How energy innovation in indoor vertical farming can improve food security, sustainability, and food safety?

Dafni Despoina Avgoustaki, George Xydis*
Department of Business Development and Technology, Centre for Energy Technologies, Aarhus University, Herning, Denmark
* Corresponding author: *Email address:* gxydis@btech.au.dk (G. Xydis)

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1. INTRODUCTION

Sustainability of resources and safety in the food production line is a major issue globally. By 2050, it is expected that the global population will reach the 9.8 billion people, 2.4 billion people more that need to be fed (United Nations, Department of Economic and Social Affairs, 2015). Today, agriculture occupies land equal to the size of South America in order to cover the demand of the global population. Based on the assumption that the minimum daily demand of a single person is minimum 2000 kcal, if we maintain the same agricultural practices, we will need additional land equal to the size of Brazil (2.1 billion acres) to cover the global food demand (Despommier, 2009). On the other hand, according to Lotze-Campen et al. (2008), the land used for agriculture is projected to be transformed for other purposes such as urbanization, energy production, or infrastructure growth. It is worth to mention, that another crucial challenge that will significantly affect agricultural production in the upcoming years is the rapid increase of the global temperature, as per each degree of temperature rise, 10% of existing agricultural land will be lost (Despommier, 2010). Nowadays, climate change is a huge issue since it is expected that the upcoming 50 years will outstandingly affect the agricultural process. The significant increase of the carbon dioxide emission levels from a global perspective—since it constitutes an important impact factor of agricultural productivity—can influence the global economy via the effects on the agriculture's total production rate. In specific, based on Mulatu’s et al. (2016) research conducted for Ethiopia, indicates that the impact of CO_2 emissions will decrease 3.5% to 4.5% the real agricultural GDP since it will lead to lower the agricultural productivity and subsequently reduce the amount of traded and non-traded crops. Such population increase certainly indicates a significant rise in the required food production, raising concerns on the deficiency, the quantity, and the quality of future food products. We should also take into account the fact that nowadays food travels daily thousands of miles from the production areas to the urban consumers, in order to meet the demand, releasing huge amounts of CO_2.

Less developed countries such as Ethiopia that were mentioned above, apart from global climate change will have to face and other enlarged problems concerning food safety. For example, human excrements that are used as fertilizers (estimation of 50% of the global farming) can cause diseases such as cholera, typhoid fever and numerous parasitic infections (Despommier, 2010). Nowadays, even the more developed counties have to face food safety and security problems even if this kind of infectious diseases have been eliminated. It is worth to mention the pandemic of our age, COVID-19 caused by virus SARS-CoV-2 that was initially reported in the province of Hubei, Wuhan in China. The disease is estimated to have originated from a seafood market in Wuhan where wild animals were traded such as marmots, bats, snakes and birds (Zhou et al., 2020). The specific family of viruses, coronaviruses, are known to be transferred from animal to humans. According to Zhou et al., 2020, it is mentioned that 96% of the genetic makeup of COVID-19 is matched with the coronavirus found in bats. The uncertainty that is caused globally via COVID-19 has caused apart from multiple deaths and lockdowns to most of the European countries, will affect significantly the economy and will cost trillions of dollars in the global economy, during 2020 and beyond (UNCTAD, 2020).

Food safety is a major issue of our era, as there are multiple reports of cases worldwide over the last years that have caused food recalls due to bacterial infectious diseases leading to loss of billion dollars. Why do we seem to have so many outbreaks concerning food production these days? Only in the US, despite the attempts to provide a safe food supply, every year are recorded 48 million foodborne illnesses, 128,000 hospitalizations and 3000 deaths (CDC, 2013). In 2017–18, E.coli O157: H7 outbreak in the US caused sudden eruption linked to consumption of leafy greens and the romaine lettuce. The pathogen was mainly reported in the regions Yuma, AZ and Salinas, California, where greenhouse installations that produce more than 90% of the leafy vegetables and greens in the United States are based. E.coli contamination in the production line almost all of the times originates from the irrigation water used in the fields. Additionally, further risk in the contamination process from various bacteria and pathogens comes from the washing of field-grown products after they are harvested, while this step can spread contamination to the whole production. The most regular technique that outdoor farming applies after harvest is to dunk lettuce heads in water tanks from rainfall or irrigation, while most greenhouses apply triple washes with running water from the local network.

Vertical farms are a novel type of farming in a controlled-environment with a total replacement of solar radiation with artificial lighting that provides the necessary nanometers of the spectrum for the growth and development of plants. In vertical farms, plants grow in soilless cultivation systems such as hydroponic (roots are immersed in multiple substrates, i.e., perlite, rockwool enriched water with nutrient solution), aeroponic (soilless air/mist solution) or even aquaponic (co-cultivation of fish and hydroponic plants) systems that allow stacking multiple layers or columns of plants horizontally or vertically. Vertical farms are located in completely isolated spaces from outdoor environment with thermally insulated installations (especially when at the top floor of the building) and airtight structures that give the opportunity to the farmers to control the environment in terms of temperature, humidity and CO_2 (Avgoustaki and Xydis, 2019). Since vertical farms can theoretically be placed anywhere in the urban network, they allow local, nutritious and fresh consumption for consumers. In specific, a study conducted by Jill (2008), mentioned that food sourced from conventional farming uses 4 to 17 times more fuel compared to locally grown food and emits 5 to 17 times more CO_2. Meanwhile, vertical farms may be able to increase the productivity rate in highly urbanized areas that can lead to improvements in the food security of the community.

The purpose of the following subchapter is to compare the different farming techniques of outdoor farming, greenhouses and vertical farms in between them in terms of input of resources, the final product in terms of safety and the shelve life of the products in terms of nutrient status and freshness. Additionally, we will examine the above criteria for lettuce, which is one of the most important cultivated species in vertical farms and will give us access to multiple data. Lettuce belongs to the basic daily diet products; its nature is fragile and can be easily contaminated and spread diseases among the population.

2. COMPARISON IN RESOURCES INPUT AND SUSTAINABILITY BETWEEN DIFFERENT FARMING TYPES

In order to make more understandable the concept of resource use efficiency, in Fig. 1 the essential resources for growing plants under various farming types are shown. The most vital for plant growth is water, CO_2, light, nutrients, electricity (for ventilation purposes) and heating.

As shown in Fig. 1, the definition of resource use efficiency (RUE) is given by the ratio of the final plants production to the total input. In order to calculate the total input of a system, we have to summarize the input of resources, the environmental pollutants and the production system.

In order to evaluate the sustainability and efficiency of a production system in the food industry, we have to assess three key directions of the system.

- RUE: the amount of necessary resources to produce.
- The cost performance: the ratio of the sales amount to the production cost.
- The vulnerability of the system, meaning the deviation of the yield production per year and the quality value per product unit.

Water is absolutely necessary for all food production such as vegetables, fruits, grains, meat etc. Based on Nederhoff and Stanghellini (2010), the water use for the global food production reaches at 5400 km^3 and has a rapid increasing rate. The irrigation water-use efficiency can be researched under different scopes and multiple concepts such as storage, delivery distribution of the water to the farm or out of the farm. Additional systems that can affect water use efficiency is the ratio of water that is delivered for irrigation and the water that supplies the system.

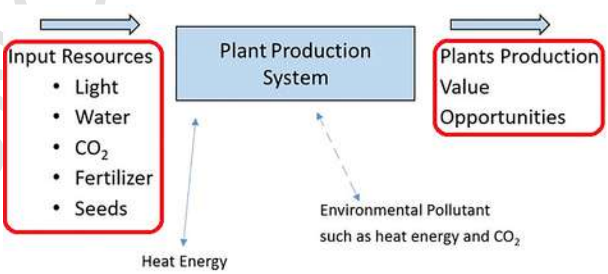

Fig. 1. Resource use efficiency (RUE) concept of a plant production system.

There are various ways we can calculate water use efficiency as one of the major resource inputs in food production that can be accomplished with agronomic ways, engineering or even economic approaches. More analytically, irrigation efficiency estimates the ratio between the diverted water and the consumed by the cultivation, thus it provides water-use measurements that estimate the performance of the irrigation system. On the other hand, water use efficiency is considered an economic concept that in practice evaluates the farm, as it is calculated by the crop yield unit of water diverted (kg/m^3).

In terms of energy consumption, it is one of the reasons that causes greenhouse gas emissions (GHGs) contributing at the rising global warming. The main gases released by agricultural production are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Since the global policy makers, organizations, researchers, retailers and producers try to propose and implement novel techniques that identify and reduce GHGs, it is necessary that we will focus and refer to the status of emissions under each farming type and propose mitigation measures in the sector.

In order to describe sustainability in agriculture, it is not enough to relate sustainability with the field only from the resources perspective. Understanding and evaluating what constitutes a sustainable farming system, it is of vital importance, to furthermore understand the economic and social terms that influence the contemporary issues, values and perspectives of a unique system. Economic efficiency reflects to the value that is relative to the cost. In order a resource to reflect an economic value, has to be rare and difficult to obtain, for the market prices to allocate the use of this resource for competitive purposes. For example, even if air and water are essential resources for life giving them high "intrinsic" value, nevertheless under most circumstances they have no economic value due to their sufficiency levels in the environment (Ikert, 2001). They only obtain an economic value in cases of scarcity due to, e.g., high levels of pollution or drought.

2.1. Traditional farming

2.1.1. Status of resource use efficiency

Traditional farming is the type of agriculture where plants are shown and grown in the land field in soil. Even if is the most ancient way that people use land, over the last decades with the technological breakthroughs and the numerous innovations introduced, outdoor farming has changed. Sensors, satellites and advanced machinery allow farmers to apply more targeted (and precision) agriculture to treat the fields individually according to the needs of the crop and the soil, by dividing it in smaller parts in order to take into consideration the variability level of each unit. To complete the whole picture of climate change issues, an additional evolution process that crucially reduce the growth rate of plants is soil degradation due to excessive floods and droughts.

Traditional food production systems offer food solutions for people from the beginning of human history. Over time, additional innovative techniques were applied in traditional farming in order to rise the productivity rate and reduce the cost and the crops overall footprint. In terms of resources, conventional farming seems to have an increase demand for water use (Table 1) as traditional agriculture uses almost 70% of the available fresh water globally. Furthermore, a very common problem in terms of sustainability in water use efficiency of conventional farming is the limited soil water-holding capacity that results from the limited mulching of the soil and the consistency in the same fertilizers/soil-preparation practices. Scientific results (Pimentel et al., 2005) have shown that this maintenance of these practices lead to low soil moisture status and low conservation levels of conventional farming systems.

The most used approach for conventional farms is the irrigation efficiency and the water use efficiency. It is worth to mention that the more water applications are applied in a crop, the higher the water delivery losses are. In order to improve the water use efficiency, many farmers apply a combination of hydroponic systems with drip irrigation and smart scheduling of water distribution. Hydroponics successfully address the challenge of soil drought and salinity that reduces both yield and crop quality. It should be noted that a decisive factor for the selection of hydroponic systems is the high irrigation water needs that renders the requirement for recirculating water. It becomes apparent that combination of water–saving technologies with limited-water application technologies (such as close-loop hydroponics, drip irrigation, mulching and smart scheduling of water supply) are the most effective solutions for optimizing water use efficiency.

Regarding land use, growing and producing food to respond to the expanding demand of the world has led agriculture production and food scarcity that can be difficulty bridged. Today's farmlands, occupy almost 50% of the global habitable land (ourworldindata.org). We gathered the footprint of the various resources that meet the demand for lettuce production via traditional farming techniques. Worth noticing that deforesta-

TABLE 1 Summary of annual data for outdoor farming.

Resources efficiency	Traditional farming (lettuce)	Citation
Water use efficiency	250 L/kg lettuce/year	Barbosa et al. (2015)
Water use	Irrigation and rainfall Approx. 250 L/m^2	Coyle and Ellison (2017)
Energy use	0.3 kWh/kg/year	Barbosa et al. (2015)
CO_2 emissions	540 kg/tons of lettuce	Gerecsey (2018)
Light source	Solar radiation	
Pest control use	EPA-approved pesticides, herbicides and fungicides as also traditional methods as plowing, weeding and mulching	
Yield	3.9 kg/m^2/year	Coyle and Ellison (2017)
Land use	275 days/year	Coyle and Ellison (2017)
Land use efficiency	93 m^2 for 1 kg lettuce/day	
Harvests per year	2 per year	Coyle and Ellison (2017)
Food miles	3200 km	

tion is a major problem, since forests are continuously sacrificed against farmland that leads to climate change acceleration and soil inability to maintain water at lower levels. Depending on the cultivated variety, the techniques and the season, traditional farmed lettuce has a cultivation cycle between 1.5 and 2.5 months. Therefore, farmers have the ability to grow multiple successive crops in the same field throughout a yearly cultivation period in order to increase their yield and income. Additional techniques that open-field farmers follow in order to increase their yield and income per hectare (ha) of cultivated land is the density of planting, fertigation (combination of fertilization with irrigation) application and the use of healthy transplants grown in nurseries. Assuming that romaine lettuce growing in the Mediterranean is planted in distances of 30–50 cm between the rows and 20–35 cm between the plants, then the resulted yield reaches at 75,000–220,000 plants per ha (Savvas et al., 2015). By increasing the planting distance per row by 1 cm, it can lead to a 76% reduction of the total production. Harvest period vary depending on the type or the variety of the cultivated crop. For the romaine lettuce grown outdoors, the harvest period is between 55 and 70 days with a typical yield of 25–30 tons/ha.

The energy use in outdoor farming is mainly linked to fossil fuels for operations such as soil plowing, sowing, fertilization, harvesting etc. Additionally, further electricity is required for pumping (water irrigation), which in developed countries can reach up to 20% of the total fossil fuel usage (Despommier, 2010).

Conventional farming, unfortunately, is associated to higher emissions in comparison to other types of farming. The majority of the emissions is directly linked to the transportation of the products, also known as food miles. The amount of miles that is required in order for food to travel from the producer to the consumers could release between 11 to 666 kg of CO_2 emission depending on the location of the farm (Gerecsey, 2018). Since farmlands are often located many kilometers away from the urban centers, where the majority of the end-user is located. Food miles emissions represent on average 62% of the total emissions released throughout traditional farming. Another important source of CO_2 emissions that is linked to traditional farming is the significant amounts of food waste. Even if food waste is not only linked to traditional farming, maladministration and mismanagement on-farm losses, and non-marketable crops put traditional farming under the spotlight of high shares of carbon footprint.

For the estimation and assessment of the economic efficiency of farming, significant role in the calculation, the resources that bear an "economic" value have played a role. In traditional farming, there is limited motivation to protect and evaluate the quality, use and water maintenance, air, solar radiation and in some cases even soil fertility and productivity. The costs of a farm can vary between two main categories: the variable costs (operational expenses-OPEX) and the fix costs (capital expenses- CAPEX). In the category of variable costs, all the expenses that cover particular farming actions in a specific period of time such as seeds, fertilizers, chemicals, labor are included. On the other hand, in the fix cost category, all the expenses that will be incurred regardless the process and status of production, building expenses (rent, installations, land) and equipment (irrigation system, machinery) are included. Thus, the economic efficiency consists from a combination of technical and other components. Based on Aurangzeb et al. (2007) and a research that conducted to compare the economic efficiency between traditional farming and mechanized farming systems, it is pointed out that the net income in mechanized farms is significantly higher due to the higher yields/ha than the one of traditional farms. This effect of traditional farms could be explained by the longer time periods in soil preparation, limited tillage practices as well as the high cost requirements of labor expenses (specifically in seasonal workers during harvesting and sowing) in comparison to the high technology and mechanization farming systems. Last, another factor that highly affects the final quantity of production is biodiversity. For this reason, the selection and maintenance of mono-cropping techniques that provide a uniformity in the applied practices, can reduce the labor costs and make harvesting easier. However, by cultivating only one-species crops in the entire field, it can highly influence the biodiversity and make crops more susceptible to pathogen infections. To avoid this effect, traditional farmers apply chemicals and genetically modified organisms to maintain a simple farming system. This practice, though, requires a lot of continuous input of resources and energy (cost).

2.1.2. Solution for increasing sustainability in traditional farming

The innovative and high quality mechanization and technological innovation can lead to the increase of production and hence income. Multiple practices become more and more vital in traditional farming, as they improve the efficiency of resources use in general and can overall enhance sustainability. Concerning the water usage, there are several approaches that new farms bring along in the field and can optimize the existing severe water waste situation. Common agronomic measures such as improved crop husbandry and changed crop mix driven by the crop selection, can have a huge impact in improvement of water usage. Furthermore, there are various cultivation techniques such as modification of the irrigation infrastructure, which can also influence positively the water use efficiency. Last, management actions such as optimal irrigation planning and frequent maintenance irrigation system scheduled maintenance can also influence positively the system's efficiency (Wheeler et al., 2015).

2.2. Greenhouses

Due to the growing population, farming has shifted to technologies that enhance significant scale-up of the production via innovative technologies. Greenhouses are types of installations, designed to protect and enlarge the cultivation season of various crops. Plants growing under greenhouses can grow protected from severe weather conditions such as hail, snow, extreme low temperatures or excessive heat, while at the same time can allow cultivations of out-of-season species. Greenhouses first introduced in the 17th century but only on the 19th century were commercially applied in the global market. According to their installed area, greenhouses can be presented with various coverage materials such as plastic, glass, polyethylene and rigid that protect crops from the variability of the outdoor conditions, diffuses solar radiation and traps moisture, which contributes to increased plant growth. The coverage system allows farmers to control the cultivation environment according to each crop preference, as they can apply different techniques that will maintain the heating and the cooling requirements to the desired levels. This way, inside the greenhouses, farmers can develop and maintain the desired microclimate and create a more predictable environment that enhances the final plant yield, achieving higher quality and reduced water consumption compared to open field crops.

There are different greenhouse systems that are diversified according to the energy flow inside the greenhouse and the resources flow in the production line. In more details, open greenhouses refer to the structure of the irrigation system, meaning that they do not collect the drained water of the crops for reuse (usually have soil-based crops). These systems seem to have low level of water usage efficiency as they are affected by water losses due to soil depletion and constant water drainage, which drains the excess amount of water with fertilizers. This waste of resources cause significant problems to the environment. Usually growers can control the amount of drain as part of the management strategy of resources they follow. The percentage of drain can number between 5% and 50% of the water supply, but can be improved by reusing this drain in the irrigation system. Additionally, open greenhouses use window openings as the only mean of dehumidification and cooling technique.

There are also the semi-closed systems of greenhouses that have a smaller cooling capacity and window openings, combined with mechanical ventilation air-cooling systems. The combination use of mechanical systems and window openings depending on the cooling demand. Concerning the irrigation systems, semi-closed greenhouses reuse the drained nutrient solution by collecting it to a tank that is constantly topped-up with fresh water. In some cases is followed water disinfection in order the collected drain water to be purified for avoiding diseases spread in the crop. To avoid imbalances in the nutrient solution, farmers use various techniques such as bleeding or dumping. In specific, bleeding techniques remove constantly 10% of the drain water, while in the dumping technique the mixing tank gets completely emptied and refilled with fresh water enriched with nutrient solution.

Finally, closed-systems refer to absolute mechanical support of the cooling and dehumidification system by air treatment units. The air treatment unit consists of a heat exchanger that is connected to a ventilator. The purpose of the ventilator is to withdraw air from the interior of the greenhouse, cool it, dehumidify it, and then distribute it back into the greenhouse. Furthermore, in closed-systems water usually follows a close loop that allows the collection, recycle and re-distribution of the irrigation water both for irrigation purposes but also for cooling and heating purposes from inside the distribution pipes between the plant lines (Qian, 2017). Concerning the irrigation system in closed-systems of greenhouses, the water does not follow the procedures of bleeding or dumping that are followed in semi-closed systems. On the other hand, the water is constantly recirculated in the mixed tank as it is automatically topped up with the correct and precise amounts of fresh water and each nutrient element. The growers are aware of the status of each nutrient element and are able to adjust it precisely in order not to disrupt the nutrient balance. This process becomes possible because of the high evolvement of automations, sensoring and programming in close greenhouse systems and achieve a 10–50% better water use compared with open greenhouse systems (Nederhoff and Stanghellini, 2010).

2.2.1. Water use in greenhouses

Greenhouses have different techniques for irrigation and water collection and highly depend on if greenhouses use soil based techniques or soilless for crop production. Another factor that highly influences the final water use and water use efficiency is the type of the system, meaning it is an open system, a semi-open system or a closed-system. However, as can be retrieved from Tables 1 and 2 the big difference in water use efficiency can be explained primarily because of the higher production accomplished in greenhouses compared to traditional farming but also because of the lower transpiration in greenhouses. Transpiration is the most important factor that influences the water uptake by 90%, thus the control and reduction of transpiration rate can have a huge impact on the water use. Transpiration is highly affected by the status of humidity and the irradiation levels inside the greenhouse. The higher the humidity inside the greenhouse the lower the transpiration levels are. If growers manage to control these two factors in the optimal levels for each crop, then there is reduced transpiration level per m^2, which means lower water usage and therefore better water efficiency.

The selection of the applied irrigation system, has also a significant influence. Drip irrigation is one of the most popular irrigation techniques in greenhouses. Water is located at the foot of each plant with the use of a pipe. Drip irrigation has the advantage of saving large water amounts

TABLE 2 Summary of annual data for a hydroponic greenhouse plant.

Resources efficiency	Greenhouses (lettuce)	Citation
Water use efficiency	20 L/kg lettuce/year	Barbosa et al. (2015)
Water use	Hydroponics or soil 200 L/ m^2 or 400 L/m^2 respectively	Coyle and Ellison (2017) and Ntinas et al. (2017)
Energy use	60–180 kWh/kg/year	Graamans et al. (2017)
CO_2 emissions	352 kg/ ton of lettuce	Gerecsey (2018)
Light source	Solar radiation and artificial light that operate 2–4 h/day	
Pest control use	Indoor environment Fermont traps	
Yield	41 kg/m^2/year	Coyle and Ellison (2017)
Land use	365 days/year	Coyle and Ellison (2017)
Land use efficiency	9 m^2 for 1 kg lettuce/day	
Harvests per year	6–7 per year	Coyle and Ellison (2017)
Food miles	800–1600 km	

and also can control and maintain the humidity levels of the soil or the hydroponic substrate in constant levels. In that way, water stagnation and puddling of the selected substrate mean can easily be avoided. Finally, drip irrigation allows the targeted and limited fertilization being dissolved, in the watering system.

Other irrigation systems are the micro sprinklers that spray water in a range around two meters according to the pressure of the selected nozzle type. This system is mainly used in soil-based greenhouses with sandy soil texture. Another very commonly used system is the irrigation with diffusers and is mainly used in narrower areas and the pressure of the diffuser depends on the nozzle that regulates the water supply and flow. Finally, other irrigation systems applied in greenhouses are irrigation with hose and underground irrigation mainly found in soil-based greenhouses and present low level of water efficiency.

2.2.1.1. Hydroponic systems

Most of the modern greenhouses apply hydroponic solutions that allow plant to grow without soil. In more detail, the word hydroponic comes from the Greek words “Ύδωρ + Πονέω” translated as “Water + Cultivate,” meaning that plants do not grow in soil but in mineral nutrient solutions in water solvent. Various substrates in the market replace soil such as perlite, rockwool and zeolite. Because of the nature of this technology, plants are permitted to dip directly in their roots into the nutrient-rich solution and subsequently plants can absorb faster the nutrients and in an easier way in comparison with soil-based crops. Because of this process, plants grown in hydroponics form smaller root system and can divert more energy for growing their leaves and stems. Additionally, smaller root allows more plants in the same area to be grown and harvest higher quantities in comparison to the outdoor farming. The above-described capacity of hydroponic systems, boosts the ability of growing food in limited areas as greenhouses can be. Hydroponics consist of a total automated system that pumps water, and pipe-system can be completely auto-controlled. Under various handlings and monitoring of every aspect that can be practiced in hydroponic systems, the growers can result into optimal food production results. More specifically, this process gives the opportunity to farmers to control the whole irrigation process of the crops according to the demand of each species and the seasonality. In addition, they can have access to data that can optimize the development rate and the resource footprint of the plants such as (a) the quantity of water that is distributed in each plant, and (b) the amount of nutrient solution that was given to the plants.

Hydroponics offer a big advantage as they are usually installed in close or semi-close loops that return the excessive water with the enriched nutrient solution back to a collective tank in order to re-distribute it back to the cultivation area. In contrast to the hydroponic solutions, traditional farming experiences huge amounts of resource and water waste as farmlands face the negative effects of soil degradation and the harmful effect of eutrophication (when nutrients from agricultural land create massive increase of phytoplankton populations leading to reduction of oxygen and nutrient reduction of from water and suffocation of multicellular water organisms). Unfortunately, in traditional agriculture, excess supply of phosphates and nitrates in the soil can cause nutrient run/off and leaches. Furthermore, the close or semi-closed loop of hydroponics categorizes them as more efficient in terms of sustainability process for water efficiency in comparison with traditional farming where most of the water is drained to lower levels of soil that plants cannot access.

2.2.2. Indoor air control

Greenhouses consist of air-sealed cultivation rooms where are installed various automations and technologies that can control and provide the optimal environmental conditions for each crop. According to factors such as location, size of installation, height, outdoor climate conditions, greenhouses use different technologies that can properly adjust the indoor environment to the ideal air conditions.

2.2.2.1. Heating

Heating is one of the most important processes for space heating inside the growing room, when the outdoor conditions and too hostile for the plants' growth. For heating purposes, the technologies that are usually used vary according to the demand of each case. In general, heating systems use the interior hot air of the greenhouse to transfer heat through a heat exchanger to the stored water that is used as a thermal storage medium. A very common and cheap technique is using water heating systems that consist from plastic bags and ground tubes filled with water placed inside and between the rows of the plants. During daytime, this system absorbs and traps the solar irradiation and during nighttime, the stored heat is transferred in the interior of the greenhouse by releasing heat (Sethi and Sharma, 2008). There are electric heaters operated via a thermostat or an automatic timer in order to rise the inside temperature to the desired levels. Additional techniques used for heating are rock bed storages, movable insulation and ground air collectors.

2.2.2.2. Cooling

Cooling is a technique of similar importance with heating as it enables to reduce the thermal energy inside a greenhouse and maintain the optimum temperature in each growing stage of the crop. Various techniques are used around the world according to the specific climatic conditions, the size and the demand of each case. Such techniques can be natural or forced ventilation, fogging and misting, roof cooling and fan-pad systems, as well as shading and reflection systems. The most successful systems are the composite systems since they are giving the opportunity for both heating during the winter period and cooling during the summer period. According to Sethi and Sharma (2008), the most promising composite system is the earth-to-air-heat exchanger system (EAHES) that operates with the underground constant temperature of Earth mass and utilize it to transfer or dissipate heat from or to the greenhouse.

2.2.3. Light proofing

According to botanists plants are diversified to “long day” plants and “short day” plants based on the photoperiodism needs—meaning on how many hours of light they have to be exposed during the day in order to grow. Artificial lighting is a technique that provides greenhouses supplementary lighting in case that the solar radiation does not completely meet the photosynthetic demand of each plant species for optimal growth and development. Efficient and proper use of lights in horticulture and with additional boost of reflectors can provide apart from the optimal levels that are required for photosynthesis also can benefit the greenhouses with additional heating (Fig. 2). Heat and energy loss is a common issue in greenhouse and artificial lighting. The latter can become an effective solution that mitigates these losses and add an additional value on the required lighting solutions. The most common types of lamps that are used in greenhouses are high pressure sodium lamps, lighting emitting diodes (LED) lamps and ceramic metal halide lamps.

2.2.4. Energy use

Energy use into a hydroponic production line is mainly meeting the demand of artificial lighting, heating and cooling loads as well as water pumps. The energy that meets the water pumping needs in a hydroponic system for lettuce is estimated by the average pumping time that is

Fig. 2. Indoor farming small scale unit with additional reflectors.

needed to irrigate the plants and the corresponding nominal power of the pump. Based on the calculations of Kublic et al. (2015) it was estimated that the average irrigation duration for lettuce is four and a half hours of total pumping daily.

The energy related to the heating and the cooling loads in a lettuce production greenhouse is estimated by using the following equation

$$Q = U * A * \left(T_{\text{in}} - T_{\text{out}}\right) \tag{1}$$

where

- Q = Heat that is lost or gained due to the outdoor temperature ($\text{kJ} * \text{h}^{-1}$)
- U = Total heat transfer coefficient ($\text{kJ} * \text{h}^{-1} * \text{m}^{-2} * {}^{\circ}\text{C}^{-1}$)
- A = Surface area of greenhouse (m^2)
- T_{in} = Temperature inside the greenhouse
- T_{out} = Temperature outside the greenhouse

The heat transfer coefficient depends on the coverage material of each greenhouse, while the efficiency of cooling and heating systems depends on the height of the greenhouse ceiling. The loss of heat depends on the external climatic conditions and it is a decisive factor of the air technique modification to be used.

Artificial lighting usage depends on the photoperiod necessary for each species and the active hours of sunlight that plants can absorb for photosynthesis purposes. The active time that lamps have to operate is highly relevant with the location of the greenhouse, meaning that greenhouse areas with limited solar irradiation hours (North part of Europe, i.e., Netherlands, Denmark) have higher demand on artificial lighting in comparison with areas under sunshine (southern part of Europe, i.e., Spain, Greece, Italy). Furthermore, the duration of the supplementary lighting depends on the nature of the cultivated plants in photoperiodism (if they belong to “long day” or “short day” plants as we mentioned before) (Avgoustaki et al., 2020). This characteristic can differentiate the need of the plants in total daily radiation and according to the outdoor sunlight, the extra hours that artificial lamps need to operate should be estimated. The ultimate purpose of artificial radiation is to provide to the crop the indispensable Photosynthetic Active Radiation (PAR) in mol/m^2/day for optimal yield production. In order to calculate the energy of a mole of photons that reach the canopy the following equation is used:

$$E = \frac{h * c}{\lambda} + \frac{L}{mol} \tag{2}$$

where

- E = the energy per mol of photons (J/mol)
- h = Planck's constant (6.626×10^{-34} J*s)
- c = Speed of light (2.998×10^{8} m/s)
- λ = Wavelength of light (m)
- L = Avogadro constant ($6.022 * 10^{23}$ mol^{-1})

The result value of the above calculation of the energy demand of artificial lighting in the greenhouse is in [kJ/kg/year].

2.2.5. Carbon footprint

Food production and consumption is constantly rising, having a significant environmental impact making the implementation of more sustainable practices in food production necessary. In order consumers to satisfy their demand for off-season vegetables and fruits, the necessity of heated greenhouses for production is continually increasing. As it is mentioned in the traditional farming section, food transportation causes huge amounts of GHG emissions. However, this number is lower in comparison to the GHG emissions corresponding to heating hydroponic greenhouses in cold climate areas (Ntinas et al., 2020) that try to meet high yields in order to meet customers demand. When heating of greenhouses is achieved with the use of natural gas, the consumed energy can reach the 31.6 MJ with 2.02 kg of CO_2 for the production of 1 kg of tomatoes. Since the majority of greenhouses use fossil fuels to meet their heating demand such as natural gas, diesel, fossil fuel and liquid petroleum gas, it is of vital importance to strongly limit the greenhouses heat losses, upgrade the heating systems and to shift in utilization of renewable energy sources (Xydis et al., 2020). Heat losses can be minimized with the use of double glazing coverage material or with the use of multiple screens. The upper goal of these measures is to increase the environmental sustainability of greenhouse production lines.

2.2.6. Renewable energy

As it has already been mentioned, greenhouses combine different energy technologies, automations and digitalization for plants' monitoring, controlling and harvesting. Greenhouses is a type of farming that can provide the option to connect with renewable energy resources in order to increase the sustainability of such systems and the energy efficiency of the various treatments that are necessary for mass food production (Manos and Xydis, 2019). Different types of renewable energy sources such as solar, wind, geothermal, hydroelectric, biofuels, biomass etc., are found all over the world bringing the possibility to greenhouse plants to produce yields under a more sustainable, economical and cost-efficient way (Xydis, 2015a). Energy policy strategies in a national and a global level, have as a high priority the support of electricity generation and heating from renewable energy and biofuels (Xydis, 2015b). Over the last decades significant improvements in a big variety of significant renewable energy systems, which are ground source-based, solar-based energy systems and wind-based energy systems have been made (Koroneos et al., 2009, 2017). These can be for example electricity-driven heat pumps instead of traditional combustion-based heating systems consumes 25–65% less energy in comparison to a conventional fuel heater (Avgoustaki and Xydis, 2019). Another advantage that heat pumps present 1.3–2.6 times higher energy efficiency compared to fossil fuel heaters as also 56% -79% reduced CO_2 emissions in the cultivation area in comparison with the conventional. There are also examples of greenhouses that use several solar systems that store energy or other photovoltaic systems (PV) that undertake the conversion of solar energy to electricity that meets the heating and cooling needs of greenhouses. Based on research conducted by Ntinas et al. (2017), greenhouses that utilize renewable biofuel (wood pellet) present 3–5 times lower global warming potential in comparison with a greenhouse that use fossil fuels for heating purposes (0.4–0.7 kg of CO_2 per 1 kg of harvested tomatoes), even when the required energy is the same for both cases.

2.2.7. Land use efficiency—Labor

Greenhouses in the Netherlands use complex technology for production of various cultivars that gather multiple operation during the production such are nurseries, growing bedding plants and transplants. These systems are highly automated and occupy land approximately 10 ha or more (Kozai et al., 2016). Even if these machineries occupy a lot of potential cultivated space, they reduce the labor cost and therefore the production cost. Without the use of highly automated technology, the average work force required in greenhouses for cultivating purposes is estimated at approximately 8 workers per a 500 m^2 production area.

According to Penissi et al. (2019) greenhouses produce 112 g of fresh weight of romaine lettuce per m^2 daily while traditional farming produce 10 g of fresh weight of romaine lettuce per m^2 per day. As it can be retrieved from Table 2, the required land use for obtaining 1 kg of fresh romaine lettuce daily is 9m^2 presenting almost 90% of decreased land usage in comparison to traditional farming.

2.2.8. Cost efficiency

In greenhouses there are different variables that based on their priority can offer different benefits to the farmers. These could be the location of the greenhouse, the product type, the access to capital, the required work force and other requirements. High significance in the cost efficiency is also the upfront cost and the ongoing growing cost of the greenhouse that can also lead to higher cost depreciation and development rates of the production unit. Based on a comparative study conducted by Avgoustaki and Xydis (2020), a greenhouse farm consisting of a semi-closed system of 675m^2 of growing space in Denmark, the OPEX and CAPEX related with the farm were analyzed. Their results showed that by assuming that the wholesale price of greenhouse produced greeneries reached at 7.37€/kg, the annual yield production of harvested products reaches at 16,875 kg/year. It is also presented that the capital expenses for the installation of the greenhouses was calculated at 216,123 € including the hydroponic system and grow unit racks, natural gas, heating and ventilation system, light connection (for supplementary radiation), and electricity distribution. Additionally, for the operational expenses the total amount of expenses rises to an annual cost of 152,802 €, including the leasing costs, the electricity demand costs (lighting, ventilation), the natural gas heating cost, the water demand, the labor requirements, the packaging expenses and finally the use of organic material (seeds and nutrients). Different greenhouse scenarios were presented and a cash flow analysis in a 20-year projection, indicated that the cumulative gross profit increased in parallel with the increasing wholesale price of greeneries. More specifically, the payback period was calculated much longer than the operational period of the 20 years resulting in negative prices of the Net Present Value (NPV), unless the wholesale price of greens increases to 10.37 €/kg or more.

2.3. Indoor vertical farms

Indoor vertical farming is an innovative type of closed plant production system that provides the opportunity of a controlled-environment agriculture, which can be controlled according to the crop regardless of the weather conditions. Indoor vertical farms use artificial lighting as radiation source in order to cover the demand of plants for growth and development via photosynthesis. Vertical farms are based in soilless cultivation techniques such as hydroponics, aeroponics or aquaponics.

In addition to the hydroponic systems that recirculate the nutrient solution and benefit greenhouse cultivations, vertical farms use systems that condense and collect the water that is transpired by plants at the cooling panel of the air conditioners and continuously recycle and reuse it for irrigation.

Some principles concerning the structure elements permeate closed-systems of vertical farms. More specifically, vertical farms are thermally well-insulated and nearly airtight structures that are covered with opaque walls. This characteristic makes the farms capable to totally protect the inside crops from the outdoor climatic conditions and make them able to maintain the indoor conditions to the desired levels without having thermal losses. Another characteristic that differentiate vertical farms from greenhouses is the multiple layers of stacked plants in the vertical racks or horizontal columns. This way, the construction provides maximization on the possible yield per unit of land in comparison to both greenhouses and outdoor farming. More specifically, vertical farms, according to the size on the installation, have a multilayer system mostly between 4 and 16 rows or columns with approximately 40 cm of distance between the layers (can slightly vary according to the selected cultivated crop). Inside vertical farms air-conditioners or heat pumps, which principally are used to reduce the heat generated from the lamps and provide cooling and dehumidification for the crop are installed. Furthermore, air-conditioners help to eliminate the water vapor that plants transpire in the cultivation area. Fans are installed in order to circulate the air in the culture room; at first to achieve a constant and stable spatial air distribution and secondly to improve the photosynthesis and transpiration status of the plants. Key factor in the optimal operation of vertical farms is the CO_2 delivery units that stabilize the CO_2 levels in the cultivation area at around 1000 ppm during photoperiod (when lamps are on) in order to increase the level that plants photosynthesize. An important characteristic of vertical farms is the nutrient solution unit that distributes the nutrients to the crops, the electrical conductivity control unit (EC) and the pH controller that monitors the level of the nutrient solution.

Last, it is very important to analyze the radiation systems inside vertical farms as part of the total structure essentials. As mentioned above, vertical farms are equipped with artificial lighting due to absolute lack of solar radiation. Lighting is a key factor in plants development and depending on the selected lighting solution, plants can present differentiations in morphology, flowering and biomass production. Light is electromagnetic energy that includes visible as also invisible wavelengths. Sunlight is a free resource input that provides plants the whole spectrum of several wavelengths, 97% of it is within the range of 280-2800 nm (Kozai et al., 2016). However, according to a number of researchers over the last decades (Hogewoning et al., 2010; Kim et al., 2004; Lin et al., 2013; Liu et al., 2011), it is reported that the most important wavelengths for photosynthesis, morphology of plants and flowering are the wavelengths in the visible (400–700 nm) and the infrared (700–800 nm) spectrum. Lighting emitting diodes (LEDs) offer advantages in comparison with other types of lamps such as fluorescent, incandescent, high-pressure sodium or high-intensity discharge (HID) lamps. These advantages are the robustness, they produce, a stable output that is immediately activated after the electric current flow, have long life (approximately 100,000 h), the opportunity of controlling the light output etc. For this reason, vertical farms focus on applying lighting recipes that combine different nanometers and can promote plants' growth. Apart from the spectrum selection of the lamps crucial factors for plants are the dimensions of light, meaning the intensity of light during photoperiod and the duration that lights operate.

What has literally been neglected is the potential of indoor vertical farms to act as a demand response provider (aggregators). It may sound weird, but indoor vertical farms could under a multi-value business models create the opportunity to the vertical farm owners to focus on their crop production and at the same time absorb inexpensive electricity offered. Usually plants require some hours daylight and fewer darkness. It has been proven that by selecting the hours throughout the day that are not expensive to give the required light, and “give darkness” when electricity price is expensive, has not a significant impact on plants' growth and development. Under a mass deployment scenario of such units in major urban environments (Xydis, 2012), the owners and operators of the indoor vertical farms could create an additional profit under such an approach by entering into contracts with companies in a utility electric region. The opportunity to earn (or at least save) significant amounts will or course be related to the size of the indoor farms and create multiple revenue streams.

2.3.1. Water use efficiency (WUE)

Indoor vertical farms have thermally insulated walls and high level of airtightness that allows a better cooling by air-conditioners during the time that lights operate. This process is functioning even during cold winter nights, as the interior temperature can be increased due to the operating lamps that constantly generate heat in the cultivation rooms. The ultimate goal of air-conditioners is to maintain the indoor temperature at the desired levels. However, during the cooling process, a lot of the water portion is lost due to evaporation of plants or evapotranspiration. Indoor vertical farms have heat pumps with cooling panels, which can condense and collect this water, recycle it and via the close irrigation loop, reuse it for watering the plants. According to Kozai et al. (2016), only a small part of the irrigated mass water is getting lost to the outside because of the high level of airtightness inside the vertical farm. It is also pointed out in this research, that the airtightness level of vertical farms should not exceed the $0.02\ h^{-1}$. This is suggested because this level of airtightness helps to reduce the CO_2 losses to the outside environment and at the same time to maintain the sanitize level inside the farm by preventing pathogens, bacteria, dust or insects to enter the area of cultivation.

Greenhouses compared to indoor vertical farms, do not provide the opportunity of collection, reuse and recycle of the water masses that evapotranspired from plants, because the majority of the water is lost via the ventilation process to the outside area and furthermore most of the water vapor of greenhouses is mainly condensed at the inner walls, making impossible its collection process.

Another remarkable point that influences the resulted transpiration in indoor vertical farms is the operation of the artificial lighting. More specifically, when lamps do not function, the relative humidity of the room can reach up to 100% (little transpiration in the culture room), and cause physiological and morphological disorders to the plants. In order to solve this issue, farmers operate the lamps in rotation after dividing them in groups (two or three) and each group operates for 12–16 h per day. With this action, a constant heat generation during the day from the lamps that aligns with the 24-h function of the heat pumps that dehumidificate and cool the air in the culture room can be achieved.

In order to calculate the water use efficiency in indoor vertical farms the following equation is used:

$$WUE = \frac{Wc + Wp}{Ws}, \tag{3}$$

where

- *Wc* is the water mass (or weight) that is collected in the cooling panel of the air conditioners for recycling purposes ($kg{*}m^{-2}{*}h^{-1}$),
- *Wp* is the alteration in the water mass that is detained by plants and hydroponic substrates ($kg{*}m^{-2}{*}h^{-1}$) and
- *Ws* is the irrigated (or supplied) water mass to the indoor vertical farm.

2.3.2. CO_2 use efficiency (CUE)

In general, CO_2 use efficiency in indoor vertical farms is around 0.87–0.89 (when the level of airtightness is between 0.01 and 0.02 h^{-1}) and the concertation is around 1000 ppm—unlike greenhouses which achieve approximately a 0.5 CUE with closed ventilation system and airtightness level of 0.01 h^{-1} and CO_2 concentration level at 700 ppm (Yoshinaga et al., 2000). Based on these data we can estimate that the CUE of indoor vertical farms is 0.88/0.5 = 1.8 times higher compared to the greenhouses that do not operate the ventilators and provide CO_2 enrichment in the culture room. This phenomenon can be explained because of the amount of CO_2 that is released to the outside area from the culture room and keeps increasing with the level of airtightness but also with the difference between the CO_2 levels inside and outside. The fact that the CO_2 concentration for enrichment in an indoor vertical farm is usually around 1000–2000 ppm in comparison to the greenhouses that have around 700–1000 ppm can be explained based on that.

In order to calculate the CUE the following equation is used:

$$\mathrm{CUE} = \frac{Cp}{Cs + Cr} \tag{4}$$

where

- Cp is the net photosynthetic rate (μmol m^{-2} h^{-1}),
- Cs is the enrichment rate of CO_2 (μmol m^{-2} h^{-1}) and
- Cr is the rate of respiration of the workers (if there are) in the culture room (μmol m^{-2} h^{-1})

2.3.3. Light energy use efficiency (LUE)

The light energy of the lamps that is send in the canopy aims to provide the necessary energy that plants need to grow and photosynthesize. However, the salable part of plants can only fix maximum 1–2% of the electrical energy as chemical energy. The remaining 98–99% of the electrical energy that is not absorbed by plants is converted to heat energy into the culture room and the remaining is removed by air-conditioners to the outside area (Avgoustaki et al., 2019). The above-described effect can also explain the negligible heating costs in well thermally insulated indoor vertical farms even in the winter cold nights.

Nevertheless, indoor vertical farms are based in automations and precision agriculture and all the input resources are measured and validated in order to provide the optimal results in the cultivated crop. For this reason, all farms focus on measurements and optimization of the light energy use efficiency both of the lamps and the plant community. What is important for these measurements in the definition and estimation of the PAR, which in other words, is the wavelengths of light that are in the visible spectrum of the 400–700 nm and are the ones that drive photosynthesis. PAR is not a measurement of light; rather it defines the type of light that is necessary for plants to photosynthesize. Apart from the type of light, farmers need to know and further metrics of light such as the amount and the spectral quality of PAR.

In order to estimate the light energy use efficiency of lamps (LUE_L) we use the following equation:

$$LUEL = \frac{fD}{PAR_L}, \tag{5}$$

where

- f is the convention factor from dry mass to chemical energy that is fixed in dry mass (around 20 MJ kg^{-1})
- D is the increase rate of dry mass of the whole unit of plants or only the salable part of plants in the indoor vertical farm (kg m^{-2} h^{-1}) and
- PAR_L is the photosynthetic active radiation emitted by the lamps (MJ m^{-2} h^{-1})

Respectively, in order to estimate the light energy use efficiency of the plant community (LUE_P) is provided by the following equation:

$$LUEp = \frac{fD}{PARp}, \tag{6}$$

where:

- PAR_P is the photosynthetic active radiation that is received at the surface area of the cultivation.

Based on the calculations and experiments conducted by Yokoi et al., 2003, it is shown that indoor vertical farms have 1.9 to 2.5 times higher LUE_P in comparison to the greenhouses. Only 1% of the light energy is actually converted into salable portion of plants. Nevertheless, there are different techniques which can be applied and can improve the conversion factor to 3% or a little higher. A simple technique that can be followed is the application of interplant lighting, upward lighting, and use of reflectors (Fig. 3). Traditional lighting that is located only on top of the crop can cause undesirable shading in dense crops by uneven light distribution and lead to senescence of the leaves that are in lower levels. On the contrary, the application of interplant lighting can provide access of light also in the lower levels of the plants, improve the distribution of light and therefore improve the photosynthetic rate of the crop. According to Dueck et al. (2006), the photosynthetic rate of leaves in low levels is usually negative or nearly zero, but the application of interplant light

Fig. 3. Upward lighting, and use of reflectors in a small-scale experimental unit.

can increase it in positive values. Well-designed reflectors can significantly enhance the LUE_L as they can reduce the vertical distance between the canopy and the lamps and increase the distance between the plants or the density, since plants constantly grow. Same positive results by interplant lighting have been reported also in greenhouse canopies. The most suitable lamp selection for interplant lighting technique is LEDs as they have small volume and they perform lower surface temperatures in comparison to fluorescent and other types of light sources. LEDs have been proven beneficial for reducing the EUE_L also due to the higher conversion coefficient from electrical energy (0.4) compared to the fluorescent lamps (0.25). Although the capital cost of LEDs is generally higher than the cost of fluorescent lamps, LEDs have longer operational life and the prices have considerably decreased over the last couple of decades and is expected to continue decreasing.

Apart from the lighting adjustments, other modifications can improve the LUE_L such as the control of the environmental conditions. The environment of plants and the ecophysiological status of plants can be enhanced by the optimal selection of air temperature, CO_2 concentration, water vapor pressure deficit (VPD), air current speed as well as the combination of pH, electric conductivity (EC) of nutrient solution. These parameters have to be set according to the selected cultivated species.

Another way to improve the LUE_L as well as the EUE_L of the salable part of plants, is to reduce the dry mass of the nonsalable parts of the plants. In indoor vertical farms, the most frequently selected crops for cultivation are leafy vegetables such as lettuce, small fruits and herbs and it is important to limit the percentage of the root mass into less than 10%

of the total mass of the plant (Kozai et al., 2016). Due to of the cultivation technologies used in indoor vertical farms this is an achievable measure only by minimizing the water stress of plants by controlling the water vapor pressure deficit of the room. If the selected crop is root species, then we can significantly increase the salable portion by harvesting earlier than usual in order to have an edible aerial part. Finally, other factors that can also help in increasing the relative annual production capacity (per unit land area) of indoor vertical farms are:

- Limitation of the culture period between transplanting and harvesting by optimal monitoring and controlling of the environmental conditions
- Increase of the ratio of cultivation area under each farming type (field, tier, floor, culture bed)
- Increase of the salable part of plants as also the percentage of salable plants.

According to Kozai et al. (2016), it is stated that by applying the above-described techniques, the relative production capacity per land area unit in an indoor vertical farm of 10 layers can rise up to 200–250 times higher compared to outdoor farming, considering that indoor vertical farms already produce 100–150 times more yield than traditional farming (Table 3). In practice, those techniques could double the efficiency of the whole system.

2.3.4. Fertilizer use efficiency (FUE)

Indoor vertical farms use culture beds that are isolated from soil usage and the nutrient solution that enriches the irrigation water is distributed through pumping to the plants. Because of the high-automated process of irrigation, the nutrient solution is drained from the culture beds that plants are growing and it follows a close loop by returning to the central nutrient solution tank for recycle and reuse. In order this process to be achieved, nutrient solution is rarely removed to the outside area. This process usually takes place once or twice per year when the level of certain ions such as Na^+ and Cl^- are not well absorbed by plants and the percentage in the culture beds exceeds the normal levels, requiring discharge. In order this measure to be implemented, the supply of fertilization closes for some days and plants already planted can absorb the nutrient elements existing in the culture beds (Kozai et al., 2016). On the contrary, the fertilizer use efficiency of greenhouses and of fields in tradi-

TABLE 3 Summary of annual data for an indoor vertical farm.

Resources efficiency	Indoor vertical farms (10 layers—lettuce)	Citation
Water use efficiency	1 L/ kg lettuce/ year	Barbosa et al. (2015)
Water use	Usually hydroponics or aeroponics Approx. 11 L/head	Coyle and Ellison (2017)
Energy use	250 kWh/kg/year	Graamans et al. (2017)
CO_2 emissions	158 kg/ton of lettuce	Gerecsey (2018)
Light source	Artificial light that operate 10–24 h/day	
Pest control use	Indoor cultivation Sterilize environment	
Yield	80–120 kg/m^2/year	Coyle and Ellison (2017)
Land use	365 days/year	Coyle and Ellison (2017)
Land use efficiency	0.3 m^2 for 1 kg lettuce /day	
Harvests per year	8–12 per year	Coyle and Ellison (2017)
Food miles	43 km	

tional farming is relatively low and occasionally can cause on the soil, surface salt accumulation.

In order to calculate the Fertilizer Use Efficiency (FUE) the following equation is followed:

$$FUE = \frac{Iu}{Is}, \tag{7}$$

where:

- I_U is the absorption rate of plants of ion element I that are in the organic fertilizer and
- I_S is the supply rate of ion element I into the indoor vertical farm.

It is worth to be mentioned that the ion element includes the basic elements of fertilization solutions such as nitrogen (NO_3^- and NO_4^+), phosphorus (PO_4^-) and potassium (K^+).

2.3.5. Electrical energy use efficiency (EUE)

Artificial lighting apart from a key element in the growth of plants indoor, it does increase the energy consumption of vertical farms. Shamshiri et al. (2018), noted that three major operational expenses in a vertical farm are the electricity cost with 25–30% of the total cost, the operational costs (OPEX) with 27% of the total cost and the capital expenditures (CAPEX) with 18–20% of the total cost. Indeed, energy consumption is a significant cost of indoor vertical farms and can be used as an measure for their sustainability levels. Many research groups and institutes focus on developing innovative technologies and optimizing the lighting recipes in order to reduce the energy footprint of vertical farms and create a more sustainable and cost efficient type of farming. Even if the demand for purchased energy is much higher in indoor vertical farms than in greenhouses, the energy efficiency of the former is significantly higher (Graamans et al., 2017). Indoor vertical farms, since are in absolute controlled systems face high efficiency when operating with renewable energy (Xydis et al., 2020). There are multiple examples of vertical farms that are operating under smart grid systems that generate energy for the demands of the farm via wind turbines or solar panels or even geothermal energy. Additional roles in the vertical farm systems towards increasing their efficiency have the connectivity with resourceful batteries that provide the opportunity for smart use of cheap stored electricity from the hours that the electricity prices are lower. An approach gaining constantly more and more attention also under the dynamic pricing concept, where also accurate forecasting plays a crucial role (Karabiber and Xydis, 2019).

In order to calculate the energy use efficiency for the lamps (EUE_L) is followed the below equation

$$EUEL = \frac{f * h * D}{PARL}, \tag{8}$$

where:

- h is the conversion coefficient of electrical energy to energy of photosynthetic active radiation that is emitted by lamps. For the latest technology of LEDs this number reaches the 0.3–0.4 (Kozai et al., 2016).

Apart from the energy that is consumed in order to meet the lighting demands, the energy demand of the heat pumps for the cooling (or heating) processes in the indoor vertical farms should be added to the equation. This type of efficiency is often referred in literature as coefficient of performance of heat pumps for cooling purposes. The coefficient of performance of the heat pumps, in a specific room, increases when the outside temperature decreases. The electrical energy use efficiency for cooling by heat pumps (EUE_C) is calculated by the following type:

$$EUEc = \frac{H}{A}, \tag{9}$$

where:

- H is the heat energy that the heat pumps remove from the cultivation area ($MJ*m^{-2}*h^{-1}$) and
- A is the consumption of electrical energy by the heat pumps (air conditioners) ($MJ*m^{-2}*h^{-1}$).

It is worth to mention that the total energy consumption of indoor vertical farms is defined by the sum of the energy consumption of the lamps, the heat pumps/air-conditioners and the electricity demand of other equipment used for the optimal function of the farms such as nutrient solution pumps and air circulation fans. If we focus only in the electricity cost demand of indoor vertical farms, lighting accounts to approx. 80% of the annual electricity energy use (assuming fluorescent lamps of 40 W), while the electricity cost demand for air conditioning is around 16% and 4% the electricity demand of the auxiliary electrical equipment (Kozai et al., 2016).

Table 3 presents the estimated representative values of resource use efficiencies in an indoor vertical farm that use artificial lighting. It could be concluded (from Table 3) in comparison to Table 1, that the relative production capacity per land area unit in an indoor vertical farm of 10 layers is 76 to 116 times higher compared to traditional farming and 40 to 80 times higher compared to greenhouse production.

2.3.6. Land use efficiency (LUR)—Waste management

Indoor vertical farming is a type of farming which by definition is developed to provide enough production in order to meet the local demand in urban areas with continuous increased demand for fresh and nutritious fruits, vegetables and herbs. In general, the most frequently cultivated species are plants that have higher profitability and have a relatively high price. A significant factor on crop selection is the crop to have a short production cycle in order to reduce the required electricity costs for lighting, heating and cooling of the crop and therefore can be harvested as early as possible. Additionally, growers prefer plants that have high harvested yield, meaning a high portion of the crop that can be harvested and sold. For example in crops like lettuce and herbs, growers can harvest and sell the whole unit of the plant, while in tomatoes or peppers they can sell only the harvested fruit but at the same time. Therefore the electricity used for the rest of the plant, could be considered as a product waste. Another key issue in crop selection is the height of the plants, meaning that it is way more preferable the crop to have a compact status in order to be able to reduce the growing distance between multiple plants and grow more at the same available area. Plants are also selected according to the perishability level that they present after harvesting and reaching the market. Since indoor vertical farms are mainly located in urban or suburban areas, their goal is to produce crops that can increase their self-life (even of perishable crops), by shortening the harvesting and delivery time to the market. Another parameter taken into account when selecting crops is the situation in the local market. If, for instance, tomatoes are missing for some reason from the market, then depending on the price they can get, they could be preferred against of another fruit or herb that is in abundance and its price cannot climb up. Finally, most suitable crops are those that have year-round productivity in order to be affordable for the farmers to have a year-round market demand that can be profitable despite the continuous operational expenses. The constant production in a yearly basis of the same crop selection, allows also maintenance of the same, specific engineering settings of the crop, avoiding the modifications in the automations' selection that could cause abnormalities from a horticultural perspective.

Due to the concept of indoor vertical farming and the technology used in the cultivation areas, growing in an urban environment do not advantage the crops due to possible shading of the building, non-fertile soils or dormant soils. This fact can also be considered as one of the major drawbacks as the land price in urban areas is relatively high. Concerning this approach, indoor vertical farms are often installed in large warehouses, industrial factories or even abandoned buildings, where the prices are low. According to Kozai et al. (2016), it is stated that indoor vertical farms can produce the same yield of lettuce heads and other leafy greens in only 1% of the land required by traditional farming and 10% compared to a greenhouse construction. Based on Tables 1–3, it can be retrieved that the land use efficiency of indoor vertical farms (0.3 m^2) required for obtaining 1 kg of fresh romaine lettuce per day is almost 97% reduced compared to greenhouses and 100% compared to traditional farming. An indoor vertical farm of 10 layers can produce 3110 g of fresh weight of romaine lettuce per m^2 per day (112 g FW/m^2/d for greenhouses and 10 g FW/m^2/day for traditional farming). Adenaeuer (2014) mentions that the increase in yield between indoor vertical farms and traditional farming can be increased by 1.5 due to the technology and by 709 due to the technology combined with the stacking ability of the plants. Depending on the stacking area and the volume of harvest, cultivation care and crop preparation techniques, the work force can highly vary. Avgoustaki and Xydis (2020), propose that 0.18 workers are necessary per 10,000 kg of yield, resulting in 35% of the annual operational expenses of the farm (depending on the labor cost in each country). The same work force is required for a greenhouse production and approximately half of it for an open field farm. More analytically, according to Savvas et al. (2015), in soil-based crops the labor numbers 34,000 €/ha while a hydroponic greenhouse or indoor vertical farm requires around 64,000 €/ha as production cost. This demand is met by both permanent and by seasonal workers that will be hired for specific labor-intensive operations of the farm (like pruning and harvesting) throughout the year.

Indoor vertical farms have the advantage that allows them to generate bio-waste as bio-product during the process of edible biomass production. According to the cultivation system that plants grow in (hydroponic, aeroponic or aquaponic), the opportunity to farmers to collect easily all the by-products after the harvest period such as leaves, roots with fibers, stems, or even damaged vegetable and fruits and use it as well waste is offered. Based on Adenaeuer (2014), the bio-waste that is collected and used in indoor vertical farms can be 2443 metric tons per year and with daily plant wastes that are collected for the indoor farms of roughly 8.11 tons. Since indoor vertical farms use advanced close loop systems, present also the possibility to convert the daily amounts of biowaste and after careful processing to useful resources material for the crop as liquid fertilizer or biofuel (Nikas et al., 2018). The are several cases of installation of indoor vertical farms that have designed specific lines of biowaste management in their production line that only serve this specific purpose.

It should be stressed that indoor vertical farms have the option to implement high tech equipment for conversion of food waste into energy production via anaerobic digestion. More specifically, this technology is a biogas recovery system that captures methane from food waste and convert it to heat, steam and electricity to meet the energy demands of the farm. This process requires a close-loop system, which creates biogas from organic material by piping it into the turbine generator. The electricity that is finally produced meets the high-energy demand of indoor vertical farms such as the operation of the lamps. Anaerobic digestions is also compatible with aquaponic systems by receiving the organic waste of both fish and plants to produce electricity (AgSTAR, 2020).

2.3.7. Cost efficiency

One of the key factors that influences the selection of the farm system is the selling price of the products. According to Tasgal (2019), traditional farming products are 3 to 5 times cheaper in comparison to greenhouse an indoor vertical farming products. More specifically, traditional farming lettuce price usually costs less than 1€/head, while greenhouses lettuce and indoor vertical farm lettuce cost 2–3€/head. Additionally, based on the same study, the significant upfront capital requirements of indoor vertical farms can highly limit the pool of market participants. This happens because both the land prices, rents and acquisition of high-technology equipment are significantly higher in comparison with the leasing cost of farmland.

On the other hand, Avgoustaki and Xydis (2020), by conducting a comparative analysis between indoor urban farms and greenhouses presented slightly different results. In more detail, they assumed an indoor vertical farm with the same growing space and wholesale price of the greeneries as in the greenhouse facility, of 675 m^2 and 7.37 €/kg respectively. An interesting point is the massively increased production yield that can be achieved in an indoor vertical farm compared to greenhouses, reaching at 33,750 kg of fresh greeneries being annually harvested. The operational expenses of indoor vertical farms according to the examined case reached at 150,800 €/year resulting in almost similar numbers with the greenhouse facility. However, the biggest cost of indoor vertical farms noticed were the capital expenditures reaching at 321,763 € per grow unit, with the most costly equipment the lamps and integral connection of lamps, installation of growing unit racks and the electric distribution of electricity. Subsequently, based on their model and the different cash flow analysis, indoor vertical farms present profitable investment opportunities with a high Internal Rate of Return (IRR) and a payback period between 3 and 6 years with a wholesale price equal or more than 6.36 €/kg.

Another research conducted by Liaros et al. (2016), a case scenario of a small IUVF of 100m^2 growing area inside an apartment was presented, showing profitability to smallholders under various scenarios. Worth to mention at this point, micro indoor farming in small growing spaces such as containers, garages or even simple rooms can be profitable depending on the demand and the flexibility to rearrange different cultivation parameters aiming for the optimum result. Similar findings were also supported by Ucal and Xydis (2020). On the other hand, based on a report conducted by Agrilyst (2017) indoor micro-farms can be very costly, nevertheless, there are multiple marketing strategies for optimizing the results.

3. COMPARISON IN FOOD SAFETY ISSUES BETWEEN DIFFERENT FARMING TYPES

According to the United Nations (UN) projections, the global population will exceed 9.8 billion until 2050, all requiring to meet their food demand. Additionally, UN estimate that 80% of the global population will be located in urban areas by that time. In order all this increased food demand to be met, it is necessary to produce 70% more nutritious and fresh food. However, at the same time, land experts such as agronomists and ecologists, already warn of the growing shortages in agricultural land, necessary for sufficient food production (Al-Kodmary, 2018). When it comes to high quality food, the fact that already food prices are climbing high also due to limited agricultural resource inputs such as water and energy is a matter of great concern. Over the last decade, the increase demand for more farmland in order to meet global food demand it becomes more and more obvious. As an immediate effect a lot forest areas are substituted by new farmlands in order to supply this demand. At the same time, since cities constantly grow in terms of area they occupy, a lot of farmland is lost due to this expansive urban development. It is important to convert the global production line to a greener form for both human beings but also for the planet. This implies that food production will not sacrifice the attention for the human health against the commercial profit. According to World Health Organization, more than half of the farms globally, still use for fertilization purposes of their crops raw animal waste that can attract insect as flies or contain weed seeds or even diseases which can contaminate the cultivated crops. Subsequently, these techniques can highly affect people's health and can cause diseases.

Nowadays, the majority of the food is produced in large, industrialized farms and is transported, distributed and sold in supermarkets, grocery stores or multinational food outlets. Agronomists, engineers and farmers in order to reduce the production cost and resource footprint of food production and at the same time increase the variety of the available food species for the consumers have developed various techniques. The high centralization level of food supply can allow the possibility of infection from foodborne pathogens and toxins that can poison large numbers of consumers. Food usually travels thousands of miles every day leaving huge possibilities for contamination threats as it can be infected in one country and develop pollutant populations in another. Because of the high logistic complexity of food supply, it is worth to mention the advantages and drawbacks of each farming type during the whole supply chain. What follows is an exploration of the three subjected farming types, including outdoor farming, greenhouses and indoor vertical farming. We will compare and evaluate products and growing process under the scope of food safety practices.

3.1. Traditional farming

3.1.1. Food safety status of traditional farms

Outdoor farming is applied for thousands of years, allowing an unprecedented human development. However, over the past years the continuously increasing demand of the population has led farmers to apply chemical inputs for nourishing of plants, fighting pests, insects and improving soil quality. However, because of its nature, crops growing in the open field are facing all the difficulties from severe weather conditions and the danger of infection from various insects and pathogens. Traditional farming is a type of agriculture that allows to multiple plant pathogens, bacteria and insect pests to affect crops, causing scalable losses in global crop production. After heavily tilled farming applications, severe irrigations and monocropped selections, soil has been seriously affected causing depletion of its nutrients, highly requiring additional nutrient solutions that can improve its fertile condition, making it appropriate for cultivation.

Once crops are harvested, a big after-harvest process and logistic supply has to be followed in order food to be transported from the farmer to customers' table. When we are talking about vegetables and greeneries there is a high level of perishability that needs to be confronted. Crops have to keep cool in order to maintain the high fresh and nutritious status. In order farmers to retain a high value for their products, after harvesting, food is transported from the field to processing facilities that are responsible for the cutting, washing of plants in cold water applying centrifugation methods in order to remove the excess water from the products. After removing the roots and fulfilling the described procedure, products begin to decompose. An often procedure that farmers follow is to treat their production with chlorine compounds and/or antioxidants that expand preservation during and after washing. Continuously, food is usually packaged and stored in refrigerators and very low temperatures in order to remain in inertia status. However, outdoor farmers are not able to perform refrigeration between harvest and transport of the products for water processing, making it more uncertain in pathogens infection. In order groceries to arrive from the processing facilities to the shelves of the markets, they require on average 2000 to 3500 km, resulting to 4–6 days in transportation. According to Kublic et al. (2015), every three days, products lose 30% of their nutritious value after being harvested and roots' removal, meaning that consumers finally receive severely influenced vegetables in terms of nutritional value.

According to the Centers for Disease Control and Prevention, each year, “roughly 48 million people (1 in 6)” are food poisoned in the United States. In terms of food safety what products of outdoor farming face is the severe contamination from improper use of manure, either from human fecal that is used as fertilization mainly in developing countries or from contaminated Concentrated Animal Feeding Operations (CAFOs). Even if it has been proven by various researchers as a great nutritious source for the crops after proper compostable process, on the other hand the absence of carefulness, targeted application and lack of sanitation can lead to transmission of various types of parasites. A serious parasite that is worth to be mentioned is Geo-helminths (hookworm, *Ascaris* and whipworm), that can survive their eggs in soil for years when they find the right climate conditions, causing diarrheal diseases as well as permanent learning deficit to children (Hotez and Pecoul, 2010). E.coli was a foodborne illness that took high publicity after infecting approximately 265,000 people and causing about 100 deaths, after severe pollution of agricultural water reservoirs in farms of California. To summarize, even if there are multiple technological automations, innovations and outbreaks in outdoor farming over the last decades, the nature of this agricultural type is very open to foodborne illnesses, illnesses extremely difficult to be traced rising the total risks.

3.1.2. Solutions for safety status improvement for outdoor farming

Because of the importance of food safety and in order to avoid further foodborne illnesses, there are several rules that force outdoor farmers to enhance the safety status of their production for the overall benefit of the population. The strictest and most widely recognized organization of food control audits is the Global Food Safety Initiatives (GFSI), which was established in 2000 to reduce and control the risks associated with food production as also to streamline and improve the overall food safety while reducing the operating costs. Various certifications are provided to farmers including the Safe Quality Food (SQF) and Hazard Analysis Critical Control Points (HACCP) that set the necessary rules and prerequisites of a high-level food safety status. This includes some of the following rules:

- It is of significant importance the control and validation of the agricultural water. To be more specific, there are rules that prerequisite the testing of the water quality that is applied via irrigation to the crops, but also the water related to the tangential purposes such as hand-washing of the workers during or after harvest, the ice that refrigerates food and the surfaces that food contacts with.
- Biological adjustments are often applied in soil for or particular nutritional uses that replace chemical fertilization. It is of vital importance that farmers who follow these techniques to follow specific guidelines for the use of raw manure (such as animal and human feces) as also for the use of stabilization compost in order to maintain a high level of sanitation.
- There are rules concerning the compliance of domestic and wild animals either they are working in the farm, invade in the farm or graze.
- Finally, there are high requirements in workers' health and hygiene that need to be followed in order to prevent the contamination that may source by humans.

3.2. Greenhouses

3.2.1. Food safety status of greenhouses

As has already analyzed, there are greenhouses that are soil-based and the more advanced use hydroponic solutions. In hydroponic greenhouses, plants are transported several times according to the growing stage and are monitored throughout the different growing cycles. That give the opportunity to apply the exact resource requirements in every stage, in comparison with soil-based greenhouses and outdoor farms, where the plants remain in the same position until their harvest.

Another significant advantage of greenhouses in relation with outdoor farming is the high geographical flexibility of installation as it allows a significant reduction of the transit time of the products from the harvesting and processing point to the final consumers.

Greenhouse plants in an industry that constantly growing, with today's list accounting half of the tomato production and 1/3 of the global pepper production that are distributed in the fresh market (Brauther, 2010). Greenhouses are a significant driver of national economies of the agricultural sector because of the high profit margin as also the opportunities for high added-value products. Unlike traditional farming products, greenhouse production is highly protected from dangerous elements and various contaminants.

However, the technologies that are applied for monitoring and controlling of the environmental conditions do not guarantee crops free of microbes and pathogens. The management practices applied in greenhouses are these that can conduct to growth, survival and spread of foodborne pathogens. A severe contamination thread could be spread by processing equipment since crates and baskets that are used for transportation of products, from propagation tools or even for surfaces that food contacts with.

Irrigation water is one of the most important food safety risks even in greenhouses as it can be drawn from a wide variety of uncertain sources such as municipality supply, rainwater, underground aquifer, reservoirs or surface water. Greenhouses that use untreated surface water as irrigation source face high contamination risks. For example, in 2013, *Salmonela Saintpaul* (CDC, 2013) found to have infected cucumber greenhouses in US that caused the infection of 84 individuals across the country as they consumed imported vegetables with questionable irrigation water status.

3.2.2. Solutions for safety status improvement for greenhouses

Because of the high risk of infection of consumers, even from more controlled agricultural systems (compared to outdoor farming), regulations for food safety have become stricter by establishing new standards for food production (Produce Rules). The four areas that these standards focus on are the followings:

- Health and hygiene

This practice targets in maintaining hygienic conditions of the personnel that is occupied in the greenhouse factories, involving criteria for personnel cleanliness, handwashing and use of appropriate gloves. Even if handwashing is considered one of the simplest and cost-efficient practices, it has been reported that only 22% of greenhouses practice handwashing before the harvesting process.

- Irrigation water quality and management

Since water quality is one of the most crucial and contentious factors, it seems absolutely necessary the mandatory establishment of rules that control the water baseline quality profile. Greenhouses withdraw water from a bog variety of sources such as municipality supply, wells, reservoirs and surface ponds. By checking and understanding the quality of the quality of various water sources can provide important information and reduce the risk of contamination. By regulation, greenhouses have to determine frequently microbiological testing on the water sources. Furthermore, greenhouses that apply hydroponic solutions in semi-close or closed loops that circulate, recycle and reuse water, have to include filtering treatments that remove possible pathogens before re-applying it. Methods that are effective and efficient in water recycling is UV light or disinfectants.

- Animals and waste

Significant measure for the protection of crops from foodborne pathogens is also to eliminate the restriction of domestic and wild animals at growing activities inside the greenhouses as well as in the outside area of the buildings. Practices that contribute in discouraging animal intrusions can be for example the rapid weeding that will minimize rodents attraction and protection.

- Sanitation of equipment, tools and greenhouse surfaces

Foodborne pathogens are usually found all over the greenhouse environment such as harvesting bins and boxes and tarp floor covers of the greenhouse (Ilic et al., 2014). According to Produce Rule, all the tools and equipment that used in the production line should be inspected, cleaned, sanitized and maintain in this condition throughout the whole production, harvesting and post-harvesting process, in order to prevent contamination.

Greenhouses in comparison with traditional farming have the advantage of the three-key elements application that can eliminate contamination risk: innovations, automations and control. In specific, innovations provide to greenhouse farms a more secure food safety support such as water filtration systems, integrated pest management and higher quality control systems. Automations can reduce the danger of contamination or cross contamination as they minimize or decrease the introduction of foreign specimens. Finally, biometric systems provide to growers the ability to detect tracking information concerning the plants. After harvesting, the produce is set up in a traceability system from the greenhouse plant to the customer delivery service.

3.3. Indoor vertical farms

3.3.1. Food safety status of indoor vertical farms

Leafy greens, vegetables and herbs are considered of high-risk crops since they are usually not cooked but eaten raw. The usual process of consumers is to rinse their purchased greeneries after purchasing them from their grocery store and then consume them. This is not a particularly effective and protective procedure, since harmful pathogens need interference of chemicals to be detached from plants. Outdoor farming and most of the greenhouses perform triple-wash on the harvested plants in order to mitigate the contamination risk, as a post-harvest process. This process consists of the pre-washing, a saline wash and the final bathing of greeneries in sanitizing, choline base solutions. Unfortunately, this method cause quality reduction to greeneries, as is observed loss of flavor and texture along with the concurrent risk of contamination existing and spreading under the possibility of incorrect application.

Greens that grow outdoors follow the triple-wash procedure as a post-harvest measure for increasing their health status. Harvested crops are transported in the processing facility and sorted, rinsed, put in spinners, apply a second rinse, spinner again, third rinse, sorted (again), packed, and then at the end they get delivered at the grocery market. Crops that follow the above washing method bear usually on the packaging labels such as “triple-washed” or “pre-washed”. Even if this method can provide sufficient results in harvested outdoor crops, if the water used for the triple-washing process is polluted with pathogens, then this can spread rapidly to the rest of the harvested crop. For this reason, triple washing cannot categorized as the most effective and guaranteed process.

Indoor vertical farms apply only nutrient elements in the irrigation system and completely avoid the use any chemicals during the growing period of plants, excluding all the types of pesticides, herbicides and chemical spaying for fertilization. The philosophy of indoor farming depends on monitoring and constant controlling of the crops as also of all the resources that come in and out from the farm and they are isolated from Mother Nature where many threats and contamination sources may appear. For this reason, indoor farmers suggest that their products do not need to be washed before consumption, as they are already clean by a protected and purified growing process and a quick delivery to local grocery stores.

Hermetically sealed environments, inside highly controlled spaces that are designed to offer the highest possible level of food safety particularly for the growing period, surround the cultivation rooms of indoor vertical farms. Since there are no seasons to be followed as in outdoor farming neither humidity, temperature fluctuations nor long gaps on post-harvesting processes and packaging, indoor farmers can dramatically reduce a potential contamination with precise systems. In addition, the hermetically sealed environment protects crops from being exposed to outside elements such as harmful pests, insects, fungi and bacteria.

In one of other type of such systems, aquaponics, co-cultivation of fish with plants is done. This method of cultivation uses very innovative water filtration systems, which extract solids from the fish tanks. Continuously, solid break down to beneficial bacteria that transforms them into nitrates. Then, the nitrate-rich water circulates to the plant culture area where plants absorb the nutrients and purify the water. Since the aquaponic system follows a close-loop, the clean water is circulated and reused into the fish tank.

Plants that grow in soilless systems can travel along their production process giving the opportunity to be inspected for health status. For example, after sowings, seeds are moved to germination rooms with high humidity that boosts their sprouting. Then, seedling is moved to propagation room with controlled climatic conditions that promote their development. Next, young plants usually located in the main part of the cultivated room in floating rafts, receiving a nutrient-rich water. After finishing their development and reaching their mature stage, they are daily harvested and shipped. Between every translocation of plants, there is intensive quality check to prevent crops' contamination.

High precision irrigation systems are used in order to monitor the water that travels throughout the crops. Innovative hydroponic or aeroponic methods usually draw water from filtered and drinkable sources and distribute it at each crop often without even touching the salable part of the plants. This is achieved either by the use of water in liquid form, mist or fog that sprays it only into the root section of the plants and not in the parts consumed.

Extensive sterilization and supplier are also applied methodologies of indoor vertical farms that control and assure the input resources of the farms such as seeds, nutrients that need to be absolutely safe and clean. Because of control and monitor mechanisms that are carried out indoor, there is clear advantage of indoor farms. They are aware of the cleaning status of plants and maintain it with further regulations during the cultivation period and finally harvest and deliver a healthy and fresh product.

Even if indoor vertical farms produce food safer to consume than the open field grown products, bottlenecks and hazards can still be introduced during the growing process of crops. Such threats can be dirt and bacteria transferred from the workers and dangerous threats in the nutrient medium that include chemical sources, cleanliness and water safety. Further risks can also detected at the post-harvest activities such as trimming, sorting and delivery of the products. Thus, it is of vital importance even for indoor farmers to perform high status and certified systems for detection, monitoring, testing and evaluation as in outdoor farming and greenhouses.

A study conducted by Purdue University (Wang et al., 2019), found that there is also high risk of crops contamination due to pathogen pollution in vegetables grown in hydroponic or aquaponic systems. More specifically, they reported that E.coli O157:H7 was found in fish feces and because of the circulation that close loops systems, it caused water contamination of the plant root surfaces that were in the aquaponic and the hydroponic systems. Since fish probably were contaminated by the bacteria, it is important to follow a proper and certified handling, cleaning and sanitizing process in order to reduce the contamination risk in hydroponic and aquaponics.

3.3.2. Solutions for safety status improvement for indoor vertical farms

It is a very difficult, time consuming and α costly process to control all the plants even in an indoor vertical farm for having a 100% safe food product. Indoor vertical farms use controlled environment of humidity and temperature in order to provide plants the most suitable conditions. However, in the case that unpredictable production errors occur, e.g., technical malfunctions with the engineering equipment, temperature and humidity can get out bounds to unwanted levels and create fertile environment for bacteria growth. This incident could be possibly avoided in the case of traditional farming, as the constant natural air circulation and the sunlight could smooth out some of these errors. Bacteria population are not biased, meaning they do not grow or prefer targeted geographic locations, but they are transported to different locations by human activities as they can be brought by clothes, shoes or skin. Furthermore, it should be noted that even if indoor farms consist a safer environment compared to other farming types, if a controlled environment develops for some reason bacterial infection, it will be extremely difficult to eliminate the contamination and protect the rest of the growing crop. For this reason, indoor farms follow high sanity level protocols to avoid the possibility of crops' contamination by human contact that involves all the workers involved with various cultivation processes of the plants. That include strict control by imposing the use of facemasks, hair and beard net, footbaths and clean or single-use suits, which can diminish the risk of contamination.

Another solution for further risk elimination from potential contamination, is the application of innovative technologies that operate extensive integrated pest monitoring. This can be achieved with the use of ultraviolet light outside of the farms that detect possible threats as also air curtains that are installed in every door and can control air that enters the cultivation room protecting it from the danger of contamination. Additional solution that can increase the sanitation levels of indoor crops, is the application of certified HVAC filters, in order to perform an extensive pest monitoring.

4. CUSTOMER OPINION ON INDOOR VERTICAL FARMS

Indoor vertical farms belong to a novel type of farming cooperating with innovative technologies in order to provide the safest, higher quality and most fresh and nutritious groceries. Both advocates and critics of this technology seem to recognize that indoor vertical farms under suitable circumstances (mainly of the high demand on electricity loads), could offer a solution to the safety and sustainability problems faced in traditional farming. However, consumers seem to be more skeptical and critical on this technology. Potential explanation of the consumers' skepticism is the uncertainty and lack of trust in other food innovations such as genetically modified crops, food nanotechnology and artificial irradiation that struggled to find acceptance in the market. Nevertheless, the subjective knowledge and awareness level of consumers on the indoor vertical farming is still limited, even with the excessive spread of technology and information globally, it is of vital importance to increase the education of people on this new technology by informing them on the actual growing properties and impugn the unjustified myths and dangers.

Because of the increasing demand of indoor vertical farms and their establishment in the market, many researchers have focused on designing and addressing customer surveys and other research methodologies in order to define the public opinion on this technology and the status of their trust and preference on already existing agricultural production systems. Significant angle on these researches is to explore the existing knowledge and perception of customers between the three different farming systems; traditional farming, greenhouses and indoor vertical farms, in respect of the cultivation techniques, safety, resource sustainability, quality and their willingness to buy products from each category. For this reason, primarily it was of high importance to validate that consumers are able to recognize the different agricultural systems between them in order to provide valid, clarify and comprehensive results.

Different customer studies that investigated customers' opinion on different agricultural methods show a more skeptical belief concerning novel technologies on food production. More specifically, peoples' perception with technological innovations in agriculture are associated with high risks for food production presenting low expectations on the provided benefits of technology used (Sparks et al., 1994). In another research (Coyle and Ellison, 2017) participants rated higher the greenhouses facilities and the outdoor farms compared to the indoor vertical farms in terms of naturalness in the production process and the final product. Concerning the quality status of the final product people also seem to present higher levels of confidence and trust on the greenhouse products and subsequently indoor vertical farms and finally in outdoor farming products. Naturalness seems to be a high influencing indicator for consumers' selection globally as also a critical significant factor on the usefulness of the agricultural system. According to Jürkenbeck et al. (2019), customers replied that LED lighting is not considered a too artificial tool for horticulture and slightly agreed that they do not consider indoor vertical farming too artificial concerning the overall production system. Even if consumers in general prefer naturally and traditionally produced food, nevertheless the fact that food of indoor vertical farms grow without chemical additives is highly considered.

On the other hand, under a customer research conducted by Jürkenbeck et al. (2019), it is noticed that consumers seem to present a high acceptance on indoor vertical farming concerning the offering sustainability and the high ecological footprint. People seem to select their purchased food based on their concerns on the naturalness, ethics and environmental status. In more details, 95% of the respondents in that research declare that they put an extra effort to select and buy locally grown food because of its high level in freshness, nutrition and reduced food mile emissions compared to traditional farming methods. On the other hand, a significant share of the consumers evaluates indoor vertical farming as an artificial agricultural process in order to trust their footprint outcome. For this reason, it is pointed out that knowledge, information and nutritional awareness can become a solid solution for the higher acceptance of indoor farming and irradiated food products. Respondents of the specific survey showed a strong willing on buying products that were produced in an indoor vertical farm with 46.7% of the total sample, 36.4% partly agreed on that statement, and finally only 16.8% were not willing to purchase these products. However, it should be noted that the perceived behavioral control does not influence the customers' willingness to buy, but it has some influence on the behavioral intension of willingness to purchase the product. Overall, the behavioral intention of customers to purchase products from indoor vertical farms is highly dependent on sustainability.

Under a different analysis, it has become very clear that perceived sustainability of indoor vertical farming is the main reason of acceptance. It has been observed that the more positive the resulted sustainability status of the system is, the higher and the customers' acceptance and willingness to purchase the product is. Furthermore, based on the perceived sustainability level of indoor vertical farms it seems that customers increase and their acceptance of this innovative technological food production system. Based on these results, we could indicate that the growing involvement and concern of consumers to select products from agricultural systems that present high environmental performance.

5. CONCLUSIONS

Indoor vertical farming can be very advantageous in terms of resources sustainability since because of the high technology and the soilless cultivation systems it consumes way less on natural resources (e.g., water and nutrients). Additionally, indoor vertical farms significantly decrease the CO_2 emissions that are correlated to food transportation from the producers and the processing facilities. In specific, indoor vertical farms can provide 100 times higher productivity per year per unit land area compared to traditional farming due to the zero dependence on weather conditions, seasonality and possible infections from insects, pests and bacteria. Due to the evolution of technology it is not anymore a prerequisite holding a large area of land for sufficient fresh food production, but the use of multiple layers, optimally controlled (environmental conditions and physiological parameters of the crops and minimum possible loss from crop threats). Significant characteristic of indoor vertical farms in terms of sustainability is the minimization food delivered losses. In addition, significant reductions can be observed in the cooling fuel demand, necessary to cool the production in order to be transported in long distances. This can be achieved since indoor vertical farms are usually installed in the urban or suburban areas in shaded and/or abandoned buildings (or even basements) due to the soilless farming techniques and the artificial lighting, providing access to fresh and nutritious greeneries to citizens. Finally, one of the significant benefits that indoor vertical farms provide is the ability after proper processing of the use of waste water, crop wastes and excessive CO_2 produced in urban areas, as input resources of water, nutrients and CO_2 in the culture area.

To summarize some of the basic improvements in resource savings provided by indoor vertical farms compared to the immediately following high technology cultivation system, the greenhouses are the following:

- Indoor vertical farms save 100% of the pesticide use in their interior by maintaining the culture area clean and insect-free.
- Because of the application of close loop irrigation systems and of the collection, recycle and reuse of the water vapor that plant leaves transpire, indoor vertical farms can reduce up to 95% the water consumption. Furthermore, the use of closed loops can decrease up to 50% the fertilizer usage since it is feasible to recirculate and reuse the nutrient solution.
- Significant land reduction up to 90% can be achieved with the application of indoor vertical farming, due to the important increase (more than 10 times) of the annual productivity of crops per unit land area.

- Yield variation can also reduced by 90% because of the constant monitoring and control of the crops and the lack of influence from the outdoor environmental conditions.

Food safety and traceability of products is another important factor highly relevant to indoor vertical farming. Even if it does not provide a 100% safety for consumers, despite the fact that crops grow in a controlled environment protected by wildlife, animals, birds and insects, it upgrades the safety and security feeling of the products than those that grow in open field. The majority of the selected cultivated crops of indoor vertical farms are among the species with the higher contamination risk when they grow outdoors or unprotected, because they grow very close to the ground level. Furthermore, one of the most crucial factors that greatly affect the possibility of contamination is the water quality that involves during the whole production process, including the irrigation water as also the washing water at the post-harvest processing techniques. Farmers of all categories should follow high standards and criteria for the water sources that channel water into the farms as also frequent control and monitor of the crops for potential threats of contamination.

It is now clear, that indoor vertical farms are a high necessity for tackling the challenges concerning the conservation of their resources. Nevertheless, in order to enhance the environmental sustainability and improve the efficiency and sufficiency of food production supplies for our society, it is necessary to develop more diverse, effective and ecological agricultural systems including both the traditional farms and the greenhouses. Further research and ex*peri*mentation it is absolutely necessary in order both to improve the efficiency of resources in an indoor vertical farm but also to possibly eliminate the possibilities for contamination threats and constantly provide the outmost safe, fresh and nutritious fresh fruits and vegetables to the human population.

Notwithstanding the promising benefits that are linked with indoor vertical farming, there are also important challenges in the further implementation of this farming system in the future. It is of vital importance further improvements on the efficiency and effectiveness of the equipment that will lead to a significant decrease of the energy demand of the systems. By achieving the reduction of energy demand, it will add extra value in the environmental sustainability of the system but also it would also make it more appealing for the public, the investors and the industry and will increase the viability and profitability. However, it is pointed out by Despommier (2011) that there is the opportunity for energy recovery from the non-salable crops' parts and capture of renewable sources of energy that can create zero energy building for hosting indoor vertical farms. At the same time, the whole system of indoor farming can synchronize and manipulate huge amounts of carbon and simultaneously release into the atmosphere oxygen from plants' respiration. Significant is also the start-up costs that are associated with indoor vertical farms as it is clear that it is more expensive to develop a vertical greenhouse than a normal greenhouse (Fletcher, 2012). As it has been highlighted by many studies one also key barrier that indoor vertical farmers have to confront is the public resistance to these type of products as social masses face difficulty in accepting indoor vertical farms instead if traditional farming ones because of the natural way that food is produced. Additionally, as indoor vertical farms serve the concept of local, fresh food production and they are mainly installed in urban or peri urban areas, they have also to salient the issue of affordability because of the expensive land and space use. For this reason, key factor is the productivity rate of indoor vertical farms that can maintain them profitable and keep them prevailed in the future. More specifically, if indoor vertical farms achieve to produce up to 50 times more yield compared to traditional farming, then they can offset the capital expenditures and the expensive land use. Previous research conducted by Avgoustaki and Xydis (2020), presented that indoor urban vertical farms regardless the financing scheme, are much more profitable in comparison to greenhouse constructions. In the specific work, different investment scenarios are presented based on the cash flow analyses and show that IUVF can present high IRR (Investment Return Rate) as also a payback period between 2 and 6 years. Finally, another drawback that is linked with indoor farming production is the limited variety of crops that can be produced with this technology, such as lettuce, herbs, tomatoes and berries. Even if theoretically, all types of crops could be cultivated indoors, that would not be economically feasible due to the highly increased energy demand. Thus, low-value agricultural crops such as wheat and barley will continue to grow under economically and environmentally unviable conditions. Under these circumstances, the indoor vertical farms have to face a limited production compared to the “limitless” hectares of traditional farming and a reconsideration of scaling up would be particularly costly and complicated.

The last years that indoor vertical farming gained more recognition and research interest, a plethora of new studies, prototypes and innovation designs have been presented under the academic and industrial scope. Indoor vertical farming presents a high interest and potential to play a critical role in the demanded sustainability in food of urban areas. This becomes even more important by the multiple studies that estimate and analyze the significant increased food demand in urban areas. Indoor vertical farming presents important advantages compared to traditional farming, concerning the required sustainability in our times by focusing in three main categories: environmental, economic and social.

There is a high demand for further development in automation. This will be scaling up the projects in order to create more feasible scenarios both from economic and commercial perspective. Future research is necessary towards a holistic approach via the investigation and the analysis of the full life-cycle of indoor vertical farms and the impact to the environment compared to the traditional farms and greenhouses.

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Abstract

Food safety is an important scientific field, but at the same time a discussion topic of modern society that occupies more and more space of our every day time, dealing with the preparation of food, with its nutritious value, and various transportation and storage ways aiming at preventing food-related sickness. This work compares traditional farming with greenhouses and indoor vertical farming focusing on the challenges and the opportunities for each category. The scope of this work was to stress the role of indoor vertical farming towards this direction. Indoor vertical farms can produce high quality and virus-free products that can be locally distributed, inside the urban environment that such investments take place, saving annually millions of tons CO_2 emissions. Beyond that, in this work it was pointed out how energy plays a role in food safety in such systems. It was stressed that indoor vertical farms can act as a de-

mand response aggregator. In large scale units it could play a role to adjust their production according to different electricity prices offered in different time zones throughout the day. This way, the owners under a multi-value business model will create the opportunity to the vertical farm owners not only to improve their production but at the same time absorb inexpensive electricity offered, by creating an additional profit mechanism (multiple revenue streams) under such an approach by entering into contracts with companies in a utility electric region.
Keywords: Energy innovation; Indoor farming; Electricity prices; Hydroponic systems; Land use efficiency