› Plant factories in Japan – history, current status and perspectives towards a more sustainable society

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Plant factories – also known as plant factory with artificial lighting (PFAL) – enable the consistent and efficient year-round production of high-quality plants in any location. In this article, the concept and social significance, technical components and advantages, history, current status, and challenges associated with plant factories will be discussed. Future perspectives towards evolutionary, resource-autonomous and socially integrated plant factories will be introduced.

Concept and social significance

A plant factory is essentially a fully enclosed facility for plant cultivation with environmental control. Its high insulation and almost airtight structure, with environmental control, minimizes the effect of external environmental fluctuations allowing high-quality plants to be grown consistently and efficiently all year round, regardless of location, weather conditions, or season. Plant factories hold the potential to simultaneously address multiple global challenges in fields such as food safety and food security, the environment and ecosystems, energy and resource utilization, and human health and quality of life. In the face of worsening global and local issues, including climate change, the depletion of natural resources such as water, and the decline and aging of the agricultural workforce, plant factories have been gaining attention worldwide as a sustainable form of agriculture.

Key components of plant factories

Plant factories are designed to enable precise control of the cultivation environment, thereby supporting stable and efficient plant production. The core of such systems lies in highly insulated and almost airtight facilities, which minimize external environmental fluctuations and allow environmental parameters to be precisely managed according to specific cultivation objectives. Within these controlled environments, artificial lighting – where light-emitting diodes (LEDs) are the most widely used – replace natural sunlight, with spectral quality, photosynthetic photon flux density (PPFD), and photoperiod being adjustable to optimize photosynthesis, morphogenesis and the accumulation of functional metabolites (Figure 1).

In addition to lighting, plant factories integrate multiple environmental control systems, including air conditioning (temperature, relative humidity, airflow, CO_2) and hydroponic nutrient supply systems. Advanced environmental control technologies coordinate these components, ideally allowing dynamic adjustment of cultivation conditions in response to plant traits or phenotypes, plant developmental stages, or production goals. Such precise and integrated control not only ensures uniform and predictable yields, but also provides opportunities for enhancing plant quality, improving resource-use efficiency and supporting sustainable production. Minimum ventilation is necessary in the unlikely event that volatile organic compounds (VOC) accumulate in the cultivation room.

Advantages of plant factories

Despite the initial capital investment required for construction, plant factories offer several economic and agronomic advantages. A closed cultivation system with precise environmental control enables shortened cultivation cycles, year-round production and significantly higher productivity per unit area, particularly when multi-layer cultivation systems are employed. The productivity of plant factories can exceed that of conventional open-field farming by more than one hundred times (Kozai, 2013). Furthermore, plant factories provide opportunities for the production of plants with enhanced quality or functional components, achieved through controlling environmental factors such as light (e.g., PPFD, spectrum, etc.) and other elements of the aerial environment and nutrient solutions.

In addition to their agronomic and economic benefits, plant factories also exhibit important environmental and resource-use advantages (Kozai and Hayashi, 2023). The closed cultivation environment and recycling of drainage water from air-conditioning systems have been shown to reduce water consumption by more than 90%. Likewise, closed-loop management can substantially decrease fertilizer use, thereby reducing both input costs and potentially adverse environmental impacts as well. The exclusion of external pests in plant factories eliminates the need for pesticides, producing plants that are safe for consumption and can be eaten without washing due to cultivation in strictly controlled sanitary conditions. At the same time, plant factories can minimize postharvest losses, increasing the edible portion of biomass (percent marketable part of plants or merchantability ratio: the weight of marketable product divided by the weight of harvested plant, which is generally 80-90% in Japan) (Kozai et al., 2018; Kai and Okabe, 2023), and contribute to a reduction in transportation costs and environmental burdens through localized production in urban and peri-urban areas.

Integrating technology and research

Plant factories operate within highly insulated and almost airtight facilities, theoretically enabling precise control of environmental parameters. A distinguishing feature of these systems is their capacity for simple and accurate acquisition of time-series data, allowing real-time monitoring of plant growth, or visualizing and analyzing interactions between

Figure 1. Interior view of cultivation room of plant factory. Source: Japan Plant Factory Association.

plant phenotypes and the environment and cultivation management, thereby improving resource-use efficiency (Hayashi et al., 2022; Kozai and Hayashi, 2023). These data-driven capabilities facilitate predictive production planning, enable detailed analysis of productivity dynamics, and provide unique opportunities to conduct fundamental plant science research in parallel with commercial plant cultivation. Furthermore, its application in selection of seedlings for grading and breeding is also anticipated (Hayashi et al., 2022).

Collectively, these characteristics underscore the dual role of plant factories: they function not only as innovative agricultural production systems that enhance food security and sustainability, but also as experimental platforms for advancing knowledge in plant physiology, environmental control and systems science.

History and current status

Research on plant responses to environmental conditions in environmentally controlled facilities began in the 1950s and in Japan in the 1960s, utilizing environment-controlled chambers known as phytotrons (Mitchell, 2022). Since then, various research institutions, universities and private companies in Japan have continuously advanced plant factory research and development with commercial applications in mind (Hayashi, 2024).

In the 1980s, Japanese commercial plant factories primarily employed high-pressure sodium lamps with single layer cultivation systems, followed in the 1990s by fluorescent lighting with multi-layer cultivation systems. Since the 2010s, LEDs have become the standard for the cultivation of leafy greens in commercial plant factories in Japan. Broadband white LEDs, incorporating red, green and blue wavelengths, have become increasingly common since 2015, enhancing the flexibility and efficiency of plant growth management (Hayashi, 2024). Today, over 80% of the plant factories employing LED lighting for commercial production use white LEDs exclusively (JGHA, 2025).

Currently, there are approximately 200 commercial-scale plant factories of varying sizes operating in Japan. In commercial production, approximately 90% of factories cultivate lettuce varieties (JGHA, 2025). The other crops commercially cultivated on a large scale in Japanese plant factories include herbs like basil, and, in some cases, strawberries. Experimental cultivation of root vegetables, tubers, grains and wasabi is also underway, alongside ongoing research and limited commercialization of genetically modified plants for pharmaceutical applications (Goto, 2011; Hayashi, 2024).

In Japan, large-scale facilities producing up to 10 tonnes of lettuce per day have become quite common. Automation and mechanization are progressively being implemented with the expansion of these facilities. In highly automated plant factories producing lettuce, approximately 70% of the production processes have been automated, including the primary transplanting of seedlings (Figure 2). In Japanese plant factories engaged in the commercial production of lettuce, more than 50% of the total labor hours are devoted to harvesting and postharvest operations, including trimming and packaging (JGHA, 2025). Unlike baby leaf lettuce, which is relatively amenable to automation, each head of lettuce – typically weighing 100 to 250 g – requires postharvest adjustment and trimming after harvesting. At present, these operations are predominantly performed manually in Japanese commercial plant factories.

Hygiene management is also prioritized in the operational management of plant factories in Japan (Figure 3). Consequently, the demand for vegetables produced in plant factories – which require no washing – is expanding, especially in the food processing and food service industry for use in salads, sandwiches, rolls and in restaurants. Lettuce grown in plant factories and sold in supermarkets is typically packaged, and in some cases, it is explicitly stated that they do not require washing and are pesticide-free.

In the United States, plant factories, also known as indoor vertical farms, produce cherry tomatoes and Japanese strawberries using solar power on a large scale. Those products are available for purchase from mass retailers in multiple cities. Moreover, cultivation and research on cannabis (*Cannabis sativa* L.) for medical or regulated recreational use is expanding across North

Figure 2. Automation of transplanting in plant factory. Source: Shinnippou.

America, Europe and other regions in the world. In Japan, recent legal amendments now permit regulated cultivation of cannabis for research and approved purposes (Nakaoka and Hayashi, 2025).

Key challenges

Current plant factories still have substantial room for improvement. The productivity of plant factories can be characterized in terms of resource inputs, including materials, electric energy, labor hours and cultivation area, as well as financial viability. Table 1 presents the estimated productivity of major commercial plant factories operating in Japan (Kozai et al., 2022). These estimates represent the volume of marketable products (lettuce), as most large-scale commercial plant factories in Japan produce and package whole heads of leafy lettuce rather than precut products. Further improvements in resource productivity and financial viability are required.

In large-scale commercial production, achieving uniform plant growth is critical, maintaining desirable plant morphology and preventing physiological disorders such as tip burn, while ensuring consistent quality by cultivating plants that meet customers' requirements under hygienic conditions.

Although plant factories – with thermal insulation and almost high airtightness – offer advantages such as reproducibility, predictability, observability, traceability and controllability, a major challenge remains in that these benefits have not yet been fully realized for research and commercial production (Kozai and Hayashi, 2023). In addition, issues related to system scalability persist, particularly from the perspective of the social implementation of research outcomes.

A critical area for future research is the elucidation of interactions between plant phenotypes and the cultivation environment, including the microenvironment, and cultivation management (Hayashi et al., 2022; Kozai and Hayashi, 2023). Beyond the construction of scalable cultivation systems, there is a need for more precise environmental measurements, considering two- or three-dimensional variations, and standardization of measurement methodologies, as well as the development of non-destructive, non-invasive time-series phenotyping techniques that can be applied under plant factory cultivation conditions (Kozai and Hayashi, 2023).

Figure 3. Hygienically managed cultivation room of plant factory. Source: Shinnippou.

Future perspectives

It is expected that plant factories will make optimal use of artificial intelligence (AI) technologies to enable non-destructive, non-invasive and continuous phenotyping throughout plant growth processes for environmental control (Hayashi, 2024). This will facilitate the elucidation of complex interactions among plant phenotypes, microenvironments – including the surrounding condition of individual plants – and cultivation management practices. Such knowledge will, in turn, contribute to environmental control systems that incorporate business factors and ultimately enable precise phenotype control.

As illustrated in Figure 4, the utilization of digital-twin-based simulators within cyber-physical systems (CPS) can accelerate the research and development of cultivation environment simulations, automated systems and robotics. These approaches also hold promise for enhanced training and education, mental health and even for fostering plant-based entertainment, such as digital games and other media connected with the physical cultivation system. The implementation of decentralized, resource-autonomous and evolutionary plant factory systems interconnected through the internet would enable simultaneous, high-speed, and reproducible plant production and research, while promoting data sharing across facilities. Furthermore, such systems could facilitate on-site selection and breeding during production. In 2012, a trial project using a well-designed small plant factory system was launched in the Kashiwa-no-ha residential district of Kashiwa city, Chiba prefecture, Japan. Vegetables grown in household spaces are connected through a network linking people's homes, sharing information and communicating, receiving advice, and developing the community (Kozai, 2013). This can be extended to networks that link schools, local communities, hobby growers' groups,

Table 1. Estimated resource productivity of commercial plant factories in Japan (Kozai et al., 2022).

Resources applied	Range of resource productivity	Range of monetary productivity (kg USD^{-1})	Range of production cost (USD kg^{-1})
Electric energy	0.11-0.14 kg kWh^{-1}	0.645-0.755	1.09-1.28
Labor hours	7.7-10.0 kg h^{-1}	0.591-0.770	1.18-1.63
Cultivation area (per day)	0.25-0.33 kg m^{-2} d^{-1}	0.482-0.645	1.28-1.72
Other resources	-	0.609-0.827	1.00-1.36
Total	-	**0.166-0.219**	**4.55-5.99**

In 2019, 1 USD and 1 Euro were 110 and 130 JPY, respectively. Note that wages ($ h^{-1}) are around two times higher in the USA and some European countries than in Japan as of 2021.

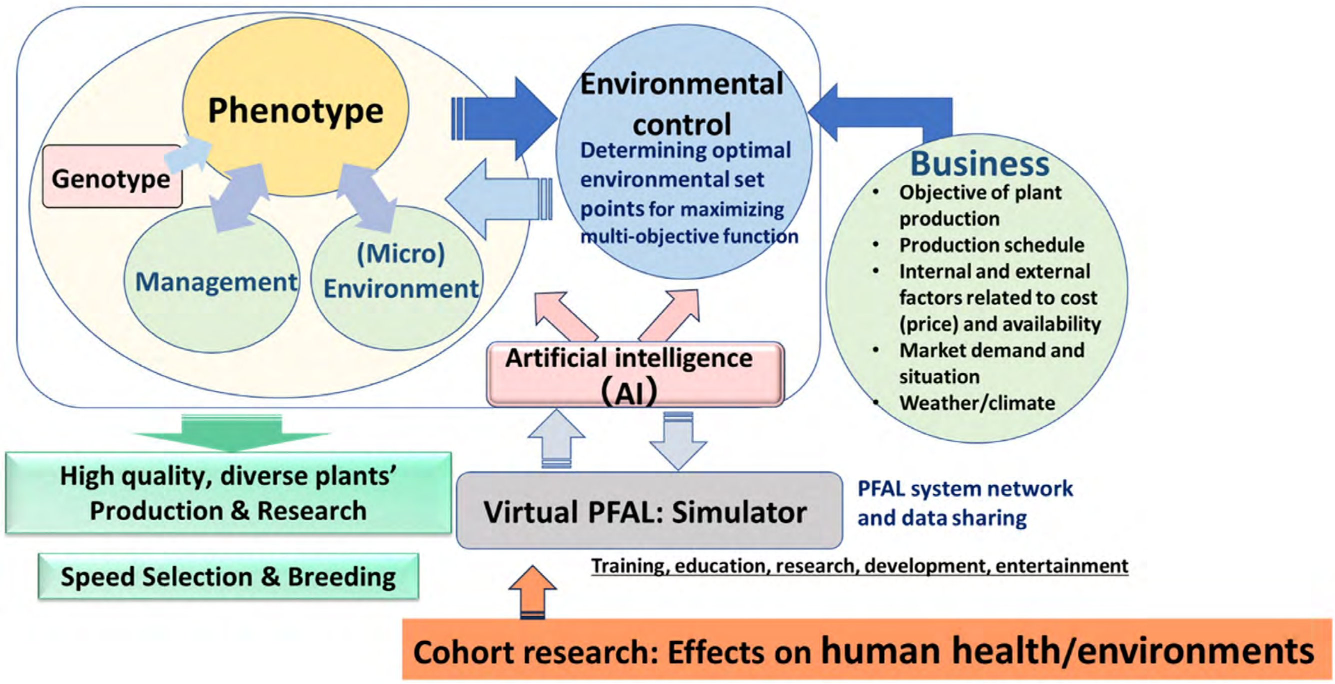

Figure 4. Integrated framework for environmental control based on plant phenotyping, incorporating business factors, phenotype control, and cohort studies on human health and environmental impact. Source: Revised from Hayashi (2024).

restaurants, hotels and hospitals, accumulating and utilizing data.

Plant factories can also serve as comprehensive educational tools that integrate biological, chemical, physical and engineering perspectives, while encompassing energy, environmental and resource considerations. As part of plant cohort research, studies and analyses examining the impacts of both plant factories and factory-grown plants on human physical and mental health, as well as on the environment, are becoming increasingly important. The traceability inherent in environmentally controlled plant production offers opportunities for integration with medical, life sciences and agricultural research, as plant production processes including time-series phenotypes, environment and management, along with genotypes, can be visualized and shared to subsequently assess plants' medical impact on humans.

In the coming years, the realization of resource-autonomous, circular and evolutionary plant factories is anticipated to promote diversification in both the application of factory-grown plants and the use of plant factory technologies. Consequently, plant factories are expected to play a key role as part of the social infrastructure in sustainable and smart societies. The use of such technologies will extend beyond commercial producers and researchers to include citizens, who may engage in plant factories as part of citizen science, thereby fostering community development across cyber and physical spaces – from local to global scales – and eventually space farming as well (Kozai et al., 2025).

With the multidimensional expansion of AI-driven plant factories, the focus will shift from simply "how to cultivate plants" towards "how to design plants." Given their multidisciplinary nature, plant factories not only function as comprehensive learning tools, but also exhibit strong affinities with fields such as sports, design and arts. For plant factories to become more deeply embedded in society, it will be essential to adopt an artistic or rather, aesthetic and creative approach in order to create beautiful plant factories that inspire hope in people.

In the future, plant factories may serve as essential instruments for integrating academic, industrial and civic activities, giving rise to new business models such as social enterprises capable of addressing multiple social challenges simultaneously. Ultimately, integration with human cyber-physical systems is envisioned, considering the development and dissemination of humanoids or digital humans, as well as the advancement of the digital society. Beyond solving global issues such as poverty, food insecurity and health disparities, resource-autonomous and aesthetically designed plant factories are expected to contribute meaningfully to human well-being, community development and sustainable regional planning.

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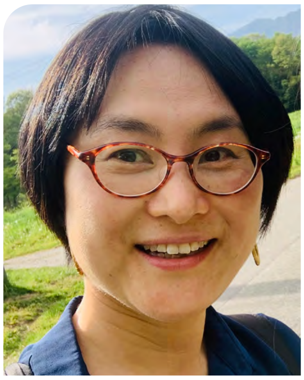

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