a variety of safe and nutritious food products that are not feasible to produce in an artificial environment (cereal crops, livestock). Vertical farming could reduce the ecological effects resulting from agricultural activities in Mexico, permitting the restoration of thousands of hectares currently damaged by traditional agriculture, thus providing an opportunity to preserve the biodiversity of local regions.

In Mexico, the problem facing the population is a problem of access by the most vulnerable communities to food, rather than to the food production capacity of the country. Nevertheless, the country faces diverse environmental problems caused by the unsustainable management of agriculture, particularly land use and water management planning. Because of bad practices in agriculture and water management, the country continues to accumulate environmental liabilities due to the externalities generated by this sector. As shown in Table 3, the introduction of a large number of small units of protected agriculture in several communities in the southern states of the country (Campeche, Chiapas, Guerrero, Oaxaca, Puebla, Quintana Roo, Tabasco, Veracruz and Yucatán) is proof that protected agriculture technology in the country could contribute to a better management of the land use, by creating green environments to produce food products in both rural and urban areas of the country. Metropolitan areas, such as Mexico City, Guadalajara, Monterrey, Puebla and

Tijuana, can contribute significantly in reducing the carbon footprint due to the agriculture and food production activities in the cities.

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