Sustainability Perspectives of Organic Farming and Plant Factory Systems—From Divergences towards Synergies

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1. Introduction

With the exponential growth of the global human population reaching 10 billion by 2050 [1], the demand for foods is increasing by 60% [2]. If food consumption of humankind increases the way it is now, 10^9 hectares of natural ecosystems will be converted for agricultural use by 2050. This habitat destruction generates conflicts between agricultural food, feed and energy crop production, and urbanization [3,4], causing unprecedented ecosystem simplification [5]. Conventional land cultivation contributes to climate change by increasing soil carbon release to the atmosphere [6]. Weather extremities cause serious losses, reaching ~1% average decrease in plant-based food calories (~3.5×10^{13} kcal/year) which would lead to a severe situation in food-insecure countries [7,8].
It seems to be evident that conventional, soil-based open-field agriculture is unsustainable, as it uses excess amounts of water and agrochemicals [9,10]. Agriculture as a whole is responsible for 70% of global freshwater demand, and requires 34% of global land surfaces [11,12] in order to provide the world’s population with adequate amounts of food. Agrochemical overuse is responsible for the pollution of the environment, which ultimately impacts the economy and society on a local and global scale as well [13,14].

Therefore, the interest is turning to technologies that decouple plant production from natural ecosystems in terms of land use, seasonality, and weather fluctuations. A conventional solution for these issues can be controlled environment agriculture (CEA); within this broad term, plant factories (PF), synonymously called vertical farming (VF) systems in Europe [15], possess high space utilization efficiency, have independence from natural ecosystems, and have less impact on the environment [16]. Although it seems totally opposing, plant factories and organic farming (OF) share a common effort in creating a closed system, use reusable or recyclable materials, minimize water and energy inputs, and reduce the usage of synthetic chemicals (fertilizers, herbicides, and pesticides), while OF excludes them entirely. However, they are trying to achieve this very similar goal with a completely opposite approach, one with integrating plant production into the natural ecosystem and the other with the artificialization of growth factors [17]. Disconnecting plants and living ecosystems, however, seems to be a life-changing step on a historical scale, which fundamentally changes everything we currently know about agriculture.

Researchers have posited that environmental degradation might have been the main reason behind the disintegration of several ancient cultures [18–20]. Furthermore, every social (including agricultural and industrial) transformation was partly or mainly induced by environmental issues in the past [19].

The world demands innovations, or at least changes, from the actors of the food chain. The digital transformation of agriculture called Agriculture 4.0 [21,22] has become reality. Authors characterize it with a list of the most cutting-edge technologies that already proved their existence in small-scale or experimental environments. These technologies include PFs, aquaculture, aeroponics, cultured meat, microalgae, the Internet of Things, sensor technologies, autonomous plant production units, big data, drones, and artificial intelligence, among others. Agriculture 4.0 is further characterized as a game-changing innovation [23] and a cross-cutting step [24], as it impacts society, the economy, and agriculture and induces substantial transformations in the traditional human–environment–food relations. This disruptive technological change has the potential to replace previous practices due to its unequivocally superior nature [25]. These technologies can make human interception totally unnecessary (or very limited) in agriculture. According to Sinha [25], these technologies “will (…) free up farmers” and replace low-skilled labor with tech companies who will “probably do it much cheaper and faster.” PFs have higher skilled labor requirements than conventional agriculture [26,27]. This also contributes to the dismissal of unskilled workers, especially in rural areas, where the situation of employment is more vulnerable.

Transparency is identified as one of the key elements of digital transformation in general to ensure connectivity among the actors along the food chain [23,28]. Free information flow supports the willingness of farmers to introduce digital innovations in their own food production systems. On the other hand, knowledge about proper environmental settings, such as optimized light parameters (light recipes), can be realized as a market advantage; therefore, the intention of high-tech agricultural firms to share such information is rather limited. The compatibility of good practices is further limited by the site-specific characteristics of PFs [26]. However, although reasonable, agro-industrial concealments do not enhance global food security, and this further supports the assumption that such technological innovations are available only for developed countries, where food surpluses already cause issues [29].

Following the considerable costs of investments worldwide estimated at over 1 billion USD [26], intelligent solutions are already operating both in PF facilities and in organic
production units. According to policy makers, agricultural digitalization has priority on a global scale, as the EU Commission Report called “The Future of Food and Farming” declares connecting farmers to the digital economy as its main aim in order to progress towards sustainable food production and farming [30]. The Horizon 2020 framework provides EUR 1 billion of funding sources for agricultural digitalization in the EU [31]. The Common Agricultural Policy (CAP) of the European Union (EU) aims to enhance the EU’s agricultural competitiveness through various forms of funding. Since 2014, in addition to supporting intensification CAP has been expanded to include a growing number of programs aimed at reducing the negative impacts of agriculture. Farmers have obliged to reduce chemical use and adopt good farming practices in exchange for subsidies. In the period of 2023–2027, in line with the Green Deal the goal is the increase in the share of organic areas in the EU [32–34]. Although soil-based open-field agriculture seems to be pushed into the background in the light of high-tech PFs, it is important to bear in mind that the production of the ten crops produced on the biggest surfaces worldwide—wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), rice (*Oryza sativa* L.), soybeans (*Glycine max* L.), barley (*Hordeum vulgare* L.), sorghum (*Sorghum* sp.), rapeseed (*Brassica napus* L.), dry beans (*Phaseolus vulgaris* L.), cotton seed (*Gossypium* sp.), and millet (*Panicum* sp.) [11]—is not suitable for or not profitable under indoor circumstances. Moreover, to take the vegetable or special crop production indoors and therefore remove these crops from outdoor production would decrease farmers’ ability to diversify their crop rotations. Today, both OF and PF production are considered sustainable; these systems are suggested to be competitors of each other for the future of agriculture, and hence in ensuring global food safety. However, neither system is capable of covering the sophisticated dietary needs of the increasing world population in today’s consumption patterns.

The aim of this review is to investigate divergencies and synergies of OF and PF systems in view of the sustainability perspective. The interpretations of sustainability in OF versus PF are discussed, both on a theoretical and practical level, choosing growing media, plant species use, and socio-economical aspects as the main contrasting factors of these systems. Additionally, the regulatory background of OF and PF systems is clarified. Based on the aims of the sustainability perspective, the following hypotheses were identified:

- H1: OF and PF systems are competitive with each other due to their main characteristics; they possess diverging developmental directions.
- H2: The legislation of OF on a global scale does not allow for a transition between OF and PF systems.
- H3: There are no alternative growing media which are compatible with the preferences of both OF and PF systems; therefore, the legislative barrier is insurmountable.
- H4: There are no sharp boundaries among OF and PF systems regarding the profitable production of plant species and varieties.
- H5: Local food production provides broader perspectives for OF systems and is less relevant for PFs.
- H6: Consumers prefer OF products over PF products.
- H7: Both OF and PF systems can be considered as sustainable.

The outlined hypotheses form the fundamental structure of this paper.

2. Materials and Methods

Systematic search queries were conducted in the ScienceDirect and MDPI databases, as well as Google Scholar, to identify key articles regarding the assessment of sustainability in OF and PF systems, either individually or comparatively. A prioritization was given to experiments and reviews focusing on the selected subtopics of the current review, including growing media use, plant species and variety use, regulatory background, and socio-economic perspectives. These elements were chosen because they provide illustrative insights into the divergencies and complementarities that can enhance food security while reducing impacts on natural ecosystems.
The keywords used in this study included sustainability, Agriculture 4.0, organic farming, vertical farming, controlled environment agriculture, plant factory, growing media, species and variety use, EU and US organic regulations, socio-economic aspects, and combinations thereof. Papers were considered as relevant when they exhibited a comparative attitude regarding OF versus PF systems, at least in one relevant subtopic of the present review. Over 350 papers were collected and arranged into subgroups according to the subchapters of the review. Finally, over 200 references were included to present a balanced and unbiased comparison of OF and PF systems.

For the representation of the connection of sustainability with OF and with PF systems, ScienceDirect and Google Scholar search engines were used. The number of results per year was recorded for both databases; the number of results per scientific field was recorded for ScienceDirect results. Graphs were prepared based on the recorded datasets.

To visually illustrate the similarities and differences between OF and PF systems, we used the visualization tool commonly applied in mathematical set theory, with the two sets to be compared and their intersection (legislation, plant breeding, and local food systems). Limitations were identified for studies dealing with OF and PF systems from a different perspective to maintain the focus on the topics that illustratively describe the divergent approaches of the two systems. Therefore, this review does not extensively deal with questions regarding energy consumption, plant protection, investment costs, IT solutions, and the time dimension of sustainability. Publications dealing exclusively with the above topics were considered beyond the scope of this study.

3. Results and Discussion

3.1. Assessing the Term ‘Sustainability’ in OF and PF Systems

Sustainability has become a prevalent buzzword in recent agricultural innovations, first mentioned in 1987 in the report of the UN World Commission of Environment and Development known as “Our common future”. The concept of sustainability or sustainable development was created as a solution for the exigent environmental issues and it became the central core of every development policy since the 1980s both at national and international levels [19]. This led to the initiation of numerous local projects; however, their impacts remained relatively limited in addressing environmental challenges. Sustainability can be used to describe both organically certified food production and PF systems, as both demonstrate a certain level of sustainability.

Although the conceptual framework of sustainable agriculture is fully packed with ideas [23], three main directions arise with significant differences between each other: these divergent systems are agricultural intensification, high-tech agriculture, and the agroecological approach [35]. Both systems aim to produce crops in a sustainable way to preserve and maintain ecosystem resources [17].

According to Tiessen et al. [36], the intensification of agricultural production in general would not meet the requirements of sustainability when heavily relying on high external inputs. A much more complex and conscious approach is to rely on biological processes within the farm [37], which is called agroecological intensification (AEI). Practices like mulching, intercropping, crop rotations, integrated soil and nutrient management, soil and water conservation, the judicious use of pesticides, the use of organic inputs, and the balanced and more efficient use of fertilizers [38] are affecting soil health and fertility in a positive way.

According to Phalan [39], two alternatives emerged to convert agricultural lands to more nature-friendly land and to make “more space for unfarmed habitats”. The land sparing–sharing model intensifies OF in terms of yield levels and increases habitat for wildlife. Gonella and Renna [17] integrate the PF approach into this concept by realizing land sparing through the utilization of non-agricultural areas and compressing crop production within a multi-level artificial environment, while OF would be regarded as a means of land sharing with natural ecosystems.
While OF initiatives date back to the 1920s, a PF was first mentioned in 1980 as an innovative technology developed in Japan. It is believed that the term ‘sustainability’ shows a traditionally stronger association with OF than with PFs. This is evident when checking the number of studies in Google Scholar, using the search strings (‘sustainability’ AND ‘organic farming’), (‘sustainability’ AND ‘plant factory’), and (‘sustainability’ AND ‘vertical farming’) over the last four decades (Figure 1). However, the difference in the number of studies is gradually growing and indicates a closer position of OF with sustainability than with PFs.

Figure 1. Number of studies in Google Scholar database dealing with the combined topic of sustainability AND organic farming, sustainability AND plant factory, and sustainability AND vertical farming in the period of 1980–2022. The above-mentioned combinations were used as search strings on the public search page of Google Scholar https://scholar.google.com/ (accessed on 15 May 2023).

At the same time, when the so-called gray literature is excluded and the hard-science-focused ScienceDirect is used with the same settings (Figure 2), it is visible that the difference between the pair of terms is not as high as it was in the case of the previous search, but OF still has some advantage.

Upon closer examination of the representation of the use of ‘sustainability’ in different scientific fields during the same period (Figure 3), it seems evident that sustainability has become a ubiquitous term in every scientific topic. At the beginning of the millennium, about 20,000 articles mention this term, while up to 2023 a six-fold increase was experienced in the total number of sustainability-related publications. It is important to note that the meaning and the context of the application can be fundamentally different; therefore, our investigation is limited only to relevant scientific topics.
Figure 2. Number of studies in ScienceDirect database dealing with the combined topic of sustainability AND organic farming, sustainability AND plant factory, and sustainability AND vertical farming in the period of 2000–2022. The above-mentioned combinations were used as search strings on the public search page of ScienceDirect https://www.sciencedirect.com/ (accessed on 15 May 2023).

Figure 3. Number of studies within a scientific field in ScienceDirect database dealing with the topic of sustainability in the period of 2000–2022. Columns represent data within a given year. The size of the blocks representing the number of studies within a scientific field corresponds to their ratio (%) within a given year. Numbers within blocks represent the number of studies published in a given scientific field and year. Definition and categorization of articles was automatically performed by ScienceDirect search engine. Data collected on the public search page of ScienceDirect https://www.sciencedirect.com/ (accessed on 21 May 2023).
It seems apparent that among the relevant fields the ratios of environmental science, of energy, and of earth science show a constant increase, justifying the importance of sustainability related to natural ecosystems and to energy use. The number of environmental-science-related articles showed a ten-fold increase in the last 23 years; this is the field with the highest ratio among the other fields in 2023. The topic of energy shows similarities in terms of study number increase, while its ratio is rather limited in the last year of the assessment. Interestingly, articles related to agricultural and biological sciences show only a six-fold increase, and their ratio does not show a significant increase over the years. A constant decrease was detected in terms of the ratio of articles classified into the category of biochemistry, genetics, and biotechnological sciences, possibly due to the low or zero acceptance of genetically modified organisms in organic systems.

3.2. Characteristics of OF and PF Systems

Looking back to the history of humankind and agriculture, until recent decades, farming was strongly linked to open fields; the light of the sun was the only resource that provided the necessary energy for photosynthesis. At the beginning of the last century was the first initiative to use artificial light sources for plant production.

PFs as a form of CEA are mostly or totally isolated from natural ecosystem services and thus from natural cycles which ensure the internal re-utilization of resources, such as water, nutrients, energy, and organic matter. Plant factories with artificial lighting (PFALs) totally exclude sunlight [40,41], while some PF types use artificial light in a supplementary manner. According to Statista, 51% of the world’s indoor production was via hydroponic technology in 2019, 20% aeroponics, 9% aquaponics, and 6% others, and only 13% used soil-based growing media [42]. PFs can operate in different sizes. Industrial types are for the mass production of cash crops, while small- and medium-sized facilities or equipment can be deployed into urban environments [43,44]. On the other hand, a PF is a mimic of natural processes and possesses total independence from the environment. PFs are capable of totally excluding pests, diseases, and weeds, as well as pollution [45]. This type of food safety is highly appreciated by consumers [46] and also by producers [47]. The key for this sterility, in addition to the exclusion of living soil, is the minimum air exchange of the inside and the surrounding environment [48]. The fragility of this clear environment depends on the level of a PF’s isolation from outer sources [3,49], including human intervention. Additionally, growing food in a sterile enclosure separated from nature increases its fragility towards the smallest failure (prolonged power cuts, lack of raw materials for the technology, etc.), which can lead to the destruction of crops within a short time.

PF facilities can be operated year round with a total independence from the environment, which results in higher plant biomass production as a compensation for higher investment costs [50]. Although PFs produce more crops per land unit than open-field agriculture, their energy consumption is so high that an area 20 times the initial surface area would need to be covered with solar panels to serve their energy needs [51].

OF, on the other hand, aims to integrate agricultural production into the natural ecosystem, to reduce the erosion of natural processes, and to revitalize resource cycles. In this way, OF is exposed to natural harms, such as abiotic and biotic stressors, but at the same time, it can benefit from ecosystem services, such as soil microbial activity or natural beneficial organisms. The continuous adaptation to a changing environment makes the system more stable in the event of a disaster or technological failure. The exclusion of synthetic agrochemicals as well as of genetically modified organisms (GMOs) is the key factor for consumers in choosing organic products. In comparison with PFs, open-field systems require minimal investment costs; therefore, these systems can be considered as the most effective form of production from an economic point of view [50]. However, despite any technological development achieved in the past decades, plants still suffer from the uncertainties of the living environment; these uncertainties have an impact on yield in
terms of quantitative and qualitative traits. The presence of pollutants, such as mycotoxins and heavy metals, is also unavoidable to a certain extent in natural systems [52,53].

OF is similar to PFs in terms of aiming for a closed production system (Figure 4), but ‘closed’ is interpreted differently in these systems. While OF aims to minimize wastes and maximize recycling within a production unit, PFs rather exclude unwanted production factors, which will be artificially recreated after optimization.

In summary, H1 was rejected (H1: OF and PF systems are competitive with each other due to their main characteristics; they possess diverging developmental directions) due to the common commitments of OF and PFs in producing high-quality food and in excluding pesticide use and in their open-minded approach towards Agriculture 4.0. innovations. When the aims of OF and PF systems are compared, similarities can be identified. Therefore, competitiveness is less relevant; however, significant differences in implementation do exist.

### 3.3. Legislation of OF and PF Systems

The PF system focuses on production, aiming to provide as much food as possible in a limited space [54]. OF focuses on value production that can provide food for all in sufficient quality and quantity [55].

Whether the PF product can be certified as organic is controversial between different parts of the world [56,57]. The ability to harmonize the elements of the two systems is not primarily dependent on innovation and economics, but on the legal regulation of OF. The use of hydroponics is questionable, and there are complaints about the use of unnatural chemicals, e.g., of chemical fertilizers in PF systems [58]. Current knowledge suggests that, although apparently opposite, organic and high-tech soilless cultivation have several common or converging points in view of a sustainable use of resources [17]. PFs can therefore easily take over elements of OF, and vice versa, but the resulting crops will not automatically be certified as organic.

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**Figure 4.** Comparison of general characteristics of OF and PF systems. The Venn diagram shows the commonalities and differences of the two systems. The two cycles represent the main characteristics of organic farming and plant factory systems. The place where the two cycles overlap is where the common properties are shown.
The currently accepted international (IFOAM) and regional (EU, Soil Association, etc.) standards and legislation for OF clearly state that soilless cultivation is prohibited in certified farming. The IFOAM General Assembly 2021, at the request of the Soil Association, has taken a clear position on the incompatibility of hydroponic farming and OF [59]. According to them, one of the most important principles of OF is growing in living soil [15,60], which is not compulsory in PF systems. Individual regions and countries can decide for or against the above principle by adopting their own legislation. For example, the United States Department of Agriculture (USDA) and its National Organic Program (NOP), the US certifying body, accept products from hydroponic farming as certified organic in some cases, i.e., if all the materials used in their production are permitted in OF; but these cases are not precisely defined in the rules [61]. The European Union legislation in force from 2022 categorically prohibits the cultivation of plants without soil [62], thus excluding hydroponics, which is specifically mentioned [63]. However, this does not mean that no crops grown in aquatic environments can be certified as organic.

According to the Regulation 2018/848 EU (29), sprouted seeds are exempted and can be certified in soilless cultivation. In the case of aquatic plants, production and certification are included in the rules for aquaculture (2018/848 EU, Annex II, Detailed production rules referred to in chapter III, Part I: Plant production rules, 1. General requirements, 1.1., 1.2.) and for aquatic organisms reared in a natural environment, and specifically detailed rules for the production of algae are highlighted (2018/848 EU, Chapter III, Production rules, Article 15—Production rules for algae and aquaculture animals). Other aquatic plants for human consumption are not named and are subject to the general aquaculture production rules. EU legislation 2018/848 does not specifically mention the cultivation of aquatic plants for animal feed purposes, so they should also be assessed and certified according to the general rules. Accordingly, the legal possibility exists to cultivate azolla in a plant factory system, for example [64], and to certify it as organic feed.

The entire PF system can therefore be operated as OF in some specific cases, but the economics of implementation must be judged based on local conditions. The legislation allows for the possibility to have certified and non-certified production units on the same farm (2018/848 EU (19), (21), (22), (24)). The Regulation regulates in detail the conditions for the operation of such farms but does not directly mention the specific systems of soilless farming: only aquaculture is mentioned (Article 9, General production rules, 7, (b)). If the need for the production and certification of aquatic organisms produced in a PF system were to become widespread, it would be essential to add the relevant provisions to the legislation. The issue of certified OF systems producing both certified organic and non-organic products is important because currently the range of marketable organic products allowed for soilless cultivation is very narrow, and it is questionable whether there is an economic rationale for developing systems for only organic production [17].

In the US, soillessly grown vegetables can be effectively certified as organic if grown in compost-based growing media (compost or compostable plant materials which are considered comparable to soil) in containers. Some PF facilities are certified organic producers and/or implement aquaponics in the US [65]. The National Organic Standards Board (NOSB) in the US passed a final recommendation in April of 2010 on production standards for terrestrial plants in containers and enclosures. This prohibits hydroponic production of organic crops, with an exception for mushrooms, sprouts, and microgreens, and allows container production of organic crops under specific provisions that support natural and diverse soil ecology within the container [66]. At that time, some national certification agencies (such as California Certified Organic Farmers) had already certified organic hydroponic operations, while other regional certification agencies refused to certify hydroponic and other growing systems that are not soil-based [67]. The certification body Control Union UK and the Association for Vertical Farming (AVF) launched a certification scheme for sustainable indoor farming including an eco-label that is tailor-made for VF. There are certified organic nutrients
designed for hydroponic growing and hydroponic operations can start up without the three-year transition required for land.

Mexico, Canada, Japan, and New Zealand also prohibit hydroponic vegetable production from being sold as organic in their own countries [17]. In China and Singapore the green light is given to local VF operations to apply for organic certification with a special emphasis on the use of natural fertilizers, such as manure and compost [57].

Experiments are being carried out to develop livestock farms where manure can be recycled for biogas production and as a source of plant nutrients for open-field production, as well as for closed-loop hydroponic fodder production [68]. In these systems, azolla, which can be used as a source of protein, can be well integrated as an aquatic crop, and its certification does not face any legal obstacles; however, green fodder grown in hydroponics [69] no longer complies with the EU legislation of OF because it cannot be interpreted as sprouted seeds and these green fodder plants do not naturally grow in water.

However, EU legislation does not prohibit greenhouse cultivation, in which artificial climate control is allowed. Thus, the experience of PF operators can be used in these systems, as far as they concern climate control or biological control. In particular, researchers see great potential based on their results on lighting control [70], but there are also potentials for linkages in the field of automation in general [71].

Beyond the legal issues, however, the linking of the two systems raises the question of whether this is contrary to the principles of OF, which aim to minimize dependence on external resources. The question has been raised not only by the involvement of the PF system and hydroponics in general, but also by the increasing involvement of GPS-based technologies involving robotics and precision farming [72]. Increasing dependence on external information and resources is contrary to the aimed stability of OF and thus fundamentally not only inconsistent with the principles but also with the approach of EU organic legislation, although it does not conflict with any specific paragraphs. EU Regulation 2018/848 (point 18) states that the selection of plant varieties should focus on “adaptation to diverse local soil and climate conditions”. This means that the principle is to favor the use of natural conditions rather than artificially created environments and is therefore opposed to complete plant factory system involvement. A regulatory-based summary is presented in Figure 4, taking practical aspects into account regarding the plant species suitable for OF and PFs and including their overlap as well.

As a conclusion, regulatory barriers arise from the acceptance or rejection of living soil as a growing medium. Therefore, PFs cannot be certified as organic in the EU. The exceptions are as follows (Figure 5): 1. sprouted seeds or chicory heads; 2. ornamentals and herbs sold in pots that are not adapted to soil production; 3. seedlings and transplants to facilitate organic production; and 4. some crops grown in Finland, Sweden, and Denmark in possession of organic certifications before 28 June 2017 [73]. In the US and in some countries in Asia, PFs using hydroponics can be certified as organic [57]. Sustainability standards for PF production do exist, which are not equal to organic labels but can be informative for consumers and might support PF producers to realize higher incomes in turn for their costly production protocols. H2 was therefore rejected (H2: the legislation of OF on a global scale does not allow a transition between OF and PF systems), as exceptions were identified as bridges among the two systems.
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Figure 5. Possible EU regulatory overlapping of OF and PF system in terms of plant crop groups. The Venn diagram shows the commonalities and differences of the two systems. The two cycles overlap is where plant groups are shown which are able to produce in both systems. Outside the middle section the organic farming side include plant groups grown in OF systems. The plant factory side include plants species produced in PF systems.

3.4. Assessing Sustainability in the Key Components of Plant Production

3.4.1. Sustainability of Growing Media

Soil is one of the key challenges when the sustainability of agriculture is discussed, especially because it provides the basis for the functioning of ecosystems [35]. In OF, the aim is to develop a closed system, preferably using locally produced organic by-product material as a growing medium. These materials vary from region to region, from farm to farm. Contrarily, PFs are the most advanced closed systems, especially with rainwater harvesting and material recycling. Soilless cultivation was developed to solve issues regarding soil-borne diseases, salinity, and soil exhaustion or low fertility. The most commonly used soil substitutes worldwide are rockwool, perlite, peat, and coconut fiber in the production of fruits, vegetables, and cut flowers [74,75].

Most PFs currently use hydroponic methods, where plants grow in water, or aeroponic techniques, where the plants are suspended in nutrient mist. However, some PFs also use geoponic (substrate- or soil-based) technology (Figure 6). Soilless cultivation is more sensitive to mistakes, as there is not much of a buffer in the system [17].

Various inorganic and organic materials have been tested recently to find growing media with favorable physical, chemical, and biological properties for root fixation and the short-term storage of water and nutrients (Table 1). It is also important to meet the economic conditions (processing costs: grinding and composting; transport costs: distance from the origin of the materials) and the need for low environmental impact in terms of locality, reusability, and biostability [74].
The two main functions of a medium are to support the roots and to provide optimal conditions for the uninterrupted uptake of water and nutrients. A medium has the physical and chemical properties that allow roots to develop, has a durable structure, has neutral chemistry, has good water and air capacity, is free from pathogens and pests, and does not contain substances harmful to plants and humans [76,77]. Chemical activity and surface charge are important properties of a medium; therefore, it can be described as an active (e.g., peat and tufa) or a neutral (e.g., rockwool and sand) material [74,78].

Supporting and nutrient supplying often cannot be clearly separated for the materials used in organic production. Usually, the appropriate structure and nutrient content for a particular plant species can be achieved by mixing several materials. Despite the impressive amount of data available on the use of alternative peat substitutes, especially of composts, the results on their suitability vary and are not sufficiently detailed. Plant responses to different media components are highly dependent on the plant [79].

The dual function of media in PF systems is generally not fulfilled; inorganic media do not contain any (or much) nutrients and, due to their low colloidal content, they have a low adsorption and buffering capacity [80,81]. Nutrients in such systems are supplied by synthetic fertilizers, the use of which is prohibited in OF. Only authorized substances specified in regulations can be used as growing media and nutrient supplements for organic production. Some media are commonly used in PFs but are not allowed in OF because they are not natural (like plastics: urethane sponge, polystyrene, and phenolic resin) or are not soil-like materials; those combined with fertilizer solutions (e.g., mineral wool) are considered as unsustainable and exhausting for the environment.

In contrast, there are organic materials available that are compatible with PF system requirements. These materials are capable of binding and then continuously releasing excess amounts of nutrients and irreversibly bind unwanted, dangerous substances. Organic
materials decompose during the growing period under greenhouse conditions due to high temperatures and a continuous water supply [80,81]. For the decomposition of organic matter, the activity of soil microorganisms is essential [82].

Soilless techniques were initially developed to solve soil problems in protected cultivations and innovations initially targeted at improving performance and economy, but sustainability soon became the main objective for their further development. In today’s practice, this means a process of transition from peat-based growing media to renewable organic media [17].

The recyclability of organic media is not feasible. They are usually mixtures, and the components cannot be separated. On the other hand, their nutrient content reduces at the end of cultivation and their structure and volume is very likely to change. However, their afterlife can still be sustainable because they can be reused instead of recycled, thus solving the problem of organic waste, e.g., they can be used to improve poorly structured soils.

Disease control is a key factor in the reusability of substrates, which is usually addressed by sterilization [78], but in the case of organic materials, it also means the destruction of beneficial organisms; therefore, this practice is not feasible in organic farming.

Commonly used closed-cultivation media have their own limitations. Research has therefore intensified in the last decade to replace them, or at least to reduce the consequences of large-scale use [83].

Peat is the most widely used component of growing media in the EU [84], and its use is also permitted in organic seedling production [34,63]. It is considered an essential material in both conventional and organic seedling production. Even if the use of peat-based substrates is contrary to most principles of OF, its use is allowed in organic production. Peat mining has a high environmental impact due to its role in the global carbon cycle, as it is the most important long-term carbon sink in terrestrial ecosystems. Peat can be considered as a non-renewable resource [74]. Currently, national and EC legislation have strong restrictions on extraction [85]. The main concern about rockwool is disposal; reuse can have negative effects on human health [74].

Compost is a low-cost media component with high nutrient content and resistance to soil-borne diseases. The maturity of the compost is an important characteristic for its use. It determines the compressibility, the microbial-related oxygen consumption, the nitrogen immobilization, and the phytotoxicity of the material. The physical properties limit the proportion of compost in the growing medium. It has a high density, low water content available to plants, and might have high EC and pH, so it is not recommended to apply it at rates higher than 50%. At the end of the life cycle, it can be further used for soil enrichment.

In summary, H3 was rejected (H3: there are no alternative growing media which are compatible with the preferences of both OF and PF systems; therefore, the legislative barrier is insurmountable), as several alternative growing media are available (Table 1) which could serve efficiently in both systems.
Table 1. Compatibility of different inorganic and organic growing media with different cultivation systems and EU organic regulations and assessment of their afterlife.

<table>
<thead>
<tr>
<th>Growing Media</th>
<th>Cultivation System</th>
<th>Meets EU Organic Regulation *</th>
<th>Material Afterlife</th>
<th>Renewability of Source</th>
<th>Nutrient Level</th>
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<td>sand</td>
<td>hydroponics, geoponics</td>
<td>yes</td>
<td>reusable, other use **</td>
<td>non-renewable</td>
<td>no</td>
<td>[17,78,86]</td>
</tr>
<tr>
<td>gravel</td>
<td>hydroponics, geoponics</td>
<td>yes</td>
<td>reusable</td>
<td>non-renewable</td>
<td>no</td>
<td>[78]</td>
</tr>
<tr>
<td>volcanic tuff/lava rock (riolite, zeolite, and basalt)</td>
<td>hydroponics, geoponics</td>
<td>yes</td>
<td>other use **</td>
<td>non-renewable</td>
<td>low</td>
<td>[74,78,87]</td>
</tr>
<tr>
<td>pumice</td>
<td>hydroponics, geoponics</td>
<td>yes</td>
<td>reusable, other use **</td>
<td>non-renewable</td>
<td>low</td>
<td>[86]</td>
</tr>
<tr>
<td>perlite</td>
<td>hydroponics, geoponics</td>
<td>yes</td>
<td>reusable, other use **</td>
<td>non-renewable</td>
<td>no</td>
<td>[17,78,86]</td>
</tr>
<tr>
<td>vermiculite</td>
<td>hydroponics, geoponics</td>
<td>yes</td>
<td>not reusable, other use **</td>
<td>non-renewable</td>
<td>no</td>
<td>[17,78,86]</td>
</tr>
<tr>
<td>silt</td>
<td>hydroponics, geoponics</td>
<td>with conditions</td>
<td>not reusable, other use **</td>
<td>non-renewable</td>
<td>low</td>
<td>[88]</td>
</tr>
<tr>
<td>peat moss (Sphagnum)</td>
<td>hydroponics, geoponics</td>
<td>authorized, not sustainable</td>
<td>reusable a few times, other use **, and biodegradable</td>
<td>non-renewable</td>
<td>low</td>
<td>[74,86,89]</td>
</tr>
<tr>
<td>coconut coir</td>
<td>hydroponics, geoponics</td>
<td>yes</td>
<td>with limitations, other use **, and biodegradable</td>
<td>renewable</td>
<td>low</td>
<td>[17,86,90]</td>
</tr>
<tr>
<td>biochar</td>
<td>geoponics</td>
<td>with conditions (only from plant origin)</td>
<td>other use **, biodegradable</td>
<td>renewable</td>
<td>low</td>
<td>[76,91,92]</td>
</tr>
<tr>
<td>dried digestate residual after production of biomethane gas</td>
<td>geoponics</td>
<td>yes</td>
<td>other use **, biodegradable</td>
<td>renewable</td>
<td>low</td>
<td>[93,94]</td>
</tr>
<tr>
<td>fish fertilizer derived from aquaponics</td>
<td>aquaponics</td>
<td>no</td>
<td>biodegradable</td>
<td>renewable</td>
<td>high</td>
<td>[94]</td>
</tr>
</tbody>
</table>

natural growing substrates from organic sources

<table>
<thead>
<tr>
<th>Growing Media</th>
<th>Cultivation System</th>
<th>Meets EU Organic Regulation *</th>
<th>Material Afterlife</th>
<th>Renewability of Source</th>
<th>Nutrient Level</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>composted plant materials: leaf compost/leaf mold, Posidonia (seaweed) compost, and spent mushroom compost</td>
<td>geoponics</td>
<td>yes</td>
<td>other use **, biodegradable</td>
<td>renewable</td>
<td>high</td>
<td>[17,95,96]</td>
</tr>
<tr>
<td>municipal solid waste compost</td>
<td>geoponics</td>
<td>yes</td>
<td>other use **, biodegradable</td>
<td>renewable</td>
<td>high</td>
<td>[17]</td>
</tr>
<tr>
<td>food processing wastes compost</td>
<td>geoponics</td>
<td>with conditions</td>
<td>other use **, biodegradable</td>
<td>renewable</td>
<td>high</td>
<td>[74]</td>
</tr>
<tr>
<td>animal manure compost</td>
<td>geoponics</td>
<td>yes</td>
<td>other use **, biodegradable</td>
<td>renewable</td>
<td>high</td>
<td>[17,92,97]</td>
</tr>
<tr>
<td>sheep’s wool compost/manure</td>
<td>geoponics</td>
<td>with conditions</td>
<td>other use **, biodegradable</td>
<td>renewable</td>
<td>low</td>
<td>[98,99]</td>
</tr>
<tr>
<td>sewage sludge</td>
<td>geoponics</td>
<td>with conditions</td>
<td>other use **, biodegradable</td>
<td>renewable</td>
<td>high</td>
<td>[17]</td>
</tr>
</tbody>
</table>
| paper waste                                         | geoponics           | with conditions               | other use **, biodegradable                  | non-renewable          | low            | [74] }
Table 1. Cont.

<table>
<thead>
<tr>
<th>Growing Media</th>
<th>Cultivation System</th>
<th>Meets EU Organic Regulation *</th>
<th>Material Afterlife</th>
<th>Renewability of Source</th>
<th>Nutrient Level</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>several shells or hulls (rice hulls, almond shells, hazelnut husks peanut hulls, and olive husks)</td>
<td>hydroponics, geoponics</td>
<td>yes</td>
<td>other use **, biodegradable</td>
<td>renewable</td>
<td>low</td>
<td>[74,86]</td>
</tr>
<tr>
<td>dry plant residues (cereal straw, palm fiber trunk waste, switchgrass (<em>Panicum virgatum</em> L.), extracted sweet corn tassel (<em>Zea mays</em> L.), giant reed (<em>Arundo donax</em> L.) wastes, kenaf fiber (<em>Hibiscus cannabinus</em>), and Bagasse (sugarcane pulp))</td>
<td>geoponics</td>
<td>yes</td>
<td>other use **, biodegradable</td>
<td>renewable</td>
<td>low</td>
<td>[74,86,100]</td>
</tr>
<tr>
<td>pressed fruit residues (olive pomace, grape pomace)</td>
<td>geoponics</td>
<td>yes</td>
<td>other use **, biodegradable</td>
<td>renewable</td>
<td>low</td>
<td>[74]</td>
</tr>
<tr>
<td>wood fiber (wood chips/sawdust/bark)</td>
<td>hydroponics, geoponics</td>
<td>yes</td>
<td>other use **,</td>
<td>renewable</td>
<td>low</td>
<td>[74]</td>
</tr>
<tr>
<td>vermicompost: earthworms/compost worms/<em>Eisenia fetida</em> (<em>Eisenia</em> sp.), <em>Endrillus eugeniae</em>, <em>Perionyx excavatus</em>, <em>Dendrobaena veneta</em>, and <em>Lumbricus terrestris</em> with microorganisms (or diluted extract)</td>
<td>geoponics</td>
<td>yes</td>
<td>other use **, biodegradable</td>
<td>renewable</td>
<td>high</td>
<td>[92,101,102]</td>
</tr>
</tbody>
</table>

'synthetic substrates' consist of processed materials (modified)

<table>
<thead>
<tr>
<th>Growing Media</th>
<th>Cultivation System</th>
<th>Meets EU Organic Regulation</th>
<th>Material Afterlife</th>
<th>Renewability of Source</th>
<th>Nutrient Level</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>mineral wool</td>
<td>hydroponics</td>
<td>no</td>
<td>reusable with limitations, non-recyclable</td>
<td>non-renewable</td>
<td>no</td>
<td>[74,86,103]</td>
</tr>
<tr>
<td>expanded clay granules</td>
<td>hydroponics</td>
<td>no</td>
<td>reusable, and biodegradable</td>
<td>non-renewable</td>
<td>no</td>
<td>[74,78,86]</td>
</tr>
<tr>
<td>polystyrene (Styrofoam)</td>
<td>hydroponics</td>
<td>no</td>
<td>non-reusable, non-recyclable</td>
<td>non-renewable</td>
<td>no</td>
<td>[78]</td>
</tr>
<tr>
<td>polyurethane sponge/foam</td>
<td>hydroponics</td>
<td>no</td>
<td>reusable a few times, not recyclable</td>
<td>non-renewable</td>
<td>no</td>
<td>[78,104]</td>
</tr>
<tr>
<td>phenolic resin/phenolic foam</td>
<td>hydroponics</td>
<td>no</td>
<td>non-renewable</td>
<td>no</td>
<td>[78,86]</td>
<td></td>
</tr>
<tr>
<td>foamed glass (growstones)</td>
<td>hydroponics</td>
<td>no</td>
<td>reusable, recyclable</td>
<td>non-renewable</td>
<td>no</td>
<td>[78,86]</td>
</tr>
<tr>
<td>water absorbing crystals/polymers (super absorbent hydrogel)</td>
<td>hydroponics, geoponics</td>
<td>no</td>
<td>reusable, natural-based hydrogels are biodegradable</td>
<td>non-renewable, renewable</td>
<td>no</td>
<td>[100]</td>
</tr>
<tr>
<td>polyester fleece</td>
<td>hydroponics</td>
<td>no</td>
<td>non-renewable</td>
<td>no</td>
<td>[78]</td>
<td></td>
</tr>
<tr>
<td>expanded shale</td>
<td>hydroponics, aquaponics</td>
<td>no</td>
<td>non-renewable</td>
<td>no</td>
<td>[86]</td>
<td></td>
</tr>
</tbody>
</table>

* Commission Implementing Regulation (EU) 2021/1165 of 15 July 2021 authorizing certain products and substances for use in organic production and establishing their lists (text with EEA relevance, 2021) and also in the US due to legal harmonization; ** can be used for other purposes at the end of its life cycle.
3.4.2. Species and Variety Selection and Breeding for OF and PF Systems

Plants grown in a closed, controlled growing environment have different characteristics than those grown in organic conditions in an open field or greenhouse environment with natural light.

In OF, managing various abiotic and biotic stresses is the most important breeding objective to achieve adequate yields. Plants must be able to adapt to the constantly changing environment. OF therefore aims to utilize the diversity of agricultural crops [105]. Exploiting the multifunctionality of crops in the farming system is an important aspect [106].

Although the general cultivation objectives of OF and PF are similar, special characteristics are required for organic cultivation (Figure 7).

![Figure 7. Crop breeding strategies for OF and PF systems. The Venn diagram shows the commonalities and differences of the two systems. The two cycles represent the main variety characteristics which are advantages for organic farming or for plant factory systems. Where the two cycles overlap is where the common properties are shown.](image)

It is important for the organic varieties to be effective in the exploration and exploitation of resources [107]. Adaptation to the site is a priority, which also ensures increased yields. Organically grown plants need vigorous early growth, and dense canopies suppress weeds. Varieties with high levels of resistance against pests and diseases and early ripening are preferable, which require less care [108].

In PF systems, these factors do not affect crop production. The primary concern is to reduce costs and optimize the use of infrastructure. In general, the most commonly grown species are those with higher profitability and relatively high prices. An important factor in crop selection is that the crop should have a short production cycle to reduce electricity costs for lighting, heating, and cooling and allow for early harvesting. The harvestability of the whole plant is also important, e.g., lettuce (Lactuca sativa L.) can be harvested whole, unlike maize, where only the cobs are marketed. The rest of the plant, together with electricity costs, is considered as waste [109].

PFs require plant characteristics such as small, compact size up to about 30 cm in height, tolerance to high-density planting, rapid development, short life cycle, low root to shoot ratio, maximum tolerance to artificial illumination due to closed systems...
(preference for low light flux, 100–150 µmol m\(^{-2}\) s\(^{-1}\) on leaf surface), and preference for CO\(_2\) supplementation [110–112]. The small size allows for high single density in shelf system cultivation, which is a requirement for profitable PF management. Low-energy LEDs can be placed close to the plants, reducing the growing space [113]. Breeding appropriate phyllotactic patterns of low stature and larger leaf area is the primary strategy to maximize the light output efficiency of LED lighting [112]. Plants must also meet consumer needs such as taste, color, texture, and specific nutritional content [114]. In these systems, preference is given to crops that allow farmers to meet year-round market demand and thus remain profitable despite ongoing operating costs. Growing the same range of crops continuously throughout the year also allows the same specific technical settings for the crop to be maintained, avoiding the potential technical and operational problems of constantly changing automation [109].

Indoor farms represent a group of integrated technologies that can be configured in different ways for producing different crops. These crop types include leafy vegetables, herbs, tomatoes, flowers, and microgreens [115]. The ratio of plant groups growing in PFs is as follows: leafy vegetables and herbs 56.71%, fruit vegetables 11.19%, and fruits 5.97% [116]. Lettuce was found to the most studied and the most cultivated species (28%), followed by cabbage (7.5%) and basil (5.9%).

Leafy vegetables currently grown, such as lettuce (Lactuca sativa L.), spinach (Spinacea oleracea L.), and brassicas (Brassica sp.), are small, can be harvested after a short period of time, have a high harvest index (unlike fruit, all above-ground biomass is harvested), have relatively low photosynthetic energy requirements, and grow well in soil-less systems. They also have a high value per unit weight, which is a prerequisite for the economic viability of high-tech farms [114]. It is important that the ratio of root mass of lettuces is less than 10% of the total plant mass [117]; these plants are the most commonly used in cultivation and research [118–120].

The main crops grown under glass in the traditional sense are tomatoes (Solanum lycopersicum L.), cucumber (Cucumis sativus L.), and peppers (Capsicum sp.) [74]. However, the varieties grown this way are not currently suitable for use in PF systems.

The PFAL system provides the opportunity to apply or modulate mild stress conditions to meet specific needs for shape, flavor, and secondary metabolites [117]. Lighting is the factor that most influences plant productivity and quality in PFs and varies at different growth stages (germination, vegetation, and flowering) [121]. Therefore, most studies are about the effectiveness of LED lighting [48,113]. Studies have shown that increased light intensity generally promotes the growth of lettuce [122,123], and it is believed that the growth-promoting effect is well established only within a certain range of light intensities. In order to maximize the economic benefits of lettuce growth in a closed production system, in addition to high quality and quantity, it seems important to optimize light intensity [119]. Meng et al. [120] noted that lettuce grown in an indoor farm with a controlled light spectrum was sweeter and tastier and had more acceptable taste than lettuce grown in natural sunlight. Ke and colleagues [124] studied the effect of light quality on the growth vigor of tomatoes. Light quality had a significant effect on stem length, dry weight, and dry matter percentage of dwarf tomato.

The effect of lighting on strawberry (Fragaria x ananassa) fruit quantity and quality has been studied by Maeda and Ito [125]. Significant differences were found in fruit volume, soluble solid, ascorbic content, and anthocyanin content as a function of different lighting times and intensities. Regulating phosphor concentration and the light spectrum can control plant growth and fructose accumulation in strawberries [126].

Larger plants have larger fruit sizes, which have higher metabolic needs and take longer to develop and mature [127]; therefore, dwarfing genes have utmost importance in breeding for PF systems. Edited tomato varieties are well suited for indoor growing systems. Kwon and his colleagues [127] have produced a small, semi-determinate tomato variety with small grape-like berries; groundcherry (Physalis pubescens L.) was also optimized for PFs [128]. Here, in addition to the growth vigor, miraculin production, which influences the
sweetness of the fruit, was also genetically introduced into the plant. At the same time, it is important that a compact body shape is not combined with overly dense foliage, because the plants’ light utilization and thus their yields will be reduced. A dense canopy makes it difficult to monitor individual plants [50].

The annualization of woody perennials has the potential to make them suitable for growing in PF systems. With induced mutation, Várkonyi et al. successfully performed attempts to change the growth habit of kiwifruit (Actinidia chinensis Planch.) from a woody climbing perennial into a short determinate woody perennial, an early flowering plant which would be desirable in allowing indoor cultivation [129]. Arable crops such as tobacco (Nicotiana tabacum L.), as well as cereals such as maize (Zea mays L.), rice (Oryza sativa L.), and barley (Hordeum vulgare L.), are the most used whole-plant systems in plant molecular farming for pharmaceutical purposes. However, their fragility and irregular shape make them difficult to manage in automated, robotic, or conveyor belt cultivation systems [50]. The primary purpose of growing cereals such as wheat in PFs is to germinate wheatgrass as a nutrient-rich raw material for fruit juices [130,131]; besides in experiments, arable plants are unsuitable for PF production. Gene editing, genome modification by biotechnological means, is fundamentally supported in the breeding of crops grown in PF systems [110]. The genetic or non-genetic manipulation of growth hormone effects would allow crops to be adapted in shape to PF multilayer cropping systems [112]. At the same time, PFs can provide space for breeding activities all year round, thus reducing the time needed for variety breeding [132]. In organic breeding, the use of GM technology is banned, thus preventing the utilization of such advances. Organic plant breeding is a holistic approach where the process of breeding, including technical, ethical, and socio-economic aspects, is equally as important as the final product (cultivar) with its characteristics [108,133]; therefore, it is a much more time- and effort-demanding process.

As a summary, H4 was rejected (H4: there are no sharp boundaries among OF and PF systems regarding the profitable production of plant species and varieties) after identifying the main preferences of breeding for OF and PF systems, which show strong divergencies in terms of plant species characteristics and of the acceptance of GM products.

3.5. Assessing Sustainability from a Consumer Socio-Economic Perspective

3.5.1. Local Food Production

Both OF and PF systems aim to reduce the food miles between the producers and the consumers, as this helps in reducing environmental impacts and increases food safety through enabling accessibility to crop production resources [134,135]. Transportation to longer distances is not necessary, as the produce is consumed within a certain distance; therefore, the fuel consumption and the corresponding environmental impact converges to zero. Also, when crops are consumed or processed within a short time, storage aspects (including space, temperature, humidity, sterility, packaging, etc.) and, again, the inherent environmental impacts can be skipped [26].

Although policymakers continue to support local food systems (LFSs) based on the assumption that ‘local’ is inherently good, a review of the scientific evidence confirming (or refuting) their multiple benefits is missing, leading to possible counter-productive policies [136]. Also, in LFSs, particularly in short food supply chains, food safety and quality are mostly based on trust between producers and consumers [137,138]. Moreover, international food trade has the potential to provide a more nutritious and diverse food supply, especially in countries where agroecological conditions do not allow for year-round, food-diverse production [139].

PFALs have the potential to mitigate greenhouse gas (GHG) emissions due to the shorter transport distances involved in the distribution of the produce [140–142]. However, it could be more energy efficient to transport large volumes at the same time rather than small amounts around a city. The transport home from the grocery store is one of the largest shares of GHG emissions of a product from a life cycle perspective [143]. In certain cases, the generated GHG emission of an imported product can be lower than that of a
local product [144]. Wind, tidal, and geothermal energies show promise for low carbon footprints [145]. Local food systems do not automatically generate less GHGs than global food systems [136]. Integration of the PF with the building energy system can reduce GHG emissions of the production up to 40% [146]. The next-generation PFALs (n-PFAL) are expected to play a significant role in achieving a substantial portion of the 17 Sustainable Development Goals (SDGs) to be achieved by 2030 [147].

According to Wong et al. [27], urban PFs provide the possibility to bring nature closer to the city, and additionally, they can provide subsistence to qualified personnel. At the same time, moving production from agricultural lands to cities results in the reduction in skilled labor needs in rural areas. Additionally, automated urban PFs require a lower number of agricultural workers with higher or different qualifications; therefore, released rural manpower potentials cannot be transferred automatically to urban agricultural facilities.

As PFs have the possibility to move the whole production close to urban inhabitants, OF production still has to mobilize products to the consumers in a highly organized manner. For this, OF uses socio-economic involvement [148] called community-supported agriculture (CSA). In this model, farmers and consumers share the costs of the production, the responsibility, and the crops produced. This democratic system aims to provide reliable food for the members and a fair price for the expenses of the farmer, which is in accordance with the principles of OF, although the scheme can be applied in conventional farming as well. Although the popularity of local and regional and even transnational-level CSAs shows to be increasing [149,150], their role in global food supply systems is still marginal [151].

The key to success during the unprecedented disruption caused by Coronavirus disease 2019 was the strategic reconstruction of marketing channels through the adaptive use of a heterogeneous set of information communication technology (ICT) tools, e.g., Google-form-based ordering sheets, even if this required profound modifications of other stages of production or the restructuring of whole business strategies. Although digitalization in short food supply chains has considerable potential for increasing resilience [152,153], a digital inclusion agenda may be needed globally before ICT tools become a general source of resilience among small-scale producers [154,155].

As more than half of the world’s human population lives in urban areas and this is expected to reach two-thirds by 2050 [1], reducing the cost and environment-polluting effect of the transportation of food from rural to urban areas is an acute need. According to its definition, urban farming covers activities to produce crop plants for local use in an urbanized area [27]; urban farming is one of the most popular concepts in the idea of agricultural democratization [156]. Food resilience of highly populated areas can be developed by the installation of PFs into urban environments [26]. Depending on technological investments, production can be implemented on genuine soil within city limits, via simple hydroponics, in protected facilities or, ultimately, in PFs standing alone or installed in residential buildings. PFs not only allow for the usage of abandoned buildings, rooftops, and unused soils, but also of soils unsuitable for agricultural production (contaminated, depleted, or poor soils and areas with ground surface covered with concrete) within cities [17]. The diversification of crops must be planned according to available resources: highly demanded and highly valued crops should be produced in closed facilities, while mass-produced ones are suitable even for the genuine soil of empty plots.

In summary, H5 was rejected (H5: local food production provides broader perspectives for OF systems and is less relevant for PFs), as several common features have been identified (Figure 8) that can enhance the complementarities among OF and PF systems in terms of food resilience, space utilization, and GHG reduction.
were the only arguments they had. Furthermore, people thought that the concept could
decide whether to choose to plant factory vegetables or not is the price of the product [158].

According to a French survey conducted in organic shops, the customers did not have
knowledge about the differences between OF and PFs. The concept of indoor and outdoor
farming side includes characteristics of urban production in OF systems. The plant factory side
includes properties of PF systems.

3.5.2. Consumers’ Attitudes toward PF Products

The term ‘plant factory’ is generally used in sources outside Europe, as ‘factory’ recalls
industrial pollution in European consumer minds, while, in contrast, Asian consumers
believe that soilless production is free from contaminations and therefore prefer PF products
over conventional ones [15]. The future of PF production mainly depends on the consumer
acceptance of PF products [115]. Differentiation among open-field, greenhouse, and PF
products is not always possible [157]. The first factor considered when consumers decide
whether to choose to plant factory vegetables or not is the price of the product [158].

PFs, in the form of indoor plant production PFALs, remain novel or even unknown
to many people [157,159,160]. Consumer insight studies illuminate the mix of potential
advantages and disadvantages of PFs to consumers: improved security in food supply,
shorter supply chains, all-year crop production, higher yields, and less pesticide and
herbicide use (advantages), but high energy use and premium pricing, concerns over health
risks, and concerns over fully automated IT systems (disadvantages) [157,160–163]. The
results of a study in Russia indicated that respondents’ attitudes are heterogeneous and
related to their region of residence, income level, and opinions regarding nutrients, safety,
and taste. Misconceptions or lack of knowledge were behind several opinions [163]. In
a multi-method research approach, the majority of consumers in several countries (US,
UK, Singapore, and China) using online surveys indicated a positive sentiment toward
vertical farming (VF). On the other hand, high energy use and premium prices contributed
to negative attitudes about VF [164].

Choice tests demonstrated that hydroponic crops were significantly less attractive
than their organic soil counterparts but were still accepted by consumers overall [165].
According to a French survey conducted in organic shops, the customers did not have
knowledge about the differences between OF and PFs. The concept of indoor and outdoor
were the only arguments they had. Furthermore, people thought that the concept could
be the future of agriculture, whereas they would choose the cheaper price between two products from OF and PFs [166].

Similarly to the labeling regulations of OF products, the application of a ‘plant factory label’ was recently suggested (Figure 9) so as to allow farmers to realize the extra costs of production over conventional technology [167]. It is also expected that with the development of PF technologies and the increase in production volume, PF product prices will be lower [26]. However, by learning from past experiences, it is important to see that agricultural decisions are never successful without the consensual acceptance of every stakeholder, including society [168].

![Logos about certification in different production systems. Logos allow farmers to realize the extra costs of production over conventional technology. Left to right: Sustainable Indoor Farm (SIF) Certificate, organic product (US), and organic product (EU). Sources: SIF, USDA, and EC.](image)

Figure 9. Logos about certification in different production systems. Logos allow farmers to realize the extra costs of production over conventional technology. Left to right: Sustainable Indoor Farm (SIF) Certificate, organic product (US), and organic product (EU). Sources: SIF, USDA, and EC.

In summary, H6 was rejected (H6: consumers prefer OF products over PF products), as there is a lack of knowledge about both systems, which leads to individual bias. The price-sensitivity attitudes of consumers will increase with future energy crises.

3.5.3. Economic Sustainability of OF and PF Systems

At the farm level, numerous sustainability assessment methods have been developed, for example, the sustainability assessment of food and agriculture systems (SAFA), sustainability monitoring and assessment routine (SMART), response-inducing sustainability evaluation (RISE), and multi-criteria assessment (MCA) [169]. The SAFA framework consists of four spheres of sustainability: good governance, environmental integrity, economic resilience, and social well-being. In the comparison of a conventional farm, an organic farm, and a PF in China, the organic farm had the highest scores in total. It performed best on the social and environmental spheres of sustainability compared to other farms. The scores of the PF were volatile compared to the other farms. It is still difficult to assess the financial sustainability of this innovation because it is at a premature state [170].

Strategies for improved resource use efficiency include water use efficiency (grams of fresh weight per liter of water consumed, WUE), land surface use efficiency (daily productivity per unit of land used, LUE), and energy use efficiency (yield per unit of electricity consumed, EUE) [171].

Water scarcity is a significant problem in many parts of the world. One of the most frequently touted benefits of indoor farming is the reduced use of water [172]. Closed irrigation systems applied in PFs are considered water efficient, as they are capable of providing sufficient amounts of moisture and nutrients for optimal plant development [173]. Due to minimal water consumption, PFs can be a good option in regions where the access to water is limited [174], especially when the high investment costs are covered. Since high-tech greenhouses also generally use closed-loop hydroponics, the positive impact of PFs on minimizing freshwater pollution compared to greenhouses is more limited [175]. In comparison with open-field cultivation, where approximately 30% of the applied fertilizer is leached into deeper soil layers [176], the nutrients in a
recirculated fertilizer solution can be utilized at a high percentage, which can be considered as less demanding in terms of economic and environmental perspectives as well. In contrast, recirculation enables the establishment of algae and bacteria in the solution, in addition to the root excretions of the crops; these together can limit the development of crops [177]. Chemical, physical, and UV-based solutions are available for the removal of undesired components [178]. Another issue is the selective nutrient utilization of plants, which can cause fertilization imbalances responsible for limitations in plant development. Although high-precision ion sensors are available, due to their high price and to compatibility issues, EC sensors are more widespread for monitoring. Huebbers and Buyel [50] suggest using the application of sensors which are capable of detecting nutrient deficiencies indirectly, i.e., by leaf size and color.

Improved land use and management techniques are found to reduce nutrient leaching, and indoor farming also can help avoid these externalities [172]. The N footprint was reduced by 37%, at 363 M g N year$^{-1}$, and the P footprint was reduced by 36%, at 71 M g P year$^{-1}$, by a PF compared conventional agriculture in a study in Miyagi Prefecture, Japan [54]. According to a Japanese study, PFs reduced the use of irreplaceable resources for food production, i.e., phosphorus, water, and land area, at the expense of additional energy consumption compared with conventional Japanese horticulture systems [179]. On the other hand, OF has its own measures against nutrient leaching, such as the use of organic nutrient sources (manure, green residues, compost, etc.) that are slowly becoming available for the plants [180], soil life support, and the use of cover crops [181,182] and/or deep rooting plants [183] capable of taking up the already leached N sources.

Opportunities to move from open-field farming to indoor farming could potentially have significant impacts on air quality and the production of GHGs, especially through the conversion of open-field agriculture to forests [184]. However, current PFs cause higher greenhouse gas emissions than conventional systems. Solar-light PFs are more efficient, but less widely applicable. By employing emerging energy technology options, energy consumption can be reduced sufficiently to be competitive with that of conventional horticulture systems [179]. In a recent Italian study with lettuce grown in climate-controlled growth chambers, electricity accounted for 77–93% of the environmental impact and 64% of the economic costs of production [185]. By adopting movable LED lamps, it was possible to half the cost of lamps per unit of growing surface [186]. PFALs consume electricity mostly at night and in the early morning and late evening when electricity consumption in office buildings and homes is lower. The optimization of energy consumption through a systematic graph-theoretical method is a good alternative [187]. Another possibility to cut down on costs is to integrate PFs into the current infrastructure by sharing temperature, electricity, and finances. Synergies with businesses in proximity and host-building synergies can improve the material and energy efficiency of urban PFs.

The environmental perspective of PFs compared to conventional organic production is as follows: (1) both PFs and OF are pesticide-free applications, and PFs keep the cultivated area clean and free from pest insects [184]; (2) PFs show a 99% reduction in water consumption; (3) PFs show a 99% reduction in land use compared to conventional agriculture due to higher productivity per production area; (4) PFs show a 30–50% reduction in plant defects; (5) PFs have extremely higher energy costs in comparison with OF [188]. Therefore, H7 was rejected (H7: both OF and PF systems can be considered as sustainable), as both systems have their weak points.

4. Future Directions and Trends

The plant factory is not an ultimate answer for all existing sustainability problems but can contribute significantly by providing solutions to existing problems [189]. However, the co-existence of the OF and PF systems is more beneficial when good practices are adopted by both, within the boundaries of the regulatory background. Based on the literature reviewed, the following trends are expected in the future:
- The role of open fields will be of paramount importance due to the degradative processes that threaten living ecosystems.

- A practice-based allocation of species and varieties will result in the separated production of cash crops and mass-produced crops; valuable (and PF-compatible) species will be produced in controlled environments. As a consequence, the agrochemicalization of arable fields will be reduced and the emphasis will be laid on sustaining living soils.

- Accelerated urbanization will contribute to the reduction in fields appropriate for organic production; therefore, synergies will be forced.

- The intensification of mass production is an inevitable requirement of humanity—both systems have to be intensified for this aim.

- The economic viability of PFs will be improved; future energy crises and consumer expectations will drive the increased sustainability of PFs. The modularity and miniaturation of PFs may be a solution.

- The occurrence of global epidemics cannot be excluded; therefore, local supply chains will be strengthened. The self-sufficiency of a community starts with common cooperation in food ordering and food production and ultimately ends in community PFs.

- The term ‘sustainability’ has become worn out; re-definition of its meaning is required.

- There is insufficient knowledge both about OF and PFs in society. This gap exists in the heads of experts and of laymen. In order to achieve any progress, information campaigns are needed.

- With technological progress the price of PF products will decrease; consumer awareness will develop towards PF products due to targeted information campaigns by related stakeholders.

- The integration of PF solutions to urban environments will reach architectural levels; premium apartments with direct PF access will become a market advantage in the real estate sector.

- Production on genuine soil is the main identifier of OF; therefore, no progress is expected in terms of regulatory updates, at least in Europe. It is possible, though, that in the US and Asia the regulation of the growing media of OF will become more permissive, which will result in conflicting interests in global certification equivalence.

5. Conclusions

What is the role of OF and PF systems in the sustainable global agriculture of the future? In this work, the multi-perspective approach of sustainability, using scientific sources, provides the opportunity to give a sophisticated answer to this question. Most studies dealing with PFs justify their existence referring to human population growth and to challenges in soil-based crop production, such as climate extremities, resource depletion, and soil-borne pathogens. However, the mass production of staple crops in PF facilities is technically challenging and economically not viable due to physical and economic limitations. This implies that PFs alone will not be able to solve the world food crisis but can substantially contribute to food security in the future. The same is possibly true for OF. At the same time, several Agriculture 4.0 innovations fit very well into organic systems, such as LED-based supplementary light, pre- and post-harvest light treatments, sensor technology, and AI-based solutions. Agriculture 4.0, however, can easily become dominant and suppress any other sustainability approaches, such as deep adaptation or traditional technologies (agroforestry, agroecology, or permaculture). For the comparison of OF and PF systems, the easy-to-understand set of theory figures proved useful.

The main conclusion of this review is that OF and PFs have similar targets but different historical backgrounds, approaches, and focus. The environmental benefits of PFs are in competition with OF, including prevention in the use of fertilizers and pesticides, farm-land preservation, and reduction in food miles. The standards and regulations, however, hinder joint action and marketing, but science can help to identify mutual concepts and joint structures for a modern urban and rural life. These processes impact stakeholders
(consumers, farmers, processors, traders, and legislators, as well as standardization bodies, certification bodies, and authorities in national/regional/international levels) to a different extent, as they possess differences in terms of information, knowledge, decision making, financial background, and goals. To sum up, consumer needs, expectations, and knowledge determine the sustainability of the products produced for them; therefore, consumer education and awareness is particularly important. A great opportunity for farmers and processors lies in working together to establish and effectively operate sustainable farming systems (e.g., OF and PFs) and to promote their interests. Without uniform regulations and standards, it is difficult to compare the quality of products from OF and PF systems on the world market, which leads to further problems in consumer perception. The success of OF and PF schemes depends to a large extent on their ability to meet consumer expectations and their credibility in terms of sustainability, in which sustainability labels can play a key role in communication. Individual, organizational, national, regional, and global responses to sustainability challenges show a great level of heterogeneity. Approached from a decision-theoretic point of view, there are typically many alternatives with many factors with different decision weights; in addition, stakeholders have bounded rationality. Sustainability criteria tend to take a back seat to economic considerations; therefore, incentives and subsidies and a coherent system of regulation, monitoring, and certification can be particularly important. The present global processes envisage the trends of the future (threats to living ecosystems, plant species allocation, urbanization impacts, agricultural intensification, economics of PFs, local supply chains, education about OF and PFs, consumer acceptance of OF and PF products, and discrepancies in global regulations), which will certainly trigger further research in the scientific community.


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References
8. Ray, D.K.; West, P.C.; Clark, M.; Gerber, J.S.; Prischepov, A.V.; Chatterjee, S. Climate change has likely already affected global food production. PLoS ONE 2019, 14, e0217148. [CrossRef]


74. Gruda, N.S. Increasing Sustainability of Growing Media Constituents and Stand-Alone Substrates in Soilless Culture Systems. *Agronomy* 2019, 9, 298. [CrossRef]


76. Medyńska-Juraszek, A.; Marcinkowska, K.; Gruszka, D.; Kluczek, K. The Effects of Rabbit-Manure-Derived Biochar Co-Application with Compost on the Availability and Heavy Metal Uptake by Green Leafy Vegetables. *Agronomy* 2022, 12, 2552. [CrossRef]


121. Touliatos, D.; Dodd, I.C.; McInish, M. Vertical farming increases lettuce yield per unit area compared to conventional horizontal hydroponics. *Food Energy Secur.* 2016, 5, 184–191. [CrossRef]


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