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Plant Factories with Artificial Lighting: prospects for achieving sustainable development goals

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Abstract

This study aims to highlight the significance of Plant Factories with Artificial Lighting as a viable food supply solution for the global population, particularly in the context of the United Nations (UN) Sustainable Development Goals (SDGs) that target hunger and social inequalities. A thorough search was conducted across multiple databases, including MDPI, ScienceDirect, ResearchGate, Google Scholar, Springer Science+Business Media, and Frontiers Media, using relevant keywords. The articles reviewed indicate that, despite the inherent challenges of this emerging and costly technology, Plant Factories with Artificial Lighting (PFALs) have significant potential to advance the SDGs. By tackling critical issues such as food scarcity, adverse socioeconomic conditions, and environmental sustainability, PFALs could fundamentally transform the food production landscape. Despite financial challenges and limited accessibility primarily affecting stronger economies, ongoing technological advancements and research offer a hopeful outlook for Plant Factories with Artificial Lighting (PFALs). Addressing these obstacles could reduce initial costs, enhancing accessibility and positively impacting low-income populations. By overcoming these hurdles, PFALs have the potential to drive innovative and sustainable solutions to food, environmental, and social issues, ultimately contributing to equitable global development.

Keywords: resource efficiency, urban agriculture, food security

Introduction

The Food Waste Index report, published by the United Nations Environment Programme in 2021, highlights the need for new production concepts to reduce food waste and improve agricultural quality and yield. Supported by several targets of the Sustainable Development Goals (SDGs), the report emphasizes that in order to feed a growing global population and protect the environment, it is crucial to minimize waste and develop methods that use fewer resources and require less environmental management.[1]

Current challenges in agricultural production, such as climate change, water and land scarcity, and food waste, are exacerbated by the growing global population. The global population is expected to reach 9.7 billion by 2050, putting additional pressure on already overburdened food systems.[1] Food insecurity has been on the rise, especially in developing countries, where millions lack access to adequate food. Food waste is alarming, with around one-third of global production being lost annually, depending on food availability and prices.[2]

Plant Factories with Artificial Lighting (PFALs) are emerging as a viable solution to these challenges, offering a production system that uses less water and land and can be installed close to consumption centers to minimize waste. PFALs enable faster harvest cycles and are reliable for improving yields in controlled environments, addressing food insecurity.[3] However, high production costs and consumer resistance to more expensive products still pose significant challenges. The growth of the PFAL market suggests a promising future, but financing options remain a concern.[4]

To support the United Nations' Sustainable Development Goals, agricultural engineering and agronomy can develop strategies that enhance food security. These fields focus on improving equipment and inputs for planting, harvesting, and storage.

This article aims to highlight the role of agricultural engineering and agronomy in combating hunger through vertical farming, emphasizing technological innovation and responsible production in line with the UN's objectives.

Vertical farming offers a promising approach to boost food production while using less land. Thus, further research on this technique is essential to understand its contributions to sustainability and economic implications.

Material and methods

A bibliographic survey was conducted using databases such as MDPI, ScienceDirect, ResearchGate, Google Scholar, Springer Science+Business Media, and Frontiers Media. The keywords employed included vertical farming, plant factory, urban agriculture, plant factory with artificial lighting, hydroponics, productivity, light quality, daily light integral, sustainability, greenhouse, microenvironment, controlled environment, controlled environment agriculture, artificial lighting, production cost, light energy use efficiency, management, indoor farming, smart agriculture, energy demand, horticulture, food security, urban farming, plant factories, automation, LED, and supplemental lighting.

The review focused on articles that highlighted the advantages of vertical farming, discussing their applications, implementations, associated risks, challenges, costs, and benefits. Our aim was to explore the potential of vertical farming in relation to the United Nations Sustainable Development Goals. The publication timeframe was set from 2015 to 2022, as this period reflects the most extensive body of work on this emerging technology. Articles not aligned with the research question, as well as review papers that referenced Plant Factories with Artificial Lighting (PFALs) without making them the primary focus, were excluded from the sample, along with abstracts, conference proceedings, and editorials.

The analysis conducted identifies 51 studies that address PFAL, covering topics such as the use and consumption of resources such as energy and inputs, production capacity, the use of the Internet of Things (IoT), and process mechanization. However, only the study by Lombardi & Lombardi (2022) broadly discusses the role of Vertical Farms in alignment with the Sustainable Development Goals (SDGs), albeit without giving specific emphasis to the role of PFALs in this context, and Kozai, T[4] brings the potential of n-PFALs and the technologies that can be incorporated into them are discussed in the context of achieving the Sustainable Development Goals (SDGs) by 2030. Our aim was to investigate the feasibility of integrating PFALs into some of the United Nations Sustainable Development Goals (SDGs). Among the 17 SDGs, we selected six that could potentially benefit from the adoption of PFALs, such as Promoting sustainability, reducing hunger, Fostering sustainable industrialization, Making cities and human settlements sustainable, Ensuring sustainable patterns of production and consumption, and undertaking actions to mitigate the effects of climate change. Given the scarcity of studies connecting PFALs to the SDGs, we proposed to outline the application of PFALs as a collaborative strategy for the aforementioned goals, without neglecting their limitations.

Revision

Characteristics of PFALs

PFALs (Plant Factories with Artificial Lighting) represent a closed plant production system (CPPS), where all inputs used are designed to ensure minimal emissions to the external environment. The numerical data presented in the following sections were sourced from PFALs that meet the following six criteria[4]:

1) All walls and roofs must be optically opaque, relying exclusively on light emitted by lamps as the sole light source within the cultivation area.
2) The cultivation room must be nearly airtight under standard operating conditions.
3) The walls and floor must provide effective thermal insulation.
4) A hydroponic cultivation system must be employed.
5) Entry to the cultivation room (sanitary area) is restricted to workers wearing disinfected clothing, who must pass through an air shower.
6) The propagation and growth of pathogens, insects, and small animals must be strictly monitored, recorded, and minimized.

A key distinction between PFALs and traditional indoor or vertical farms is that PFALs utilize lamps as the only source of light. In contrast, indoor farms typically incorporate a plant cultivation area that harnesses solar light through glass windows, while vertical farms often feature rooftop greenhouses that also utilize sunlight.[5]

The advantages of PFALs over conventional systems include:

a) The ability to be built anywhere since they do not rely on sunlight or soil.[6]
b) The cultivation environment is not affected by external factors.[7]
c) Production remains consistent throughout the year and is approximately 100 times more productive than field production.[8]
d) Product quality can be enhanced by manipulating the environment.[9,10]
e) The products are pesticide-free, eliminating the need for washing before consumption.[11]
f) The products have a longer shelf life.[12,13]
g) The system reduces transportation costs (from final product to consumer).[14]
h) Resource use is highly efficient, with minimal pollutant emissions.[3]

However, PFALs also face a number of challenges and disadvantages, including:

i. High initial and production costs.[15]
ii. High costs for electricity, labor, and materials (seeds, fertilizers, packaging, delivery, among others).[16]
iii. Lack of information on environmental control and cultivation.[17]
iv. High operational costs of equipment.[18]
v. Low financial returns.[19]
vi. Competition with conventional products.[20]

Contribution of PFALs to the Sustainable Development Goals (SDGs)

When analyzing the articles selected in the review, we identified among the authors an approach on the following themes related to PFALs:

a. Climate change
b. Water use and deficiency
c. Land use and deficiency for cultivation
d. Food waste
e. Population growth
f. Food insecurity.

These themes are associated with several SDGs, which were chosen for this study:

SDG 2: End hunger, achieve food security and improved nutrition, and promote sustainable agriculture:

I. Point 2.1 of SDG 2 establishes the imperative to eradicate hunger by 2030, ensuring universal access to safe, nutritious, and sufficient food all year round, with special attention to the poor as well as people in vulnerable situations, including children.
II. Point 2.4 of SDG 2 advocates, by the year 2030, for the assurance of sustainable food production systems, as well as the implementation of resilient agricultural practices. Such practices should aim to increase productivity, preserve ecosystems, strengthen adaptation capacity to climate change, extreme weather conditions, droughts, floods, and other disasters, and also progressively improve land and soil quality.
III. Subitem 2.a of SDG 2 aims to increase investments, including strengthening international cooperation, in rural infrastructure, agricultural research and extension services, technology development, and gene banks for plants and animals. The purpose is to expand agricultural production capacity in developing countries, with a special focus on the least developed ones.
IV. Subitem 2.b of SDG 2 advocates for the correction and prevention of restrictions on trade and distortions in global agricultural

markets, including the simultaneous elimination of all forms of export subsidies and export measures with equivalent effect, as established by the mandate of the Doha Development Round.

SDG 8: Promote sustainable, inclusive and sustained economic growth, full and productive employment, and decent work for all:

A. Point 8.2 advocates for achieving higher levels of productivity in economies through the implementation of strategies encompassing diversification, technological modernization, and innovation. This notably includes a focus on high value-added sectors and labor-intensive sectors.

B. Point 8.4 stipulates the need to gradually improve, by 2030, global efficiency in resource consumption and production, as well as to endeavor to decouple economic growth from environmental degradation. This is aligned with the Ten-Year Framework of Programmes on Sustainable Consumption and Production, with developed countries leading this commitment.

SDG 9: Build resilient infrastructure, promote sustainable industrialization and foster innovation:

Point 9.4 establishes the goal of modernizing infrastructure and rehabilitating industries by 2030, aiming to make them sustainable. This implies increased efficiency in resource use, as well as greater adoption of clean and environmentally responsible technologies and industrial processes. This initiative should involve all countries, considering their respective capacities.

SDG 11: Make cities and human settlements inclusive, safe, resilient and sustainable:

Point 11.6 stipulates that by 2030, it is necessary to reduce the negative environmental impact per capita in cities, with special attention to air quality, municipal waste management, among other aspects.

SDG 12: Ensure sustainable consumption and production patterns:

Point 12.3 establishes the goal of halving global per capita food waste by 2030, both at retail and consumer levels and throughout production and supply chains, including post-harvest losses.

SDG 13: Urgent action to combat climate change and its impacts.

a) The system applied in PFALs offers alternatives and solutions to the main issues concerning agricultural production and the environment:

b) Climate Change: In PFALs, no chemical products such as pesticides, chlorine, or herbicides are used. Thanks to controlled and climate-controlled conditions, rigorous biosafety procedures are implemented to eliminate pests, insects, and diseases, eliminating the need for fungicides and herbicides.[21–24] PFALs can reduce carbon emissions by using renewable energy sources such as solar panels and wind energy, reducing the need for fossil fuel-powered equipment.[23]

c) Water and Land Use and Scarcity: In addition to not using soil for planting, according to Sarkar and Majumder[23] and Al-Kodmany,[21] PFALs consume about 10% of the water used in traditional farms, with water treatment to ensure high quality, resulting in a 70% reduction in water usage compared to conventional farming.

d) Food Waste: PFALs can be strategically installed near sales points or distribution centers to reduce the time between harvest and delivery to the end consumer, decreasing storage and refrigerated transport costs.[21] Installing PFALs in urban warehouses ensures deliveries in climate-controlled environments, resulting in a lower carbon footprint and longer-lasting products for customers.[22]

e) Population Growth: PFALs offer faster harvest cycles, thanks to the control of factors such as temperature, humidity, and light, enabling greater crop turnover annually compared to traditional agriculture.[21] With continuous harvesting and accelerated plant growth in a controlled environment, the harvest time is reduced compared to traditional agriculture, increasing the food supply capacity in a shorter period.

f) Food Insecurity: By optimizing productive efficiency in restricted spaces, PFALs are recognized as one of the options to expand food production. It is widely acknowledged that the main contributors to food insecurity include reduced food availability due to issues in the production process, such as periods of rainfall scarcity directly impacting crops; degradation in the quality of available food for consumption; challenges related to supply; rising food prices; decreasing wages or loss of income sources; poverty condition; and the influence of climate change.[25]

Through literature review, it became feasible to discern various aspects inherent to PFAL that align with the Sustainable Development Goals (SDGs). Multiple characteristics inherent in these structures meet the principles stipulated by the SDGs, such as:

Objective 2. End hunger, achieve food security and improved nutrition, and promote sustainable agriculture

As addressed by Touliatos et al.,[8] production in PFALs remains constant throughout the year, being approximately 100 times more productive compared to conventional methods in open fields. This finding distinguishes the PFAL system as a reliable and assured source of food production. Furthermore, as emphasized by Chen et al.,[10] and Bantis et al.,[9] controlled environment manipulation in PFALs can result in significant improvements in the quality of cultivated products. It is added that, as highlighted by Roberts et al.,[11] production in this context occurs free from pesticides, ensuring the safety and nutrition of the resulting products.

According to the analysis of Song et al.,[6] PFALs can be established in any location, regardless of the external environment. This characteristic gives them effectiveness in adapting to climate change. Moreover, as underscored by Kozai et al.,[3] the system demonstrates notable efficiency in resource use, with minimal pollutant emissions, thus contributing to environmental preservation.

Given that PFALs represent a pioneering technology in continuous evolution and adaptation to new markets, it is imperative to allocate more resources to research and technological development. These researches may encompass genetic investigations, including genetic modifications, aiming to optimize food development in PFALs. As previously mentioned by Chen et al.,[10] and Bantis et al.,[9] controlled environment manipulation in PFALs can lead to substantial improvements both in the quality and quantity of cultivated products. This focus requires robust and continuous investments to ensure the effectiveness and viability of PFALs in meeting the objectives outlined by SDG 2.a.

The ability of PFALs to be deployed in any location, regardless of external climatic conditions,[7] positions them as a disruptive system in food supply. This fact makes them an innovative system in overcoming obstacles related to food provision. Food products previously impossible to cultivate in certain locations due to climatic restrictions, soil conditions, or water availability can now be produced and made available in these regions, increasing food diversity and eliminating value distortions caused by imbalances between supply and demand.

Goal 8: Promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all

PFALs present a diversified complementary model of food production, characterized by technological modernization in a high value-added sector, thus fostering the enhancement of specialized workforce skills. As highlighted by Kozai et al.,[3] PFALs demonstrate high efficiency in resource use, minimizing pollutant emissions. Moreover, as pointed out by Roberts et al.,[11] these practices do not require the use of pesticides, and according to Song et al.,[6] they do not require soil for planting, thus characterized by a model of high efficiency in natural resource use and reduced environmental degradation.

Goal 9: Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation

The production model adopted in PFALs represents an innovative and more sustainable way of food production. This is due to the ability to exert greater control over the production process, the applied use of the Internet of Things (IoT), comprehensive management of pollutant emissions, and minimization of natural resource loss, as highlighted by Kozai et al.[4]

Goal 11: Make cities and human settlements inclusive, safe, resilient, and sustainable

When considering the installation of PFALs near food distribution centers, we notice a reduction in traffic and transportation of food in urban centers. This implies a decrease in carbon dioxide emissions from vehicles. Consequently, by reducing heavy vehicle traffic, it is possible to contemplate an improvement in urban planning for the implementation of alternative transportation systems with lower pollutant emissions.[21]

Goal 12: Ensure sustainable production and consumption patterns

Agroecological and Long-Term Family Practices (PFALs) can be strategically deployed near points of sale or distribution centers to reduce the interval between harvest and delivery to the end consumer. This results in a decrease in storage and refrigerated transportation costs, as highlighted by Al-Kodmany in 2018.[21] The installation of PFALs in urban warehouses ensures deliveries in climate-controlled environments, resulting in a lower carbon footprint and more durable products for consumers, as emphasized by Ribeiro in 2019.[22] The generated products have an extended shelf life, thus reducing the incidence of disposal, as evidenced by Hayashi et al.[12,13]

Goal 13. Take urgent action to combat climate change and its impacts

In PFALs, the use of chemicals such as pesticides, chlorinated, or herbicides is prohibited. The implementation of rigorous biosafety procedures, made possible by controlled and climate-controlled conditions, eliminates pests, insects, and diseases, thus eliminating the need for fungicides and herbicides.[21–24] Furthermore, PFALs have the potential to significantly reduce carbon emissions by adopting renewable energy sources such as solar panels and wind energy, decreasing reliance on fossil fuel-powered equipment, as pointed out by Sarkar and Majumder in 2015.[23]

Results and discussion

After reviewing the literature, we were able to identify which characteristics of PFALs align most closely with the SDGs. To enhance understanding, we have developed the Table 1 below, highlighting the SDGs and the PFAL characteristics that correspond to each specific objective:

Table 1 Summary table of PFAL criteria related to the SDGs

SDGs (Sustainable Development Goals	PFAL performance
Goal 2. End hunger, achieve food security and improved nutrition, and promote sustainable agriculture.	Increased cultivated production capacity[8] Improved quality of cultivated product[9,10] Elimination of pesticide usage[11] Higher resource use efficiency[3] Reduced pollutant emissions.[3,21–24] Adaptation to climate change[7] Technology development[7] Investment extension[3] Enhanced agricultural infrastructure[21] Disruption to food supply system[21]
Goal 8. Promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all.	Technological modernization in a high value-added sector[4] Enhanced specialized workforce skills[4] High efficiency in resource use[3]
Goal 9. Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation.	Innovative and more sustainable food production method[4] Greater control over the production process[8]
Goal 11. Make cities and human settlements inclusive, safe, resilient, and sustainable.	Reduction in food traffic and transportation[21] Improved urban planning[21]
Goal 12. Ensure sustainable production and consumption patterns.	Waste reduction[21] Decreased storage costs[21] Reduction in disposal[21] Extended product shelf life[21]
Goal 13. Take urgent action to combat climate change and its impacts (*).	Lower CO^2 emissions Biosafety procedures[22] Elimination of the need for fungicides and herbicides[21–24]

Source: author

As mentioned previously, PFALs have an intrinsic and crucial role in achieving the SDGs, addressing issues such as food shortages, unfavorable socioeconomic conditions, environmental preservation and optimization of food production. However, it is essential to recognize that these efforts face specific challenges that require attention and strategic approaches if the SDGs are to be effectively achieved. Through literature analysis, the author identified the main challenges that PFALs must face to meet the SDGs (Tabe 2):

Table 2 Challenges of PFALs regarding the SDGs

Challenges	Impacts on the SDGs
High initial cost: The construction and implementation of PFALs may require a significant initial investment in technologies, infrastructure, and automation systems.	This may hinder access to these technologies for poorer communities, conflicting with SDG 1 (No Poverty).
Energy consumption: Lighting systems, temperature control, and other technologies in vertical farms can increase energy consumption.	High energy consumption can contribute to carbon emissions, negatively affecting SDG 13 (Climate Action).
Technological and innovation challenges: The technology used in PFALs is constantly evolving, and the lack of standards can make it challenging to adopt consistent innovations.	Lack of access to advanced technologies may hinder the achievement of goals related to sustainable production (SDG 12).
Consumer acceptance: Some people may be wary of food grown in controlled environments and question the quality or food safety. The high cost of the product does not cater to low-income individuals.	This may negatively influence the acceptance of sustainable agricultural practices, indirectly impacting SDG 2 (Zero Hunger and Sustainable Agriculture).
Regulatory challenges: The lack of specific regulation for PFALs can create legal uncertainties and challenges in complying with food safety standards.	Lack of regulation may hinder vertical farms' contribution to goals related to food security (SDG 2) and health (SDG 3).
Scalability and production efficiency: Ensuring economic viability and production efficiency on a large scale can be challenging.	The ability to expand production efficiently is crucial to meeting zero hunger (SDG 2) and sustainable production (SDG 12) goals.
Social and employment issues: Automation in PFALs may reduce the demand for labor, affecting jobs in the agricultural sector.	This may have implications for SDG 8 (Decent Work and Economic Growth) and require solutions for retraining and creating alternative jobs.

Source: author

The articles analyzed revealed a clear trend toward the development of innovative alternatives in cultivation methods, incorporating new concepts and methodologies that make use of technology, especially when adopting the Internet of Things (IoT) in the production control system. In addition, approaches such as the methodology for rational use of electrical energy, cultivation methods adapted to different types of vegetables and analysis of the light spectrum stood out. The underlying objective of these approaches is to improve production capacity, while seeking to reduce resource consumption.

It was clear that these innovations have the potential to positively impact the production of various crops. However, it is worth noting that the technical and economic optimization of these practices requires more careful attention. The consensus points to the urgent need for advances in technological development and production methods, which are fundamental for the consolidation of PFAL as a viable alternative for agricultural production in sustainable urban centers.

The next generation of PFAL, when implemented, is expected to integrate advanced technologies such as LEDs, robotic/automated units, and enhanced cultivation units with production management software. In addition, increased public acceptance is expected. These advancements have the potential to not only significantly improve productivity, but also address pressing economic, environmental, and social issues associated with agricultural production.

Conclusion

Plant Factories With Artificial Lighting (PFAL) represent a transformative opportunity for achieving the Sustainable Development Goals (SDGs), despite the inherent challenges associated with this emerging and often costly technology. These facilities have the potential to address critical issues such as food scarcity, socioeconomic disparities, and environmental sustainability, thereby redefining the future of food production. PFALs offer innovative solutions to food insecurity by enabling year-round cultivation in controlled environments, which can significantly increase yields and improve the availability of fresh produce. This is especially important in regions where traditional agriculture faces constraints such as limited arable land, adverse weather conditions, and resource scarcity. By enhancing food availability, PFALs can contribute to reducing hunger and improving nutritional outcomes for vulnerable populations. However, financial barriers remain a significant hurdle, particularly for lower-income communities where access to such technology is limited. As research and development in the field progress, there is a strong expectation that technological advancements will lead to reduced initial costs, making PFALs more accessible to a broader range of communities. This accessibility is crucial for amplifying the positive impact of PFALs, particularly in underserved areas. The vertical farming model exemplifies the potential for not only combating hunger but also promoting energy efficiency and reducing waste. By optimizing resource use, PFALs can contribute to more sustainable agricultural practices and foster responsible investment in food systems. Given the urgency of the global food crisis and environmental degradation, further research and investment in this area are essential.

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Conflicts of interest

The authors declare there are no conflicts of interest.

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