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Review

An Evaluation of Research Interests in Vertical Farming through the Analysis of KPIs Adopted in the Literature

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Abstract: Vertical farming has gained increased attention in recent years due to its capacity to reduce the environmental impact of agricultural production in terms of water consumption and soil and fertilizer usage. In the literature, many works describe and evaluate applications of vertical farming. However, no work addresses the issue of classifying the KPIs for vertical farming and highlights both the most assessed aspects and the lack of evaluations. The main contribution of this study is to conduct a literature review to identify and classify the KPIs used in vertical farming. To this aim, we first proposed a methodology to define the KPI categories. Then, we identified the KPIs used in the literature, and we classified them according to the defined categories. Finally, we analyzed the obtained results. As a result, a collection of 78 KPIs were compiled and organized into the proposed categories. The analyses on the frequency of the KPIs allow us to conclude that the KPIs related to productivity are the most used as compared to those related to sustainability and quality. Furthermore, very few papers perform a cross-category evaluation. This study underscores the necessity for a more balanced consideration of productivity, quality, and sustainability in the context of vertical farming.

Keywords: controlled-environment agriculture; vertical farming; indicators; sustainability; resource management; plant production system

Citation: Fasciolo, B.; Awouda, A.M.M.; Grasso, N.; Bruno, G.; Chiabert, P.; Lombardi, F. An Evaluation of Research Interests in Vertical Farming through the Analysis of KPIs Adopted in the Literature. *Sustainability* **2024**, *16*, 1371. https://doi.org/10.3390/su16041371

Academic Editors: Hossein Azadi and Jan Hopmans

Received: 1 December 2023
Revised: 11 January 2024
Accepted: 1 February 2024
Published: 6 February 2024

1. Introduction

As defined by Sharath Kumar et al. [1], vertical farming (VF) is a multilayer indoor plant production system in which all growth factors, such as light, temperature, humidity, carbon dioxide concentration (CO_2), water, and nutrients, are precisely controlled to produce high quantities of high-quality fresh products year-round, completely independent of solar light and other outdoor conditions.

Early and rough implementations of vertical farming can be found in the 20th century [2], but all of them faced problems related to technology constraints and high energy demands. Then, researchers took steps to address this issue by seeking more sustainable and cost-effective production methods to bring VF into the sphere of sustainable agricultural production. Indeed, in recent years, sustainable agrifood production has become a pivotal element for several sustainable development goals (SDGs), and a lot of scientific research has focused its attention on it [3,4]. Among the frontiers of sustainable agriculture, VF is gaining more and more interest from both the scientific community and the market [5]; for instance, since the primary contributor to the highest energy usage is the lighting system, it is feasible to diminish this consumption by finely tuning both the intensity and spectrum of the light, as suggested by Modarelli et al. [6].

Alongside energy consumption optimization, another research interest in VF is production monitoring and control, which are crucial to optimizing resources and reducing waste and, thus, promoting a more sustainable production system. Recently, researchers have focused on the digitalization of the system using remote and autonomous control systems to apply the concept of the Internet of Things (IoT) to farming [5,7–10]. Such an approach is becoming widely used, and some authors have already introduced a new acronym to describe the application of the IoT in an agricultural system: the IoP, the Internet of Plants [11]. In the context of this work, following the definition of Lee et al. [12], we refer to VF production systems (VFPSs) as VF systems equipped with an IoT architecture.

VFPSs are claimed to be able to overcome traditional agricultural systems under three dimensions: sustainability, productivity, and quality [13,14]. However, these concepts are meaningless without the availability of indicators and monitoring systems able to track the performance of agricultural production systems towards these ideals [15]. The measurement of the performance of a production system serves as an effective tool to ensure a balance between the needs of production and environmental sustainability. Indeed, measuring performance permits the identification of areas of inefficiencies or inadequacies within the system, enabling subsequent adjustments to optimize resource use, minimize waste, and mitigate environmental impact [16]. Since traditional agriculture and VF share the same goal, several KPIs that have been developed for the first one may be applied to the latter. Nevertheless, a completely different production system needs a set of dedicated KPIs that inherit the traditional ones and are enriched by new ones and that are able to properly address the VFPS's features.

Reviews of indicators for traditional agricultural systems, especially reviews focused on the sustainability aspects, are already present in the literature. For instance, Nadaraja et al. [17] managed to complete an indicator list covering the three sustainability pillars focusing on plantations. Sannou et al. [18] focused their work on the social sustainability of agri-food systems in general. Moreover, Velasco-Muñoz et al. [19] proposed a set of indicators for measuring the circularity performance of agricultural production systems.

To the best of the authors' knowledge, not many works have been published on the analysis of KPIs for vertical farming. In particular, no work provides a classification of VFPS KPIs or revises the existing KPIs used to evaluate a VFPS, even if many papers have pointed out the pivotal role of selecting and using valuable KPIs to visualize the alignment of the performance with the system requirements [20]. Indeed, the goodness of KPIs must be related to the final objective, which may vary a lot in the VF context, including overall cost reduction, resource optimization, sustainability, gross production, and others [20,21]. The economic dimension of VFPSs has received a lot of attention, and proper KPIs have been developed [13,22]. Another interesting study focused on the environmental impact of VFPS through the implementation of LCA and thus the development of sustainability KPIs [23]. LCA allows for quantifying the potential environmental and human health impacts associated with a good or service from its respective resource consumption and overall emissions [24]. Applying LCA to a VFPS can provide solid and transparent evidence of its actual sustainability [25]. On the other hand, other dimensions have been considered more poorly, for instance, climate monitoring, tracking of the quality of the product, as well as the functioning of the machine parts [22,26,27].

Hence, there is a lack of robust metrics and indicators to properly evaluate all the different aspects of a VFPS [28]. A preliminary attempt of the classification of KPIs for vertical farming was presented by Grasso et al. [29], even if it did not include an extended literature review.

Thus, the main contributions of this work are as follows: providing a functional model of a VFPS, selecting and classifying the KPIs used in those systems, and providing insights about the frequencies of the KPIs used in the literature.

To this aim, the following research questions (RQ) were formulated:

- RQ1: What are the main categories in which the VFPS KPIs can be classified based on their objective?
- RQ2: What are the most frequently used VFPS KPIs and categories?
- RQ3: Do the researchers exhaustively evaluate VFPSs by considering all the KPI categories?

The research method used to answer these questions was inspired by the idea of literary discovery [30], which emphasizes the development of new knowledge by making use of bibliographic data found in the form of peer-reviewed papers, conference proceedings, and other legitimate forms of the scientific literature.

The proposed methodology is composed of four steps. Firstly, we identified the KPI dimensions, starting from the definition proposed by Reganold et al. [31], which divides the indicators into the main classes of productivity, sustainability, and quality. Simultaneously, we identified VFPS elements that can be evaluated. This was carried out using an IDEF0 model, which allowed us to properly describe the system in each of its parts or elements. Then, the KPI dimensions and VFPS elements were merged to obtain the final categories. Finally, we performed a literature review to find all the papers addressing the evaluation of VFPS to retrieve the KPIs, and we associated each of them with one category. This allowed us to evaluate the frequency of each KPI and understand which ones are the most used.

Overall, the paper is structured as follows: Section 2 describes the methodology. The results, including the retrieved KPI descriptions and classifications, are reported in Section 3. After the identification and classification of the KPIs, the obtained results were analyzed to understand which are the categories that are frequently considered for the evaluation of VFPSs and how frequently a cross-category evaluation is conducted (Section 4). Finally, Section 5 reports the conclusions.

2. Methodology

The methodology is divided into four steps. The first three steps are related to the identification of the KPI categories, while the fourth step is devoted to the literature review to identify the KPIs and their frequencies. The four steps are described in the following subsections.

2.1. KPI Dimensions

We identified the three main dimensions of KPIs for a VFPS, which are the same as for a traditional farming system, i.e., productivity, sustainability, and quality, by the definition of Reganold et al. [31], which outlines the objective of a farm to produce adequate quantities of high-quality food, preserve its resources, and be both environmentally safe and successful. Then, we further specialized each dimension.

The productivity dimension is divided into system productivity and crop productivity to separate the KPIs used in order to evaluate how a plant grows in a VFPS (crop productivity) and the ones used to evaluate the productivity of a VFPS viewed as the actual plant production system (system productivity).

The sustainability dimension is divided into economic, environmental, and social elements, following the common definition of Purvis et al. [32].

The quality category is divided into nutritive value (e.g., vitamin content), deliciousness (e.g., taste, color), safety (e.g., bacterial load), and logistic feasibility (to monitor the ease of transport and storage of crops before sale) [33,34].

2.2. VFPS Elements

Once the KPI dimensions had been defined, we analyzed the elements that compose a VFPS. We recall that the term vertical farming refers to any soilless farming technique that operates in a controlled environment. Moreover, we refer to a production system in a controlled environment that can have from one to several levels of cultivation. Therefore, the model's boundaries include the growth of the crop from the germination stage to the harvesting stage, omitting all pre-production and post-production stages.

To model VFPSs and identify their main elements to be linked to the KPI dimensions, the IDEF0 formalism was used [35]. IDEF0 is a modeling technique that combines graphics and text to represent complex systems in an organized way. The model consists of hierarchical diagrams that gradually provide more detailed descriptions of a system's functions and interfaces. An IDEF0 model shows how the system's functions are interconnected and how they operate. It is commonly used for understanding, analyzing, and designing systems, as well as specifying requirements and supporting integration activities [36].

In an IDEF0 model, the primary element is the graphic diagram, which includes boxes, arrows, and interconnections. Boxes represent the major functions of the subject being modeled. These functions can be further detailed in child diagrams until the subject is described at the necessary level for a specific project's goals. The top-level diagram offers a general and abstract representation of the subject. As you move down the hierarchy, the diagrams become more detailed, providing a comprehensive understanding of how the system functions and interacts.

The sides of the function box have standardized meanings in terms of box/arrow relationships. The role of an arrow is determined by the side of the box with which it interfaces. Arrows entering the left side of the box represent inputs. These inputs are the data or objects that the function consumes or transforms to produce outputs. Arrows entering the box from the top side represent controls. Controls specify the conditions or requirements needed for the function to produce accurate outputs. Arrows leaving the box on the right side are outputs. These outputs are the data or objects that are generated or produced by the function. Arrows connected to the bottom side of the box represent mechanisms. Mechanisms are the means that support the execution of the function, identified by upward-pointing arrows.

The IDEF0 formalism was used to represent VPFSs and identify their elements. The elements that compose a VFPS are all its inputs, outputs, mechanisms, and controls.

We identified three input elements for VFPSs: seeds, environmental inputs provided to the plant to ensure efficient growth (i.e., water, nutrients, CO, temperature, humidity, light intensity, light spectrum, energy, space, and substrate), and packaging material used to prepare the finished product.

The output elements were identified as crops (divided into edible parts and non-edible parts) and environmental outputs (i.e., nutrient surplus, water, and oxygen).

The mechanism elements were divided into the workforce, environmental technologies, and the mechanical structure. Environmental technologies (i.e., sensors, actuators, and microprocessors) enable the system to control and monitor the environmental inputs necessary for crop growth. On the other hand, the workforce includes all the operators who perform non-automated system functions. The level of labor involved in crop growth depends on the system's automation level. Finally, the mechanical structure supports the crop's growth, providing the frame of the cultivation system, such as a grow chamber and an irrigation system.

Five control elements were identified: government regulations (i.e., all the regulations that the production system must comply with to conform to the law of a given country), resource constraints (i.e., economic and physical limitations that the cultivation system presents, such as space and energy limitations), crop shape and color (constraints on color or shape concerning market demands), growth constraints (controls based on the physiological parameters of the plant to determine whether the plant is growing healthily or not), and environmental constraints (indicating the ranges of environmental inputs for the plant to grow healthily).

The A-0 diagram was further specified into two functions: growing, and harvesting. Growing refers to the growth cycle of the crop, which varies depending on the crop type being considered. Harvesting, however, means the stage of harvesting, packing, and storing the final product.

Figure 1 shows the VFPS top-level diagram (named A-0) and A0 diagram.

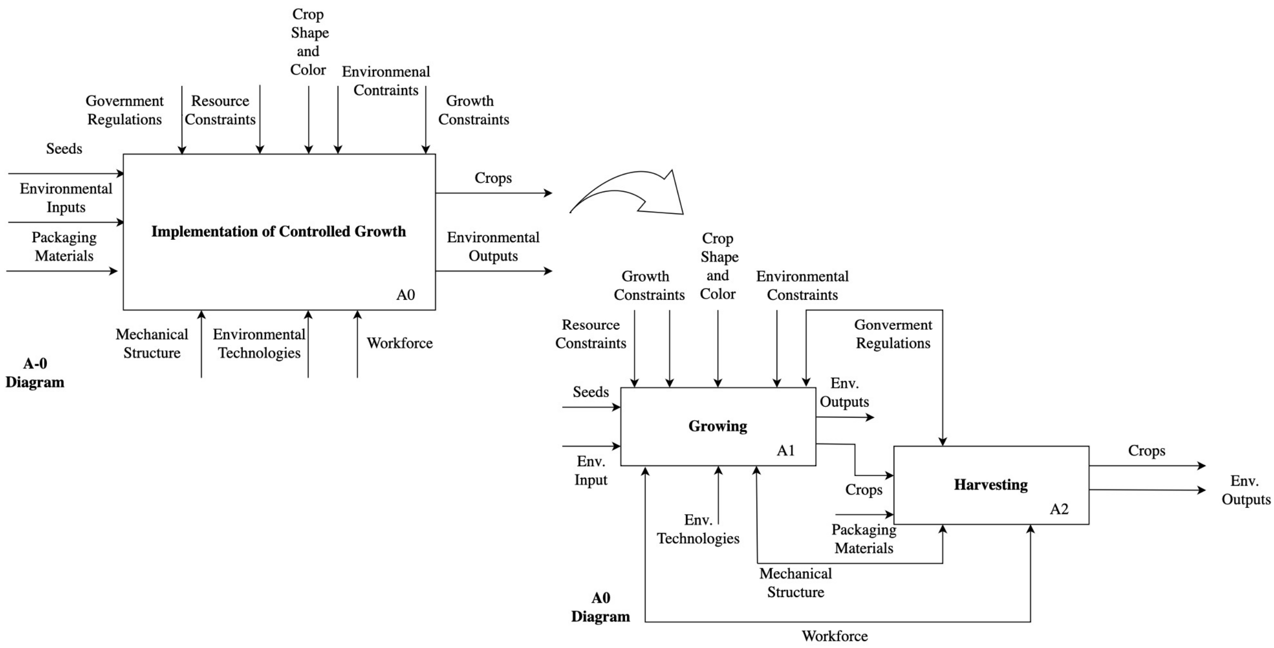

Figure 1. VFPS A-0 and A0 diagrams.

2.3. Final KPIs Categories

Each VFPS element identified in the second step is mapped to one or more dimensions identified in the first step, originating the final KPI categories as summarized in Table 1.

Table 1. KPI dimensions and VFPS elements. The table is structured as follows: the left side lists KPI dimensions (first column) and sub-dimensions (second column). The right side lists IDEF0 VFPS elements, divided into element type (third column), element (fourth column), and element component (last column), as described in Section 2.2.

	KPIs Dimensions			VFPS Elements
Dimension	**Sub-Dimension**	**Element Type**	**Element**	**Element Component**
Productivity	Crop productivity	Output	Crops	Edible part Non-edible part
	System productivity	Output	Crops	Edible part Non-edible part
		Mechanisms	Environmental technologies	Sensors Actuators Microprocessor
			Mechanical structure	Frame
Sustainability	Environmental	Input	Environmental input	CO_2 Light Energy Temperature Humidity Space Water Substrate Nutrients
		Output	Environmental output	Nutrient surplus Water Oxygen
Quality	Nutritive value	Output	Crops	Edible part
	Safety	Output	Crops	Edible part Non-edible part
	Deliciousness	Output	Crops	edible part
	Logistic feasibility	Input Output	Packaging materials Crops	Packaging materials Edible part

Regarding productivity, the crop productivity dimension includes the output element of crops in the IDEF0 model. Indeed, this category includes all the KPIs measuring plant physical characteristics. On the other hand, the mechanism elements of environmental technologies and mechanical structure are included in the system productivity dimension because the KPIs of these categories are related to the plant production system. In this sub-dimension, the output element of crops is also included, since the KPIs of this category are related to the crop's physical characteristics.

Considering sustainability, all the identified elements belong to the environmental sustainability dimension. This is because social and economic sustainability extends beyond the boundaries of the VFPS, and quantifying them only within the system boundaries can lead to a distorted evaluation. Indeed, inside the mechanisms of the IDEF0 model, the workforce element is the only element not described through KPIs because it should fit inside the social sustainability dimension.

The environmental sustainability category includes the environmental inputs and environmental outputs of the VFPS. This category includes all the KPIs that measure the consumption and efficiency of the utilization of the inputs provided to the system.

Regarding quality, all the sub-dimensions include the output element of crops, since the KPIs evaluating the nutritive value, safety, deliciousness, and logistics feasibility are computed by analyzing the grown crops. In addition, the logistic feasibility also includes the input element of packaging materials.

There were eleven identified KPI categories, and they were created through the merging of the identified dimensions and the VFPS elements (fourth column of the table). It can be noticed that the considered VFPS elements were only the inputs, outputs, and mechanisms of the IDEF0 model. Controls were not used to define the categories because they represent the requirements needed for the function to produce accurate outputs and thus impose limits on the production system.

At the end of these steps, it is possible to answer RQ1 (What are the main categories in which the VFPS KPIs can be classified based on their objective?). The identified categories to classify the VFPS KPIs are the eleven ones reported in Figure 2. In Section 3, we describe how we classified the KPIs found in the literature into the proposed categories. Because some KPIs can be related to multiple categories, some categories were merged.

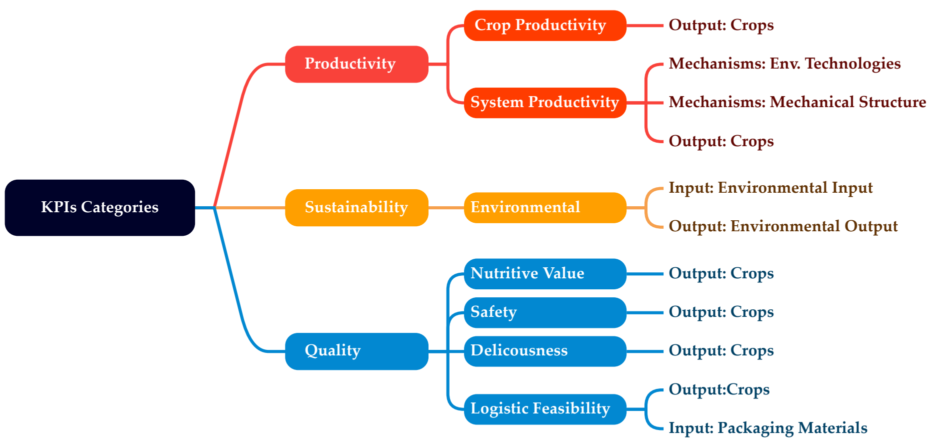

Figure 2. Categories for the classification of VFPS KPIs.

2.4. Paper Selection from the Literature

The identification of the KPIs started with a literature review on the Scopus database that was selected due to its broad thematic scope and interdisciplinary papers. The period covered by the analysis was 2010–2023 due to the lack of diffusion of vertical farming in the literature and in practice before that period [5]. Moreover, only peer-reviewed articles written in English were selected.

The keywords used to develop the search queries are shown in Table 2, where "Key Performance Indicator" and "Vertical farming" or their synonyms are the main constructs. Scopus search engine allows either to perform an exact search or a loose phrase. Loose phrases allow the inclusion of more items in the search, by the use of the special character *. For instance, searching farm * will return results like farm, farms, farming, and so on.

Table 2. Queries Keywords.

Construct	Keywords	Search Query
Vertical farming	Vertical farming Hydroponics Aeroponics Aquaponics Biophonic Controlled-environment farms (CEA) Plant factory with artificial light (PFAL)	"Vertical farm *" OR hydroponic * OR aeroponic * OR aquaponic * OR bioponic * OR "controlled environment farm *" OR CEA OR "Plant Factory with Artificial Light *" OR PFAL
Key performance indicators	Key performance indicators (KPI) Index Metric indicator Performance evaluation	kpi OR "key performance indicator" OR metric * OR index * OR indicator * OR "performance evaluat *"

The keyword search was performed only on the article titles and keywords. In May 2023, this query retrieved a total of 178 articles. Out of these documents, 19 were not possible to acquire or read because the full text was not found, or it was not in English. Moreover, after initially examining the abstracts of these articles, 59 were considered out of scope since they do not propose any KPIs for vertical farming. Then, manual insertion of articles was also conducted in this phase because there were articles that did not appear in the literature search (not satisfying the search criteria) but proved to be useful for KPI identification. Thus, a total of 10 articles were added, which led to a total of 110 articles being identified, as shown in Figure 3.

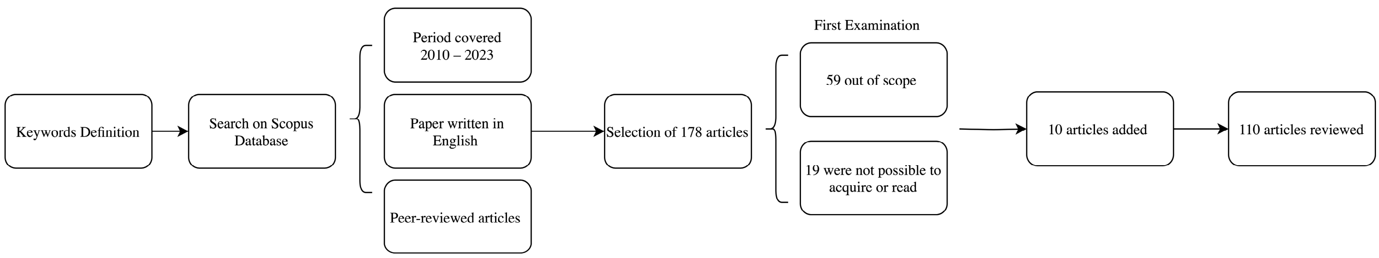

Figure 3. Paper selection flowchart.

The initial screening of the abstracts (first examination), where 59 articles were found to be out of scope, was divided between three independent reviewers. Subsequently, the screening process based on the analysis of the full text of the 110 articles was carried out by nine students. To avoid bias caused by the students' lack of experience, at a later stage, some papers were rescreened by three PhD students. For every paper, we documented the identified key performance indicators (KPIs) in an Excel file. Each column in the file represented a cumulative list of KPIs up to that point, while each row corresponded to the articles screened up to that moment. Consequently, the Excel table was systematically updated for each paper.

The analysis of the identified papers allowed us to identify the KPIs used in the literature to evaluate VFPS and to answer the remaining research questions. The results of this analysis are reported in the following section. The obtained KPIs are presented in a tabular form and classified in the categories defined in Section 2.3.

3. Results

After completing the screening process based on the analysis of the full texts of the selected papers, 78 indicators were identified. The KPIs were classified in the categories defined in the previous section. Furthermore, since the KPIs belong to different hierarchical levels, they are presented in a three-level hierarchical way. Level I represents KPIs that give more general information, while in levels II and III, there are KPIs that still assess the same element but give more detailed information.

For each KPI, the theoretical definition is given, together with the frequency of its citations in the analyzed papers. The frequency of each KPI is indicated in brackets in the tables of this section.

3.1. Productivity KPIs

Table 3 reports the KPIs found in the productivity dimension.

Table 3. Productivity dimension KPIs. The first and second columns together list the merged productivity categories. Then, for each category, three levels of KPIs are listed (columns three to five) along with their frequency of appearance in brackets.

Productivity Category		KPI Level I	KPI Level II	KPI Level III
Crop Productivity	Output: Crop	Dry Weight (47)	Root Dry Weight (2) Shoot Dry Weight (2) Fruit Dry Weight (1)	Dry Root Biomass Content (1) Dry Leaves Biomass Content (1)
		Fresh Weight (44)	Root Fresh Weight (8) Fruit Fresh Weight (3) Shoot Fresh Weight (3)	
		Leaf Area (40)	Leaf Area Index (3)	
		Shoot Length (27)		
		Numbers of Leaves (8)		
		Root Length (6)		
		Stem Diameter (6)		
		Yield (5)	Harvest Index (14)	
		Root-to-Shoot Ratio (3)		
		Number of Fruits (3)		
		Root Diameter (1)		
		Number of Flowers (1)		
		Flower Size (1)		
System Productivity	Output: Crop Mechanism: Environmental Technology and Mechanical Structure	Overall Equipment Effectiveness (8)	Uptime (9)	Mean Time to Repair (1) Mean Time to Failure (1)
			Percentage of Usable Fresh Weight (6) Relative Yield (5)	
	Output: Crop	Percentage of Usable Dry Weight (3)		
		Gross Production (14)		
		Net Oxygen Produced (3)		
		Cycle Time (Germination) (7)		
		Cycle Time (Growth) (21)		

In the output crops, in the crop productivity category, the fresh weight and dry weight are the total weight and the dehydrated weight of the entire crop, respectively [37]. Their citation frequency was 47 and 44, respectively. These two indicators were both divided into root, shoot, and fruit weight at level II. The leaf area index (LAI) is a level II KPI computed as the ratio between the leaf area and the surface occupied by the plant [38]. Leaf area had a higher citation frequency compared with LAI, which were 40 and 3, respectively. Other level I KPIs included leaf area, shoot length, number of leaves, root length, and stem diameter [39,40]. The yield KPI refers to the amount of biomass produced per unit of area or volume within a given time frame [41]. The harvest index is a level II KPI that measures what proportion of a crop's yield is harvested relative to the crop's overall above-ground biomass. [42]. The harvest index had a higher citation frequency than the yield KPI at 14 and 5, respectively. Moreover, there is the root-to-hoot ratio KPI, which is the ratio between the root and shoot dry weight [43]. Level III KPIs included dry root and leaves biomass content, which was the proportion of root and leaf samples composed of dry matter or biomass, respectively, excluding the water content.

Finally, at level I, the number of fruits, root diameter, number of flowers, and flower size [44] with dry root and leaves biomass content were the ones least cited in the literature.

The categories of crop, environmental technologies, and mechanical structure system productivity were merged because some of the found KPIs need elements of all three categories to be computed. Specifically, the level I KPI was the overall equipment effectiveness (OEE), a widely used KPI for industrial production systems, which is computed as the product of the availability, performance, and quality of the production system [45]. However, as can be seen in Table 3, the citation frequency of the OEE was lower compared to the main crop productivity KPIs, such as dry or fresh weight. From the perspective of a VFPS, the OEE can be computed by multiplying the following level II KPIs: uptime, relative yield, and percentage of usable fresh weight. The uptime is defined as the amount of time the VFPS is running concerning the maximum possible time the system can run [27], the relative yield is the achieved yield as a percentage of the maximum possible achievable yield by the system [46], and the percentage of usable fresh weight is the amount of fresh weight after the removal of bad produce [47].

The last level I KPI is the percentage of usable dry weight, defined as the amount of dry weight after the removal of bad produce [47].

Finally, the uptime indicator has two level III KPIs, already defined for industrial production systems: the mean time to repair (MTTR), i.e., the time it takes to recover from a system breakdown or failure, and the mean time to failure (MTBF), which is the average time between system breakdowns [45].

In the output crops, in the system productivity category, four level I KPIs were found: gross production, i.e., the weight of the sellable produce harvested per m^2 of growth area per year [27], and the net oxygen produced, i.e., the amount of harvestable O_2 produced by the agricultural production system [48]. The cycle time (germination)is the time spent by the plant during the germination phase (time needed to go from seed to the first leaf), and the cycle time (growth) is the time spent in growth, i.e., the time from the growth of the first leaf until harvest [49].

In the productivity dimension, the KPIs with a higher citation frequency were all from the crop productivity category. They were fresh and dry weight, which were cited in 40% and 43% of the articles, respectively, followed by the leaf area, which was cited by 36% of the articles.

3.2. Sustainability KPIs

The categories of environmental input and environmental output in terms of environmental sustainability were merged because some found KPIs need elements of both categories to be computed. In level I, there were the following KPIs:

- Resource use efficiency (RUE), i.e., the ratio of the final plant production to the total input [50];
- Energy consumption, i.e., the decrease in the primary energy consumption required to produce a unit of agricultural product [51];
- Greenhouse gas (GHG) emissions, i.e., greenhouse gases emitted by agricultural activities that constitute a group of gases contributing to global warming and climate change [52].

In level II, there were KPIs related to RUE and energy consumption. Specifically, macro- and micronutrient use efficiency is defined as the absorption rate of nutrients by the plants and the supply rate of nutrients to the cultivation system [22]. Water use efficiency is defined as the ratio between the water used and the water withdrawn for the water sector [53]. CO_2 use efficiency is the ratio of CO_2 fixed by the plants to the amount of CO_2 supplied naturally or artificially to the plants [22]. Electrical energy use efficiency is defined as the efficiency of the overall electrical energy used by the plants [22]. Light and land use efficiency describe the efficiency with which the plants use the incident light and growing space, respectively [54,55]. Finally, electricity consumption for lamps and cooling is the ratio of the energy consumed in different sectors to the number of crops produced [22].

Level III contains the main three macronutrient KPIs. These use-efficiency KPIs are defined as the absorption rate of the specific ion element by the plants and the supply rate of the element to the cultivation system [56]. The KPIs of the main three macronutrients had a higher frequency than the level II KPIs of macronutrient use efficiency, as can be seen from Table 4. Moreover, level III contains the electrical use efficiency for lamps and cooling. These KPIs are defined as the efficiency of the electrical energy for lighting or cooling used by the plants [22].

Table 4. Environmental sustainability dimension KPIs. The table lists three levels of KPIs belonging to the sustainability dimension (columns three to five) along with their frequency of appearance in brackets, while the first and second columns point to the sustainability categories.

	Sustainability Category	KPI Level I	KPI Level II	KPI Level III
Environmental	Input: Environmental Input, Output: Environmental Output	Resource Use Efficiency (7)	Macronutrient Use Efficiency (6)	N Use Efficiency (12) P Use Efficiency (10) K Use Efficiency (7)
			Micronutrient Use Efficiency (4)	
			Water Use Efficiency (17)	
			CO_2 Use Efficiency (9)	
			Electrical Energy Use Efficiency (10)	Electrical UE Lighting (5) Electrical UE Cooling (4)
			Light Use Efficiency (21)	
			Land Use Efficiency (10)	
		Energy Consumption (5)	Electricity Consumption for Lamps (4)	
			Electricity Consumption for Cooling (3)	
		GHG Emissions (3)		

Table 4 summarizes the KPIs associated with the environmental sustainability category.

In the sustainability dimension, the KPIs with the highest citation frequency were LUE (light use efficiency) and WUE (water use efficiency), with citations in 19% and 15% of the analyzed papers, respectively.

3.3. Quality KPIs

In the quality dimension, the KPIs were divided according to Table 5.

In the nutritive value category, in the first level, there were four KPIs: the total soluble solids (TSSs), i.e., the total amount of carbohydrates, sugars, acids, pigments, flavors, and nutrients in the crop [57], the fatty acid content, i.e., the type and amount of fatty acids [58], the energy content, i.e., the bioenergy available within a food, also known as the calorie content [59], and digestibility, i.e., the difference between the number of nutrients ingested minus the number of nutrients excreted in the feces [60].

In this category, the KPIs of level II were all related to the TSS. Indeed, these included the vitamin content, mineral content, sugar content, fiber content, and soluble protein content [57]. Moreover, there was the KPI of prebiotic compounds, which can stimulate the activity of the intestinal microbiome [61]. Finally, the KPI of antioxidant compounds is related to any biological molecule able to inhibit an oxidative reaction [62].

Table 5. Quality dimension KPIs. The first and second columns list the quality categories. For each of these categories, two levels of KPIs are listed (columns three and four) along with their frequency of appearance in brackets.

	Quality Category	KPI Level I	KPI Level II
Nutritive Value	Output: Crops	Total Soluble Solids (2)	Vitamin Content (3) Mineral Content (9) Fiber Content (1) Prebiotic Compounds (1) Antioxidant Compounds (4) Protein Content (7) Sugar Content (2)
		Fatty Acids (1) Energy Content (1) Digestibility (1)	
Safety	Output: Crops	Nitrate Content (12) Natural Toxic Compounds (12) Hazardous Compounds (12) Bacterial Load (3)	Heavy Metal Content (4) Probiotic Compounds (1)
Deliciousness	Output: Crops	Prestige (1) Ease of Use (2) Color (9) Texture (3) Taste (3) Relative Water Content (5) Leaf Succulence (1)	
Logistic Feasibility	Output: Crops, Input: Packaging Materials	Transport Efficiency (2) Suitability for Storage (1) Shelf Life (1)	

In the safety category, the four level I KPIs were as follows: the nitrate content, which is relevant due to the negative effect of nitrate on human health [63], natural toxic compounds, i.e., any biological compound synthesized by the crop that can harm humans [64], hazardous compounds, which includes all the compounds present in the plant-growing environment that are dangerous for human health; polycyclic aromatic hydrocarbons, polychlorinated biphenyl, heavy metals, and other compounds belong to this category [65], and bacterial load, which represents the total amount of bacteria present on the crop. Bacterial load has a general value; generally, the higher its value, the shorter the shelf life of the product. However, bacteria are variegated, and they may speed up the degradation process as much as they can be helpful for the diet [66].

The level II KPIs included the heavy metal content, which is part of the hazardous compounds KPI, and probiotic compounds [61], which fall under the category of bacterial content. If heavy metals are present in the environment, they are absorbed by the plant and eaten by the consumer [65]. Heavy metals are widely known because of their effect on plants, microorganisms, and human wellbeing; moreover, they last in the soil for an indefinite amount of time, even though recent studies have proposed methods to reduce their toxicity [67]. On the other hand, probiotic compounds are specific bacterial species that are able to colonize the human intestines, where they help the digestion process [68].

The Deliciousness crops category contains just level I KPIs. Prestige is based upon the product properties, interactions with people (e.g., aspired and/or peer-referenced group), and hedonic values (e.g., sensory subjective beauty); therefore, it is difficult to assess it. Blum et al. [69] proposed a scale to measure it. Ease of use is a psychological factor that drives the customer to choose one product rather than another, as mentioned by Giusti et al. [33]. Color/appearance, texture, and taste/aroma are other KPIs related to the deliciousness of the final product, as listed by Giusti et al. [33]. Finally, leaf succulence can be calculated as the water content per unit of leaf area [70], while the relative water content is the ratio between the actual crop water content and the maximum amount of water that the crop can reach [71].

The categories of crop and packaging materials logistic feasibility were merged, because some of the found KPIs need elements of both categories to be computed. Transport efficiency considers the suitability of the product for transportation, that is, the possibility of piling up and how much space is left empty [72]. Shelf life is the period within which the vegetables must be used; otherwise, they must be wasted [73]. Finally, suitability for storage measures the capability of a certain vegetable to be safely stored. It depends on genotype differences alongside agronomic management practices and best postharvest technologies [74].

The KPIs with the highest citation frequency in the quality dimension were all from the safety subcategory. Indeed, natural toxic compounds, nitrate content, and hazardous compounds all had the same citation rate: 11%.

4. Discussion

This work reviewed the KPIs of vertical farming with an Internet-of-Things (IoT) architecture. Evaluating and monitoring the performance of a production system is crucial for identifying inefficiencies and shortcomings, allowing for adjustments that optimize resource utilization, reduce waste, and mitigate environmental impact.

To identify relevant KPIs, a research method inspired by literary discovery was employed, emphasizing the development of new knowledge through an extensive literature review on the Scopus database.

Then, the identification and categorization of the KPIs was carried out, laying the basis for addressing RQ2 (What are the most frequently used VFPS KPIs and categories?) and RQ3 (Do the researchers exhaustively evaluate VFPS by considering all the KPI categories?).

From the analysis described in Section 3, it is possible to answer RQ2 and RQ3. Figure 4 shows the absolute number of articles that contained the KPIs of the indicated sub-dimensions. It can be seen from the figure that the most-used KPIs were the ones belonging to crop productivity. This is understandable, since measuring the size/weight or quantity of the crops produced by the system is the most direct indicator of the system's performance. Furthermore, it is easy to measure these crop productivity parameters, since most of them do not require highly specialized tools or knowledge, unlike in the case for some quality-related KPIs.

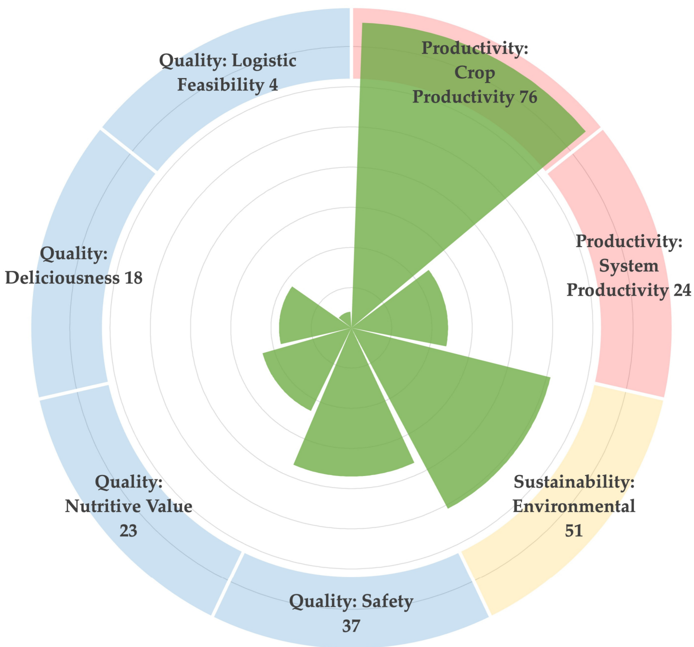

Figure 4. Number of articles that used a KPI belonging to a specific sub-dimension.

Environmental sustainability KPIs were also very prevalent in the literature, since around 46% of the articles used one or more environmental KPIs. These KPIs are being used more and more in articles recently. This can be attributed to the increased interest of the scientific community in the environmental challenges faced by our world today.

The least-used KPIs belonged to the quality dimension, specifically the sub-dimensions of logistical feasibility and deliciousness, where the first one was mentioned in less than 4% of the selected articles, and the latter was mentioned in 16% of the selected articles. In the case of logistical feasibility, this could be because many authors may consider these KPIs as outside of the scope or outside the border of vertical farming systems (shelf life, for example). On the other hand, the low number of citations of the deliciousness category can be attributed to a lack of ability to empirically measure the value of these KPIs, since they are subjective and depend on the user's perception (such as prestige and ease of use).

The KPIs belonging to nutritive value and safety were slightly more mentioned in the literature (21% and 34% of the articles). A possible reason for this is the 'ease of measure' effect. Easily measurable indicators require simple and cheap instrumentation to be measured (biomass, size, etc.), and are thus more frequently used. On the contrary, others require expensive and complex instrumentation, knowledge, and properly qualified staff to be properly assessed (vitamin content, mineral content, etc.). We found that the first ones were more cited than the others. Moreover, to properly evaluate the importance and weight of the selected KPIs, other methods need to be implemented (e.g., a balanced scorecard and analytic hierarchy process (AHP)), because, as we have shown, frequency is not a robust indicator of a KPI's importance.

Thus, as an answer for RQ2, it was found that dry weight was the most-used KPI in the scientific literature, followed closely by the fresh weight and leaf area indices. Moreover, the six most-cited KPIs all belonged to the crop productivity dimensions, making it the most prevalent dimension in the literature by far.

Finally, no article was found that provides a complete representation of all the dimensions, as shown in Figure 5. Indeed, most articles focus on one or two sub-dimensions (66%), and, more specifically, crop productivity KPIs were found in 69% of the articles mentioning one or two sub-dimensions. As mentioned before, this can be attributed to the ease of measurement and the degree of system understanding provided by this type of KPIs. Therefore, the answer to RQ3 is that VFPSs are not evaluated exhaustively, and the KPI sets that are used consider mostly one or two sub-dimensions at max.

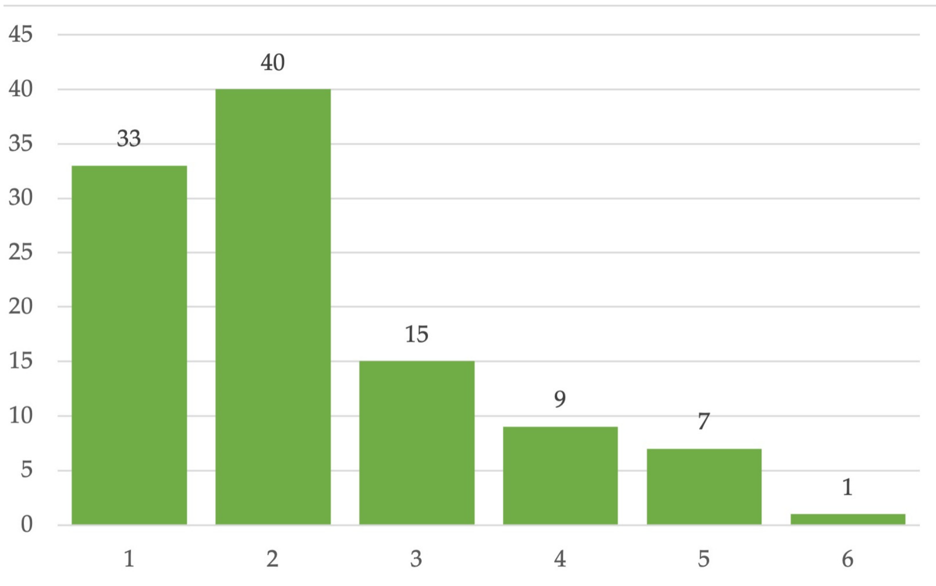

Figure 5. Histogram of the number of KPI sub-dimensions covered per article.

Moreover, almost all the articles with four or more sub-dimensions always included environmental sustainability and crop productivity. It can be concluded that researchers consider these aspects to be more important and more functional to include in their research regarding the assessment of the level of performance of vertical farming systems.

To the authors' knowledge, there is a lack of research in the literature on the analysis of KPIs in vertical farming systems. Few works have been published offering a multidimensional classification of KPIs for VFPSs. Notably, most existing studies concentrate on a singular dimension, often emphasizing economic aspects. It is essential to acknowledge a key limitation of this study, which will be addressed in future research. Specifically, this study did not encompass a detailed exploration of the economic and social sustainability sub-dimensions in VFPSs.

5. Conclusions

In conclusion, this study aimed to address the pressing need for a comprehensive evaluation of vertical farming systems through the multidimensional categorization and selection of KPIs suitable for measuring system performance. Through an extensive literature review that analyzed over 100 scientific articles, we identified and categorized 78 KPIs representing various dimensions of vertical farming evaluation. These KPIs were classified into eleven categories, covering the critical aspects of productivity, sustainability, and quality.

To facilitate this categorization, we constructed a purpose-built model of a vertical farming production system using the IDEF0 methodology, which allowed us to propose a structured KPI classification. After assigning each of the 78 KPIs to the 11 proposed categories, we evaluated the research interest in vertical farming. This evaluation considered the utilization rate of each KPI, and we found out that the highest number of used KPIs belonged to the productivity category (100 articles out of a total of 110), followed by quality KPIs (82 appearances), and, lastly, sustainability KPIs (51 appearances). Among the productivity category, the most-used KPIs were fresh and dry weight, which appeared in almost half of the selected articles. In the sustainability category, LUE (light use efficiency) and WUE (water use efficiency) were the most-cited ones, even though they appeared in less than 20% of the selected papers. KPIs belonging to the quality sub-dimension were less cited, especially those belonging to the logistic feasibility and deliciousness sub-dimensions, whereas the nutritive value and safety sub-categories were more used and were mentioned in over half of the examined papers.

Moreover, we evaluated the number of KPI subcategories that were analyzed in each paper. We found that the majority of the articles focused only on one or two subcategories. A higher number of subcategories being evaluated may better describe a VFPS, but this kind of evaluation (covering three or more subcategories) was found in a relatively small number of articles.

Four main contributions of the present work can be identified concerning the state of the art: (i) providing a functional model of a VFPS to identify its main elements and components, which are needed to compute the KPIs, (ii) providing a taxonomy of categories for the classification of KPIs for a VFPS, (iii) selecting all the KPIs used in the context of vertical farming and classifying them into the identified categories, and (iv) providing insights about the frequencies of the KPIs used in the literature and the coverage of the categories.

The main impact of our analysis is the highlight that the majority of the research in this field tends to emphasize productivity-related KPIs, while those related to sustainability and quality are relatively underrepresented. Moreover, a notable lack of studies addressing the integration of all three dimensions highlights the need for a more balanced and multidimensional approach to assessing vertical farming performance. Thus, presenting a multidimensional categorization, this study can be a reference for subsequent evaluations that include more dimensions of a VFPS.

In our future research, we plan to expand the scope of our model to encompass social and economic sustainability aspects. We also intend to explore dynamic modeling techniques, such as UML diagrams, to capture the evolving behavior of vertical farming production systems (VFPSs). Furthermore, we aim to investigate the possibility of developing a composite indicator that comprehensively represents all the dimensions of VFPS performance, providing a more exhaustive and non-redundant evaluation tool. This research sets the stage for a multidimensional evaluation of vertical farming systems, contributing to their sustainability and success in modern agriculture.

Author Contributions: Conceptualization, B.F. and N.G.; methodology, B.F., A.M.M.A. and G.B.; validation, P.C.; investigation, A.M.M.A., N.G. and B.F.; writing—original draft preparation, B.F., A.M.M.A. and N.G.; writing—review and editing, G.B., P.C. and F.L.; supervision, G.B. and F.L.; funding acquisition, F.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Agritech National Research Center and received funding from the European Union Next-GenerationEU (Piano nazionale di ripresa e resilienza (PNRR)–Missione 4 componente 2, investimenti 1.4–D.D. 1032 17/06/2022, CN00000022) and PNRR–Decreto Ministeriale n. 1061. This manuscript reflects only the authors' views and opinions; neither the European Union nor the European Commission can be considered responsible for them.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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