Plant factory technology lights up urban horticulture in the post-coronavirus world

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Dear Editor,

The pandemic of novel coronavirus disease 2019 (COVID-19) has highlighted the critical importance of ensuring a consistent supply of horticultural products (e.g., vegetables and fruits). Worldwide quarantine and social distancing led to transportation disruptions, labor shortages, and limited access to local markets, all of which had a significant impact on producing horticultural products, post-harvest processing, distribution, and consumption in urban areas. Moreover, the traditional agricultural approach is currently facing the unprecedented challenge of feeding an expanding population, as approximately 6.7 billion people are expected to live in urban areas by 2050. Rapid urbanization brings great challenges to horticultural production. For instance, arable land is gradually shrinking, agricultural practitioners are reducing, availability of irrigation water for farming is decreasing, the cost of food transportation is increasing, and the environmental deterioration is exacerbating. Thus, critical issues in urban supply of horticultural products are whether such farming systems can enable steady and effective production, a stable and balanced supply, a shortened distribution chain, and consistent availability and accessibility of products without compromising safety concerns. In this regard, plant factories with artificial light (PFALs) represent an innovative and promising production system that has been showing great potential for stable, effective production of horticultural products both during and after the COVID-19 crisis.

PFALs are multi-layer indoor farming systems that employ green and sustainable
crop cultivation techniques, including vertical cultivation, optimized lighting recipes, energy-conserving technology, and intelligent control systems to enable horticultural production regardless of the climatic and geographic conditions (Fig. 1a)\textsuperscript{2,3}. The global indoor farming market reached 32.3 billion USD by 2020, with over 500 PFALs being operated commercially in China, Japan, Singapore, the US, and the UK. Simultaneously, there has been intensive research on increasing the productivity and sustainability of PFALs and producing horticultural high-quality horticultural products in PFALs in recent years.

Vertical cultivation technology significantly increases the productivity of horticulture due to the development of new lightweight materials for structural bracing frames and high-rise modular assembly layers and application of operating technologies (e.g., operating machinery, auxiliary robots, and automation equipment)\textsuperscript{3}. Additionally, the enhanced light efficacy and optimization of coupled environmental factors significantly promote plant growth and photosynthesis in PFALs. Numerous investigations have focused on developing “lighting recipes” to optimize the lighting conditions (e.g., intensity, spectrum, photoperiod) for a variety of purposes, including high yield, quality, and energy efficiency—depending on the plant species and stage of growth and development. In addition, several studies aimed to apply advanced lighting systems to maximize plant light interception and provide uniform illumination across all leaf surfaces while simultaneously co-optimizing other environmental factors\textsuperscript{3-4}.

Improving energy use efficiency to realize lower production costs and maximize
economic benefits is crucial for environmentally-sustainable development of PFALs. For instance, establishing energetic fluxes and applying a flexible yield-energy model could help understand the energy balance and optimize the control strategy for weather conditions, in order to minimize energy consumption\textsuperscript{5}. Moreover, it is worthwhile reducing electricity consumption related to lighting and air conditioning through multi-factor refined management, generating electrical energy using clean energy sources (e.g., solar, wind, biomass, and geothermal energy), and storing excess electricity in stationary batteries for time-adjustable usage with higher efficiency.

Rapid development of Internet of Things (IoT) devices—including optical, mechanical, and electrochemical IoT sensors, communication technologies, methods for massive Internet connectivity, data storage, and processing units—has paved the way for IoT applications in PFALs. In addition, artificial intelligence-based data analytics is a powerful tool for automation and decision-making in agriculture, while IoT-enabled accessory machinery can help increase crop productivity and reduce human resource requirements\textsuperscript{6}. Future intelligent control systems for PFALs are expected to incorporate multiple platforms with functions such as order management, seed plot scheduling, production management, environmental control, energy consumption measurement, intelligent decision support system, and marketing forecasting, and thus enable complete control of unmanned PFALs to achieve cost-effectiveness, conserve resources and energy, and reduce the requirements for labor.

Pursuing nutritional and healthy horticultural products will be an important goal
for agricultural development in the future, especially in the post-coronavirus world. Breeding cultivars that are suited to the constraints imposed by PFALs could provide a breakthrough, with the goal of selecting cultivars that are fast-growing, high-edible fraction, high-yielding, high-quality, functional, tolerant of low-light, and have high light and nutrient use efficiency. For example, Kwon et al. (2020) bred a compact, early-flowering tomato variety suitable for urban agriculture by editing the tomato stem length regulator gene (SLER), condensed shoots, rapid flowering gene (SP5G), and precocious growth termination gene (SP).

PFALs serve a variety of functions in urban horticulture, including provisioning (e.g., horticultural produce and biopharmaceuticals supply), social activity (e.g., horticultural knowledge popularization), and cultural activity (e.g., recreation and amenity) (Fig. 1b). Horticultural plants cultivated in PFALs contribute to a plentiful ‘vegetable-basket’ and healthy diets for urban dwellers. As pre-harvest factors, such as lighting, temperature, humidity, CO₂, fertilizers, and fertigation conditions, can be precisely adjusted in PFALs, it is possible and feasible to produce horticultural products with multiple objectives, including high concentrations of specific phytochemicals and high-yield products. Vaccines have played a critical role in preventing disease during the COVID-19 pandemic. Nowadays, PFAL-based manufacturing systems have been recognized as a viable alternative source of biopharmaceutical materials and vaccine candidates, with PFALs being proposed for the automated and standardized production of a variety of biopharmaceuticals at high yield, including peptide antigens, recombinant vaccines, and virus-like particles. For

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example, virus-like particle vaccines containing functional hemagglutinin for pandemic influenza can be produced in plants within a month, whereas egg- and cell-based vaccines take 4-6 months to develop. Moreover, when combined with gene-editing technology, PFALs may enable the development of numerous novel, necessary vaccines. PFALs should also allow people to farm on and inside urban buildings, and support the recovery and productive transition of vacant office space. Moreover, this type of agricultural system is often associated with leisure and recreational functions. Alternatively, PFALs could also be established inside shopping buildings, be equipped with highly modern vertical cultivation technologies, and integrate production of quality horticultural food with services such as workshops, catering, and entertainment events.

In conclusion, PFALs represent rapidly developing and promising horticultural crop cultivation systems that can produce fresh crops in an environmentally-friendly manner. PFALs have been showing great potential to address the most challenging issues in agricultural science and extended fields, such as population growth, water scarcity, loss of arable land, food safety, and supply chain challenges, and thus will undoubtedly play an important role in the agricultural revolution, food security, carbon neutralization, and the future of humankind. In addition, PFALs employ several green and sustainable approaches, thus representing a shift away from horticultural practices based on human intuition and experience towards urban and modern horticulture based on precise data management. Moreover, innovation within PFALs will promote the future integration of the current agricultural field with other rapidly developing
techniques (e.g., artificial intelligence, advanced materials, synthetic biology) and help achieve the global objectives of sustainable agriculture. Thus, PFALs represent a critical solution for urban horticulture in the post-coronavirus world.

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Acknowledgments

This work was financially supported by the National Key Research and Development Program (No. 2020YFE0203600), Central Public-Interest Scientific Institution Basal Research Fund (No. Y2021XK04), and the Agricultural Science and Technology Innovation Program (ASTIP-CAAS, 34-IUA-01 and 34-IUA-03). The authors would like to thank the help of Hui Jiang for the visualization of the figures. We sincerely apologize to colleagues in this field whose work could not be discussed or cited due to space and reference limitations.

Author Contributions
L.Z and X.Y. visualization, writing—original draft. T.L., R. G., Z.W., J.P., J.H., J. G., Y. Z., Q. L., and Q.Y writing—review & editing. Q. L., and Q.Y supervision, funding acquisition. All authors approved the manuscript.

**Competing interests**

The authors declare no competing interests.
**Figure legend**

**Fig. 1. Characteristics and functions of PFALs. A,** A typical PFAL is composed of several systems, including an external building envelope, a cultivation system, an environmental control system (temperature, humidity, and CO₂), an air ventilation and purification system, artificial lighting, a fertigation system, an intelligent control system, and accessory machines. PFALs demonstrate the following advantages: i) vertical cultivation technology that increases the productivity of horticultural products, with an annual lettuce production per m² of 120 kg, more than 40 times that of the open field²; ii) high-yield and high-quality products that are free of contamination and contain high concentrations of phytochemicals; iii) closed cultivation systems that maximize the use of internal resources (e.g., water use efficiency > 96%, fertilizers use efficiency >80%); iv) high controllability of the microenvironment surrounding the crops, allowing easy monitoring of plant development; v) continuous production throughout the year; vi) no geographical restrictions, allowing for shorter transportation distances and a smaller carbon footprint during transportation; vii) higher levels of mechanization with reduced labor costs; and viii) stable food supply regardless of the climate and pandemics. **B, In the post-coronavirus era, PFALs will serve a variety of purposes in urban agriculture; PFALs have the potential to contribute significantly to the supply of urban horticultural products, the production of high-quality food, the alternative manufacturing of plant-based biopharmaceuticals, and could be associated with urban activities, such as enriching a plentiful ‘vegetable-basket’ and offering individuals a healthy diet.**
Fig. 1. Characteristics and functions of PFAL. A, A typical PFAL is composed of several systems, including an external building envelope, a cultivation system, environmental control (temperature, humidity, and CO2), an air ventilation and purification system, artificial lighting, a fertigation system, an intelligent control system, and accessory machines. PFALs demonstrate the following advantages: i) high yield and quality products that are free of contamination and contain a high concentration of phytochemicals; ii) closed cultivation systems that maximise the use of internal resources, such as water and fertilizers; iii) high controllability of the microenvironment surrounding the crops, allowing easy monitoring of plant development; iv) continuous production throughout the year; v) no geographical restrictions, allowing for shorter transportation distances and a smaller carbon footprint during transport; vi) higher levels of mechanisation with reduced labor costs; and vii) stable food supply regardless of weather and pandemics. B. In the peri-urban areas, PFALs will serve a variety of purposes in urban agriculture. PFALs have the potential to contribute significantly to the supply of urban bio-cultural products, the production of high-quality food, the alternative manufacturing of plant-based biopharmaceuticals, and could be associated with urban activities, such as enriching a plentiful ‘vegetable-basket’ and offering individuals a healthy diet.