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The future of resilient food production—Current challenges and future opportunities

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The climate crisis is heating up, storms and droughts are hitting harder, deserts are growing, fertile land is fading, pollution is everywhere, and resources are running out—sparking mass migration and creating some of the biggest challenges of our time. Literature on vertical/indoor farming and Digital Agriculture and advanced Food Production Units (FPUs) as an integral, layered conceptual model—unifying containerized controlled-environment agriculture with IoT/CPS/AI capabilities and user-facing human-machine interfaces has been synthesized into a descriptive model. This model has been used to organize requirements and define a literature-informed technology readiness (TRL) diagnostic that quantifies research gaps and identifies future research directions. FPU are envisioned to decouple production from variable external conditions and to operate where conventional agriculture is constrained. Key design considerations should include transportability (ISO container form factor), modular scalability, energy self-sufficiency via renewables and storage, local resource collection, closed-loop water and nutrient cycles with waste-to-food pathways, and the potential inclusion of animal-based foods (e.g., insects). Shown synthesis highlights current limitations and defines research gaps in state-of-the-art systems. Most notably, the emphasis on low-calorie crops, limited crop commutability, interoperability and automation challenges, and energy/economic constraints. Framed through the FPU model, the authors outline how expanding toward calorie-dense species, integrating sensing/automation/decision-making, and deploying user-centric HMIs could help address these gaps. TRL assessments were provided across physical, digital, and user layers to quantify readiness and research needs; these are diagnostic summaries derived from the literature and do not validate any single architecture. Priority directions include: open datasets for high-calorie crops; cultivation and control strategies for longer-cycle species; sustainable AI and edge computing; robust, modular energy and storage architectures; interoperability standards; and HMIs usable by non-experts in low-resource settings. Overall, FPU were presented as one possible pathway to guide research and translational efforts toward resilient, adaptable food production in adverse and humanitarian contexts. The presented work is a scoping review coupled with a perspective paper that utilizes targeted literature searches to synthesize and structure the field rather than to exhaustively identify all studies. The presented TRL mapping is a literature-informed diagnostic to highlight maturity and research gaps, not a validation of a specific FPU architecture.

KEYWORDS

AI, climate change adaptation, CPS, food security, FPU, IoT, sustainability

1 Introduction

Advancing climate change, extreme weather events, desertification, loss of topsoil, environmental pollution as a consequence of industrialization, and a shortage of non-renewable resources, as well as related societal challenges such as mass migration are just some of the defining challenges of the twenty-first century that will force our society to radically change its current lifestyle and consumer behavior in the near future if they want to avoid societal collapse (Tainter, 1988). Under these circumstances, one key necessity is reliable, resource-efficient and resilient food production, especially as an estimated 67% of the world's population will live in urban environments in the future (Kohlhase, 2013). This makes it necessary to consider new forms of food production with efficient utilization of existing resources (need for land, irrigation, energy, etc.) (Pitesky et al., 2014; Satterthwaite et al., 2010).

For example, the climate crisis leads to difficulties cultivating established crops on the fields; insects become a new risk due to a change of host initiated by warmer environmental conditions and forces adaption of established cultivation methods (Pfitzer et al., 2022). Moreover, extreme weather events (droughts, flooding, drastic temperature fluctuations, etc.)—which increase in frequency due to advancing climate change—apply additional pressure to the sensitive system of reliable food production (Hasegawa et al., 2021). This and a shortage of non-renewable and excessive, unsustainable overuse of renewable resources requires society to rethink complete agronomic systems and to change consumer behavior. Under these circumstances, one key necessity is reliable, resource-efficient, and resilient food production—i.e., food security. This makes it necessary to consider alternative forms of food production, e.g., indoor farming, micro-agriculture, regional production, and insect protein production, with efficient utilization of existing resources (need for land, irrigation, energy, etc.) and resilience toward external factors.

The technical decoupling of the food production's growing environment from environmental influences—i.e., greenhouses and indoor farming—does not only addresses the problems described above but also enables food production to be independent of the season and soil quality, with a lower risk of insects and diseases at a constant quality level. Concepts such as vertical farming (VF) scale the two-dimensional utilization of agricultural land across a vertical third dimension. While outdoor VF setup exists, most systems are operated in indoor facilities. The growth environment is monitored, controlled, and largely automated using various sensors (temperature, humidity, etc.) and actuators, which not only increases the yield per unit area (that also scales vertically) but also requires around 70%–95% less water than traditional agriculture while providing higher yields per area of used land (Khan, 2018).

However, despite its promise and initial intention to make a relevant and valuable contribution to food security and even replace traditional agriculture, IF/VF never got close to fulfilling that promise. Today, it is seen as an add-on or an extension to classical agriculture. While IF/VF systems become more common, e.g., especially in densely-populated areas such as Singapore (Song et al., 2022; Chatterjee et al., 2020) or Malaysia (Sengodan, 2022),

they are still niche products with limited relevance (Van Delden et al., 2021). While IF/VF systems are already being used to produce salads, tomatoes, herbs (e.g., basil) (Farhangi et al., 2023; Anubhove et al., 2020), etc., their use to produce a wide range of other foods for a healthy, needs-based diet—especially in terms of calories and nutritional values—is still limited and thus barely contribute to food security (Benke and Tomkins, 2017). Attempts with limited success have been made to increase calorie density, e.g., by growing potatoes in aeroponics systems (Tunio et al., 2020).

IF/VF can only contribute to sustainable and resilient food production when shifting its focus from leafy greens and low-calorie crops to high-calorie produce while allowing for plant commutability. Moreover, the predominant assumption of crop production under resource abundance, i.e., perfect growth conditions no matter the cost for maximum output, in the context of IF/VF should be replaced by a self-sufficiency-driven approach that accounts for the fact that most involved resources are scarce and their provision cause a great deal of environmental pollution. Finally, research into and development of high-calorie-focused food production systems depends on the creation and availability of open datasets for such high-calorie crops, as well as the development and enactment of business models that go beyond fast-growing low-calorie leafy greens.

To enable a comparison between the different technologies used for an FPU, the technological readiness level (TRL) scale has been used (Mankins, 2009). TRL is a globally accepted tool for measuring progress and supporting development from idea to full implementation (Salazar and Russi-Vigoya, 2021). This framework facilitates uniform evaluation of technological maturity, allowing decision-makers to assess risk, allocate resources, and monitor progress across various technologies using a common assessment scheme. The TRL assessments are a synthesis-based diagnostic to quantify readiness and gaps; they do not imply endorsement or validation of any single architecture. Nevertheless, TRL levels have successfully proven their applicability for categorization of agricultural swarm robots (Albiero et al., 2022), autonomous vehicles (Swaminathan et al., 2025), and even for categorization of machine learning methods (Lavin et al., 2022).

This study's novelty is threefold. First, we systematize the literature into an integral, layered conceptual model of Food Production Units (FPUs) that unifies physical cultivation modules with digital agriculture functions and user-facing interfaces. Second, we provide a literature-informed TRL diagnostic across eleven modules to quantify maturity and gaps. Third, we derive module-mapped research priorities and practical design guidance, including representative performance ranges where available.

We emphasize that this manuscript is a scoping review coupled with a position/perspective: we synthesize the literature to identify knowledge gaps and then outline FPUs as a conceptual lens to organize those gaps and future research directions. We do not claim completeness of coverage or systematic exclusion/inclusion as in systematic reviews. The FPU concept here is not presented as a justified or validated solution, but as a framework for structuring research questions. We explicitly treat FPUs as an integral, layered model that combines physical cultivation infrastructure, Digital Agriculture capabilities, and user-facing interfaces. Sections 3.2–3.9 map the state of the art onto these model modules.

The remainder of this paper is structured as follows: Section 2 introduces the concept of FPU as well as its requirements and technological building blocks. Subsequently, Section 3 presents an in-depth analysis of the state of the art pertaining to the technological building blocks of FPU. Next, Section 4 discusses the findings of the review as well as limitations. Subsequent Section 5 identifies and describes research directions and required technological foundations toward FPU for resilient food production. Finally, Section 6 concludes our work.

2 Conceptual integral model: food production units

We introduce FPU as a conceptual integral model synthesized from existing indoor/vertical farming and Digital Agriculture literature. The model comprises modules spanning logistics/transportability, modularity and structural scalability, energy autonomy, local resource collection, waste cycling, crop flexibility (including animal-based food/feed), and the Digital Agriculture and user layers (automation, inspection, decision-making, and HMI). This model organizes the subsequent review (Section 3), TRL synthesis (Section 4), and future directions (Section 5). FPU extend IF/VF toward the idea of sustainable, resilient, (semi-)self-sufficient, modular, scalable, soil-less CEA systems, i.e., hydroponics, aeroponics, aquaponics, etc., that allow for the creation of farms of stackable shipping containers that grow food inside the container. Moreover, FPU also utilize concepts such as the Internet of Things (IoT), cyber-physical systems (CPS), autonomous, and cooperative smart devices the Machine-to-Everything (M2X) (Leiding et al., 2021), while expressing a high degree of automation, integrate AI-driven concepts for the (fully/partially) self-sufficient production of food with minimal human interaction and specialist knowledge required.

To maximize their utility, FPU should be designed as highly transportable systems, adhering to ISO container dimensions to ensure compatibility with standard transportation methods via rail, ship, and road (see Figure 1). Energy autonomy is another crucial aspect, achievable through the integration of renewable energy sources such as photovoltaic panels and wind turbines, enabling operation even in remote or resource-scarce environments. Furthermore, FPU should be equipped to autonomously collect vital resources like rainwater and extract necessary chemical compounds (e.g., fertilizers) from the atmosphere or the soil they occupy. Emphasizing sustainability, these units must implement closed-loop chemical cycles, minimizing waste by reusing nutrients and employing hydroponic systems to optimize water and resource efficiency. Additionally, FPU should convert organic waste into usable inputs for farming, embodying a “waste in, food out” approach. Beyond plant production, FPU should facilitate the cultivation of animal-based foods, such as insects, leveraging resources unsuitable for plant growth to provide a versatile and resilient food production solution.

Subsequent sections outline criteria of reference scenarios of FPU setups which subsequently serve to derive critical requirements as well as technological building blocks.

2.1 Reference scenarios, requirements and technological foundations

As outlined in Section 1, the impending climate crisis and its consequences, environmental pollution, resources scarcity as well as further societal challenges create a need for a reliable, resource-efficient and resilient food production that can cope with those circumstances. However, as indicated in Figure 2 some geographical areas are more impacted by those challenges than others, thus creating a scale of adverse environments.

While Figure 2 abstracts and simplifies environmental adversity dimensions in the context of food security for fictional sample regions, it outlines the diverse nature and varying levels of adversity.

- **Temperature trends & variability:** Reflects long-term temperature shifts as well as daily/seasonal fluctuations that impact crop growth.
- **Precipitation patterns:** Captures the amount, seasonality, and irregularity of rainfall or snow, influencing irrigation and drought conditions.
- **Extreme weather frequency:** Indicates the occurrence of events such as heatwaves, floods, droughts, or storms that have a negative impact on food production and related resource availability.
- **Water availability & quality:** Assesses the overall supply of freshwater for irrigation and the health of those resources by incorporating indicators of pollution or salinization.
- **Soil health & land use:** Evaluates soil fertility, degradation/erosion, desertification, and changes in land use, such as deforestation or urban expansion, directly linked to agricultural productivity.
- **Environmental pollution:** The impact of air, water, and soil contaminants from industrial or agricultural sources that harm crops and human health alike.
- **Agricultural sustainability & productivity:** Encompasses crop yield stability, diversity of crops grown, and access to critical farming inputs (like seeds and fertilizers) that determine a food system's resilience.

Depending on the intensity of each of the dimensions outlined above present in a certain region, FPU-like systems might fill different roles. In an adverse environment that does not allow for any alternative reliable and resilient means of food production, FPU may end up as the only solution to sustain a population. On the other end of the extrema scale, some regions might enjoy an environment that is not impacted at all—or only minimally—by any of the dimensions outlined above. Most regions will fall in between those two extrema and thus experience a varying level of usefulness for FPU systems that may contribute heavily to food security or just supplement existing food production systems.

In addition to the dimensions outlined in Figure 2 a temporal dimension is relevant as well. After natural disasters, or in the context of a humanitarian crises food security might be impacted for an uncertain time but once a crisis has been overcome, the environment may allow to revert back, completely or partially, to previous food production processes. No matter whether longterm

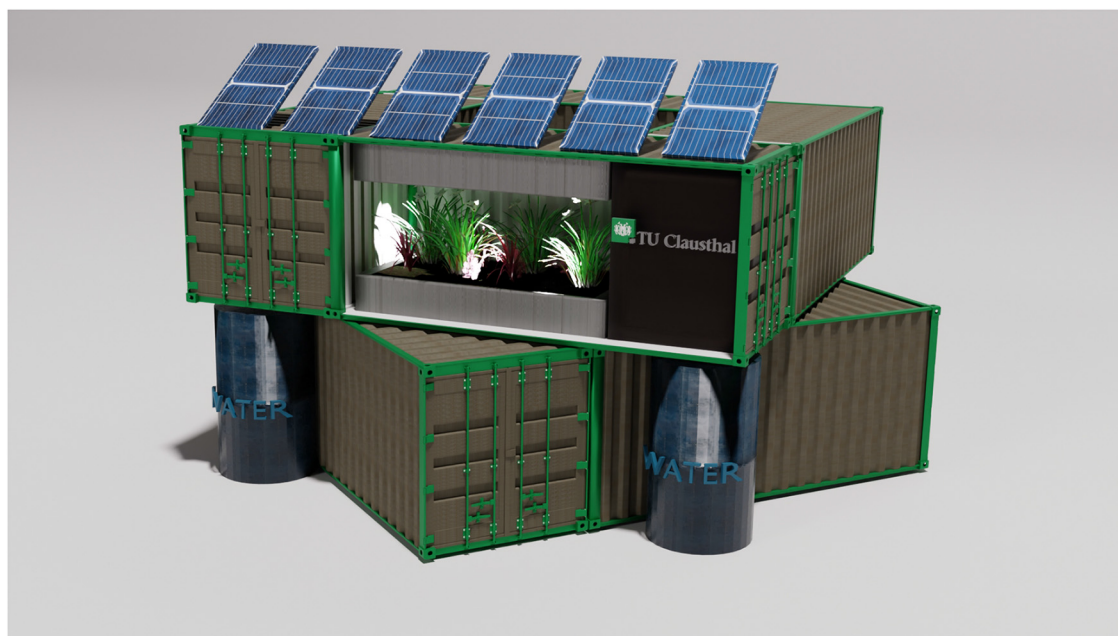


FIGURE 1
Schematic sketch of an FPU setup consisting of multiple FPCs.

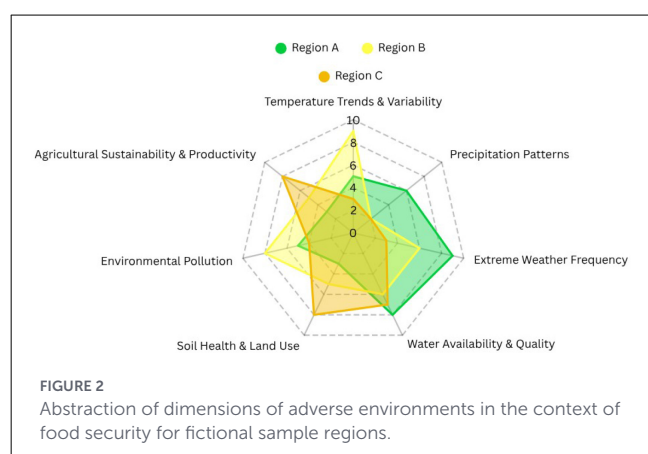


FIGURE 2
Abstraction of dimensions of adverse environments in the context of food security for fictional sample regions.

or temporary solution, the goal is to go beyond common leafy green production and instead allowing for timely, reliable access to fresh, nutritious, and calory-rich food.

Container-based FPUs offer a promising alternative: compact, modular ecosystems capable of operating autonomously in regions where conventional farming is impractical or impossible. By integrating advanced agricultural technologies, renewable energy systems, and closed-loop resource management into a standardized, easily transportable form factor, FPU can be deployed rapidly to support relief efforts, rehabilitate food supply chains, and foster community resilience. Thus, in order to deploy container-based FPUs in disaster regions or areas where conventional food production is nearly impossible (e.g., desert regions), several critical requirements must be met. These requirements can be summarized as follows:

- **Transportability:** The FPU should be mobile and easy to transport—by rail, ship, and ideally also by road. They must not exceed the dimensions of standard ISO containers. This ensures rapid relocation to changing deployment sites.
- **Modularity:** The design of the FPU must be modular so that they can be flexibly adapted to different deployment scenarios. A modular structure allows individual units to be easily connected, replaced, or expanded according to required production capacity.
- **Energy autonomy:** The containers could potentially operate with a degree of energy autonomy where feasible. For example, photovoltaic systems, small wind turbines, or other renewable energy sources might be considered, depending on local conditions. A hybrid energy generation approach may enable operation in remote or resource-scarce areas, though site-specific factors would need to be evaluated.
- **Resource collection:** FPU must be able to independently collect essential resources such as rainwater or necessary chemical inputs (e.g., fertilizers). This includes both rainwater harvesting and extraction of nutrients from the surrounding air or soil.
- **Waste utilization:** Used materials (“waste”) should be reintegrated into the production process. Inevitable byproducts or biomass can serve as input for the FPU (“Waste-in-Food-out”) to optimize resource utilization and minimize waste.
- **Flexibility of crop types:** The FPU must be configurable so that various plant species—ideally including calorie-dense crops—can be cultivated. Through user-defined parameterization of technical systems, a rapid switch from one crop type to another should be possible.
- **Production of animal-based food & feed:** FPU should not only enable plant cultivation but also the production of

animal-based foods (e.g., insects or larvae). Resource-poor residual streams that are no longer usable for plants can serve as insect feed.

- **Automation:** A high degree of automation is necessary so that operators only need to configure parameters. No deep technical expertise should be required. Sensors, actuators, and control technology should autonomously manage daily operational tasks.
- **Inspection:** Plant growth monitoring should ideally be automated via imaging systems. Various sensors (e.g., RGB cameras, 3D sensors, and spectral sensors) must be integrated to capture appearance, geometry, or physiological indicators of the plants.
- **Decision making:** Plant condition analysis should be performed using AI (e.g., computer vision algorithms) to plan treatment measures (watering, fertilizing, lighting). Furthermore, predictive modeling of future development stages should be possible to forecast harvest times or resource allocation.
- **Human-machine interface:** Even if decision processes run fully autonomously, an intuitive user interface is required to translate machine status and plant information into easily understandable language. This interface must be operable by users without specialized agricultural knowledge.

In summary, the successful deployment of container-based FPU hinges on a carefully balanced set of requirements (see Figure 3) that marry practical operability with advanced technological innovation. Mobility and modularity ensure FPUs can be transported and configured to meet evolving demand; energy autonomy and closed-loop resource management guarantee uninterrupted operation in resource-scarce environments; and high degrees of automation, inspection, and AI-driven decision making provide both reliability and ease of use. By embedding these foundations into the design of every FPU, we establish a coherent framework that supports rapid response in crisis situations, promotes local resilience, and aligns with broader sustainability goals. With these prerequisites firmly in place, Section 3 will delve into the specific hardware and software components—ranging from photovoltaic power systems and hydroponic bioreactors to sensor networks and human-machine interfaces—that together realize a robust, adaptive, and scalable containerized food production solution.

3 State of the art in sustainable vertical farming and food production from an information technology perspective

For our overview in this chapter, we selected works that address technical aspects—especially in IT—and the goals of sustainable food production. We focus on sources that highlight technological innovations, resource efficiency, and the integration of systems such as artificial intelligence, IoT, and automation. Studies on practical challenges and solutions in vertical farming were also included to offer a comprehensive understanding of this growing research field.

3.1 Approach to literature review

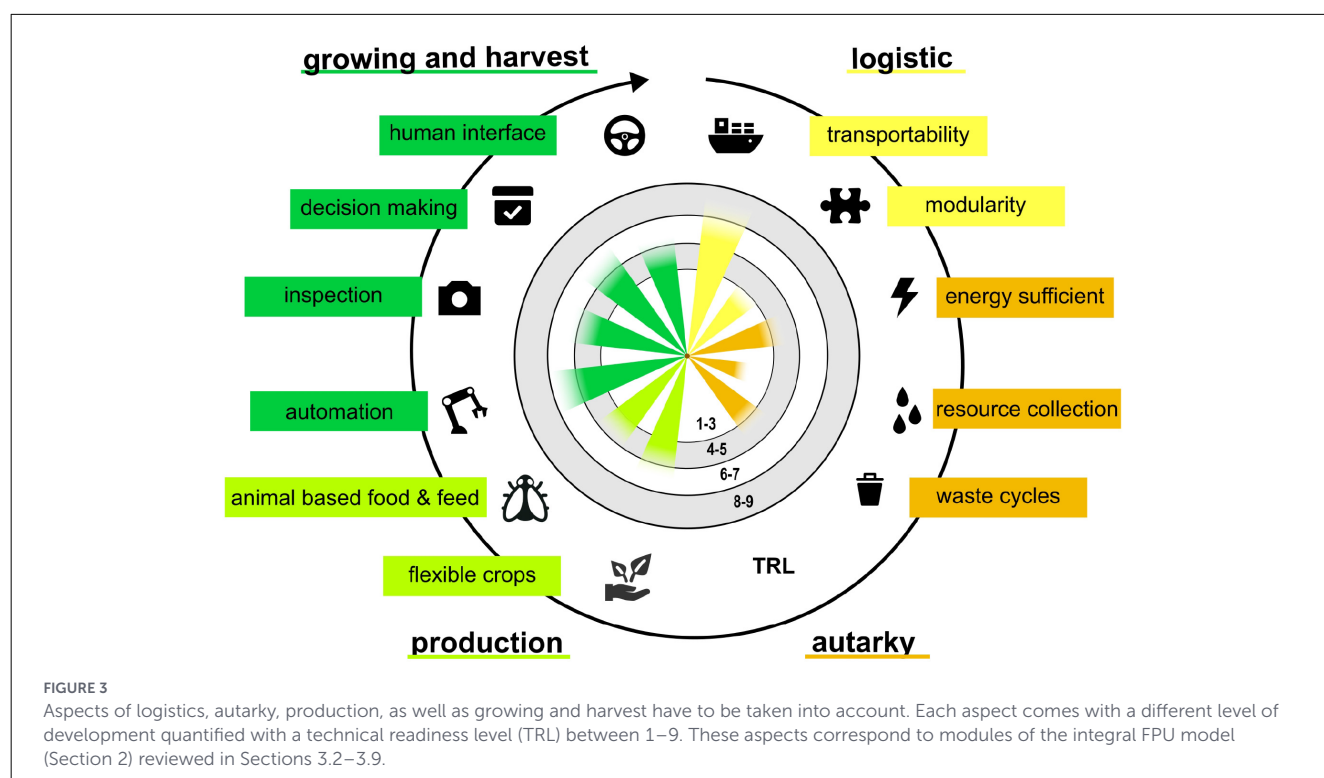
The objective of this review was not to provide an exhaustive catalog of all publications related to vertical farming or indoor agriculture, but to systematically identify literature that contributes to the technological, ecological, and operational building blocks required for resilient, container-based Food Production Units (FPUs) as introduced in Section 2. Rather than following a publication-centric review strategy, we applied a concept-centric and model-driven literature identification approach. The integral FPU model (Section 2) served as the guiding framework for literature selection. For each module of this model, targeted searches were conducted to identify representative and technically mature contributions addressing:

- transportability and modular scalability,
- resource and energy efficiency,
- local resource acquisition and waste integration,
- crop flexibility and calorie-dense cultivation,
- automation and sensing,
- AI-supported decision making,
- and human-machine interaction.

Literature searches were performed in Web of Science, IEEE Xplore, Scopus, and Google Scholar using combinations of keywords such as “vertical farming,” “indoor farming,” “hydroponics,” “aeroponics,” “aquaponics,” “resource efficiency,” “energy autonomy,” “IoT agriculture,” “AI agriculture,” “controlled environment agriculture,” “container farming,” and “food security.” Searches were iteratively refined per module of the FPU model. The selection followed four explicit criteria:

1. Relevance to FPU modules: The work had to address at least one technical or ecological building block required for FPUs.
2. Contribution to sustainability or resilience: Preference was given to studies addressing resource efficiency, food security, or operation under constrained conditions.
3. Technological or operational maturity: Studies presenting prototypes, implementations, or transferable system concepts were prioritized over purely theoretical discussions.
4. Temporal relevance: Emphasis was placed on publications from the last 10 years, complemented by seminal earlier works where necessary (e.g., hydroponic methods).

Studies focusing exclusively on plant biology without technological implications, purely economic analyses without system relevance, or conventional greenhouse agriculture without controlled-environment aspects were excluded. The identified works were then systematically mapped to the modules of the FPU model, which subsequently structured Sections 3.2–3.9. Rather than applying PRISMA-style screening or risk-of-bias scoring, the review follows a model-driven structuring strategy in which literature is selected and organized according to its contribution to the functional modules of the FPU framework, enabling cross-domain synthesis and identification of research gaps across technological, ecological, and operational dimensions. This mapping ensured thematic completeness across logistics, autarky, production, inspection, decision making, and user



interaction layers rather than completeness within a single subfield (cf. Table 1). This structured, model-driven approach allows the review to highlight technological maturity and research gaps across the interdisciplinary landscape required for resilient food production systems.

3.2 Transportability and modularity and structural scalability

Synthesis. *In the literature, transportability is largely addressed through ISO-container concepts, and container-based systems demonstrate high practical mobility at the form-factor level. However, true modular scalability beyond “adding more containers” remains comparatively immature, as most work focuses on isolated prototypes or conceptual designs rather than interoperable, plug-and-play modules deployed in the field. Consequently, the dominant gap is not containerization itself, but standardized interfaces (mechanical, electrical, data, and water/nutrient connections) that would enable rapid reconfiguration and scalable integration.*

Indoor farming systems are installed in permanently fixed structures, similar to or including greenhouses, or follow a modular, mobile approach, e.g., a shipping container design (see Figure 1). Fixed infrastructure is designed to be permanent and is typically built on-site and thus not easily transportable; relocating it requires significant effort, time and investment. However, greenhouses can be expanded if more land is available, making them scalable for large-scale, permanent agricultural operations. Their modularity is somewhat limited, as expansion usually involves substantial construction rather than simply adding more units.

Mobile infrastructure, such as FPU-like shipping container solutions, offers a high degree of transportability. These systems

are designed to be moved and can be deployed wherever needed, making them ideal for urban environments, areas with limited available land, or in adverse growing conditions that do not allow for traditional outdoor agriculture - either temporarily or permanently. Shipping containers are inherently modular—farms can easily be scaled up or down by adding or removing containers. Additionally, various interconnected modules can be combined, for example, the integration of hydroponic and aquaculture systems (i.e., aquaponics) with insect-rearing systems (see Section 3.4). This makes them highly flexible and adaptable to changing needs. While hydroponic systems, and by extend aeroponic systems and similar setups, are water-efficient (see subsequent Section 3.3), they require significant energy for artificial lighting and climate control, which can raise sustainability concerns if the energy is not sourced from renewables. Additionally, thus far, these systems are predominantly used for small, fast-growing crops, such as leafy greens and herbs, rather than calorie-rich crops.

A considerable amount of research exists on the selective aspects of transportability, modularity, and scalability of research concerning both static and mobile infrastructure. To keep this analysis concise, we refer the interested reader to comprehensive literature reviews on static infrastructure, e.g., [Vatistas et al. \(2022\)](#), [Marcelino et al. \(2022\)](#), and [Drottberger et al. \(2023\)](#), while subsequently focusing on transportable, modular, and scalable approaches. [Wichitwechkarn and Fox \(2023\)](#) discuss the advantages of vertical farms in reducing supply chain waste, minimizing transportation costs, and lowering emissions. They further present a modular, open hardware system for plant transportation and suggest that vertical farms can be integrated into larger agricultural systems.

The idea of FPU-like modular and scalable farming systems encompasses various components that cover the complete process from seed to harvest, thereby

TABLE 1 Mapping of reviewed literature to FPU model modules.

FPU module	Typical topics covered	References
Transportability and modularity	Container farming concepts, modular vertical farming setups, scalable infrastructures	Diaz, 2023; Martin and Bustamante, 2021; Rivera et al., 2023; Carrasco et al., 2024
Resource efficiency	Water reduction, hydroculture methods, optimization of growth parameters	Khan, 2018; Daniels et al., 2023; Sowmya et al., 2024
Energy autonomy	Renewable integration, energy bottlenecks, storage challenges	Hati and Singh, 2021; Kaya and Kim, 2024; Khalaf et al., 2023
Local resource acquisition and waste utilization	Rainwater use, aquaponics, greywater reuse, vermicompost, wastewater integration	Jurga et al., 2020; Mustak et al., 2024; Vila, 2019; Rakocy, 2012
Animal-based food and feed	Insect farming (BSF), multitrophic systems, waste-to-feed concepts	Barragán-Fonseca et al., 2024; Shaw et al., 2022; Romano et al., 2022
Crop commutability	Calorie-dense crops, aeroponic potatoes, hydroponic cereals, crop flexibility	Tunio et al., 2020; Sharma et al., 2018; Martí Torra, 2023
Automation	IoT monitoring, robotics, digital twins, LoRaWAN systems, autonomous control	Codeluppi et al., 2020; Mahalingam et al., 2024; Monteiro et al., 2023
Inspection	RGB sensing, plant monitoring, calibration procedures, imaging systems	Cho and Yang, 2023; Bömer et al., 2024
Decision making	AI control, multi-agent systems, predictive modeling, data-driven optimization	Chowdhury et al., 2023; Benke and Tomkins, 2017
Human-machine interface	User interfaces, conversational systems, usability and accessibility in vertical farming	Kabir et al., 2023; Ghazal et al., 2023

overlapping with subsequent sections. We will revisit these aspects later.

Existing literature ranges from conceptualizations, designs and feasibility assessments of containerized farming systems (Diaz, 2023; Liu, 2014; Martin and Bustamante, 2021; Belista et al., 2018; Rivera et al., 2023; Serecon Inc., 2021) to proof-of-concepts (Carrasco et al., 2024; Bafort et al., 2022). More papers focus on particular sub-components of smart modular farms, e.g., in

Matar et al. (2024), the authors delve into crop monitoring, water management, nutrient precision, pest control, and energy efficiency. In Mahalingam et al. (2024), the authors focus on collaborative robots in a containerized vertical farming setup, where a human farmer demonstrates tasks such as transplanting or harvesting for a robot to learn and generalize the task execution, thereby attempting to relieve humans from labor-intensive tasks associated with container-based vertical farming. Spatial constraints limit the use of automated equipment.

Equipping modular farming operations with the required hardware may also pose challenges. While off-the-shelf and even industrial indoor farming kits exist, the emergence and adoption of additive manufacturing, commonly referred to as 3D printing, allows for customization and maintenance of existing setups but also to print them yourself. In Takeuchi (2019), the author presents a pipeline to digitally manufacture hydroponic systems of different types, including different mesh forms to host the seed/plant with varying water-retaining capacity. However, the risk of micro- or nano-plastic contamination of produce has not been addressed in the paper. Other papers focus on utilizing alternative and potentially locally available resources, such as clay or waste polymers, in combination with 3D printing (Arja, 2024; Ezhilarasu et al., 2024).

3.3 Resource efficiency and self-sufficiency

Synthesis. *Across indoor farming studies, water-use efficiency is a well-established advantage of soilless cultivation, while electricity demand for lighting and climate control remains the primary sustainability and cost bottleneck. Work on self-sufficiency and local resource acquisition exists (e.g., renewables, rainwater, and reuse streams) but is typically evaluated in isolation rather than as integrated end-to-end architectures. The key research gap is therefore energy- and resource-aware operation that maximizes edible output under constrained local inputs rather than assuming resource abundance.*

Traditional outdoor agriculture benefits from the “free” provision of crucial resources such as sunlight, rainwater, soil, and nutrients. However, as outlined in previous sections, the provision of such crucial resources becomes unreliable as climate change, environmental pollution, and resource scarcity progress throughout the 21st century. While indoor farming systems, such as FPUs, decouple the growth environment from the external environment, a need for that crucial resource still exists and must be provided in some way. Thus, two critical requirements emerge: First, using resources as efficiently as possible, i.e., the maximum calorie output in relation to resource input. Second, collecting as many resources as possible in a self-sufficient manner to minimize external dependencies as well as maximize local resource utilization. Recent studies quantify the selective, partially real, and partially perceived advantages of resource efficiency in indoor farming, particularly in hydroponic/aeroponic-based vertical farming systems. One of the primary metrics of comparison to traditional agriculture is the water consumption. Khan (2018) outline around 70%–95% less water consumption in vertical

hydroponic systems compared to conventional agriculture while providing higher yields per area of used land. However, these numbers only reflect the current state and may change due to climate change-related side effects, such as higher temperatures.

Despite notable efficiency gains (e.g., in water use), electrical energy demand remains the key bottleneck of indoor-based systems. The literature presents an ambivalent picture: controlled environments increase spatial productivity, yet energy consumption (lighting, climate control, and water treatment) dominates both environmental balance and operating costs. In autonomous setups, the paradox between spatial efficiency and power dependence intensifies: volatile renewable sources and limited storage density reduce operational reliability, while lithium-based systems face technical and geo-economic constraints. The development of robust energy architectures remains an open challenge—hybrid sources, prioritizing energy management, recyclable storage chemistries, and low-power peripherals—aimed at maximizing output under resource constraints rather than ideal growth conditions.

3.3.1 Hydroculture-based systems

Within the space of hydroponics, a variety of different approaches exist – namely, nutrient film technique (NFT) (Adams, 1993), deep water culture (DWC) (Nursyahid et al., 2021), wick systems (Kang et al., 2004), ebb & flow (EF) systems or flood & drain systems (Buwalda et al., 1993), as well as drip hydroponics (Brochier, 1973). The main differentiator is the mechanism for exposing the plant's root system to the nutrient solution, either at regular time intervals (NFT or EF systems) or continuously (DWC or wick systems). The consumption of nutritional solutions is comparable among the different approaches.

However, secondary resource use may differ; for example, NFT, EF, or drip systems rely on time-controlled pumps to provide a nutrition solution to the root systems according to a predetermined schedule, which requires extra resources to build those additional system components as well as to operate them. The more technological components (such as actuators, pumps, sensors, and other electrical devices) involved, the higher the financial and resource upfront costs, as well as subsequent maintenance and operation costs.

The Kratky method (Kratky, 2008) is an example of a passive hydroponic system characterized by its non-circulating hydroponic approach, which does not require electricity, pumps, or wicks. Instead, the plants grow with their roots suspended in a nutrition solution. The nutrition solution container is filled once when the plant is placed in the system and not refilled until harvest is completed. While its simplicity is advantageous in terms of resource-efficiency, it is limited in terms of plant commutability (more in Section 3.5) since not all crops/plants tolerate a constantly in nutrition solution submerged root system, e.g., root rot (Sutton et al., 2006; Gravel et al., 2006; Amalraj et al., 2019).

Aeroponic systems (Peterson, 2012; Lakhia et al., 2018; Tunio et al., 2020) refrain from constantly or temporarily submerging the plant's root system in nutrition solution and instead spray a mist of nutrition solution onto the root system in regular intervals. That

approach also allows for the growth of plants or crops prone to root rot in hydroculture systems while adding further technical complexity and increasing the upfront as well as operational resource consumption of the system.

3.3.2 Resource-efficiency in indoor farming

Resource efficiency in indoor farming primarily focuses on input resources, such as light, water, and nutrition, but also on secondary operational services, including sensor systems, pumps, and related software. A plethora of papers analyze resource use and propose resource efficiency measures for greenhouses, indoor farming in general, or different sub-types of hydroculture systems. A selection is presented below.

Daniels et al. (2023) detail their study on optimizing wheat cultivation in vertical farms. The goal is to enhance resource efficiency (water, radiation, temperature) and reduce growth duration to maximize annual yield while minimizing costs. The authors employ a nonlinear, time-discrete hybrid model based on a universal plant model. The study highlights the potential of control theory in vertical farming. The plant growth modeling utilizes a dynamic framework based on SIMPLE (Zhao et al., 2019), which is calibrated for various crops. It is transformed into a time-discrete, nonlinear, and non-differentiable control system model, which is then adjusted to make it differentiable for optimization purposes.

Chowdhury et al. (2023) explore the use of artificial intelligence (AI) in sustainable vertical farming. They emphasize the importance of AI in optimizing resource utilization, automating tasks, and improving decision-making. The focus is on resource management and decision support. The study discusses various AI technologies, including machine learning, computer vision, IoT, and robotics, along with their applications, benefits, and limitations. It also identifies research gaps and outlines future research directions.

In a comprehensive review, Sowmya et al. (2024) explore recent advancements and innovative techniques in vertical farming. It discusses various aspects, including the importance of lighting, soilless cultivation methods, irrigation, nutrient delivery, and the application of IoT and automation. The article highlights benefits such as resource efficiency, year-round climate-independent production, and the integration of soilless techniques into urban environments. In an editorial Despommier (Despommier, 2024) focuses on the dynamic optimization of resource efficiency, product quality, and energy costs in vertical farming. The author highlights the contribution of vertical farming to the regeneration of Earth's ecosystems through reduced land use, thereby benefiting biodiversity conservation and the production of safe food. Additionally, most of the papers above, as well as many more, focus further on the optimization of growth parameters—not just from a resource-efficiency perspective but also from the optimization of yields in indoor farming.

3.3.2.1 (Local) resource acquisition and waste utilization

While utilizing resources as efficiently as possible—as discussed above—is desirable from many perspectives, it still requires resources. Depending on the source of a particular resource, the

acquisition process affects the sustainability and resource efficiency of any given food production process. Thus, acquiring resources in the most sustainable and resource-efficient way is preferable. As outlined in Section 3.2, indoor farming systems can be permanent, fixed structures similar to classic greenhouses or follow a modular and mobile approach, e.g., shipping container design (see Figure 1). While both methods allow for selective local resource acquisition, e.g., rainwater (Jurga et al., 2020; Sayol et al., 2022; Islam et al., 2025) or solar/wind power (Hati and Singh, 2021; Kaya and Kim, 2024; Khalaf et al., 2023) and wind (Weidner et al., 2022; Arabzadeh et al., 2023), permanent structures may support a more complex resource acquisition process.

Another avenue of local resource acquisition is the utilization of untapped waste streams or by-products. A frequently used approach in combination with vertical/indoor farming are aquaponic systems in which aquaculture effluents are used to grow plants (Rakocy, 2012; Palm et al., 2018; Yep and Zheng, 2019). Fish like Tilapia paired with dark leafy greens are among the most commonly used species in aquaponics (Yep and Zheng, 2019). Various studies reviewed and analyzed the contribution of aquaponic systems in the context of food security, e.g., in Egypt and South Africa (Mchunu et al., 2017; Obirikorang et al., 2021), Arabia (Memon et al., 2022; Abusin and Mandikiana, 2020; Al-Busaidi et al., 2024), or in urban settings (Kyaw and Ng, 2017; Khan et al., 2020; Laidlaw and Magee, 2016). While aquaponic systems surpass the predominant growth of low-calorie produce in many IF/VF systems due to their output of fish, the produced crops, once again, are mostly leafy greens that do not significantly contribute to food security. The primary focus is on the symbiotic cultivation of leafy greens, such as basil, lettuce, and spinach, with an emphasis on their scalability and economic viability.

Alternatively, Mustak et al. (2024) evaluated the suitability of reusing treated greywater for hydroponic lettuce cultivation. The authors examine and monitor plant growth, including leaf, branch, and stem weight, as well as yield, and assess potential health risks associated with the use of greywater, which did exceed permitted levels but did not pose health risks.

Furthermore, a 2018 master's thesis focuses on assessing the usability of brewery wastewater for soilless urban agriculture in non-circulating hydroponic systems (Vila, 2019). They demonstrated the approach's feasibility on lettuce, mustard greens, and basil.

Besides aquaponics, other underutilized waste streams may allow for the full or partial substitution of input resources. Vermiculture (Frederickson et al., 1997), and vermicomposting (Dominguez et al., 1997) in particular are discussed in the literature. Vermicompost tea, also known as worm tea, is a liquid fertilizer made by steeping worm castings (vermicompost) in water. It's a nutrient-rich brew that can be used to substitute for or reduce the need for liquid fertilizer in IF and VF, in particular. While vermicompost tea application has been studied in horticulture to enhance plant growth and yields, as well as suppress pests and diseases, there is limited research into its application in hydroponics or similar systems (Arancon et al., 2019). In addition to substituting liquid fertilizer, vermiculture can also be used to rear different types of worms as feed (e.g., in combination with aquaponics) and for composting organic waste, which can

subsequently be used again in IF setups (Arancon and Solarte, 2019).

3.4 Production of animal-based food and feed

Synthesis. *Insect farming, particularly black soldier fly (BSF), is increasingly mature as a stand-alone technology and offers a plausible pathway to valorize organic waste streams into feed or food. However, the integration of insect production into closed-loop indoor farming concepts remains underexplored, especially for space-, energy-, and hygiene-constrained container deployments. The main gap is integrated system design and validation of safe, modular coupling between plant, waste-processing, and insect modules.*

The use of insects as food and feed is gaining increasing recognition as a viable and sustainable alternative to traditional livestock production. Additionally, it has a positive impact on the environment by transforming and reusing resources that would typically go to waste (Barragán-Fonseca et al., 2024). Currently, the primary species used for animal feed production is the Black Soldier Fly [BSF, (*Hermetia illucens*), Deguerry et al., 2023]. Today, the first prototypes of an industrial production system exist and have demonstrated their practicality (Yu et al., 2023).

Additionally, preliminary research exists that aims to combine fish, plant, and insect larvae production, with the goal of developing circular, multitrophic food production systems (Shaw et al., 2022). The most common approach is to substitute fish meal-based feed for the aquaponic fish, e.g., Tilapia, fully or partially with BSF meal, e.g., in Shaw et al. (2022) and Pinho et al. (2024) to produce leafy greens.

In Romano et al. (2022), the authors supplemented aquaponics with BSF larvae frass tea in an aquaponic setup with catfish, sweet potato slips, and sweet banana peppers, observing no adverse effects on catfish growth or water quality. Zarantoniello et al. (2021) substituted 50% of the common fish meal feed of Siberian sturgeons with BSF meal in an aquaponic setup and noted among other factors “lower diet accepted that resulted in growth and survival reduction” and deduced “the necessity to improve the palatability of BSF-based diet designed for sturgeon culture.”

While the state of the art, as presented above, relies on industrial feed for BSF to produce BSF frass or BSF meal, future BSF feed compositions based on waste streams, e.g., agricultural waste products, supermarket waste, or restaurant waste, would allow for even more efficient utilization of untapped waste streams, especially in the context of local resource acquisition.

3.5 Commutability in crop types

Synthesis. *Although controlled-environment agriculture can theoretically support a wide range of species, current vertical-farming practice and much of the empirical literature focus on fast-growing leafy greens. Evidence for calorie-dense staples exists but remains fragmented and often lacks full accounting of energy, cost, and operational constraints. As a result, “crop commutability” is*

best understood as an open engineering problem: reconfigurable cultivation hardware, adaptable control recipes, and open datasets enabling reliable switching across species and growth cycles.

Although IF in general allows for the production of a large variety of crops similar to traditional agriculture, research as well as for-profit production in VF systems in particular, predominantly focuses on low-caloric produce while catering to the needs of a specific type of plant, despite its underlying concepts, e.g., hydroponics, aeroponics, etc., being able to grow a variety of low- to high-calorie produce. In fact, nearly all crop species could in theory be cultivated in controlled environments, the literature reveals a pronounced bias. Current studies and commercial systems focus predominantly on fast-growing, low-calorie species—mainly leafy greens, herbs, and microgreens—while research on calorie-dense crops such as grains, tubers, and legumes remains scarce and mostly experimental. Reported yields can be extraordinarily high but come at the cost of excessive energy demand and poor economic viability; model studies estimate indoor wheat production costs far above market value. This gap between physiological potential and economic–ecological feasibility remains largely unexplored, as does the question of system commutability—most farm modules are optimized for only one or two crops, limiting adaptation to demand or nutrient dynamics. Future research should therefore address three directions: (1) adaptive, parameterizable “plug-and-grow” architectures for diverse species; (2) feasibility studies and comprehensive energy and cost assessments of calorie-dense crops; and (3) open datasets enabling AI-driven control and yield prediction.

The most common crops in soilless VF are vegetables, e.g., tomatoes, peppers, cucumbers, strawberries, leafy greens such as spinach, lettuce, chard, various herbs (basil, parsley, oregano), and some medicinal or fodder crops (Sharma et al., 2018; Ashok and Sujitha, 2020; Yep and Zheng, 2019). Although some calorie-rich cereals such as rice or maize can also be grown in hydroponics (Sharma et al., 2018) and some attempts have been made to grow potatoes in aeroponic systems, the focus of research and industry remain on low-caloric produce and thus rarely contributes to actual food security, especially in adverse environments (Martí Torra, 2023). In addition to the lack of high-calorie products, current VF systems do not allow for easy crop interchangeability, permitting only the cultivation of one or two plant species. A future highly flexible system that allows for easy crop interchangeability should be able to adapt easily to changes in demand and support resilient and more resource-efficient food production.

3.6 Automation

Synthesis. Automation is widely considered essential for scaling indoor farms and reducing labor, but most demonstrated solutions remain subsystem-level (monitoring, dosing, harvesting) rather than integrated, fault-tolerant end-to-end operation. The literature repeatedly identifies missing interoperability standards and robustness issues (drift, contamination, failures) as primary blockers for deployment in real-world settings. Therefore, the key research need is modular, energy-aware automation that remains operable under constrained resources and limited maintenance.

Automation is a key enabler for scalable and resource-efficient vertical farming and FPU concepts, as it allows environmental control and process execution with reduced labor and tighter input management (Chowdhury et al., 2023). Current implementations commonly combine IoT sensor networks (e.g., temperature, humidity, pH, EC) with low-power connectivity and edge/cloud-based control; LoRaWAN-based modular architectures are frequently proposed for long-range, low-energy monitoring and actuation (Codeluppi et al., 2020).

At the same time, the state of the art remains fragmented. A recurring gap is the lack of interoperability standards that would allow modular, vendor-agnostic integration of heterogeneous sensors, actuators, and controllers, limiting scalability beyond isolated prototypes. Practical deployments further report that energy demand (lighting/HVAC) and automation overhead can offset efficiency gains, while robustness issues such as sensor drift, biofouling/contamination, and actuator failures destabilize closed-loop control and still necessitate manual intervention. Consequently, a key research need is fault-tolerant, self-calibrating, and energy-aware automation that can sustain operation under variable conditions and constrained resources.

Automation has been studied across several process steps, including smart irrigation and nutrient delivery (Carrasco et al., 2024; Jagannathan and Priyatharshini, 2015), crop handling and harvesting for selected crops (Toon et al., 2019; Benavides et al., 2020; Park et al., 2025; Sujatanagarjuna et al., 2023; Funami et al., 2020; Zhang et al., 2024; Onishi et al., 2019; Yoshida et al., 2022), and the use of collaborative robots for repetitive tasks in space-constrained container farms (Mahalingam et al., 2024). Digital twins are increasingly explored to simulate and optimize cultivation and operations (Monteiro et al., 2023). Emerging work also addresses automated cleaning and biosecurity, but existing solutions are typically partial (e.g., roof cleaning) and not yet comprehensive for end-to-end FPU-like infrastructures (Amin et al., 2024a,b, 2025; Manor et al., 2004; Tham et al., 2024a,b).

Overall, automation offers benefits in input efficiency, labor reduction, and quality consistency (Chowdhury et al., 2023; Carrasco et al., 2024; Mahalingam et al., 2024), but progress toward deployable FPUs depends on (i) interoperable modular architectures, (ii) robust low-maintenance sensing and actuation, and (iii) energy- and connectivity-aware control (e.g., edge operation) suitable for resource-constrained settings.

3.7 Inspection

Synthesis. Plant inspection in indoor farms is technically feasible with low-cost RGB imaging and, in principle, richer spectral sensing; however, operational scalability is limited by calibration, contamination, and the effort required to standardize data quality over time. Most studies remain laboratory-scale or crop-specific, with limited validation under continuous production constraints. The main gap is robust, standardized, low-maintenance sensing pipelines (hardware placement, cleaning, calibration, and data fusion) suitable for long-term deployment.

Imaging plants using sensors enables tracking of plant growth status over time. This requires either a sensor that is moved to the plant or a plant that is moving to the sensor. For IF/VF scenarios, even a one-sensor-per-plant option could be viable. Nevertheless,

this requires low-cost hardware (Cho and Yang, 2023). This approach enables steady light conditions per plant, simplifying image processing. Depending on the trait being targeted, the sensor resolution becomes the critical bottleneck. The smaller the trait of interest, the higher the required resolution. Low-cost approaches typically focus on RGB measurements, as multi- or even hyperspectral approaches are more expensive, and studies to use them in IF/VF for the detection of the ingredients are lacking.

While image processing is considered a key technology for precise crop monitoring, its transfer into productive environments remains limited. High-resolution and hyperspectral methods provide valuable biophysical data but are costly, energy-intensive, and rarely integrated into scalable indoor farms. Most implementations still rely on simple RGB sensing in laboratory settings. Further research is needed on automating post-processing—particularly cleaning, calibration, and multi-sensor data fusion—as well as on establishing standardized validation using reference plants or artificial test objects. Overall, methodological gaps persist between technical feasibility and operational applicability, which future work should address.

Current research focuses on the development of plant-like test specimens to establish test routines to guarantee data quality (Bömer et al., 2024), will also benefit from schemes of interactive visual analytics, such as Unger et al. (2018), Chegini et al. (2018), and Shao et al. (2017).

3.8 Decision making

Synthesis. *AI-based decision making is frequently proposed to optimize indoor cultivation, but the practical evidence base is dominated by proofs of concept and simulations rather than long-running closed-loop operation. Common limitations include sensitivity to data quality, weak generalization across crops, and limited explainability for non-expert users. As a result, the key gap is validated decision support that combines reliable sensing, explicit uncertainty handling, and human-interpretable recommendations.*

Image analysis and prediction are based on AI routines. In particular, computer vision approaches based on machine learning or deep learning are used to interpret the plant's status. Plant growing parameters, such as BBCH stage, leaf area, biomass, or ripeness, can be extracted (Weyler et al., 2021; Kim and van Iersel, 2022). Prediction is used to determine or forecast the yield or harvest date, incorporating plant development data from the past, environmental data, and metadata from the cultivar (Mokhtar et al., 2022).

Moreover, decision-making in vertical farming and FPU is essential for efficiency and scalability. Modern approaches leverage AI, ML, and the IoT to dynamically control environmental factors such as temperature and light (Chowdhury et al., 2023; Codeluppi et al., 2020; Carrasco et al., 2024), while digital twins simulate cultivation scenarios virtually to test optimizations without physical adjustments (Monteiro et al., 2023). Autonomous systems reduce human intervention through real-time adjustments (Amin et al., 2024b).

Although increasing data availability in indoor farming is seen as key to self-optimizing systems, the actual adoption of AI-based

decision tools remains limited. The literature reveals a clear gap between theoretical potential and practical implementation. Most studies present proofs of concept or simulations, while long-term and scaling experiments are largely absent. Methodological inconsistencies further constrain progress: reinforcement learning performs well in controlled settings but is highly sensitive to noisy or incomplete data. Multi-agent systems enable distributed decision-making yet suffer from coordination and synchronization issues among competing agents. Explainability also remains insufficiently addressed—a critical factor for safety-sensitive applications and acceptance among non-expert operators. Future research should focus on three priorities: (1) validation of existing models in continuous real-world operation; (2) development of standards for data quality, ontologies, and agent communication; and (3) design of hybrid decision environments that integrate machine learning with human intuition.

A promising approach is Multi-Agent Systems (MAS), where different areas of a vertical farm are independently managed. These agents communicate with each other and optimize their processes autonomously (Benke and Tomkins, 2017). The decentralized structure enhances fault tolerance and enables local adjustments. Challenges lie in data quality, IoT integration, and model scalability (Codeluppi et al., 2020; Monteiro et al., 2023; Diaz, 2023). Especially MAS requires effective synchronization to avoid conflicts (Benke and Tomkins, 2017). Thus, future research should focus on improving model scalability and optimizing MAS protocols to make decision-making more autonomous and resilient.

3.9 Human user interface

Synthesis. *While high-information dashboards exist, most HMIs in vertical farming assume expert operators and stable infrastructure, which conflicts with the FPU target context of low-resource or humanitarian deployments. Early work suggests conversational and multilingual interfaces could reduce operational barriers, but systematic evaluations of usability, trust, and failure modes are scarce. The main gap is user-centered, offline-capable interaction design that supports safe operation by non-experts.*

Beyond interaction concepts, the broader vertical-farming literature highlights that operational targets and evaluation criteria are heterogeneous and often dominated by productivity-centric KPIs, while sustainability- and user-oriented measures are less consistently addressed (Al-Kodmany, 2018; Kabir et al., 2023; Fasciolo et al., 2024; Van Gerrewey et al., 2021). Case studies on urban integration (e.g., facade/rooftop production) further underline that vertical farming is increasingly discussed in diverse socio-technical contexts, which strengthens the need for interfaces that are robust across user groups and deployment environments (Ghazal et al., 2023).

Despite growing interest in multimodal and conversational interfaces, most published HMI solutions implicitly assume stable infrastructure and expert operators, and empirical studies on trust, transparency, failure handling, and cultural/linguistic accessibility are scarce. This is particularly relevant for decentralized or humanitarian deployments where connectivity, power, and maintenance capacity are constrained. Future research

should therefore focus on (i) participatory co-design and evaluation with target user groups, (ii) adaptive and multilingual interaction concepts (potentially including LLM-based assistants), and (iii) offline-capable, fault-tolerant interface designs that communicate uncertainty and safe operating procedures under degraded conditions.

3.10 Summary

The reviewed literature consistently highlights that vertical farming and related indoor approaches can decouple production from external conditions, enabling year-round cultivation and high spatial productivity, which is particularly relevant in regions with limited arable land or unstable climates (Daniels et al., 2023; Wichitwechkarn and Fox, 2023; Chowdhury et al., 2023; Sowmya et al., 2024; Al-Kodmany, 2018; Kabir et al., 2023). Across studies, the most frequently cited advantages are (i) improved water-use efficiency through soilless cultivation, (ii) reduced land demand via vertical stacking, and (iii) opportunities for local production with shorter supply chains (Wichitwechkarn and Fox, 2023; Al-Kodmany, 2018; Kabir et al., 2023). At the same time, the evidence base also converges on several limiting factors: high energy demand and associated operating costs, labor and automation constraints (especially in space-limited systems), limited standardization and interoperability, and a continued bias toward fast-growing, low-calorie crops (Daniels et al., 2023; Mahalingam et al., 2024; Chowdhury et al., 2023; Kabir et al., 2023; Fasciolo et al., 2024; Sowmya et al., 2024). These observations motivate the FPU lens used in this manuscript: to structure the field by modules and to identify maturity and research gaps at the interface of physical infrastructure, Digital Agriculture, and human operation.

3.10.1 Practical and technical limitations and the role of computer science, AI, and data science

From a resilience and food-security perspective, a central practical bottleneck is energy supply. While IF/VF can reduce water input compared to conventional agriculture (Khan, 2018), the overall footprint and operating costs are often dominated by electricity demand for lighting and climate control (Dauchot et al., 2024; Ahamed et al., 2023; Maheshwari, 2021). For FPU-like deployments in adverse environments, this shifts the objective from “perfect growth conditions” toward maximizing edible output under constrained resources, and it elevates energy autonomy and energy-aware operation as first-order design goals. In parallel, nutrient and water management increasingly benefits from sensor-based monitoring and data-driven control (e.g., closed-loop regulation of pH/EC and phase-dependent recipes), but robust operation depends on reliable sensing, calibration, and fault handling in long-running systems.

On the technical side, two gaps dominate. First, most existing installations remain optimized for a small set of short-cycle leafy greens, with limited commutability to calorie-dense crops and longer-cycle species; achieving crop flexibility requires parameterizable cultivation modules, validated control strategies, and associated datasets. Second, data availability and comparability

remain limited: adaptive control and AI-based optimization require open, high-quality datasets spanning diverse crops, environments, and failure modes. Addressing these gaps points to concrete computer-science contributions, including interoperable modular architectures, energy- and connectivity-aware edge control, and data-centric methods (standardized schemas, benchmarking protocols, and reproducible models) that enable robust operation beyond laboratory prototypes (Woodhill et al., 2020; Hazell et al., 2007; Touch et al., 2024).

4 Discussion and limitations

Based on the literature review presented above and its analysis in the context of the reference scenarios presented in Section 2.1 the following TRL levels are suggested and discussed for aspects of transportability, modularity, energy sufficiency, resource collection, waste cycles, crop flexibility, animal-based food and feed ability, automation, (plant) inspection, decision making, and human interface design.

4.1 Limitations of this scoping review and TRL synthesis

This manuscript is positioned as a scoping review combined with a perspective paper. Accordingly, our literature search and selection were intended to capture representative contributions across the modules of the proposed FPU model rather than to provide exhaustive coverage of all available studies. We did not conduct PRISMA-style study screening, formal risk-of-bias assessment, or quantitative meta-analysis. As a result, the cited body of work may underrepresent certain sub-communities or application contexts (e.g., region-specific deployments, proprietary industrial solutions, and non-English literature), and the relative depth of evidence per module reflects the availability and accessibility of published sources. The TRL values reported below should therefore be interpreted as a literature-informed diagnostic intended to summarize maturity and highlight research gaps at module level; they do not validate or endorse a particular FPU architecture. TRL assignments are necessarily approximate because reported systems differ in their degree of integration, duration of operation, and environmental fidelity, and because readiness is context-dependent (e.g., humanitarian off-grid use vs. grid-connected urban production). Future work could strengthen this diagnostic by applying explicit, standardized TRL rubrics per module and by triangulating assessments through expert elicitation and longitudinal field deployments.

4.2 Discussion

4.2.1 Transportability (TRL 7–8) and modularity (TRL 3–4)

This is supported by focusing on standardized shipping containers, which show a high potential for transportation by air, water, or road. Nevertheless, this proof has not been demonstrated

for any kind of FPU-like system to date. Instead, the state of the art resorts to design proposals and conceptualizations (Diaz, 2023; Liu, 2014; Martin and Bustamante, 2021; Belista et al., 2018; Rivera et al., 2023; Serecon Inc., 2021) or proof-of-concepts (Carrasco et al., 2024; Bafort et al., 2022), while other papers focus on particular sub-components of smart modular farms, e.g., in Matar et al. (2024). Additionally, shipping container-style VF systems exist—sometimes even coupled with aquaponics, insect-rearing systems, etc.—on a proof-of-concept level. However, minimal integration and no relevant level of modularity beyond conceptualizations and lab tests have been demonstrated.

4.2.2 Energy self-sufficiency (TRL 3–4)

The energy self-sufficiency of FPUs is another critical issue concern of mobile FPUs. Current prototypes rely on hybrid mixes of solar, wind, geothermal, and biogas systems, yet all of these sources are spatially and temporally volatile: “renewable-energy droughts,” featuring multi-week lulls in wind and sunlight even in otherwise favorable regions, can and do occur. Compact, low-cost, high-energy-density storage solutions for such blackout periods are still lacking. Today’s lithium-ion batteries face not only technical limits but also geopolitical and resource constraints due to their reliance on lithium, cobalt, and other rare elements. Alternative storage concepts—such as iron-air, liquid-air, or gravity-based systems—are under development; however, they have so far fallen short in terms of cycle life and cost targets for field deployment.

Effective scaling of FPUs, therefore, demands intensive research into robust energy architectures and modular storage mixes that can maintain lighting, climate control, and water treatment for weeks without external supply. Key elements include: (i) adaptive energy-management systems that dynamically prioritize whatever local sources are available; (ii) recyclable, resource-lean battery chemistry with high cycle stability; and (iii) low-power designs at the FPU periphery to shave peak loads. Only when such resilient energy and storage solutions are in place can FPUs become truly reliable tools for food security in crisis and conflict zones.

Finally, automated reporting of resource consumption or a system’s footprint is often neglected perspective. Lawrenz et al. (2021) introduces the general concept of a “sustainability impact factor” (SIF), which consists of a fixed SIF (generated during production, e.g., material/energy consumption, environmental damage) and a variable SIF (usage depending impact of the service/product) to measure the sustainability impact of any given service provision in an automated manner. Integration in the context of food production systems is absent.

4.2.3 Resource collection (TRL 2–3) and waste utilization (TRL 3–4)

While solar panels and rainwater collection are used to substitute for some resource inputs, they only account for a fraction of the actual consumption of existing permanent and mobile food production structures. Little to no thought is given to deviating from the predominant approach of providing perfect growth conditions, e.g., light, temperature, humidity, hydration, etc., and

instead maximizing caloric output given a constrained resource input, e.g., sub-optimal growth conditions are tolerated. Still, local resource collection is sufficient to supply the food production.

Some food systems, particularly those utilizing aquaponics, exist and go beyond the predominant growth of low-calorie produce in IF/VF systems. Due to their output of fish, the produced crops are mostly leafy greens, which do not contribute significantly to food security. The primary focus is on the symbiotic cultivation of leafy greens, such as basil, lettuce, and spinach, with an emphasis on their scalability and economic viability. Attempts to reuse greywater and brewery wastewater have been tested in proofs-of-concepts but remain far from widespread adoption. Finally, all approaches listed above and in previous sections demonstrated separate research and refrained from any overarching integration into FPU-like systems.

4.2.4 Crop commutability (TRL 5–6)

Current available FPUs can grow different but limited crops. Here, these systems gain a TRL level of 5–6. IF/VF can, in theory, accommodate a broad spectrum of crops, yet IF/VF research and commercial practice still prioritize low-calorie produce. Most soilless VF installations grow vegetables and herbs and a few medicinal or fodder plants—despite hydroponic and aeroponic methods being suitable for both low- and high-calorie species (Sharma et al., 2018; Ashok and Sujitha, 2020; Yep and Zheng, 2019). Calorie-dense staples such as rice or maize have been demonstrated in hydroponics (Sharma et al., 2018), and potatoes have been trialed in aeroponic setups, yet these remain exceptions; thus, present VF contributes little to food security in resource-constrained or otherwise adverse settings (Martí Torra, 2023). Current systems are also optimized for only one or two crops, offering limited “crop commutability.” Developing modular, rapidly re-configurable units that can switch among diverse, calorie-rich plants would better track shifting demand, enhance resilience, and improve overall resource efficiency.

4.2.5 Animal-based food and feed (TRL 5–6)

The ability of FPUs to produce *animal-based food products* to feed humans or for refinement by feeding animals is at TRL level 5–6. This is supported as current startups (see Farminsect GmbH, Bergkirchen, Germany¹) already showed container-based solutions for highly automated breeding and growing of insects. Nevertheless, this is not integrated into FPU containers and lacks space-limited and fully self-sustaining conditions.

4.2.6 Automation (TRL 6–7)

The ability to *automate* required actions within an FPU system is defined as TRL 6–7. Current evidence for automation in VF remains confined to narrowly scoped prototypes, while

¹ <https://www.farminsect.eu/>

comprehensive systems toward fully automated FPU have not yet undergone rigorous field validation. Moreover, interoperability and comprehensive integration are inadequate: heterogeneous sensors, proprietary controllers, and bandwidth-limited networks (e.g., LoRaWAN) complicate real-time, closed-loop control. High capital costs and continuous energy demands for lighting, HVAC, and edge or cloud computing can negate resource-efficiency gains. Additionally, system resilience is under-studied; sensor drift, biofouling, and actuator failure lack robust fault-tolerant or predictive maintenance frameworks. Finally, automated sanitation and harvesting address only select crops or easily accessible surfaces, leaving stacked hydroponic racks to be serviced manually.

4.2.7 Inspection (TRL 5–6)

The ability to perform *plant inspection* to set up harvesting or fertilizer tasks can be set to TRL 5–6. While past research has shown the potential for detecting specific stresses (diseases or nutrient deficiencies), high-throughput production requires covering various stress factors simultaneously, including mixed infections and mixed deficiencies for different plant types. Additionally, this needs to be integrated into a fully automated, productive greenhouse.

4.2.8 Decision making (TRL 6–7)

Based on the digitally monitored plant status, required actions can be scheduled. On practical field sites, the application following a discrete identification of plant stress, such as diseases or nutrient deficiency, is demonstrated. Nevertheless, the integration of these routines into greenhouses has not been shown until now. In addition, aspects of resistance to fungal or viral pathogens need to be taken into account.

4.2.9 Human-machine interfaces (TRL 5–6)

A largely overlooked yet critical bottleneck concerns the user-orientation of the human-machine interfaces (HMIs) found in most current FPUs. While highly informative graphical user interfaces already have a very high TRL level, human-machine communication for non-trained operators that require a self-explanatory system is complex for a system of such high complexity. This requires a deep evaluation of the system and a good match with the existing skills of the users. These systems are designed primarily as expert tools, assuming agronomic expertise and IT proficiency—skills that are rarely available in crisis or conflict zones. As a result, FPUs fail to fulfill their strategic purpose of enabling food production precisely where trained specialists are lacking. Future solutions, therefore, must embrace actual non-expert usability: multilingual, icon-, visual-, and voice-driven interfaces similar to Hofmann et al. (2017), Karer (2020), Chegini et al. (2017), Lehmann and Theisel (2015), and Wang et al. (2017); conversational assistants that leverage large-language models to explain settings in everyday language or to auto-tune parameters;

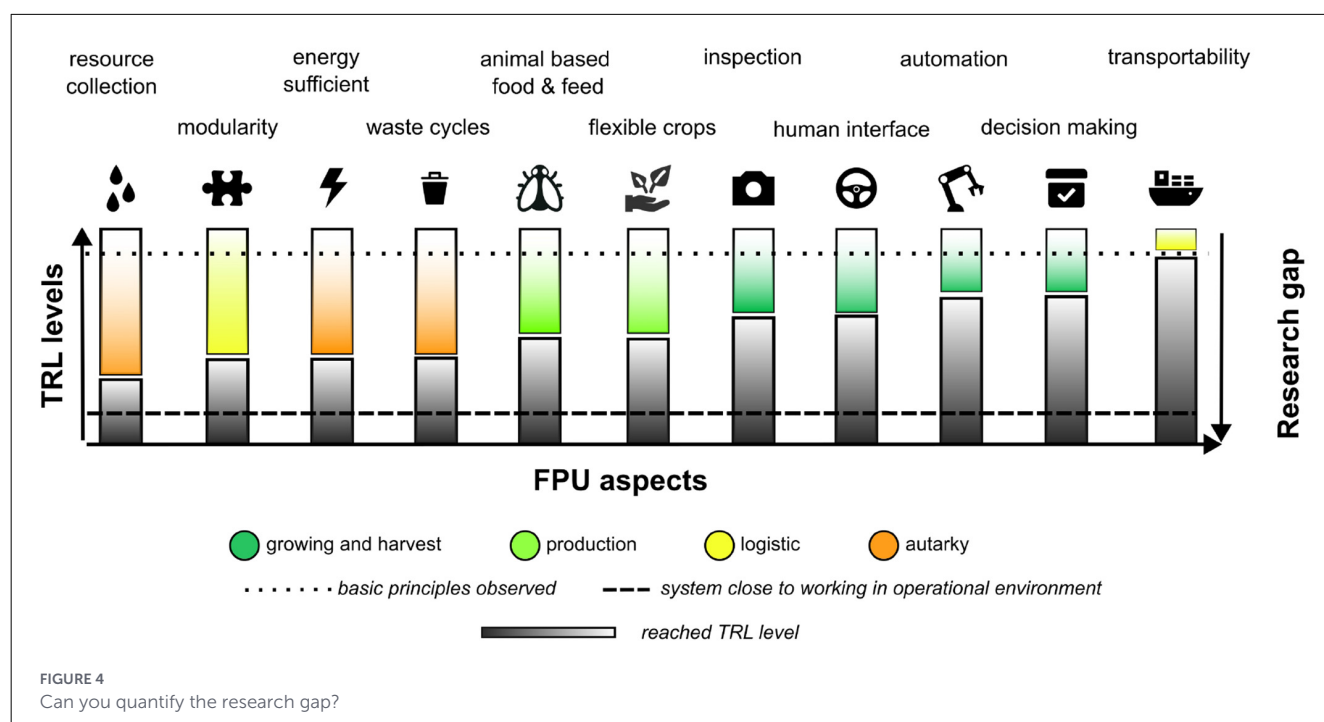
and context-adaptive dashboards that highlight only critical KPIs and actionable recommendations instead of overwhelming users with raw data.

FPUs should also embed offline-capable knowledge bases and first-run wizards that provide step-by-step guidance, even when connectivity is lost. Coupled with self-explanatory maintenance videos, AR-assisted troubleshooting, and remote support over low-bandwidth channels, this yields an operating paradigm aligned with proven principles of humanitarian logistics. Such user-centered HMIs not only enhance deployability in extreme environments but also close the research gap identified in Section 3.9: The absence of TRL-7-ready interfaces for unskilled personnel. Finally, broad accessibility boosts public acceptance of the technology—a point highlighted by Al-Kodmany (2018) for urban vertical farming but still largely unaddressed for mobile FPUs. A rigorous commitment to user-centered design is thus a prerequisite for establishing FPUs as truly scalable, resilient tools for food supply in crises.

This review has defined TRLs for FPUs, allowing for the quantification of gaps in development and research (visualized in Figure 4), where the gray area indicates the reached TRL level and the corresponding color-coded areas indicate the quantified research gap. However, these TRL levels have significant drawbacks. Many of the levels do not address system integration within new environments (Olechowski et al., 2020) or consider factors such as requirements satisfaction, environmental fidelity, criticality, or product availability (Sauser et al., 2006). Despite these limitations, this technical framework is well-established and plays a crucial role in tracking the progress of technological development. Consequently, it can be complex to assign a single TRL level to the components of the proposed FPU. These TRL assignments are a literature-informed diagnostic to highlight gaps; they do not constitute validation or endorsement of a particular architecture.

In the first world, particularly in the Western part, the consumption of insects as food is not very popular (Giacalone and Jaeger, 2023). Research on the acceptance of insect-based food, which is often dismissed due to anticipated disgust at the sensory experience, has demonstrated that interventions aimed at providing positive tasting experiences can significantly (Barton et al., 2020). In general, foods from technologies comprising vegetables from urban farming and vegetables packaged in a modified atmosphere to extend shelf life were perceived as healthier and ideal for moving one's diet in a more sustainable direction. Whereas consumers had problems associating specific benefits to foods from (a) technologies with medium consumer acceptance comprising fish reared in aquaponics systems, plant-based alternatives to animal products, and gene editing technologies, or (b) meat containing insect flour, and cell-cultured meat and fish (Giacalone and Jaeger, 2023). However, the FPUs described are intended for emergencies and are not designed to support food production in everyday life. In emergencies, customer behavior is less influential.

Utilizing FPUs to support humanitarian care in emergencies could be a significant benefit if uncovered development gaps can be overcome. This vision could include whole farms to (a) enable a permanent supply of food as harvesting is not possible 24/7, (b) not limited to human food but also for feeding livestock farming, and (c) to support local infrastructure when the local number of people is increased due to additional emergency staff. An alternative



system could modularize the components of the FPU, creating units for energy supply, recycling, and food production (Laibach et al., 2021). These can then be linked to form a modular factory that can be scaled as needed (NASA Technology Transfer, 1876). One crucial issue that has to be solved is standardization, as it is essential for optimal industrial-like production (Yang and Tomberlin, 2020). Its integration into a fully standardized FPU seems to be an optimal fit.

FPU's show a very small footprint and are a perfect match for villages with limited arable land, hard to reach by car or plane, military bases, or disaster relief, which today seems to be an exception. Nevertheless, facing climate change, desertification, and soil degradation, this could become more common in the future. Nonetheless, FPU's are an essential part of space travel (Maiwald et al., 2023) and the colonization of other celestial bodies. This requires shifting from the pre-packaged food system to the *in-situ* development of technologically advanced food systems and thus the cultivation of plant food in controlled greenhouses (Maity and Saxena, 2024).

5 Future research directions

1. Research into high-calorie alternatives is limited due to their longer growth cycles that do not correspond to short research funding schemes. As a result, limited availability of data about calorie-rich plants since research funding is often limited to 2–3 year.
2. Viable business models and lack of economic incentives: Similarly, from an economic perspective, leafy greens with short growth cycles allow for short-term cash flow since the price of a plant or its produce is not determined by its calories.

3. Overcoming limitations with computer science, AI, and data science:

Autonomous control systems through artificial intelligence (AI): AI-driven control systems take over real-time monitoring and regulation of growing conditions in VF systems. An example is the use of neural networks to predict optimal growing conditions based on historical data. These systems enable dynamic adjustment of parameters such as light intensity and humidity, reducing energy consumption while maximizing yield.

Communtability of crops: Data-driven models now allow VF systems to adapt flexibly to different plant species. A concrete example is the use of reinforcement learning algorithms, which continuously optimize the system by maximizing yield when switching between crops. This ensures greater adaptability, allowing systems to quickly respond to market demands.

Sustainable AI models: The development of sustainable AI models reduces energy consumption during model computation and application. Techniques like model pruning and quantization make models more efficient and reduce resource usage. One example is the implementation of edge computing systems, which run AI models directly on-site without a cloud connection. This reduces latency and CO₂ emissions, as less energy is required for data transmission.

6 Conclusions

This paper has examined the capacity of container-based Food Production Units (FPU's) to complement and, in extremis, substitute for conventional agriculture under mounting climatic and socio-economic stress. Our review outlines the eleven essential modules needed to create and establish environmentally

independent FPU and evaluates their operational readiness. For each module, we have identified the development and research gaps that exist. A systematic review revealed that current IF/VF deployments remain confined to low-calorie crops and operate at TRLs that are insufficient for large-scale food security interventions. We frame FPUs as an integral, layered model unifying physical cultivation systems with Digital Agriculture and user-facing modules; our TRL synthesis and research directions are organized per module of this model.

By formalizing FPU design requirements such as transportability, modularity, energy and resource autonomy, closed-loop resource cycles, crop and feed flexibility, and AI-supported automation, we delineate a pathway by which indoor farming can transition from niche urban horticulture to resilient calorie production in adverse environments. Equally critical are socio-technical dimensions. Food production systems must prioritize calorie density over growth cycle length, while conversational, language-agnostic HMIs are necessary to deploy FPUs in areas where skilled operators are scarce. Rigorous, longitudinal field trials in climatically and logistically challenging regions should replace laboratory demonstrations to validate robustness, life-cycle sustainability, and cost-effectiveness. Subsequently, we discuss the necessary advancements required for practical implementation.

If these research priorities are met, FPUs could supply diverse, nutrient-adequate food independent of arable land, stabilize humanitarian supply chains after disasters, and reduce agriculture's environmental footprint. Conversely, failure to close the identified TRL gaps risks relegating IF/VF to a marginal role and putting food security at risk given urgent challenges such as the climate crisis, increasingly frequent extreme weather events, expanding desertification, degradation of fertile topsoil, environmental pollution, dwindling non-renewable resources, and accompanying societal issues such as mass migration.

Author contributions

BL: Visualization, Investigation, Conceptualization, Funding acquisition, Formal analysis, Writing – review & editing, Data curation, Writing – original draft, Methodology. SP: Visualization, Funding acquisition, Formal analysis, Writing – review & editing, Investigation, Data curation, Writing – original draft, Conceptualization, Methodology. DL: Investigation, Writing – review & editing, Methodology, Conceptualization, Writing – original draft, Data curation, Visualization, Formal analysis.

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