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Review

A Systematic Literature Review on Controlled-Environment Agriculture: How Vertical Farms and Greenhouses Can Influence the Sustainability and Footprint of Urban Microclimate with Local Food Production

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Abstract: The rapidly growing population and increasing urbanization have created the need to produce more food and transport it safely to urban areas where the majority of global consumers live. Open-field agriculture and food distribution systems have a lot of food waste, and, in parallel, the largest percentage of available arable land is already occupied. In most cases, food produced by compatible agricultural methods needs to be frozen and travel several miles until it reaches the consumer, with high amounts of greenhouse gas (GHG) emissions produced by this process, making it an unsustainable method with huge amounts of CO_2 emissions related with fresh food products. This research contains an extensive literature review based on 165 international publications (from 2006–2022) describing and analyzing the efficiency and impact of controlled-environment agriculture (CEA) methods, and more precisely, greenhouses (GHs) and vertical farms (VFs), in the environmental footprint of food production and consumption. Based on various publications, we could draw the conclusion that VFs could highly influence a greener transition to the sustainability of urban consumption with reduced CO_2 emissions sourcing from food transportation and limited post-harvest processes. However, there is a significant demand for further energy efficiency, specifically when it comes to artificial lighting operations inside VFs. A large-scale implementation of VFs that operate with renewable energy sources (RES) could lead to significant urban decarbonization by providing the opportunity for integrated energy–food nexus systems. Under this direction, VFs could optimize the way that cities interact with meeting the food and energy demand in densely urbanized areas.

Keywords: greenhouses; vertical farms; energy demand; renewable energy sources; resource use efficiency; GHG emissions; sustainability

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1. Introduction

Crops' cultivation for food production originates almost 10,000 years, when the process was the same as now, seed was planted in nutrient-rich soils, seedlings were irrigated until they grew, crops were harvested and finally food was delivered to people for consumption [1]. Historically, the process of agriculture showed people that through cooperative treatments of arable land, they could obtain high yields and provide food for the community's demand. Meeting the food needs has helped human societies to better organize, coexist and escalate their population to the creation of today's big cities [2]. However, the continuous increase in the global population and the already occupied large area of arable land has created disproportions in the ratio of arable land per person, signifying the inability to cover the constantly increasing global food demand [3]. According to many reports, the world's population is estimated to reach over 9 billion by the year 2050 and about 70% will live in urban areas [4–6]. Increased human activity in urban areas causes excess heat in the atmosphere, and in addition, creates a greater demand for food and waste management in specific and intense populated areas, which greatly enhances greenhouse gas emissions [7].

Along with the challenge of meeting the required food demand, the world is facing many other problems. Specifically, the increasing use of fossil fuels, environmental pollution, pollution of the limited available water basins and unusual, unpredictable and severe weather phenomena, and at the same time, an increasing demand for safer food (which peaked after the outbreak of COVID-19) [8,9]. Compatible crops have limited harvests over the year and often are destroyed by weather conditions. Stable crops also require large amounts of water and fertilizers where most of them drain into the aquifer, contaminating it. Taking into consideration the disadvantages of the growing methods of compatible crops and the increasing food demand, the shift to more advanced and precise food production methods known as controlled environment agriculture (CEA) has become more urgent now than ever [10,11].

The term CEA refers to systems where crops are protected from external weather conditions and that have the ability to control, monitor and regulate the microclimate of the cultivation area in order to produce greater yields that are more stable under year-round productions [2,5]. CEA systems have advanced technological equipment and sensors for complete monitoring of the growing unit, automations and actuators to maintain uniform and desirable environmental conditions with better energy management. The use of wireless communication systems and Internet of Things (IoT) creates a communication bridge between hardware and user for important and real-time decision making [12–15].

The most common CEA systems are under coverage production systems such as greenhouses (GHs) and vertical farms (VFs). GHs use solar radiation for photosynthesis and in many cases are the main source of heating, whereas VFs use artificial lighting (AL), which also provides space heating [16,17]. VFs, compared to GHs, utilize the vertical orientation with multiple stacked layers of growing area in order to maximize yield production per m^2 of cultivation area and can be installed in a wide variety of facilities and sizes, such as warehouses, containers, abandoned buildings, etc. [18,19]. Both systems mainly use soilless cultivation methods, where water savings could reach up to 70–95% compared to conventional farming [10,19,20]. GHs are usually installed at a distance from urban areas, whereas VFs can be installed in urban or peri-urban areas, thus significantly decreasing food miles and CO_2 emissions due to transportation and reducing food waste from the food supply chain [1].

The purpose of this study is to present a more comprehensive review about GH and VF facilities, including their operation, the resource use efficiency they perform and the GHG emissions that are related with both advanced and under-coverage production systems. At the moment, GHs consist of one of the main production methods globally, mainly for fresh vegetable production, leafy greeneries and small fruits. In contrast, VFs are a novel agricultural method gaining a lot of attention, and are under development and optimization, with multiple case applications all over the world. The goal of this research is to identify the key opportunities and challenges that are related with the sustainability footprint of the two CEA production methods and address and assess the issues that are associated with food production, transportation and maintenance in order for urban citizens to have access to healthy, safe and sustainable food sources for their daily diets. Additionally, in this review are discussed and explored the key factors that are related with CO_2 emission in CEA agriculture and key actions that could further optimize their impact in both society and the environment at the same time.

2. Methodology

The current study is a systematic literature review on greenhouses and vertical farms and the influence they could have on the urban environment and citizens. Qualitative data were chosen for assessment and analysis concerning the current status of controlled-environment agricultural practices, and more specifically, greenhouses and vertical farms.

The study used keywords for the evaluation and determination of the relevant scientific literature related to: ''greenhouses", ''vertical farms", ''energy demand", renewable energy sources", ''resource use efficiency", "GHG emissions" and "sustainability". The keywords selection provided a more holistic and up-to-date research field concerning the topic and the conducted study. Firstly, scientific literature was mainly retrieved from the databases of Google Scholar, Scopus and Science Direct. Secondly, a comprehensive literature review was conducted based on the collected literature, which consists of 165 publications from 2006 to 2022, of which 92 of them refer to GHs, 54 refer to VFs and 9 refer to both of them, including 124 scientific journal papers, 6 book chapters, 4 books, 17 conference papers, 11 reports, 2 sites and 1 thesis. This review provides information about GH and VF installations, their necessary equipment for climate control and the applied cultivation methods. Additionally, it focuses on the systems that demand energy inputs in both GHs and VFs for optimal operation. Information about resource use efficiency of GHs and VFs is discussed and evaluated. Finally, qualitative data of previous publications are categorized under 5 main topics and further discussion explores the presented findings. The 5 topics are a general categorization for the areas covered by the publications and concerns: (1) operational systems (including information about structure, cladding material, shape, insulation, irrigation systems, etc.), (2) environmental conditions (temperature, relative humidity, CO_2, VPD and light), (3) energy demand, (4) renewable energy sources (RES), (5) resource use efficiency (RUE). Figure 1 illustrates the numbers of publications that are related with the greenhouses and vertical farms and how many publications reflect each of the 5 different topics of this research, as well as including references to GHG emissions. Additionally, in the pie charts we can observe the combination in the literature between the keywords that were used in this research and how often they have been met in this study. In this direction, it is easier to withdraw information concerning the interest and trends of research in the field. Therefore, it becomes clear that for VFs, the scientific research mainly focused on presenting innovative and optimized operational systems and achieving and maintaining uniform climate conditions, but there was also a high interest concerning RUE and the opportunities and challenges that characterize this agricultural method. On the contrary, for GHs, we observe that the majority of publications focused on designing and optimizing the operational systems, developing equipment and systems and the acquisition of indoor environmental conditions, and there is a limited interest on RUE and RES integration for a greener operation of these CEA systems.

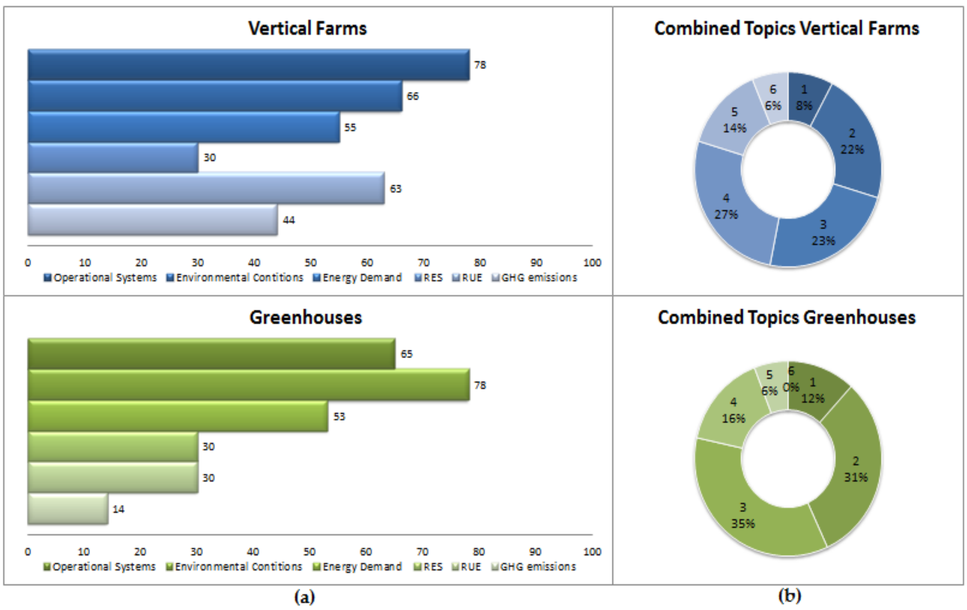

Figure 1. (**a**) Percentage for every topic mentioned in the literature and (**b**) percentage of combined topics for GHs and VFs.

3. Analysis

The transition of plant cultivation in indoor environments where the growing climate is controlled and adapted at desired conditions is referred to as CEA. The development of such systems aims to increase production volumes with the utilization of smaller areas than traditional open-field farming. The cultivation inside CEA systems is independent from external conditions and can be installed close to urban or peri-urban areas in order to contribute to reduced food miles and CO_2 emissions sourcing from transportation [1]. According to Despommier [20], the implementation of these systems can benefit the growing urban population by producing fresh food and allows the ecosystem's restoration by liberating agricultural areas. He also mentions a number of advantages over conventional agriculture such as the ability to produce crops all year round and the use of hydroponics and aeroponics systems, which can save big amounts of fresh water. Furthermore, in closed-loop systems, irrigation water is collected and reused, crops are fully protected from external weather conditions and there is no need for herbicides, fertilizers and pesticides due to the protected and controlled area of plant growth, which at the same time ensures better food safety.

Following, there is a thorough description of GHs and VFs, in order to evaluate their facilities, their operation energy demand, the applied RES and the resource use efficiency in these CEA systems.

3.1. Operational Systems

3.1.1. Structures

Greenhouses

The GH is a (semi-)controlled environment construction which uses solar energy for the photosynthesis of plants as well as for heating purposes [21]. The shape, orientation and cladding materials of a GHs are crucial factors for sunlight utilization and the adequate natural ventilation of the structure. GHs should be constructed and covered with light translucent cover materials so that enough light falls on the plants even in times when sunlight is limited in the sky. This can happen in areas where there is not enough sunshine all year round or for certain months where there is limited sunshine (mainly in northern countries). In contrast, some GHs are located in areas with high levels of sunlight or are used for special crops that demand high daily radiation for growth and development. In these cases, it is necessary to use shading materials that reduce light intensity [22]. In cases where the temperature drops below the ideal growth conditions, GHs are equipped with heating systems that provide immediate heat in the growing environment. In addition, as the thermal insulation of the GH cover material increases, the energy consumption for heating decreases. During periods with high temperatures, heat loads are released via cooling systems or simply by natural ventilation [23].

In general, advanced GH constructions include necessary technologies that ensure plant growing conditions are maintained at ideal conditions throughout the year for maximization of production volumes. Thus, the entire construction of the GH has to provide good sunlight permeability, low levels of heat losses, the capability of heat provision when it is required and ventilation system/s, and all of them should be supported by strong and durable materials [24–26].

The main factors that have to be taken into consideration when designing a GH in order for it to function effectively and have a long lifespan are presented below.

<u>Climate conditions of the outdoor environment</u>: When designing a GH, the external conditions must be taken into consideration, as they highly affect not only the internal conditions but also the stability of the building itself and its cladding materials [26]. Proper evaluation of the external conditions when choosing construction materials and the location of the GH could prevent damages from strong winds and degradation from strong sunlight, heavy hail or snow [27]. Moreover, a knowledge of weather conditions is important for the selection of the appropriate heating and cooling system that can meet crop needs even in the most adverse conditions [28].

Loads: This category includes all the loads that the construction of the GH has to withstand. These loads may be due to external factors such as storms, rain, hail, snow and seismic activity [26,29]. Other loads concern the weight of the construction itself and cladding materials, and more complex loads, such as wires, lighting, heating, cooling, irrigation systems, shading screens, thermal screens and loads from crops that require vertical development (such as tomatoes, cucumbers, peppers, etc.) [27,30].

Type and Shape: Based on the cover material, GHs could be divided into three main types: glass, rigid plastic and plastic GHs with flexible cover material [27,31]. Glass and rigid plastic GHs have longer lifespans and are usually very technologically advanced. The frames of these types are usually made of galvanized steel or aluminum, whereas for GHs that apply flexible cover materials, the frame is mainly wood, aluminum, PVC pipes or galvanized steel and can be constructed in a variety of shapes [25]. The shape of GHs directly affects the good diffusion of air due to ventilation, and therefore the uniformity in the microclimate that is formed inside. The proper shape of the GH roof can maximize the capture of solar energy, thus reducing the heating demand when it is needed [32]. Regarding the construction design, the most typical GHs in central and northern Europe are Venlo types, mainly made with metal frames, whereas in Spain and southern Europe is the Parral type, due to cheap and easy construction [27,33,34]. GHs could be single or multi-span and the most common shapes are: even-span, uneven-span, gothic, arch and quonset [35].

Cladding materials: The climate created inside the GH is greatly influenced by the properties of cladding materials. The upper purpose of the cover materials is to maximize the transmissibility of light radiation, which consists of the following main spectra ranges: ultraviolet (UV) (100–400 nm), visible part of the spectrum (400–700 nm) and near-infrared radiation (NIR) (700–2500 nm). From the mentioned spectra ranges, 400–700 nm refers also to photosynthetic active radiation (PAR), which is the one that is mainly absorbed by plants, and is responsible for activating the process of photosynthesis and consequently plant growth [36].

Glass is preferred due to the high transmission performance of PAR, reflectance of NIR, low transmission of UV light, durability and long lifespan, but glasshouses have greater heat losses [34,37]. Plastic films are easy to handle as they are very flexible and have low cost and lower heat loss compared to glass, but their main disadvantage is their short lifespan. Rigid panels can be made out of silica glass, polyvinyl chloride, fiber glass-reinforced plastic, acrylic and polycarbonate. The rigid panels are characterized by good light transmission in the PAR part of the spectrum, low transmission of UV radiation and good thermal insulation. Their disadvantage is that they tend to collect dust, and the fiberglass turns yellow over time, resulting in reduced solar permeability [38,39].

The properties of cladding materials mainly concern the absorption or reflection of NIR parts, which are responsible for increasing temperature inside GHs, transmitting the plant growth spectrum, blocking UV radiation, reducing the accumulation of dust and moisture condensation. Usually, plastic films with specific pigments are selected for changing the spectrum ratio and materials and preserving the ability to convert direct sunlight into diffused for deeper penetration into the plant canopy. A typical example of GHs made out of plastic cladding materials with cooling properties are in tropical and subtropical regions, where temperatures inside GHs can reach values greater than the tolerable range for plant growth, due to high levels of external radiation [40,41]. Other cover materials such as thermal screens focus on reducing heat loss [42], insect-proof screens are used to prevent insects from entering the GH, thus reducing the use of chemical treatments and shading curtains are used to reduce the intensity of light when required [43,44].

Orientation: Regarding the orientation of the GH, an important design factor is also the latitude of the location, as the solar orbit and the intensity of radiation change throughout the year. Several studies have examined the effect of orientation on the GH microclimate and plant growth and they concluded that E-W orientation achieves greater collection of solar radiation and reduces heating requirements [45–47].

Vertical Farms

The term vertical farming refers to an indoor cultivation system that uses AL for plant growth and multiple stacked layers with vertical orientation, which increases the cultivation area. These systems range from very small mobile systems to very sophisticated systems in high-rise buildings for large-scale food production [17]. VFs could be divided into the following categories [18,19,48]:

1. Adaptive reusable buildings: Abandoned buildings, factories, warehouses, parking lots where they are no longer used; the existing building environment could be adjusted with the necessary equipment to accommodate a VF.
2. Plant factories with AL (PFAL): Innovative structures or devoted buildings designed specifically to support VFs for industrial scale production.
3. Containers: Modified shipping containers equipped with vertical stacking shelves, LED lights and digitally monitored management systems. Containers are a very popular type of VF as they can be easily relocated or even stacked on top of another container; therefore, the use of already occupied space is maximized.
4. In-store farm: Small-size cabinet systems, located in places of direct consumption or purchase, such as restaurants, bars or supermarkets.
5. Appliance farm: Small-scale VF construction intended for installation into the home or office.
6. Deep farms: VFs located in underground tunnels, such as subway stations that are no longer in use or abandoned mineshafts.
7. Balconies and rooftops: Flat areas of the buildings' roofs and balconies that are used for simplified or more complex VF techniques.

Vertical farms consist of closed and controlled growing facilities, as mentioned above. For this reason, the structure and the selected operational elements of the farm mainly depend on the business model and not on the external weather conditions of the facility. The majority of farms usually install basic technology systems for indoor climate uniformity (light, fans, AC) and due to the high level of thermal insulation, the indoor cultivation climate can be adjusted depending on the desired levels for each crop.

VFs are closed production systems that meet certain requirements in terms of growth area to provide a safe and controlled environment for crops, safe food production line, lower CO_2 emissions and maximized resource use efficiency. In order for VFs to be considered a closed cultivation system and satisfy the above-mentioned parameters, the cultivation and installation area should be properly designed to fulfill the hygiene requirements and be technologically equipped in order to control and maintain the environmental conditions at desired levels. The main elements in a VF system are shown schematically in Figure 2 and concern:

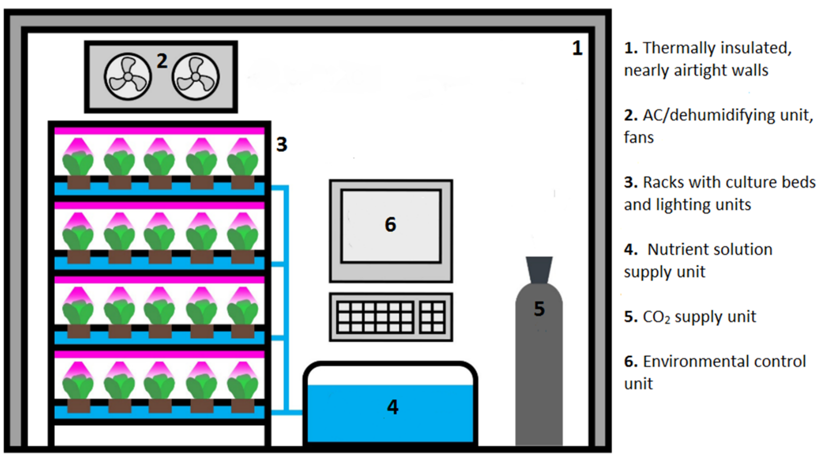

Figure 2. Main elements of a typical VF [18].

Thermally insulated walls: VFs are mainly located in buildings or warehouses and the walls surrounding them have good insulation and are opaque, in order to preserve a high isolation level of indoor crops from the external weather conditions [49]. The estimation of how well-insulated a building is, can be defined by the R-value, as the higher the R-value, the better the insulation level of the building [50]. Indicatively, for a single-glass GH, the R-value is 0.95, whereas for warehouse with 8.89 cm fiberglass batt insulation, the R-value is 13 [51].

Air conditioning unit: Inside the cultivation area of VFs, air conditioning (AC) systems or heat pumps are installed mainly to reduce the heat caused by lamps' operation. Additionally, dehumidification is necessary in order to remove the moisture added to the air due to the irrigation and the evapotranspiration from plants. Air heating is not necessary due to the latent heat released by the lighting system, except in certain cases where the recirculating air may need to be heated. In addition, VFs usually have cooling panels in the AC systems, which condense the transpiration water from recycling and reuse by the irrigation system. Another important part is the fans used for the air circulation and target uniformity of air distribution in order to improve photosynthesis and transpiration [6,52].

Cultivation racks: VFs consist of multiple layers of plants in vertical shelves or horizontal columns, thus maximizing the utilization of the available cultivation area. Shelves are equipped with AL and irrigation systems with water tanks and nutrient solution for plants, and the multilayer system usually has between 4 to 15 rows or columns, with a distance of approximately 40 cm between the shelves, depending on the size of the selected crops [53–55]. Racks are made of steel to withstand the increased weight of the lighting system. Lighting recipes are a complex topic as multiple researchers and companies aim to optimize the different light dimensions (quality, quantity and duration of light) in order to boost growth and development rate of plants with the least possible cost (high light-use efficiency). For this reason, there are a wide range of lighting solutions in the market targeting different crops, different growth stages, and of course, various impacts in the quality characteristics of plants (light can influence secondary metabolites, color, taste, aroma, etc.). LED lamps are mainly preferred for their lower amounts of heat production, which consequently reduces the cooling demand in the VFs and maximizes the number of installed shelves, since they can be placed in shorter distances between each other [56]. Another way to improve the spatial distribution of light and distribute it through the canopy surface is with the use of reflectors on the upper surface of each shelf [57,58].

Nutrient solution supply unit: Nutrient solution is supplied by hydroponics or aeroponics systems, where the drainage water follows a closed loop and returns to the central tank with the nutrient solution in order to be recycled and reused. The main components of the nutrient solution supply unit are: a nutrient solution tank, a pump, tubes for distribution of the nutrient solution, a returning system to the tank and an air pump when the plant roots are permanently dipped in the water (deep flow technique) [6,59]. Prior to reusing water with the nutrient solution, the sterilization is of vital importance in order to avoid pathogen transport to crops, which is usually achieved through ultraviolet light, membrane filters and biofilters [49].

CO_2 supply unit: An important factor for the efficient operation of a vertical farm is the CO_2 supply unit, which maintains the levels of CO_2 at around 800–1000 ppm when the lamps are on, in order to promote the process of photosynthesis. A CO_2 supply unit consist of a pure CO_2 tank, gas valves and distribution pipes [8].

Environmental control: The control unit is connected with sensors placed in the culture area in order to record and monitor the prevailing climate conditions. Important elements for monitor and control are the following: air temperature, CO_2 concentration, relative humidity, light intensity, air flow, CO_2 supply rate and parameters of the nutrient solution such as pH, electrical conductivity (EC), temperature, oxygen, water supply rate and circulating nutrient solution flow rate. Additionally, sensors measuring environmental conditions are also installed in the center of the in the cultivation area of the VF, and at some strategic locations, such as at shelf level in order to monitor the microclimate of the growing shelves and evaluate climate uniformity [18,52].

Each VF has separate areas which serve specific purposes and vary depending on the size of the unit. In general, a typical VF has areas for sowing, and seeds remain there until the stage of germination, when they are transferred to another room for the nursery stage, with a controlled environment that promotes their growth. Finally, young plants are placed in the main cultivation room, where they remain until harvest. Before the entry of the staff into the cultivation area, small rooms with sterilized air showers and hand washing ensure food safety and eliminate disease transmission to crops. Inside the cultivation room there are areas used for tool disinfection by workers and areas used for plant processing such as trimming damaged leaves, weighing and packing. Finally, there is a room right next to the growing area for cooling the packaged leaves and a last room for shipping [52,55].

3.1.2. Irrigation Systems

The irrigation system is a crucial factor for all CEA systems as it feeds plants with nutrients and water, and increases indoor humidity. Poor management can cause transmission of crops' infections, increase costs due to water waste and nutrient solution and contaminate the environment if the used irrigation water is discharged into it [60].

Hydroponics refers to systems that allow plants to grow on an off-soil substrate or in direct solution with water and nutrients [34]. Substrates used instead of soil can be of organic or inorganic origin and the most widely used are rock wool, perlite, peat, coir and zeolite, which have the ability to retain water and nutrients and also provide increased oxygen availability in the root zone [60]. The most commonly used substrate hydroponics systems are [61]:

<u>Pot method</u>: The crop is growing in clay or plastic pots with inert substrate and irrigation is mainly with a micro-sprinkler attached inside the pot.

<u>Grow bag method</u>: White bags of 1–1.5 m, filled with sterilized substrate and UV resistant, are used for 2–3 plants, placed at small holes on the upper surface and irrigated mainly with a micro-sprinkler.

The most common liquid solution culture methods are listed below [52]:

<u>Nutrient film technique (NFT)</u>: Roots are mostly in the air while their lowest part comes into contact with a continuous flow of nutrient solution 2–3 cm high, which passes through the channel where the roots are located and ends in a drainage tank from which it is recycled with the help of a pump.

<u>Deep flow technique (DFT)</u>: Plants are usually placed in a panel, which floats on top of the nutrient solution, which is constantly recycled with the help of a water pump, while sometimes an additional air pump is used to supply oxygen to the roots, which are permanently immersed in the solution.

<u>Ebb and flow system</u>: Plants are placed either in pots or in rock wool cubes, which can retain moisture for a few hours, and with the help of a pump, the level of the nutrient rises to come into contact with the substrate and then it goes down again, and this cycle is repeated at specific times each day.

<u>Wicking method</u>: A wick rope is in contact with the nutrient solution tank below the growth area, transfers water to the root system through capillary effect and does not require energy consumption.

The required elements that should be provided along with water during irrigation are divided into macro-nutrients and micro-nutrients. The most important of the required elements are nitrogen, phosphorus and potassium. Important factors that should be measured before irrigation are the electrical conductivity (EC) and pH of the nutrient solution, with ideal values of around 1.5 to 2.5 dSm^{-1} for EC and 5.6 to 6.5 for pH [62].

Greenhouses

Depending on the management of irrigated water, GHs could be categorized as open-type (the drained water is not collected for reuse and usually refers to soil-based crops), in semi-closed loop systems (the drained nutrient solution is collected in a tank but part of the nutrients and water is reused while another part is discarded) and in closed-loop systems (high-tech automations add the exact amounts of fresh water and nutrient solutions to the drainage tank so that it can be reused in the same proportions as the original nutrient solution) [63]. In semi-closed and closed loop systems, it is necessary to use filtration and disinfection systems for the nutrient solution before its recirculation to avoid transmissions of pathogens to the crop [60].

The applied irrigation system depends on the type of substrate used. The most commonly applied method for GHs is drip irrigation with the use of a pipe located above the surface of the substrate. Other systems applied mainly in soil-based GHs are furrow, plastic film mulching and sprinkler irrigation systems [64].

Vertical Farms

The most common applied hydroponic methods inside VFs are NFT, DFT, ebb and flow and drip irrigation systems for cultivations in pots with substrate [18,65]. VFs can also apply aeroponic systems, where plants' roots hang freely from the surface that supports the plants in a closed and protected environment. Nutrients and water are supplied to the roots through spray systems at regular intervals to keep the roots moist while the nutrient solution draining from the roots is re-collected in a tank and reused [66].

Type of Crops in Greenhouses and Vertical Farms

GHs: The most common types of hydroponic GH crops are cereals such as rice, maize and wheat, vegetables such as tomato, cucumber, lettuce and pepper, fruits such as strawberries and melons, fodder crops such as sorghum and grass, many types of flowers, condiments such as oregano and mints and medical crops such as aloe and coleus [62].

VFs: The environmental conditions in a VF can be adapted to the needs of each crop, so theoretically almost any cultivar could be selected for a VF. However, factors such as growth height, growth cycles and purchase price have led the cultivation of specific crops such as leafy greens, herbs, berries (strawberries, blueberries, raspberries), cherry tomatoes, cucumbers and microgreens to be the most financially viable options [6]. According to Kozai et al. [55], the most suitable plants for production on a VF are those with mature plants in less than 60 days, small height and growth at light intensity of about 100–300 µmol $m^{-2}s^{-1}$.

3.2. Environmental Conditions

CEA systems can create and preserve uniform climatic conditions throughout the year and achieve higher yields compared to traditional farming methods [13]. In order to maintain uniform environmental conditions with as little energy waste as possible, factors such as temperature, relative humidity (RH%), vapor pressure deficit (VPD), CO_2 levels and light radiation have to be monitored and the appropriate actions performed when necessary [13,24,67].

3.2.1. Greenhouses

The main systems that are used to create the required climatic conditions inside the GH are presented below.

Temperature control: Temperature inside the GH can be regulated by advanced heating/cooling systems or by simple ventilation, which directly highly depends on the deviation of the outside temperature from the desired indoor [68].

A reduction in excess heat is achieved through three basic methods: shading to reduce the incoming radiation, ventilation and evaporative cooling. The main shading techniques consist of whitewashing of the roof, use of external shading cloths, colored nets, water film over the roof, liquid foam on the walls of the GHs, blinds and reflector sheets [69]. Ventilation is divided into two main categories, natural or passive ventilation and mechanical or forced ventilation. To achieve natural ventilation, GHs have vents on the sides, on the roof or a combination of both [70]. Mechanical ventilation is achieved with fans on one side of the GH and openings on the opposite side [13]. Evaporative cooling is the most efficient method compare to the other two types because is the only method that can lower the temperature inside GHs to levels lower than the outside temperature and the applied methods are: fog systems, fan-pad system and roof evaporative cooling [69]. The fog system sprays small drops of water with high air pressure over the surface of the plants [71]. In the fan-pad system, the outside air enters the GH, passing through wet pads. In the roof evaporative cooling method, water is sprayed on the roof surface creating a thin layer of water and therefore a higher evaporation rate due to the bigger surface of free water in the atmosphere [72].

The methods used to increase the temperature in the GH are divided into two categories: active heating and passive heating. The main active heating systems are mainly categorized into heating systems with hot water pipes, which are placed near the crop, hot air heating systems and heating systems with infrared radiation [73]. Passive heating systems use solar energy to store heat in various materials such as water, rock bed and phase change materials during the day and release heat during the night when the temperature in the GH has dropped. Other ways of passive heating are with the use of mobile insulation or use of energy storage materials in the north wall of the GH (in GHs with E-W orientation) [74]. Various heating or cooling systems can be combined for greater efficiency in temperature regulation [68].

Relative humidity (RH%) control: The main reason that causes raises in RH% is plant transpiration and it is important to control it in order to avoid condensation on the inner surfaces of the GH, which favors the growth of fungi and diseases that affect plants. However, when relative humidity is below a certain level it could cause plant water stress, which reduces the growth rate of plants [12]. The most common methods for reducing RH% are ventilation, anti-drip covering materials, air-to-air heat exchangers, chilled water condensation chemical dehumidification and mechanical dehumidification, whereas increases in humidity are usually achieved with fog systems or with the use of shading curtains [13,68].

Vapor pressure deficit (VPD) control: VPD is an important indicator for determining the property of air and depends on humidity. VPD refers to the difference between the actual air pressure and the saturated air pressure. It is the main parameter for the movement of water between the plants' roots and leaves and can be used to assess the possible development of diseases, concentration capacity and irrigation demand [75]. Low values of VPD are equivalent to high values of humidity in the atmosphere. The development of mismanagement of humidity in the interior of the GH may lead to undesirable appearance of diseases, whereas on the contrary for high values of VPD there is low humidity in the atmosphere, which promotes a high transpiration rate of plants [76]. According to Shamshiri et al. [77], a range of VPD between 0.5 to 1 kPa is satisfactory for most crops, and the value of VPD can be adjusted by ventilation, fog systems and humidification or dehumidification systems depending on the needs of the crop [24].

Carbon dioxide (CO_2) control: The concentration of CO_2 in the growing environment directly affects the rate of photosynthesis of plants, and therefore the growth rate [12]. Consumption of CO_2 during the process of photosynthesis causes a reduction in the percentage of carbon dioxide inside GHs, which leads to the creation of a pressure deficit with ambient air [78]. According to Jin et al. [79], the optimal content of CO_2 for the growth of plants is about 1000 ppm; however, air CO_2 concentration is about 400 ppm and during the day can be lower than 150 ppm inside the GH.

The main methods for CO_2 enrichment inside the GH are through natural or mechanical ventilation, with compost from crop residues or animal manure, exhaust gas from fossil fuels or RES and from pure liquefied CO_2 [79,80]. Other techniques suggest the use of specialized absorbents that trap CO_2 from the ambient air and inject it into the GH environment [81,82].

Light control: GHs usually have systems for photoperiod regulation depending on the crop needs [83]. The daily light integral (DLI) refers to the amount of photons of PAR per square meter (m^{-2}) per day (d^{-1}) or mol m^{-2} d^{-1} of PAR, and each plant has its own ideal values for each growth stage. DLI is a function of photosynthetic photon flux density (PPFD) (µmol m^{-2} s^{-1}) and photoperiod; the daily measurement of its value in GHs helps to perform the appropriate interventions to maintain its value at a desired level [84].

Supplementary artificial lighting (AL) or shading is used to adjust the photoperiod inside GHs. The lamps used for AL are mainly light-emitting diodes (LED) and fluorescent bulbs [83]. In recent years, lighting emitting diodes (LEDs) have more application due to the ability to adjust their operating intensity, their immediate performance as soon as they are powered by electricity, their long lifespan and their ability to deliver specific wavelengths [85]. In contrast, in hot and sunny areas, shading the GH is a method used both to reduce the temperature and to regulate the intensity of incoming radiation. Shading is achieved through whitewash shading, thermal screens and movable plastic nets [86].

3.2.2. Vertical Farms

For control and maintenance of the required air and root environment zone, VFs are equipped with the necessary sensors, automations and monitoring and activation systems at all stages of cultivation. Technology hardware is interconnected via wireless communication systems and IoT in order to create a communication bridge between those systems and the user [14,15]. Data inputs are collected to computer controllers, and, through user commands or through automations, the operation of respective system is activated when necessary. These systems mainly concern the activation of the lighting, cooling system, ventilation, recirculating fans, dehumidification system, nutrient solution controller, pumps and CO_2 supplier [87,88].

The optimal climate conditions that promote yield production are different for each crop, and Kozai et al. [55] states that an average value of CO_2 of about 1000 ppm and a horizontal air velocity of 0.3–0.5 ms^{-1} in the growing area cause is beneficial for good diffusion of CO_2 and moisture into the leaf area of the plants. Furthermore, a ventilation rate of 0.01–0.02 h^{-1} for well-insulated and airtight VFs is desirable to avoid pathogens, pests and the development of large amounts of ethylene where it may be harmful [5]. Carotti et al. [89], in their lettuce growth experiments, observed highest efficiency at PPFD of 200 µmol $m^{-2}s^{-1}$, 24 °C air temperature, 28 °C root zone temperature with a constant CO_2 concentration of 1200 ppm, vapor pressure deficit of 0.58 and 0.34 kPa under light and dark cycles, respectively, and 16 h photoperiod.

3.3. Energy Demand

Energy requirements in CEA systems are related to the maintenance of optimal indoor microclimatic conditions for plant growth, crop productivity and formation of conditions in off-season periods [90]. Many crops are very sensitive to sudden changes in the environment. For this reason, ensuring a reliable and stable energy source is essential for avoiding crop damages due to power outages [16]. Electricity, fossil fuels, natural gas and RES are used to control the conditions of the indoor environment, and their consumption depends on various factors, such as latitude, climate, cultivation practices, crops, design and technological equipment [83,91].

3.3.1. Greenhouses

For GHs the highest energy requirements are consumed for heating and cooling purposes. Heating is mainly provided by burning fossil fuels such as diesel, coal, wood fuel, fuel oil, liquefied natural gas and liquefied petroleum, which are related with high CO_2 emissions [92]. According to Tong et al. [93], it is necessary for the GH industry to reduce the use of fossil fuels for energy production as CO_2 emissions are very high, and they mention two ways: Firstly, it is the design of energy-saving GHs that present less energy requirements and losses. The second way is to improve energy efficiency and use

RES instead of fossil fuels that are directly related to CO_2 emissions. One proposed method is the replacement of traditional heating systems with electric heat pumps. From their experiments, the hourly consumption for heating with a heat pump was 0.22–0.56 MJm^{-2} and with kerosene heater it was from 0.42–0.76 MJ m^{-2}, while the corresponding hourly CO_2 emissions were from 9.5–24 g m^{-2} and 31–55 g m^{-2}, respectively.

The energy consumed for heating and cooling can be 65–85% of the total energy requirements in a GH. It has been clarified that the total annual energy needs in southern Europe can number 220–320 MJm^{-2} while for northern Europe this value rises up to 3600 MJm^{-2} [94,95].

Another important factor of energy consumption in GHs is the use of supplementary AL. Crops grown during winter months or in Northern latitudes may not meet their daily light demand, and supplemental lighting is often necessary [96]. The use of electricity for supplementary lighting can consist of up to 30% of the energy demand of a GH, and in some cases the cost of AL can rival with the cost of heating and cooling [91,97].

The next category of energy consumption in a GH concerns the electrical consumption of mechanical equipment and automations. However, the energy demands for these systems are very small compared to the microclimate control systems. Many times, the use of RES to meet all or part of the energy needs of these systems is an environmentally and economically attractive option, especially in areas where electricity is unavailable or unreliable [83,98].

Heating/Cooling: In order to make correct estimations, all heat transfer parameters that offer heat gain or heat losses in the system must be taken into account. During winter months when the outside temperature is lower than the GH's, the most common causes of heat loss are due to convection and conduction [99,100]. Important parameters to take into consideration when calculating the thermal balance are heat losses from air exchanges, long-wave radiation heat losses, perimeter and floor heat losses and heat losses due to plant evapotranspiration. The most important parameters that provide thermal gain into the system are CO_2 generators, supplemental lighting, solar radiation, motors and recirculating fans [101,102].

Ahamed et al. [102] found from their simulations that during the coldest months, solar radiation contributed about 44–64% of the total heating requirements whereas during the summer months it was about 83–86%. From the other systems of a GH, thermal gains were about 13–56% of the annual demand for heating, specifically, supplementary lighting with HPS lamps provided about 38%, CO_2 about 6.5% and recirculating fans contributed about 3.8%. It was mentioned that about 40% of the total heat was lost by convection and conduction, followed by heat losses via infiltration at 32% and long-wave radiation at 21%, whereas thermal losses through evapotranspiration from plants were about 9% during cold months.

Tataraki et al. [103] collected the available daily meteorological data from all European countries from 2008–2018 and conducted simulations for heating and cooling demands with the use of a combined cooling, heat and power (CCHP) system. According to their results, the northern countries had higher heating demands, with three of them (Sweden, Finland and Estonia) exceeding the value of 600 kWh $m^{-2}y^{-1}$ and the rest ranging between 200 and 600 kWh $m^{-2}y^{-1}$, whereas four of the southern countries (Spain, Portugal, Greece and Cyprus) had heating demands under 200 kWh $m^{-2}y^{-1}$ (Table 1).

Technological equipment: The required sensors that every GH has are temperature, humidity, CO_2, light and substrate moisture sensors as well as sensors for recording the outside weather. The described sensors (apart from substrate moisture level) are usually placed in the center of the GH and at edge points without equal distances, in order to provide a more well-distributed depiction and the minimum possible variation of the microclimate profile inside the GH [104,105]. Many intelligent monitoring systems have been developed in order to better understand crop needs, achieve better energy savings and emission reduction results, predict extreme environmental conditions, make timely decisions to maintain indoor conditions, reduce diseases and reduce pests and the use of pesticides and fertilizers for higher food production. In recent years, several IoT communication protocols were used towards this purpose [12]. The controlling systems of GHs have actuator devices for heating, cooling, ventilation, fans, humidifiers, dehumidifiers, curtains, light bulbs, CO_2 supply valves, water and nutrition pumps so that an action can be automated when its execution is deemed necessary by the system [105].

Motors and Pumps: Motors used inside GHs mainly concern functions such as opening windows or roof vents, screen motors for shading and motors for the operation of fans. Pumps are mainly used for irrigation and fertilization, for circulation of water in heating systems, for supplying water into cooling systems such as fog or fan-pad systems or in cases with double plastic cladding material for air supply in the interval of the two plastics [95,106].

Table 1. Energy demand for operation systems of a GH.

Category	Type	Energy Consumption or Operating Power	GH Characteristics	Location	Source
Heating	Gas	≈383 kWh m^{-2} y^{-1}	Four-span gable roof, double-layer PE film, 1125 m^2, tomatoes,	Simulation, (Saskatoon, Canada)	[102]
Heating	Natural gas, coal, heavy oil	≈549 kWh m^{-2} y^{-1}	Venlo-type, double-layer PE film, 81,000 m^2, peppers, h = 3.2 Wm^{-2} °C^{-1}	Leamington (Ontario, Canada)	[107]
Heating	Coal	≈100–291 kWh m^{-2} y^{-1}	Gothic roof, plastic-covered, 10,003 m^2	Simulation (5 regions of southern coast of Turkey)	[108]
Heating	Gas	≈412 kWh m^{-2} y^{-1}	Venlo-type, glass, 10,000 m^2, h = 5.7 Wm^{-2} °C^{-1}	Simulation (Sweden)	[21]
Heating	Gas	≈144 kWh m^{-2} y^{-1}	Venlo-type, glass, 10,000 m^2, h = 5.7 Wm^{-2} °C^{-1}	Simulation (Netherlands)	[21]
Cooling	Fan-pads, circulation fans	11.9 kWh total consumption	Glass, multi-span, 2304 m^2	Shanghai (Southeast China)	[72]
Cooling	Natural ventilation, fogging system	≈185 kWh m^{-2} y^{-1} (sensible cooling)	Venlo-type, glass, 10,000 m^2, h = 5.7 Wm^{-2} °C^{-1}	Simulation (United Arab Emirates)	[21]
Cooling	Natural ventilation, fogging system, heat exchanger, air-cooled chiller	≈700 kWh m^{-2} y^{-1} (dehumidification) ≈844 kWh m^{-2} y^{-1} (sensible cooling)	Venlo-type, glass, 10,000 m^2, h = 5.7 Wm^{-2} °C^{-1}	Simulation (Netherlands)	[21]
Lighting	HPS lamps	≈206 kWh m^{-2} y^{-1}	Venlo-type, glass, 10,000 m^2, h = 5.7 Wm^{-2} °C^{-1}	Simulation (Sweden)	[21]
Lighting	600 W HPS lamps	90 Wm^{-2} for 48 μ$molm^{-2}s^{-1}$, 54 Wm^{-2} for 24 μ$molm^{-2}s^{-1}$	≈75 m^2 compartment in GH	University of Aarhus (Denmark)	[109]
Lighting	HPS lamps, LEDs	19,578 kWh (HPS) and 4697 (LEDs) for five months	Glass, two different light treatments in ≈18 m^2 each, tomatoes	West Lafayette (USA)	[110]
Ventilation	Fan motor	≈9.7 kWh m^{-2} (from March to October)	Glass, 500 m^2	South-West Greece	[111]
Irrigation	Pump water from deep wells	≈s3 kWh m^{-2}	26 GHs study, average 2000 m^2, basil	Esfahan (Iran)	[112]

h = heat transfer coefficient (Wm^{-2} °C^{-1}).

3.3.2. Vertical Farms

Photosynthesis in VFs is based entirely on AL, thus leading to significant increases in energy demand. In addition, the high planting density and increased number of bulbs in limited spaces create growing conditions that require further energy consumption to cover the operation of the ventilation, cooling and dehumidification systems [113]. In large-scale VFs from 5000 m^2 floor area and above, automations for seedling, transplanting, packaging and even transporting within the farms have major significance. Large-scale VFs may also apply autonomous elevators capable of crop irrigation and inspection via cameras, in order to reduce labor cost but under increased energy demand requirements [52,114]. In a typical VF, the predominant cause of energy consumption is sourcing from AL operation, which represents approximately 60% of total energy demand. The energy consumption for cooling, dehumidification, ventilation and water pumps is lower, percentages vary according to the occasion and some indicative values are approximately 30, 10, 10 and 20%, respectively [115–117]. Finally, lower amounts of electricity are demanded for the operation of sensors, computers and actuators, and in some cases for heating [115,118]. Table 2 shows the energy demand of different operating systems inside a VF.

Table 2. Energy demand for operation systems of a VF.

Category	Type	Energy Consumption	Production Area	Location of VF	Sources
Lighting	600 W HPS lamps	1374 kWh m^{-2} y^{-1}	506 m^2	Simulation	[4]
Lighting	LED (250 μmol m^{-2} s^{-1} light intensity)	560 kWh m^{-2} y^{-1}	1296 m^2	Simulation (Netherlands)	[117]
Lighting	LEDs	26,490 kWh y^{-1} for 60,000 plants' production	N/A	Basement of an urban residential building in Stockholm	[119]
Lighting	LED (500 μmol m^{-2} s^{-1} light intensity)	≈1128 kWh m^{-2} y^{-1}	50,000 m^2	Simulation (Sweden)	[21]
Cooling	HVAC (forced circulation), fancoil unit, air-cooled chiller	≈86 kWh m^{-2} y^{-1} (Sensible cooling) ≈506 kWh m^{-2} y^{-1} (LED cooling)	50,000 m^2	Simulation (Sweden)	[21]
Cooling	HVAC system	≈48 kWh m^{-2} y^{-1}	1891 m^2	Simulation (Riyadh, Saudi Arabia)	[120]
Cooling	Chiller	≈404 kWh m^{-2} y^{-1}	1712 m^2	Simulation (Minneapolis, USA, cold-humid climate)	[118]
Heating	Natural gas boiler	≈932 kWh m^{-2} y^{-1}	1712 m^2	Simulation (Minneapolis, USA, cold-humid climate)	[118]
Heating	HVAC system	≈29 kWh m^{-2} y^{-1}	1891 m^2	Simulation (Seattle, USA)	[120]
Dehumidification	HVAC system	≈222 kWh m^{-2} y^{-1}	50,000 m^2	Simulation (Sweden)	[21]
Dehumidification	HVAC system	370 kWh m^{-2} y^{-1}	1296 m^2	Simulation (United Arab Emirates)	[117]
Irrigation	Pump	≈18 kWh m^{-2} y^{-1}	506 m^2	Simulation	[4]
Irrigation	Pump	2190 kWh y^{-1} for 60,000 plants' production	N/A	Basement of an urban residential building in Stockholm	[119]

Several studies have been conducted on developing and optimizing methods for further reduction in energy demand in VF systems. The main focus of research targets the development of more efficient and suitable LED lights for indoor horticulture, use of smart monitoring systems that optimize the operation of climate control equipment, automations for reductions in labor costs and more precise cultivation protocols for increased yield and quality. Finally, significant research exploits the usage of RES to limit the operating costs and reduce the environmental footprint of the farms [5,87,88,121–124].

3.4. Renewable Energy Sources (RES)

The increasing prices of fossil fuels as well as the high price of electricity have made more urgent the necessity of developing energy savings strategies and using alternative energy sources for GHs' operation. In order to meet the energy demand and at the same time reduce energy dependence on fossil fuels and GH gas emissions, energy sources such as solar, wind, geothermal and biomass are utilized [125].

Solar energy is the most widespread and abundant RES that has been successfully used for heating and electricity generation. One way to harness solar energy is by heating various materials such as water, rock beds and phase change materials during the day, and they release the absorbed heat during the night [74]. Another way is by using photovoltaic (PV) panels for electricity generation, which are suitable in areas where there is enough sunshine and in areas where they are away from the electricity grid or for direct heating of liquids that pass through pipes and are stored in a tank in order to heat the crop through the heating system [126,127]. Voulgaraki and Papadakis [128] and Yildirim and Bilir [129] found in their simulations that PV panels can meet more than 40% of the thermal requirements of GHs. Perez-Alonso et al. [130] attached 24 flexible thin film modules to the cover of a 1024 m^2 GH located in Almeria, Spain, which covered approximately 10% of the roof surface, and showed that the yearly electricity production was 8.25 kWh m^{-2}.

Geothermal heating and cooling systems use components to extract heat from ground, ground water and surface water sources and use it for GH energy needs. The temperature inside the ground is almost constant over time in order to be used for cooling in summer, where the ambient temperature is higher and for heating in winter, where it is lower. Such systems consist of grounded pipe systems that form the grounding system, a heat pump and a heat distribution system and are usually known as ground-source heat pumps (GSHPs) [125]. Aljubury and Ridha [131] used ground water in an indirect-direct evaporative cooling unit for cooling a 5 m^2 experimental GH, with one indirect evaporative cooling heat exchanger and three pads for direct evaporative cooling, and observed a decrease in GH temperature of about 12.1–21.6 °C and an about 8–62% increase in relative humidity. Chai et al. [132] reported that the daily costs for heating a Chinese solar GH and a glass covered multi-span GH in Beijing, China, with a GSHP system, were 8.9% and 12.9%, respectively, lower than a gas-fired heating system, and CO_2 emissions were decreased by 41.9% and 44.6%, respectively, compared to a coal-fired heating system.

Wind energy that is generated by the movement of air masses from areas with high atmospheric pressure to neighboring areas of lower pressure, at speeds depending on pressure difference, can be converted into electricity using wind turbines [92]. Vox et al. [127] concluded from their tests, that with an average yearly wind velocity of 2.6 ms^{-1}, a 1 kW wind turbine could produce an average daily value of 0.53 kWh of electricity, whereas in Ozgener's [133] experiments a 1.5 kW wind turbine was able to meet 3.13% of the annual energy needs. Shahbazi et al. [134] found from their experiments that a wind turbine with 10 kW output power could generate an output power of 2394.2 W and supply 10 fog pumps.

Biomass is a renewable and sustainable energy source that can reduce CO_2 emissions compared to fossil fuels [135]. Biomass combustion boilers use biomass with low moisture content, which can be either in its raw form or in the form of pellets, briquettes, chips, etc., for heat and CO_2 production. Generated heat is used by the heating system to heat the GH while the produced CO_2 can be used for enrichment purposes [136]. Sanchez-Molina et al. [78] developed a biomass-based boiler system, which used commercial almond shells, wood pellets, pine and olive pits as a fuel and recovered CO_2 from flue gases in order to enrich an 877 m^2 polyethylene cover GH.

Combinations of RES to meet the energy requirements of CEA have also been studied, such as the example of Esen and Yuksel [137] where they designed a solar, biogas and GSHP system for providing the energy demands of a 24 m^2 polycarbonate cover GH located in Turkey. In addition, Anifantis et al. [138] developed a mathematical model in order to analyze the energy efficiency of a combined heating system consisting of a PV panel (8.2 kW), a GSHP (2.2 kW) and a hydrogen generation plant (2.5 kW) for heating a 48 m^2 tunnel-type GH in southern Italy.

In the case of VFs, the necessity for RES integration is even greater as their production depends entirely on energy consumption, especially for the most important factor which is to provide the necessary quantity and quality of the light spectrum. According to Teo and Go [139], the estimated annual energy consumption per m^2 of a VF in Malaysia is about 3500 $kWhy^{-1}$.

The main RES used in VFs are based on the utilization of solar radiation through solar panels, wind energy using wind turbines, hydroelectric power generation, biomass, biofuels and geothermal energy [3,140]. The development of renewable energy systems has led to the use of electricity-based technologies, such as heat pumps, which consume 25–65% less energy compared to a fuel-fired unit and at the same time reduce carbon dioxide emissions by 56–79% [54].

The building facility of a VF can be enriched with integrated PV panels for the production of electricity in order to meet part of the energy demand requirements and also sell excessive electricity loads to the grid when it is in surplus or not in use at the time [141,142]. Another option is the installation of batteries that store the electricity generated by the PV panels (or other forms of RES) and use it in times with no electricity generation due to insufficient sunshine or any other limiting factor [143]. Xydis et al. [144] carried out a case study for the installation of a wind farm where the generated electricity would be used to power indoor hydroponics units, thus reducing energy consumption from the grid that is based on fossil fuel power and therefore reducing the environmental impact of the farm.

3.5. Resource Use Efficiency (RUE)

The term RUE, for any type of cultivation, mainly refers to the amount of inputs used per unit area or for the production of 1 kg of either fresh or dry biomass. Important inputs for the sustainable operation of a CEA system are the required amounts for water and nutrients, land use and production in the corresponding area, lighting and energy consumption, CO_2 use per kg of biomass, CO_2 emissions and other variables which refer to labor, food traveling and processing [53,143,145]. CEA systems aim to maximize RUE in order to reduce the production cost, increase yield per unit area with optimized use of resources, reduce CO_2 equivalents and, in general, evaluate the sustainability status of the production systems [1,146,147].

The comparison of RUE between GHs and VFs is very complex to conduct accurately since factors such as technological equipment, cover materials, latitude and integration with RES can significantly affect the efficiency of the system and the demanded amount of resources. Therefore, only an approximate estimation has been conducted based on previous studies. Table 3 presents the results of different resources usage between GHs and VFs for lettuce production.

Table 3. Resource use efficiency of GHs and VFs.

Resources	GH	Sources	VF	Sources
Energy	4.5–10.5 kWh kg_{FW}^{-1}	[145]	15.6–20.4 kWh kg_{FW}^{-1}	[145]
Water	≈10–20 L kg_{FW}^{-1}	[21]	1 L kg_{FW}^{-1}	[21]
Light	Sunlight and supplementary lighting		AL	
Yield	41 kg m^{-2} y^{-1}	[10]	150 kg m^{-2} y^{-1}	[148]
Land use	365 days per year	[149]	365 days per year	[149]

Table 3. *Cont.*

Resources	GH	Sources	VF	Sources
Harvests	6–7 per year	[149]	8–12 per year	[149]
CO_2 use	≈14–26 kg_{CO2} $kg_{DW}{}^{-1}$	[21]	≈2.1 kg_{CO2} $kg_{DW}{}^{-1}$	[21]
CO_2 utilization efficiency	Loses 0.31–0.35 kg_{CO2} $kg_{FW}{}^{-1}$	[145]	0.87 (N = 0.01 h^{-1})	[53]
CO_2 emissions	(a) 0.574 kg_{CO2} $kg_{FW}{}^{-1}$ (conventional GH) (b) 0.352 kg_{CO2} $kg_{FW}{}^{-1}$ (advanced GH)	[150]	(c) 5.7 kg_{CO2} $kg_{FW}{}^{-1}$ (conventional VF) (d) 0.158 kg_{CO2} $kg_{FW}{}^{-1}$ (green VF)	[150]
Pesticide	Use of insect screens for reducing pesticide applications	[43]	No use (due to sterilized cultivation environment)	[53]

kgFW = Kilogram of fresh weight. kgDW = Kilogram of dry weight. N = Number of air changes. (a) Non-RES use and located outside urban areas, (b) located in peripheral of urban areas and use of RES, (c) non-RES use, (d) use of RES.

As shown in Table 3, VFs are quite efficient in terms of yield production per unit area compared to GHs; however, they require larger amounts of energy inputs for their operation. Reducing energy demand and developing systems that consume less energy is essential in order for VFs become more sustainable. However, both GHs and VFs are much more efficient in use of resources compared to field crops, as large amounts of water (≈250 L m^{-2} y^{-1}) and fertilizer drain end up in the aquifer. At the same time, yields produced in fields are significantly lower (≈3.9 kg m^{-2} y^{-1} for lettuce) and they present limited harvests per year (≈2 for lettuce), compared to GHs and VFs which can obtain approximately 41 and 150 kg $m^{-2}y^{-1}$, respectively, with multiple harvests per year [10,149]. Regarding CO_2 emissions sourcing from CEA food production, VFs present the highest values equal to 5.7 $kg_{CO2}kg_{FW}{}^{-1}$ and the majority is due to energy consumption. In GHs, CO_2 emissions accounts about 0.574 $kg_{CO2}kg_{FW}{}^{-1}$, whereas in open field farms, emissions are approximately 0.540 $kg_{CO2}kg_{FW}{}^{-1}$. In cases where RES are used to support energy demand, CO_2 is significantly reduced for VFs and is approximately 3.5 times lower than open-field production, whereas for GHs it is 1.5 times lower than open fields. The CO_2 emissions of those 3 production systems associated with RUE include types of fertilizers (organic or inorganic) and machinery used (mainly in open fields), and a big percentage out of it is sourced from food transportation, refrigeration demand and food waste. This mainly concerns open field productions, and, to a lesser extent, GHs, as they are closer to urban areas and foods travel shorter distances [150].

Plawecki et al. [151] compared CO_2 emissions for lettuce production between an unheated GH close to the consumer market and an open-field production, where lettuce was refrigerated and transported for 3605 km. According to their results, the CO_2 emissions kg per kg of lettuce were 0.198 for GH production and 0.857 for farm production, with 78% of the CO_2 emissions sourcing from truck use and electricity demand for refrigeration. They concluded that local lettuce production could reduce CO_2 emissions by 4.3 times, and at the same time consumers would buy fresher food. Astee and Kishnani [152] reported in their study that 95% of the vegetables consumed in Singapore are imported and travel a distance from 350–3600 km, while the estimated CO_2 emissions due to transport are about 28,401 tons. Their studies showed that if building roofs were used for vegetable production with VF methods, they could have satisfied the country's demand by 35.5% and CO_2 emissions could have been decreased by 9052 tons annually by reduced imports. VFs cultivations within urban areas and for local production have significant advantages compare to both open-field productions and GHs, as food travels from zero to a few km, implying no need for refrigeration, and food losses are minimized until the final consumer [2].

4. Discussion

Population growth and tendencies to live in urban areas are facts that occur and are difficult to control. Population growth implies an increase in anthropogenic activity, which burdens the environment through many means, such as the need to produce more food, all intermediate systems between the production site and the consumer, and generally anything that works to serve human needs and is based on energy consumption for its operation [146,153].

The intense urbanization observed in recent years has caused the loss of large areas of agricultural land around the cities, which are constantly expanding [154]. Along with the expansion of cities is implied an increase in buildings, roads and vehicles either for the personal use of people or for the transport of goods and products that serve human needs. All the intense human activity leads to large quantities of fuel and energy consumption in limited spaces, resulting in high urban pollution. The above-mentioned parameters contribute to the creation of the phenomenon known as urban heat island (UHI), in which there are excess air temperatures over urban areas and their surroundings as well as increased air pollution, which is quite harmful for human health [7,155]. The UHI does not only reflect the increasing spatial temperature inside an urban or peri-urban area. Urban microclimate is highly influenced by different types, sizes and localizations of buildings and it may have different effects depending on the building's matter and energy footprint. Nevertheless, the urban microclimate does not only alter with actions inside the city but also with actions outside of it. Based on previous research and studies, leading actions and interpretation of VFs and advanced CEA systems could lead to unified and more efficient energy–food nexuses that are specifically designed to cover the local demand and are based on specific cases of urban environment.

Another factor contributing to urban air pollution is the daily increasing arrival of refrigerated trucks into cities for food distribution. This high rate is caused by the gradual desertion of rural areas due to urbanization and the growing food demand in urban areas [154,155]. At the same time, the Food and Agriculture Organization of the United Nations (FAO) (FAOSTAT 2020) [156] states that worldwide calories consumption per capita per day has increased by 7% from 2000 to 2018 to approx. 2870 kcal, which means that more food is required to cover the population needs. Therefore, the higher population in the urban areas creates additional requirements for the collection and management of human waste, contributing to the increase of the UHI phenomenon.

According to the FAO (FAOSTAT 2020) [156], the global requirements of average nutritional energy per inhabitant per day has been steadily growing over the last few years, but the arable land per capita from 2018 has decreased worldwide by 15% since 2000 and corresponds to about 0.21 ha per capita. At the same time, the FAO states that the use of chemical fertilizers has increased by 40% since 2000 and the total of fertilizers used in 2018 was 188 million tons. Simultaneously, the world is facing challenges posed by climate change and the inability to exploit further arable land due to erosion or adverse weather conditions, while about 80% of the available arable land has already been utilized [6,20,157]. Despommier [158] characteristically stated that if farming techniques continue as they are, in 2050 arable land the size of Brazil (1 billion ha) will be necessary to meet global food demand.

The increasing need for food distribution in cities has an impact not only on the micro-environment of urban areas but also on the environment in general, as food travels many km until it reaches its final destination. Food miles refer to the distance that crops travel from the cultivation point to the consumer. In most cases, crops travel several km and need to be stored in special packages and often refrigerated in order to be preserved until they reach their destination. Especially in cases where the weather does not favor the cultivation or food is not produced locally, crops are imported from other countries, thus greatly increasing the miles they need to travel from farm till fork [157]. In addition to the fuels consumed in traditional farming methods for agricultural operations, food transport includes trucks, ships and airplanes, which consume large amounts of fuels both for food transportation and preservation via cooling methods [6,20]. Even for crops from large GH facilities, the distance requirements for food traveling could be several miles in order to reach urban centers [1]. For example, Benis et al. [2] presented data for 4 megacities (Lisbon, Singapore, Paris and New York) (above 10 million inhabitants) about their demand for fresh tomatoes (kg capita^{-1}y^{-1}). According to their results, Singapore and Paris imported 100% of their needs, Lisbon 86% and New York 91%, with their imports mainly sourcing from open fields and GHs, and travel distance was calculated between 556 and 3260 km. In addition, the estimated CO_2 emissions associated with irrigation, energy demand of operational systems and transportation, as CO_2 equivalents, varies from 1.033 to 3.857 $kg_{CO2}kg_{FW}{}^{-1}$.

Regarding food exports and imports, the FAO (FAOSTAT 2020) [156] states that the monetary value of global food exports in 2018 was about 1.38 trillion USD whereas in 2000 it was 380 billion USD, with vegetables and fruits accounting for the largest share of exported food, equal to 23%. The corresponding price for imported food was approximately 1.46 trillion USD. According to the FAO (FAOSTAT 2013) [159], about 1/3 of the produced food in the world is lost or wasted while in terms of arable land, food waste accounts for 28% of the total agricultural land. Approximately 3.6 $GtCO_2$ was the carbon footprint from food waste in 2011 and it represented about 8% of total anthropogenic GHG emissions, whereas the 2012 market value for food wastes was USD 936 billion (FAOSTAT 2015) [160]. In the European Union (EU), in 2012, 88 million tons of food waste were generated and the corresponding cost was around 143 billion euros. The food produced in EU for 2011 was around 865 kg per capita and the food waste 173 kg per capita, meaning that about 20% of the food produced was wasted [161]. The latest estimates from the United Nations Environment Program (UNEP) (2021) [162] indicate that in 2019 about 931 million tons of food waste were generated. Vegetables contribute to over 20% of the carbon footprint from food waste and are second in the list, with cereals to be the first, contributing 36%. In the total food wastes, about 25% were vegetable waste, with the highest amount from the other commodities (FAOSTAT 2015) [160]. The same report states that about 64% of food losses occurs during agricultural production, post-harvest handling, storage, processing and distribution phases and the rest at the consumption phase, which means that about 2/3 of food waste occurs in the interval of production site and the consumer.

In contrast, crops cultivated in VFs within urban areas are transported only for a few miles until they reach their destination with no need for cooling. There are also cases of super-local productions where VF facilities have supermarkets inside, transportation demand is eliminated and the consumers have access to hyper-fresh food [163]. Food production in urban areas not only reduces direct CO_2 emissions from transportation vehicles, but also reduces the indirect CO_2 equivalents related to food waste during the stages mentioned earlier, as there is minimal food post-harvesting treatment. Installing GHs closer to urban areas is another solution that could also contribute to reduced food wastes and CO_2 emissions, and thus make food production more environmentally friendly. Another important advantage of local and fresh food production by CEA systems is the high food security and safety, as these products are free from pathogens that develop during post-harvest management (transport, refrigeration, storage, etc.) [1,2,164].

The major disadvantage of these two CEA systems is the higher energy consumption for their operation (especially for VFs), and therefore the increased GHG emissions when the energy comes from fossil fuels or natural gas. Several studies focus on the development and optimization of energy saving strategies and better management of energy consumption as well as passive systems that release heat that has been accumulated during the day. Typical examples used in GHs for energy savings are well-designed cladding materials, either for more sunlight diffusion or for permeability to specific wavelengths. In this direction, overheating in their interior can be avoided. Additionally, heat storage into water or phase change materials and materials with greater thermal insulation are used to reduce energy demands for heating [21,74].

Food requirements for the growing population are something that could be achieved by intensifying CEA systems, but it is also necessary to accomplish it in an environmentally friendly way. The implementation of these cultivation systems and the simultaneous development and use of RES could become the solution for more sustainable urbanization. As presented in Table 3, the usage of RES could greatly reduce CO_2 emissions (about 97% in the case of VFs) in CEA. In the coming years, large-scale and small-scale RES applications within cities, such as PV panels on the roofs of buildings, utilization of waste for biogas and biofuel production etc., could lead to integrated green systems. Labrador et al. [165] mentioned batteries' use for the storage of excess electricity generated by PV panels, which could consequently be distributed to other VFs through fuzzy logic control, to improve power consumption and reduce the carbon footprint. Al-Kodmany [157] mentioned in his work already existing CEA systems that use biogas produced from organic waste for heating, CO_2 enrichment and electricity production, while plant residues are recycled by biogas facilities. Other CEAs implement systems for recycling, reusing and composting both the water used by the building they are located at and the plant residues, thus contributing significantly to the discharge of the city's recycling system [146].

In addition to RES, new systems and methods for maximizing the utilization of inputs and energy sources under a more efficient production should be developed. Focused research on CEA improvements could not only increase their efficiency and production volumes, but also reduce the environmental impact and improve the atmosphere in urban areas. For example, developing more efficient LED lamps could reduce energy consumption of VFs and/or the development of more efficient circular and co-cultivation systems in GHs could optimize their efficiency and reduce their waste. Improving the efficiency of heat exchanges could lead to reduced air temperature levels inside the VF and consequently reduced energy demand and CO_2 emissions. Instead of using artificial CO_2 supply units in VFs, suitable air filtration systems could be further developed to provide natural ventilation and the use of CO_2 carbon honeycombs could enhance CO_2 capture from ambient air and thus enrich the VF cultivation area.

Finally, advanced CEA systems with total control of the environmental parameters present high resilience by working under hybrid system solutions that can perform as load flexibility units, such as electric vehicles and heat pumps in the modern grids. To be more specific, VF units integrated with photovoltaics, wind turbines and storage units could cooperate under unified platforms. Under this scope, autonomous and fully-controlled CEA farms can work more efficiently as subunits of the energy grid systems by fully exploiting the use of the curtailed and/or to-be-rejected power that can be stored and allocated for the production needs of the urban farms for local leafy production [166]. In this direction, VFs could operate under intermittent lighting schedules, and, by shifting the energy demand response, could significantly reduce their energy footprint, enhancing the sustainability status of indoor food production within the cities.

5. Conclusions

The growing population and the increasing need to produce more food should be addressed through environmentally friendly methods, as it is already highly contaminated by human activity and traditional agricultural methods. At the same time, more advanced and controlled food production systems are necessary in larger applications with less wastes and no pathogens. From this conducted literature review about the two CEA systems, GHs and VFs, could be inferred the following conclusions:

- CEA systems enhance the capability of producing large quantities of food all year round, without being affected by external conditions, by applying advanced technology for desired and uniform indoor climate conditions.
- Intense urbanization and urban densification are significant challenges that have a negative impact on regional sustainability and simultaneously have an important role in the energy matter flow and balance, and in general, the global energy.
- The capability of VFs to be installed in indoor spaces and close to the consumers creates a big opportunity for local food production that significantly influence the decarbonization of cities and food losses due to transportation and refrigeration, downscaling the UHI phenomenon that is observed in urban areas. A large-scale deployment of VFs in highly urbanized areas would be translated to million tons of CO_2 savings worldwide.

- Simulation models would provide a meaningful insight to quantify accurately the CO_2 equivalents and the energy consumption in VFs in order to evaluate their impact on the green sustainable agenda. In that way, it would be possible to accurately examine the net emissions that are generated or saved, and more precise actions could improve these bottlenecks. There is still demand for more measuring data and metrics that could evaluate and track the performance of specific quantifiable metrics for the activities and operations of VFs that could consequently improve the resources efficiency and manage the carbon footprint in urban areas towards a sustainable development agenda.

A combination of the existing agricultural systems seems to be the most efficient solution by applying smart and IoT tools and RES collaboration in order to minimize the energy demand and lead vertical farming to a greener transition for local fresh food production. Under this scope, VFs could become in the upcoming years significant players in the circular economy in urban areas, assisting in the alleviation of GHG emissions and heat in urban areas related with food production and consumption. However, VFs still have to optimize their challenges in terms of resource use efficiency and sustainability under operating with renewable energy sources to power their technological components. For this reason, further research on integrated models of VF operation and optimization of the light efficiency achieved with more efficient LED combined with advanced and precise lighting protocols is necessary.

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Abbreviations

The following abbreviations are used in this paper.

GHG	Greenhouse gas	EC	Electrical conductivity
CEA	Controlled-environment agriculture	NFT	Nutrient film technique
GH	greenhouse	DFT	Deep flow technique
VF	Vertical farm	E-W	East-west
AL	Artificial lighting	VPD	Vapor pressure deficit
RES	Renewable energy source	CCHP	Combined cooling, heat and power
PAR	Photosynthetic active radiation	PPFD	Photosynthetic photon flux density
NIR	Near-infrared radiation	DLI	Daily light integral
UV	ultraviolet	HVAC	Heating, ventilation and air conditioning
PFAL	Plant factory with artificial lighting	GSHP	Ground-source heat pumps
AC	Air-conditioning	UHI	Urban heat island

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