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In recent years, several global issues related to food waste, increasing CO2 emissions, water pollution, over-fertilization, deforestation, loss of arable land, food security, and energy storage have emerged. Climate change urgently needs to be addressed from an ecological and social perspective. Implementing new indoor urban vertical farming (IUVF) operations is one way to combat the above-mentioned issues as well as foodborne illnesses, scarcity of drinking water, and more crop failure due to infection from plant pathogens and insect pests. A promising production mode is plant factories (PFs), which are indoor plant production systems completely isolated from outside environment. This
paper mainly focuses on the comprehensive review of scientific papers in order to analyse the different applications of urban farming (UF) based on three different dimensions: a) the manufacturing techniques and equipment used; b) the energy that these systems require, the distribution of energy, and ways to minimize the energy-related cost; and c) the technological innovations applied in order to optimize the cultivation possibilities of IUVF.

Keywords separated by ' - '

Plant factories - Urban farming - Water-food-energy Nexus - Energy demand

Foot note information
Plant factories in the water-food-energy Nexus era: a systematic bibliographical review

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Abstract
In recent years, several global issues related to food waste, increasing CO2 emissions, water pollution, over-fertilization, deforestation, loss of arable land, food security, and energy storage have emerged. Climate change urgently needs to be addressed from an ecological and social perspective. Implementing new indoor urban vertical farming (IUVF) operations is one way to combat the above-mentioned issues as well as foodborne illnesses, scarcity of drinking water, and more crop failure due to infection from plant pathogens and insect pests. A promising production mode is plant factories (PFs), which are indoor plant production systems completely isolated from outside environment. This paper mainly focuses on the comprehensive review of scientific papers in order to analyse the different applications of urban farming (UF) based on three different dimensions: a) the manufacturing techniques and equipment used; b) the energy that these systems require, the distribution of energy, and ways to minimize the energy-related cost; and c) the technological innovations applied in order to optimize the cultivation possibilities of IUVF.

Keywords Plant factories · Urban farming · Water-food-energy Nexus · Energy demand

1 Introduction
Urbanization and extremely rapid growing populations change city features and convert them into chaotic mazes. Considering that the world’s population has reached 7.6 billion and will number almost 9.5 billion people by 2050, we have to support and improve the agricultural footprint needed for the constant cultivation of everyday products for consumption (Langelaan et al. 2013). Today, we use land equal to the size of South America in order to grow food and raise livestock to feed the global population. Since each person daily requires a minimum of 1500 cal, the calculations show that with the increase in population and the farming practices that are applied globally today, we will have to cultivate another Brazil’s worth of land, i.e., 2.1 billion acres (Despommier 2009). As the global population is growing at a rapid speed, at least 60% more food production will be needed (Carey et al. 2016). The constant migration into urban areas lead to air, noise, and water pollution due to factors such as concrete buildings and hard surfaces, lack of vegetation, increase of urban heat islands, and global warming, among others. With 75% of the global population projected to be located within urban areas in a few decades, we will experience a “global generational amnesia” on how to grow food (Barthel 2013).

Today, agriculture uses approx. 70% of the Earth’s available fresh water for irrigation, making it inappropriate for drinking as it is being polluted with pesticides, chemicals, and herbicides. In fact, in a few years, it will be impossible to find drinkable water, especially in certain densely populated regions. As stated by Barbosa et al. (2015), the amount of water used to produce 1 kg of lettuce using traditional agriculture techniques is comparable to filling a big freezer. It is now more than ever necessary to design and apply innovative growing techniques in indoor environments. Indoor urban vertical farming (IUVF) is a novel type of indoor cultivation that uses up to 90% less water for the same yield production of lettuce. Areas where staple food crops are cultivated already face difficulties with efficient irrigation (e.g., drought and/or unstable rainfalls), while at the same time, household water demand continues to increase due to urban expansion along with the desire and the expectations of a better quality of life.

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One of the most demanding costs of farming is the consumption of huge quantities of fossil fuels. According to Despommier (2009, 2013), 20% of all gasoline and diesel fuel is consumed in the US. The price of food directly related to fuel prices was one of the reasons why food costs almost doubled in most parts of the world between 2005 and 2008.

A big part of the agronomic society believes that giving industrial farming more intensive cultivation methods with heavily mechanized farming consortia using genetically modified plants and more powerful agrochemicals can increase the growth of crops with massively higher yield efficiency. This, however, is only a short-term solution: the rapid shift in climate will continue to rearrange the agricultural landscape, spacing even the most promising and sophisticated strategies. For a low-carbon-driven society, sustainable greenhouse plant production systems will play an important role in plant production, as these provide the opportunity to cultivate plants at low cost while improving the water economy as well as reducing CO2 emissions and fossil fuel consumption.

When leafy vegetables grow outdoors, they tend to vary in quality and productivity due to weather conditions, soil fertility, texture, organic matter, pH, and many other factors. In contrast, when plants are cultivated in greenhouses, productivity and quality greatly increase. Indoor farming can offer many advantages over open-field agriculture; the most important is that it allows farmers to control the conditions that are crucial for the optimal growth, survival, maturing, and harvesting of the plants, while also ensuring the maximum yield per square foot of growing space. Today, there are many methods for greenhouse cultivation in terms of construction and treatment techniques. A wide variety of vegetables and fruits (50% of the greenhouse plants that are globally grown are tomato cultivations) as well as some species of fish (e.g., tilapia and trout) prosper under almost ideal conditions of temperature, humidity and CO2 by employing IUVF.

There are different types of IUVF according to the shape and the size of the farm. It can be from a simple two-layer system of vertical cultivation benches one above the other, to a large warehouse with multiple stories. It could be a shipping-container with indoor cultivation either in columns or in vertical layers or urban building-based farms (abandoned buildings, rooftops) for local food production (Despommier 2010). One of the basic common characteristics of this type of farming, is the growing system that is either hydroponic (soilless nutrient solution), aeroponic (soilless air/mist solution) or aquaponic (co-cultivation of hydroponic plants and fish). IUVF are thermally insulated constructions and nearly airtight structures as the purpose is to be isolated from outdoor environment totally controlled in terms of temperature, humidity and CO2. Since we want to maintain an indoor temperature for the crops, which is different from the outdoor temperature, it is very important to provide thermal insulation specifically in the top floor of the building. This can be achieved by either cavity walls, loose fill insulation, lightweight foam concrete or low density aggregate. Bacteria and disease control is of vital importance in the IUVF as it can reduce the infection and yield loss. Furthermore, in IUVF since water is traceable, the nutrients and the environment is totally closed, managing to reduce the risk of potential air or moisture contamination making this technology a sustainable food process. The cleanness of the systems can be achieved with either floor cleaner, specific worker suits, dosing systems or quality sensors, which monitor constantly the farm (Barthel and Isendahl 2013; Besthorn 2013; Benke and Tomkins 2017).

1.1 Advantages of IUVF

As observed by many researchers (Despommier 2012; Kozai 2016), IUVF has many advantages over open-field agriculture. IUVF provides a sustainable way of cultivation, and it helps prevent climate change, since the cultivation does not produce any agricultural runoff. IUVF and all the closed loop cultivation use almost 70% less water compared to conventional outdoor farming; aquaponics techniques (Cunningham 2017) use even 90% less water. Since the cultivation room is located in a closed, protected environment, the crops are not affected by severe weather conditions (e.g., floods, heatwaves, and drought). Furthermore, IUVF can be established wherever in the world (e.g., in abandoned buildings in cities), as this method of cultivation does not require soil or sunlight for the growth of the plants. In other words, this type of agriculture can be located anywhere, thus minimizing the food miles. IUVF leads to significantly reduced pre-harvest of crop or even an elimination of the crop prior to harvest (‘pre-harvest shrink’), which will establish the option for buying on-demand, ultra-fresh, locally grown, pathogen-free food. This can lead to job creation in the primary sector of the economy – both in urban and suburban areas – as there will be a need for more labor to run the nursery, manage seed germination, transplant the seedlings into vertical farms, facilitate resource procurement and management (water nutrient, growing systems, lighting systems, and automation), and monitor the plants’ growth. Additionally, well-engineered IUVF can minimize or even eradicate the possible post-harvest losses associated with microbes (plant pests) without the use of toxic pesticides. Nutrient solutions used do not contain any metabolic by-products from human metabolism, thereby avoiding altogether the problem of fecal contamination of food sources by design. Moreover, IUVF can be combined with aquaculture, mushroom culture, and fermentation systems for mutual efficient use of their respective wastes as resources. Last but not least, waste water, vegetable waste, and CO2 produced in urban areas can be reused, after proper processing, as essential resources (water, CO2, and fertilizers) for growing plants in IUVF. Waste to energy can happen in many different ways in the built environment (Nikas et al. 2018; Sotiropoulos et al. 2018).
In IUVF, in specific, waste heat energy can be used for heating greenhouses in winter and for other purposes (Omer, 2007).

The recent technologies create a new environment of cultivation both for businesses and for the urban public with new possibilities and perspectives. Multi-layer vertical growing systems are installed in Plant Factories (PF) in order to save growing space in urban areas. Usually, cultivation areas are located miles away from urban areas, for which reason farmers and transportation companies have to travel long distances to reach the hot spots of the food markets. PFs can speed up the transition towards a more sustainable production.

Researchers’ estimation in terms of the productivity of PFs vary according to the means of cultivation, the selected crop, and the techniques used. According to Kozai (2015), PFs have higher (more than 100 times) annual productivity per unit of land area compared to open-field agriculture. Additionally, depending on the greenhouse installation (if includes artificial lighting or not) the yield production can be around 3-4 kg m⁻² y⁻¹ of dry weight production, in comparison with IUVF that their productivity is more than 5 kg m⁻² y⁻¹ of dry weight production. Graamans et al. (2017), state that for the production of 1 kg dry weight of lettuce, almost 250kWhe is required in a PFAL installation, in comparison with a greenhouse with artificial lighting that requires approximately 210 kWhe of energy.

It should be stressed that PFs provide water savings when cultivating plants; vegetables are planted in hydroponic substrates (e.g., perlite, coconut fiber, rock wool, vermiculite, etc.), and the water that irrigates the plants is enriched with the nutrient solution for the maximum possible yield that can be achieved (Khandaker and Kotzen, 2018). PFs reduce soil and water pollution compared to conventional outdoor farming practices, involving an excessive use of fertilizers, chemicals, and soil improvers. PFs exclusively use hydroponic solutions, and in this way, the nutrients are mixed with the water and follow a circulating procedure.

This literature review aims at providing the interested parties in PFs with a comprehensive understanding of 1) how they can contribute to minimizing energy consumption in crop production; 2) the energy use efficiency of electrical energy and renewable energy demanding on the production system; 3) the improvement and integration of the new technologies and digitalization trends for improving the growth of plants as well as monitoring the plants in order to gain a competitive advantage in the real market. Based on an extensive statistical analysis of 93 scientific and management consulting studies, this research addresses the following: First, it maps the evolution of hydroponic, closed-loop systems and the sustainable agriculture over a period of almost a decade. Second, the research reveals the top six main trends associated with energy consumption and energy demand in hydroponics. These are: 1) the theoretical aspect; 2) energy; 3) digitalization; 4) environmental control; 5) cost demand; and 6) cultivation techniques.

In relation to the energy consumption trend, the research has further mapped the geographical impact of sustainable agriculture by identifying the regions that primarily focus on sustainable agriculture, and how these regions have developed the need for and the prospects of more promising techniques that can lead to more efficient yields in terms of lower energy demand and innovative technologies. The results show that Europe (primarily Western and Southern Europe) is most active in sustainable urban agriculture, followed by Asia and the US. Furthermore, the research has identified relations of the above trends, and, finally, the research has examined the impact of digitalization in new technologies to improve and evolve urban agriculture and PFs. The results from the research have confirmed that sustainable urban agriculture and, more specifically, the innovative PFs are becoming a revolutionary trend with increasing interest not only from relevant professionals but also from organizations, companies, and academia striving to build an intersectoral water-energy-food nexus under a smart city 2.0 sustainable growth plan.

**2 Analysis**

The motivation for studying urban agriculture is that it is an innovative technology that is still complex, and this project aims to evolve demographics, water, energy efficiency, cost analysis, digitalization of pioneering technologies, cultivation techniques, and environmental controls of crops for a sustainable food production. The diversity of knowledge areas linked to the urban agriculture concept is a challenge for modern day society as cultivating enough crops to support the world’s population is becoming increasingly difficult.

In this research, reliable sources of data from different research institutions, universities, and commercially viable facilities in the form of scientific articles, journals, conference proceedings, and a number of reliable newspaper articles have been analysed. The evolution of the publications throughout the years as subtracted from the reviewed urban agriculture publications in the period 2004-2018 has been analysed. The first publication related to hydroponic cultivations was done in 2004 (Fig. 1). The number of publications on hydroponic cultivations in urban areas have increased slightly over the years, where on average 2-3 publications addressing the correlation between hydroponic systems, energy efficiency, and digitalization have been published. Nonetheless, starting with 2012, a significant increase in the number of publications can be seen in the Fig. 1, where in 2012 and 2013, 8 papers were published, followed by 11 papers in 2014, 15 papers in 2015, 12 papers in 2016, 13 papers in 2017, and 6 papers in 2018 (till June 2018).
In 2012, Professor Dickson Despommier from Columbia University, introduced the idea and the concept of sustainable urban agriculture. He mentioned the difficulties that open-field cultivation face in terms of the high demands for water, fertilizer consumption, and the huge amounts of CO2 emissions into the atmosphere due to the transportation of the products from their production site to the urban consumers. He introduced the pioneering terms of vertical farming (VF) and sustainable urban agriculture, and how these new cultivation methods would allow for greater yields, more ecologically friendly crops, and high-quality vegetables for the consumers. The concept spread rapidly throughout Europe and Asia, and around 2015, Professor Toyoki Kozai from the University of Chiba in Japan introduced the concept of PFAL (Plant Factory with Artificial Lighting), where plants are cultivated in a totally artificial environment, which can be built anywhere, thus offering improved local production for local consumption of health and safe leafy vegetables.

With 47 scientific papers (Fig. 2), Europe ranks as the most active continent focusing on Indoor Urban Vertical Farming (IUVF), followed by Asia with 33 publications, and USA with 21 publications. Taking a closer look at Europe, the IUVF publications have been distributed per European region.

Figure 3 shows that the IUVF publications predominantly originate from Western Europe (19 publications of which most come from the Netherlands and the UK), where universities and research groups have access to high-tech and well-equipped facilities to support research leading to improvements in this field. With 14 publications, Southern Europe is the second most active region focusing on HUC (Hydroponic Urban Cultivation), followed by Northern Europe (with 6 publications), where countries, such as Denmark, mainly focus on energy consumption and energy efficiency of HUC. The region that focuses least on HUC is Central Europe (with 4 publications).

By 2050, 70% of the world’s population will live in urban areas (Walsh 2009). Future megacities cities will be more ethnically and culturally diverse, significantly larger, poorer, and less well-nourished than current urban populations with a high demand for stable, accessible and nutritious food (UNFPA, 2007). Combining this information with the above graphs (Figs 1, 2 and 3), it can be deduced that the majority of the researchers who have studied the geographical impact of the evolution of sustainable urban agriculture come from modern and developed continents. This can be explained by the fact that in those regions, there is a great need for advanced and pioneering technologies that can offer consumers a more ecologically and economically sustainable agriculture. As a result, we can be convinced that the expansion and development of sustainable urban agriculture hold promise for urban locales struggling with chronic food security problems (Besthorn 2013).

The appearance and the growing research of IUVF in the most industrialised regions can also be explained by the huge unemployment rates in the urban regions. Urban agriculture provides opportunities for new job positions in cities. IUVF can help alleviate chronic unemployment issues that many urban environments are facing. In addition to creating jobs within the IUVF infrastructure, urban agriculture also contributes to the creation of ancillary jobs, such as workers, engineers, marketers, merchants etc. As stated by Liaros et al. (2016), in a number of countries worldwide, the real estate market is currently characterised by a weak demand and excess supply mainly due to high unemployment rates and taxation, liquidity shortage, and loss of confidence in the banking system; factors which lead to a sharp decline in the market. IUVF proposes a new plan for reuse of available urban space as well as production of fresh leafy vegetables and herbs for local production.

As observed in Fig. 4, less than one decade ago, hydroponic urban agriculture (HUA) trends were not a common topic of academic debates; few publications addressed digitalization and the technology achievements in urban agriculture as well as the new renewables forms of energy. The average number of published papers addressing these issues was 2-3 papers per year from 2004 to 2011. In 2012, the number of IUVF
publications increased significantly; the same year as new, innovative ideas and programming trends began to emerge in order to improve the urban agriculture and create different types of cultivations in urban areas (e.g., PFs). Following 2015, a huge interest in profitable urban agriculture started and resulted in the highest number of IUVF publications (14) registered. These publications mainly focus on energy efficiency and consumption, IUVF locations, renewable energy, and digitalization, which has increased significantly in this domain. However, a number of other papers have also been published that examine the different ways of cultivating in IUVF and how the production yield will be affected. Finally, a few papers also focus on the environmental control of HUA and how it can be improved (e.g., become more accurate and less unstable) through the progress of digitalization. In order to get a more detailed overview, the authors have aimed to show the IUVF trends in each scientific area focus (Fig. 5). The results are very diverse according to each scientific area and region (Fig. 5a). The regions focusing most on the new urban agriculture trends are Asia, USA, and two parts of Europe (Western Europe and Southern Europe). The top trends in these regions are energy and digitalization of urban agriculture. Asia is the continent with the most promising and rising interest in this new type of cultivation. As mentioned by Xu (2014), Asia is a large agricultural continent with a significant energy consumption, and the environmental pollution issues are caused by the conventional fossil fuel resources and have imposed heavy burdens on sustainable development (Manos and Xydis 2019). The second-ranked region, USA, has the same pattern as Asia with focus on energy, and digitalization. In addition, many publications include theoretical aspects of the promising IUVF, and many research groups also focus on cost demand as well as environmental control. The third- and fourth-ranked regions to focus on HUA trends are Western and Eastern Europe, respectively, with main focus on energy and digitalization. Finally, Northern Europe primarily focuses on digitalization and energy research.

Another important factor that has been studied in this research is the tendency of the published papers in the six different trends during the years. As can be retrieved from Fig.
the publications mostly focus on the aspect of energy, as it is the one area that needs more effort in optimization. Over the past decades, a major global problem has arisen related to crop yield based on energy consumption. Hatirli et al. (2005) state that the average energy consumption of a fully equipped production unit can reach 106,716.2 MJ/ha with an average yield around 160,000 kg/ha. Van Ginkel et al. (2017) found that hydroponically grown vegetables consume 30 times more energy than outdoor-grown vegetables. Sustainability and energy efficiency is a main research topic and how it can be improved under different cultivation techniques and use more renewable energy resources in farms (such as solar, wind, biomass, geo-thermal, biofuels etc.). Finally, the second significant factor of interest of the published papers is the digitalization trend throughout the years. More and more research groups focus on creating new technologies that are necessary
for a more sustainable agriculture and product production by design. Digitalization is becoming the core interest in a wide variety of functions in the new technologies, including mechanizations, selective breeding, and genetic manipulation, and leads to a significant increase in crop yields and reduced production cost in a sustainable environment.

The majority of the papers refer to more than one perspective of IUVF and are found in different combinations of the main keywords. The most common is that the published papers highlight the energy demand of IUVF in the context of renewable energy (included in the energy group), which is usually combined with a more economical and efficient use of energy as well as digitalization with state-of-the-art technologies to improve the control, monitoring and yield of the plants. As shown in Fig. 6, 34% (i.e., one-third) of the total published papers cover three different trends, 23% includes four different trends, and almost 20% of the publications combine two different trends. With Fig. 6, we can conclude that the majority of the researchers try to see urban agriculture from different perspectives and retrieve as much information as possible in terms of the potentials for improving agricultural methods and productivity to reduce energy consumption.

### 3 Discussion

#### 3.1 Energy

As Chen (2014) summarizes, systems that use fossil fuels for their optimal function face important drawbacks. These include the transportation of the fuels to the generator’s location, the disturbance of livestock due to noise and exhaust fumes released into the environment, the continued increase in fuel costs and emission that pollute the soil, and the maintenance of generators and mechanical systems. The first research results of commercialised PFs were published in 2009 (Speetjens et al. 2009), where vegetable production in greenhouses became crucial in the globe’s agriculture sector.

Pahlavan et al. (2012) estimated that electricity demand is the highest cost from the total energy input (75.68%) in a greenhouse that consumes 65.57 MWh ha⁻¹ for basil production. Out of this, 80.05% of the total energy used was direct, while the contribution of indirect energy was 19.95%. The air conditioners, which are used in the cultivation area, are mainly used for cooling purposes and dehumidification and their purpose is to eliminate heat, which is generated from the lamps. PFAL consist of well thermal insulated walls and high level of sealed walls in order to be able to cool down the temperature while the lighting is on. This process takes place during winter seasons, as the goal is to retain satisfactory internal temperature conditions. Another drawback of these systems is the low level of energy delivered by the system (water at 40°C) (Adams et al. 2007).

Today, the need for a more sustainable and efficient cultivation method as well as more and better quality products is urgent. The new types of cultivation propose soilless substrates and growth chambers located in the urban network and working in a sustainable and eco-friendly way. Generating electricity and heating from biofuels and renewable energy sources has become a high priority in the energy policy strategies at a national level as well as on a global scale. Canacki et al. (2006) note that the operational energy and energy source requirements of the greenhouse vegetable production are found between the ranges of 23,883.5–28,034.7 and 45,763.3–49,978.8 MJ/1000 m².

Studies showed that production of 1 kg dry weight of lettuce requires an input of 247 kWe in a PF compared to 70, 111, and 211 kWe in greenhouses in the Netherlands, United Arab Emirates, and Sweden, respectively which can be reduced by up to 30–40% depending on the technology applied (Graamans et al. 2018; Dyer et al. 2006; Vadiee and Martin 2013a, b). Furthermore, a reduction in the daily average set-point temperature leads to a 16% decrease in the annual energy demand. The use of fossil fuels such as kerosene, diesel, and propane to power generators in agricultural operations has caused many problems over the years. Most of the researchers seem really interested in the combination of IUVF together with the different forms of energy that can be consumed. The electrical energy fixed in the salable part of plants as chemical
energy is 1-2% at the highest and less than 1% in most conventional PFs. The remaining 98-99% electrical energy is converted into heat energy in the cultivation room (this is why the heating costs of a thermally well-insulated PF is practically zero – even on a very cold winter night) (Kozai et al. 2015).

As stated by Shamshiri et al. (2018), the three largest operational costs (excluding electricity) in the commercial IUVF are 1) labor costs (27% of the total cost), 2) electricity costs (25-30% of the total cost) and 3) capital costs (18-20% of the total cost). The packaging materials and delivery services of the production companies can reach up to 12% of the total production costs. However, indoor urban agriculture compared to open-loop systems increases the yield potential by up to 20%, and the total energy demand can be reduced by 30-40% based on the already existing technology. Vadiie and Martin (2012) note that a closed system of cultivation can supply almost three times more than its annual heating demand. The electricity consumption inside the IUVF is approx. 57% of the daily consumption for the heating system (and categorised as the most consuming part), followed by the water pump (18%), with the LED lighting consuming almost 12% (Delaeila et al. 2017). According to Kozai (2016), applying different techniques and materials can lead to reduction of electricity consumption of produce per kg in the PFs by 20-30% (50-80% theoretically). Altering the photoperiod inside the IUVF has an important effect on their energy demand (Harbick and Albright 2016; Avgoustaki 2019; Liu et al., 2019).

Energy demand and energy management are some of the most discussed subjects in the existing literature. Researchers constantly try to create a correlation between the energy consumption inside the cultivation area and how this can be controlled using different technologies. The commercial IUVF in a large-scale deployment has the highest energy demand as compared to other agricultural industry sectors. For this reason, energy management is important from a broad sustainability perspective (Vadiie and Martin 2013a, b; Ma and Chan 2016; Harbick and Albright 2016).

Indeed, the energy consumption is an important cost element for optimal production. For this reason, many researchers have focused on the possibility of combining IUVF with the different types of renewable energy (Fig. 5b). Using renewable energy is a practice toward sustainability and is suitable for developing countries without green energy (Safikhani et al. 2014). Examples of important renewable energy systems are ground source-based systems, day-lighting systems, and solar-based energy systems. Renewable energy allows users to find the most efficient, cost-effective, and eco-friendly type of energy for the operation of the growth chambers. Many new technologies have been designed for the development and industrialization of IUVF. Most of the published papers that have been examined in this study focus on renewable energy sources such as solar, wind, hydroelectric, and geothermal energy for electricity production; many of which have been tested with different cultivation techniques under different protocols (Farzaneh-Gord et al. 2013). Some of the most common research areas are photovoltaic solar panels, heat pumps for cooling (and heating) (Tong et al. 2012), superheated steam, and wind turbines (Khattab et al. 2016). In all publications, many different pioneering devices, indices, and units aiming at optimal plant cultivation with lower energy consumption and more effective use of renewable energy can be found (Chel et al., 2010; Vadiie et al., 2014).

It has been revealed that IUVF systems and/or solar thermal system would be suitable options in hydroponic greenhouse applications (Hassanien et al., 2016). Moreover, solar technologies are environment friendly, require low maintenance, have no fuel costs, and increase the overall productivity by integrated PV panels in IUVF. The majority of the publications focus on the potentials of solar energy in combination with a sustainable cultivation system (Ganguly et al. 2010; Sonneveld et al. 2010; Carlini et al. 2012; Marucci et al. 2012; Kubo et al. 2016). Well-designed, modern, and simple-to-maintain solar systems that provide the energy needed at a given location and time have also been examined. These systems have been tested and proven to be cost-effective and reliable, and, most importantly, they have increased the level of agricultural productivity worldwide. In this context, research groups have focused on designing new types of photovoltaic solar panels for electricity generation, targeting a more sustainable agricultural sector (Mekhilef et al., 2013). In the case of Murayama et al. (2016), a different type of PF system has been demonstrated in which the cultivation is located in an outdoor landscape where adjustable solar panels on the roof have been installed to absorb the solar radiation and protect the crop beneath. Another area of the research in photovoltaic panels is the analysis of their performance and the neural modeling in the modern hydroponic ways of cultivation (Pérez-Alonso et al. 2012). It should be noted that the photovoltaic solar systems allow the users to use the electricity to meet the load demand, such as a water pump, or storage in batteries (some of the systems have the added advantage of storing water) for later use, reducing system costs.

One of the most researched areas of renewable energy is that of wind power and how it can benefit IUVF. According to Xydis et al. (2017), a large-scale deployment of urban indoor small scale hydroponic units can work towards integrating greater quantities of generated wind power, participating in the market as an authorised electricity supplier. This research has revealed that hydroponic units can minimize their power supply needs, allowing the utility not to introduce expensive and less clean thermal power plants into the system in order to cover the peak demand and meet the demand by postponing it via various demand response options.

As stated by Wang et al. (2017), some of the most obvious obstacles that modern solar IUVF chambers face are the poor
heating-preserving performance (of solar thermal greenhouse), the shadowing effect (of PV greenhouse), and a series of advanced solar utilization technologies to mitigate the effects of heat loss, shadowing, and poor light condition for applicable integration. The use of double-glazing and thermal insulation provided by the rooftop farms and the natural ventilation can reduce additionally the total energy usage (Ali-Kodmany 2018).

3.2 Water efficiency

As stated by Cicekli (2014), the rise of vertical farms is inevitable, as IVU systems, among other things, recycle water for irrigation without concern for outdoor environmental conditions, thus improving product quality, sustainability, and efficiency by means of eco-friendly techniques. According to Kozai (2016), water consumption in a PFAL is around 2% in comparison with the one of greenhouses. 95% of the water transpired from the leaves of the plants concentrates as liquid water at the air conditioner and more specifically at the cooling coil panel; this is resent to the nutrient solution tank and reused in the crop. The water use efficiency of PFAL can reach up to 0.95 and the nutrient use efficiency is over 0.90 in most cases (Kozai 2016).

The root-zone temperature of the plants in the hydroponic cultivation system plays a vital role in plants’ growth and yield production in a PFAL installation. Recent research (Sakamoto and Suzuki, 2018) showed that optimal hydroponic techniques in the root-zone of the plants could develop and control the root environment regarding the plants’ requirement in humidity, temperature and nutrient absorption. The root-zone is important as it can influence secondary metabolites in multiple plant species, specifically the ones that grow under controlled environment. Low temperature in the root-zone of the plants can reduce their leaf area, the diameter of the stem and the fresh weight both of the root and the shoot zone. The consistency of the environmental conditions in the root-zone is of vital importance as it allows plants to dissolve the nutrients of the solution. Root-zone cooling system can be adjusted according to each plant selection and hydroponic installation. Suraidi et al. (2018), mention that different treatments of the root-zone temperature, according to the life stage of plants, can increase yield production. The root-zone temperature of plants is specially important when plants face low temperatures as this results in reduced growth rate of the plants as well their photosynthetic rate. According to Graamans et al. (2018), the lighting system of LEDs in the cultivation area account for 52% of the total electricity usage in the PFAL (conversion of electric power to chemical energy that promotes photosynthetic process of the plants) and the remaining 48% is distributed as sensible heat. This heat is extracted by water evaporation in the hydroponic cooling system and transformed to latent heat.

3.3 Digitalization and lighting

Most of the published papers (70 out of 92) studied the potential of minimizing energy consumption in relation to high-tech solutions. In this context, new ideas and tested protocols have been presented, including devices, automation, monitoring programs, cultivation techniques, efficient constructions, environmental controls, software and hardware equipment. In particular, the effects of the different parameters in the IUVF performance as well as the application of new methods to improve their efficiency have been studied. For this part, the research groups have tried to develop more accurate and efficient models that provide better opportunities for predicting energy consumption and demand, promoting energy efficiency and designing novel hybrid energy-saving systems and prototypes (Chen, 2014; Ntinas et al. 2014; Ismail et al. 2013; Blasco et al. 2016).

From the findings, it can be observed that sustainable methods are needed to control environmental damage and reduce energy consumption. Many sustainable solutions for improving and flourishing vertical farms have been suggested. Well-designed PFs use high-efficiency equipment for operations, including heat pumps for cooling and heating, variable speed motors on pumps, fans for moving water and air as well as LED lighting for illuminating the crops. Combining different types of technologies to improve quality, yield, and energy efficiency are in the center of the published papers with different proposals and aspects requiring extensive future research. The improvement of the cultivation procedure and the careful selection of the cultivars can lead to a massive increase in the total amount of commercial plants (Dieleman et al., 2011; Kozai 2013).

One of the most important factors that the majority of the researchers have studied is the promotion of software development for PF design and production management. In particular, the publications from Asia and USA present various technologies for vegetable breeding, hydroponics, vertical indoor cultivation structures as well as software and hardware for environmental control in IUVF (van Beveren et al. 2015). Dynamic optimization and optimal control techniques leading to a maximised crop yield, minimised energy consumption, and lower cost demand for the operation and function of the IVF have yet to be developed. Inside the chambers, sensors and controllers are installed, which constantly monitor the temperature, CO2 concentration, nutrient solution, humidity, EC and pH of the substrates, and many other factors.

The electrical energy consumption used for artificial lighting in PFs accounts for almost 60% of the total energy consumption. 17% is for the pumps and 10% for refrigerators, ACs, coolers and chillers (Fig. 7). For every euro spent on energy, 60 cents is composed of electricity consumption for...
lighting, which is why the majority of the researchers focus more on minimizing lighting costs.

Studies on LEDs as sole light source of IVF displayed the most common result of the digitalization and technology trends. Study protocols have been developed to test plant responses in various photoperiods, light intensities, and wavelengths to examine how LED lighting influences crops as compared to the fluorescent lighting (FL) as well as to test how LEDs can be used to control the circadian rhythm of plants (Higashi et al. 2015). Indeed, it is possible to improve the growth of plants by using a combination of these LED properties and well-designed reflectors that increase the ratio of light energy emitted by lamps to the energy absorbed by the plants. In a sole-source lighting mode, LEDs can also be used for transplant production as well as for production of rapid-turning vegetables and small fruit crops (Burr et al. 2015). LEDs provide focused point source light, and can be placed close to crops due to low radiant heat emissions. Some studies have more focus on the photosynthesis of plants, i.e., how the photosynthesis and how excessive light might be modified by the balance between source and sinks. Ikkonen et al. (2015) state that a short-term daily temperature drop eliminates the inhibiting effect of continuous light (CL) on the photosynthetic performance of tomato plants.

LED lamps are cost-effective and for different agricultural applications, their desired spectrum can be achieved by combining two or more types of LEDs (Ronay et al. 2015). The LEDs are more energy-efficient than the conventional fluorescent bulbs and have higher efficiency when used in a combination with solar panels. Spectral sensitivity may also extend beyond the visible wavelengths and into the ultraviolet and infrared bandwidths with potential effects on growth rates (Benke et al., 2017). Another aspect is that crop production can be increased by 5-10% compared to conventional bulbs. Cuce et al. (2016) adds that fluorescent lamps might provide better results than LEDs depending on the plant. For instance, sprouts demonstrate the fastest growth quality under far-red fluorescent lamps.

LEDs have many monochromatic colors, which become the identity of a specific wavelength beam that is useful in the leaf photosynthesis process. Cuce et al. (2016) states that the highest influence in the plant development in the optical spectrum focuses in the blue wavelength (448nm), red (634 and 661nm), with a proportion of 80% red and 20% blue light and their combination increasing the photosynthetic activity of the plants. Shamshiri et al. (2018) note that LEDs are not the only criteria for plant growth; choosing the correct planting density is vitally important for increasing crop water output and improving the light capture from the LEDs. Moreover, the planting density has an effect on the harvest of tomato in hydroponic growing systems and evapotranspiration.

In recent years, publications have followed a new trend in lighting, namely induction lighting technology. As stated by Al-Kodmany et al. (2018), this type of lighting can mimic the sunlight’s color spectrum in order to promote the development of fruits and leafy vegetables. Instead of using a lighting filament, the light uses an electromagnet to excite argon gas. For this reason, the new induction lighting technology uses less energy and can last up to 100,000 hours. In addition, it creates enough heat for growing plants without wasting energy to heat the building, and the light units are calibrated to create an ‘ideal’ microenvironment by producing high-quality lighting that is similar to daylight.

Heat pumps are widely utilised in IUVF due to their characteristic advantages, which are provided by other technologies (Cuce et al. 2016). In cold weather or at night (dark) conditions, heat pumps can be used as a heating device. When the temperature is too high, they provide cooling in the cultivation room. According to Haque et al. (2017), when the day period is absent, stomata (the pores found in the epidermis of leaves) close and carbohydrate levels become constant reflecting a continuous supply and utilization of the photosynthates. According to temperature variation, stomatal closing and opening reinstate the light flow. Under higher temperature conditions, the stomata are open and under lower temperature (dark conditions), the stomata are close. Moreover, heat pumps can be used as control devices for the relative humidity inside the cultivation room. In the published papers, heat
pumps are considered very beneficial for the control and maintenance of the temperature constancy inside an IUVF. One method of improving energy utilization efficiency and employing renewable energy sources is to use electricity-driven heat pumps instead of traditional combustion-based heating systems (Tong et al. 2012). The energy consumption is 25-65% lower in an IUVF with heat pumps as compared to a greenhouse with a conventional fuel heater. Furthermore, energy utilization efficiency of heat pumps is 1.3-2.6 times higher than the fossil fuel’s heater, and the CO2 emissions can be reduced by 56% to 79% in the cultivation compared to that of the conventional one. From a life cycle perspective, however, Al-Chalabi (2015) has found that in a recent pilot IUVF program in the UK, vertically grown produce has a carbon footprint that is much higher than conventionally grown produce, which generated energy from conventional sources of energy.

IUVF is a growing trend with a broad variety of typologies from high-tech to traditional and from private terraces to public gardens, which is expected to continue increasing in the future (Pons et al. 2015). Sanjuan-Delmás et al. (2018) demonstrate that compared to a conventional greenhouse, a high-tech PF has a better environmental performance, showing 50-75% lower impacts in impact categories, such as 0.58 kg of CO2 equivalent per kg of tomato vs. 1.7 kg, mainly due to the reduced packaging and transportation requirements. A significant percentage of the existing literature has shown test results from different hardware and technological equipment that can significantly improve energy efficiency, the cultivation techniques used in the growth area as well as the environmental control of the IUVFs. Fuldauer et al. (2018) present a method of nutrient recycling by dewatering effluents from anaerobic digesters (ADs) and applying the solid and liquid fractions of ADs from food waste in the urban environment as an alternative and innovative way. The results show a digestate enhancement from a dewatering system (gyrotary sifter coupled with a vertical hydroponic system) could be an economically feasible option to recycle nutrients of urban small-scale AD plants (with >30 L per day of digestate).

A large number of the publications refer to the different programming models that have been established to evaluate and improve the food production and energy consumption of PFs in the vegetable production market. The models tested (Janjai et al. 2010) have provided innovative methodology, framework, and a case study to analyse food-energy trade-off of IVF production in competitive vegetable markets. According to Huang (2018), the proposal for future programming models includes simulation of asymmetric firm competition in food markets, local food production, differentiation of energy demand, analysis of multiple markets and multiple PF production systems, and trade-off of transportation energy and climate-related production energy.

Several types of controllers have been developed, to improve the cultivation techniques in PFs and the environmental control. An example of such controller is that of Wahby (2015), who has presented a pioneering computer model for controlling the growth and motion of the plants inside a cultivation room. With this type of automation, a co-dependent and self-organised system is possible, with closely related symbiotic relationships, where plants support robots, and direct plant growth towards the desired areas.

Some of the papers (Siregar et al. 2016; Boulard et al. 2017) primarily focus on innovative hardware technologies that will lead to energy cost minimization through renewable energy and energy storage. These methods have resulted in immediately lower IUVF cultivation costs. The programs have been devoted to reduce energy costs through the use of facilities and equipment combined to reduce energy consumption. Various models have been studied in order to design the ideal microclimate conditions of cultivation inside the growth cabinet by testing the temperature, CO2, stomata conductance, and leaf photochemical efficiency (Janka et al. 2016). The approaches have varied from simple models and timer-based feedback controls to more advanced solutions such as model-free control strategies (Shamshiri et al. 2018; Zollner et al. 2004), nonlinear control methods (Shamshiri et al. 2018), adaptive control (Ferentinos et al. 2015) and adaptive management framework (Huang, L. 2018), robustness (Story et al., 2015; Janka et al., 2016), optimal control (Van Straten et al., 2010; van Beveren et al., 2015C; Fitz-Rodriguez et al., 2010), energy balance models (Katsuyuki et al. 2018), computer simulators (Pérez et al. 2014), and model-based predictive control (Ha et al. 2015; Zhang et al. 2015; Mahadi et al. 2017). Shamshiri (2018) has pointed out that a major disadvantage of utilizing advanced control methods in a controlled agricultural environment is the difficulty of developing a dynamic model to simulate the behavior of all the variables. Ultimately, the goal of any of these control systems is to minimize the input cost per production unit and increase return by achieving quality and high-yield production.

### 3.4 Cost demand

Many researchers have assessed urban agriculture from the aspects of profitability in various economic circumstances (Badami et al., 2015; Love et al. 2015, Shamshiri et al. 2018). One of the most important features of PFs is the lack of solar energy, which is free. This can cause problems with the financial feasibility of these systems as the productivity of their resources and/or the value of additional facilities must be in balance with this absence (Shamshiri et al. 2018). Due to the relatively higher economic investment required for PFs, they are managed with resource efficiency and production predictability to attain marketable crops.
Operational cost is one of the main problems in IUVF. Conventional greenhouses can cost around 11.39 EUR/m² (Becerril et al., 2016), and the production supplies, which include fertilizers, pesticides, etc., amount to almost 40% of the total costs (the productivity cost of a conventional greenhouse is 6 kg/m²). On the contrary, as pointed out by Kozi (2016), the annual productivity per m² (land area) of an existing PF is about 3,000 lettuce heads/m²/year (80-100 g fresh weight per head) compared to open fields [32 (= 16*2 harvests) heads/m²/ year]. In other words, the productivity of PFs is about 100 times more compared to open-field cultivations and about 15 times that of the greenhouse (200 heads/m²/year).

Hence, although results vary depending on multiple factors, the initial costs per unit production capacity of a well-established PF is approximately the same as with a high-tech greenhouse (with heaters, ventilators, thermal screens, and other equipment). According to Mendez Perez (2014), cultivation of crops such as corn and wheat is not suitable in PFs. This has been concluded by comparing and calculating the economic feasibility of PFs with conventional crop production as these type of crops require larger space that makes the financial plan unsustainable. In the same research it was stated that energy consumption costs of PFs will depend on the local utility’s reliance on coal and how much of its capacity has been converted into natural gas for electricity generation.

Love (2015) has stated that heat recovery provides thermal heat at a lower price than electric resistance heaters, is more efficient than propane, and improves the cooling performance of the refrigeration equipment.

Some of the publications have focused on the techno-economic values of PFs. More specifically, Liaros et al. (2016) note that cultivations with low daylight integral and high plant density crops are preferred in the case of PFs. Despite its high daylight integral, however, sweet basil has been found to be a viable cultivation option. As modeled by Benisa (2018), plants produced in soilless cultivation on rooftops have led to a positive net present value in terms of short food supply chains, where the yield is sold directly to the final consumer, providing a larger profitability margin to the producer. The study has showed that where higher energy requirements and higher investment costs over conventional horticulture are identified as significant constraints on the comprehensive implementation of conditioned PFs, crop productivity has played a crucial role in achieving environmental and economic viability of such facilities.

In a study by Namkung (2017), consumers’ willingness to pay more money for green practices in restaurants was investigated. Over the past few years, many restaurants in the US, Japan, and Australia have adopted green practices, following specific rules in order to be characterised as ‘green’ restaurants. The results of this study revealed that more than two-thirds of the restaurant customers (68.3%) are willing to pay extra money for green restaurant practices. 26% of the research respondents showed volition to pay up to 10% extra cost in order to dine in a green restaurant. Eco-companies utilize different renewable energy sources to reduce energy costs and CO2 emissions. According to Demicco et al. (2014) and Kozai (2016), there are already some excellent examples of applied IUVFs in eco-restaurants that use different approaches to modern cultivation with renewable energy supply. Organic food is served in eco-restaurants, and any waste is collected, classified, and recycled. Waste oils are delivered to biodiesel SMEs, and residual waste is sent to recycling plants for additional chemical treatments, converting the waste into composite materials. There are many examples of applied ideas of IUVF, and the need for new, efficient technologies for the exploitation of renewable forms of energy is of vital importance.

4 Conclusions

PFs are a new upcoming and very promising method of cultivation. Many successful companies and households around the world are beginning to use this technology to grow their own fresh vegetables in an ecological way and with as little CO2 emissions as possible. The ‘green’ agriculture is a sustainable way of producing leafy vegetables, fruits, and herbs, and PFs are one of the most beneficial options to meet the rising demand for organic and locally grown food. However, according to this literature review, there is a gap of information and data which still needs to be investigated. One of the most important factors that makes a new project and technology appealing to the public and the industry is the viability and prospective profitability. The cost of increased automation levels relative to increases in profitability is a key consideration, and should be included in a future study to justify the implementation of higher levels of automation. Based on the review, this study concludes that a more accurate economic analysis and justifications of the high start-up costs involved with IUVF and PFs are required before a large-scale commercial development. From an economic standpoint, we are well down the pathway to showing that VF cannot only be a reality but also profitable as an investment. Another important aspect of further research is the computer simulation models and adaptive analysis software tools already used. More research and developing groups need to focus on the extension of these programs, and modify the already existing ones for this specific purpose. Finally, it should be added that the energy demand and use of high-tech systems must be further explored to provide more sustainable and efficient systems that can produce a sufficient yield to meet consumers’ needs in the most eco-friendly way. The use and combination of renewable energy sources is one of the greatest improvements over the last decade and will be more than crucial for large-scale implementation in the water-food-energy nexus era.
Compliance with ethical standards

Conflict of interest The authors declared that they have no conflict of interest.

References


Mendez Perez, V. (2014). Study of the sustainability issues of food production using vertical farm methods in an urban environment within the state of Indiana. A Thesis Submitted to the Faculty of Purdue University In Partial Fulfillment of the Requirements (Master Thesis).


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