Chapter 2
Plant Factories with Artificial Lighting (PFALs): Benefits, Problems, and Challenges

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Abstract The benefits, unsolved problems, and challenges for plant factories with artificial lighting (PFALs) are discussed. The remarkable benefits are high resource use efficiency, high annual productivity per unit land area, and production of high-quality plants without using pesticides. Major unsolved problems are high initial investment, electricity cost, and labor cost. A major challenge for the next-generation smart PFAL is the introduction of advanced technologies such as artificial intelligence with the use of big data, genomics, and phenomics (or methodologies and protocols for noninvasive measurement of plant-specific traits related to plant structure and function).

Keywords Artificial intelligence · Annual productivity · Cultivation system module (CSM) · Phenotyping · Resource use efficiency (RUE) · Smart LED lighting system · Standardization

2.1 Introduction

The Dutch glass greenhouse technology is currently the most advanced in the world. The average yield of greenhouse tomatoes in the Netherlands was 60 kg m^{-2} in 2008, is estimated at around 70 kg m^{-2} for 2017, and will approach 100 kg m^{-2} in the near future by making full use of advanced technologies such as light-emitting diodes (LEDs) for supplemental lighting. Looking back on the past, the greenhouse tomato yield in the Netherlands was 9.5 kg m^{-2} in 1960, 20 kg m^{-2} in 1970, 29 kg m^{-2} in 1980, 44 kg m^{-2} in 1990, and 55 kg m^{-2} in 2000 (Heuvelink 2006). The yield in 2017 is about sevenfold than in 1960. The development of the Dutch greenhouse technology has progressed over the past 50 years through the active collaboration of Dutch industries, public institutions and governments, and a very limited number of

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private companies in neighboring countries such as Denmark, Sweden, Belgium, and Germany.

The current technology for plant factories with artificial lighting (PFALs) can be compared to the Dutch glass greenhouse technology of around 1980. Thus, the yield of the PFAL can probably be doubled, tripled, or even more by actualizing the potential benefits, solving the current problems, and taking on the challenges of the next-generation smart PFALs.

The PFAL technology with the use of LEDs has been extensively developed since around 2010 mainly in Southeast Asian regions (Japan, Taiwan, China, and Korea), the USA, and the Netherlands. It is also noted that many private companies in the fields of information technology (IT), electronics, mechatronics, housing, food, environmental control engineering, chemical engineering, and venture capital have recently become involved in PFAL research and development (R&D) and the PFAL business. Thus, the progression of PFAL technology in the next 10 years or so may be as fast as that of the Dutch greenhouse technology in the past 40 or 50 years, if the major technologies are well documented, standardized, and opened and shared with many people.

2.2 Potential and Actualized Benefits of the PFAL

The PFALs that have actualized most of the potential benefits described in this section are making a profit and expanding their production capacity; however, the number of such profitable PFALs is currently limited. To actualize the potential benefits of the PFAL, the concepts behind the benefits and the methodology for their actualization must be thoroughly understood before designing and operating the PFAL. At the same time, the vision, mission, and goals of the PFAL design, operation, and business model must be clearly established and shared with the team members.

(1) *High resource use efficiency (RUE)*, which reduces resource consumption and waste and thus lowers production costs. RUE is defined as the amount of resource fixed or utilized in the plants (F) divided by the amount of resource supplied to the PFAL (S). Namely, RUE = F/S or (S − R)/S where R is the amount of resource that is released and wasted by escaping outside the PFAL (Kozai et al. 2015). Essential resources to be supplied regularly to grow plants in the PFAL are light energy, CO_2, water, fertilizer (nutrients), seeds/transplants, and labor only. The light energy, CO_2, water, and fertilizer (nutrients) are essential resources for seeds/transplants to grow by photosynthesis.

Water use efficiency (WUE) is the amount of water fixed or held in the plants divided by the net amount of water supplied to the culture beds and absorbed by the plant roots. Since about 5% of the water absorbed by plants is fixed in the plants and the remaining about 95% is either transpired from the leaves or drained somewhere without being absorbed by the roots, the WUE for irrigation to the greenhouse is 0.05 or lower.

On the other hand, in the airtight PFAL, almost all the transpired water is condensed and collected at the cooling panels of the air conditioners and returned to the nutrient solution tank. Then, the net consumption of water is the difference in amount between the irrigated water and the water returned to the nutrient solution tank. WUE for the PFAL is around 0.95 (= the fresh weight of plants divided by the difference in weight between the irrigated water and the water returned to the nutrient solution tank) provided that there is no leakage of water from the cultivation beds or nutrient solution tank (Kozai et al. 2015). This high WUE (95% water saving) of the PFAL is a big advantage in arid regions and other water-scarce areas.

CO_2 and fertilizer efficiencies of the PFAL are also relatively high (0.80–0.90) compared with those of CO_2-enriched and soil cultivation greenhouses with ventilators closed (0.5–0.6 for both) (Kozai et al. 2015). The CO_2 emitted by plant respiration during the dark period accumulates in the air of the cultivation room and is absorbed by plants during the photoperiod. The nutrient solution is not discharged to the drain, except in emergency cases such as the accumulation of ions (Cl^-, Na^+, etc.), which are not well absorbed by the plants.

Light energy use efficiency of the PFAL, however, is still very low (0.032–0.043), although it is higher than that of the greenhouse (0.017) (Kozai et al. 2015). The use efficiencies of electric energy, light energy, space, and labor in the current PFALs need to be considerably improved in the next-generation PFALs through the application of LEDs, intelligent lighting systems, better environmental control, and the introduction of new cultivars that grow well under low photosynthetic photon flux densities (PPFD).

A recent simulation of the RUEs for lettuce production in a PFAL and a greenhouse in the Netherlands and two other climate regions provided very useful academic and practical results (Graamans et al. 2018). This type of work will become increasingly important for efficient use of resources for plant production and for a better choice from various types of plant factories and greenhouses in a given locality.

(2) *High annual productivity* per unit land area. Over 100-fold annual productivity per unit land area can be achieved without the use of pesticides, compared with the annual productivity per unit land area in open fields, mainly due to the use of multilayers (ten tiers on average), shortened cultivation period (often by half) by optimal environmental control, high land area use efficiency (no vacant cultivation space throughout the year), high planting density, and virtually no damage by weather and pest insects. The annual productivity of the PFAL with 15 tiers is roughly estimated to be 200 kg m^{-2} (fresh weight of marketable produce). It would be interesting to estimate the maximum annual productivity of the PFAL under the optimal environment using a simulation model.

Land area use efficiency is defined as ($A_u \times n \times N$) divided by ($365 \times A_t$) where A_u is the area of a unit cultivation space, n is the number of units of cultivation space in the PFAL, N is the average number of days per year during which the unit cultivation space is occupied by plants under cultivation, and A_t is the land area occupied by the floor of the PFAL. The unit cultivation space can be a cultivation panel, a tier, or a rack consisting of more than one tier. The unit of "space" is m^2 in the case of horizontally placed cultivation panels but can be m^3 in the case of vertically placed cultivation panels/tubes.

Major components of the production cost in the PFAL are electricity, labor, and depreciation of initial investment (the sum of these three cost components account for 75–80% of the total production cost). Thus, electric energy productivity (kg of produce per kWh of electricity consumption), labor productivity (kg of produce per labor hour), and space productivity (kg of produce per floor area or cultivation area) are important indices for analyzing and improving the productivity of the PFAL.

(3) *High weight percentage of marketable parts* over the whole-plant biomass. In other words, a low percentage of trimmed/damaged plant parts as waste over the whole-plant biomass. The percentage of marketable part can be increased by the proper environmental control method, cultivation system, and cultivar selection. Currently, the fresh weight percentages of marketable leafy parts and trimmed leafy or root parts of leaf lettuce plants are, respectively, estimated to be 77–80% and 20–23% in most PFALs in Japan.

Leafy parts of root crops such as carrot, turnip, and radish need to be edible, tasty, nutritious, and presentable to improve the weight percentage of the marketable parts of root crops. For example, the leafy parts and the root parts of such crops are often tasty and nutritious when harvested 15–20 days earlier than the conventional harvesting date.

(4) *High-quality plants* can be produced as scheduled by proper environmental control, cultivar selection, and cultivation system (Kozai et al. 2016). Shape/appearance, taste, and mouth sensation, as well as composition/contents of functional components such as vitamins, polyphenols, and minerals, can be controlled. However, most of such factors are still controlled by trial-and-error based on past experiences. On the other hand, researchers are systematically conducting a series of experiments to produce consistent functional components.

(5) *High controllability of plant environment*. Controlled aerial environmental factors include PPFD, VPD (water vapor pressure deficit), air temperature, CO_2 concentration, light quality (spectral distribution), lighting cycle (photoperiod/dark period), and air current speed. Controlled hydroponic culture factors include strength, composition, temperature, pH (potential of hydrogen), and dissolved O_2 concentration and flow rate of the nutrient solution.

(6) *High reproducibility and predictability* of yield and quality. Because of the high controllability of the environment all year round, scheduled and/or on-demand plant production is possible regardless of the weather. The quality of produce and the yield can be controlled by controlling the environment. For example, mouth sensation, taste, color, and flavor of lettuce can be finely

controlled to suit its use in salads, sandwiches, or hamburgers by environmental control.

(7) *High traceability* throughout the supply chain of PFAL industry, which enables a high level of risk management.

(8) *High adaptability for the location* (near or in food/meal delivery shops, etc.). The PFAL can be built without any problems in shaded areas, on contaminated or infertile soil, and in vacant rooms/buildings/land in urban areas. The PFAL can also be built in very cold, arid, or hot areas. For example, there are no heating costs for the PFAL even when the outside air temperature is below −40 °C because the walls and floor are thermally well insulated and heat is generated by the lamps in the culture room.

The PFAL is most suited to urban areas where the production site is close to the consumption site (local production for local consumption). This saves fuel, time, and labor for transportation of fresh produce and creates job opportunities for handicapped, elderly, and young people in or near their residential area.

(9) *High controllability of sanitary conditions*. Because of this high controllability, pesticide-free and other contaminant-free plants are produced. Global GAP (Good Agricultural Practice) and/or HACCP (Hazard Analysis and Critical Control Point) can be introduced relatively easily, and so a high level of risk management can be achieved.

(10) *Long shelf life* due to low CFU (colony-forming units of microorganisms) per gram, which decreases the amount of vegetable garbage or loss at home and in shops. The shelf life is estimated to be around two times longer for lettuce plants grown in the PFAL than for those grown in the field. Due to this advantage, the market price of PFAL-grown vegetables is often 20–30% higher than that of field-grown and greenhouse-grown vegetables.

(11) *No need to wash* or cook before serving, if packed in a sealed package after harvest in the culture room. This reduces the consumption of water for washing, electricity/city gas/fuel for boiling and stir-frying, and labor for washing and cooking. On the other hand, when eating fresh vegetables, the CFU per gram of vegetable needs to be lower than around 300.

(12) *Easy measurement* of hourly and/or daily rates of resource supply, production, and waste. The RUEs can be estimated online. Based on the estimation, the production costs can be predicted and subsequently reduced using the data on RUEs.

(13) *Stepwise improvement* of the RUEs, productivity and economic value of the plants is possible by visualizing the flow of energy, substances and workers in the production process and related costs/sales. To do so, models of plant growth, energy/substance balance, and production process scheduling are necessary.

(14) *Light and safe work* under comfortable air temperature and moderate air movement. There are still some problems to be solved to further improve the working environment both for large-scale PFALs with automation and small-scale PFALs in order to increase job opportunities.

(15) *Design and environment control are simpler in the PFAL than in the greenhouse* due to its airtightness, high thermal insulation of walls and floor and no solar light transmission to the cultivation space. Global standardization of the PFAL design (except for building design) is easier than that of the greenhouse design. To use solar light, which is free of charge, the greenhouse needs heating, shading and venting/cooling systems, insect screens, thermal screens for saving on heating costs, and transparent covering materials such as glass and plastic film. Those systems are not required in the PFAL. The environment in the PFAL is not influenced by the weather.

(16) *A small PFAL* with a floor area of 0.1–10 m^2 is a wonderful way to learn the principles of life science, engineering, and technology at home, school, or community center, especially when the PFAL is connected via the Internet to other small PFALs and a PFAL database for the exchange of information and opinions (Harper and Siller 2015). Through an interdisciplinary approach via hands-on experience, users acquire an understanding of the functions and mechanisms of the ecosystem, energy, and material conversion and circulation and learn the basic skills of growing plants and using advanced technologies.

2.3 Current Unsolved Problems of PFALs

2.3.1 Actions Required for Solving the Problems

(1) *Drastic reduction in initial investment and operation costs*. The operation cost per kg of fresh produce needs to be reduced by 30–50%, and the current initial cost per annual production capacity needs to be reduced by about 30% by the year 2020–2022, compared with the costs in 2017.

(2) *Sustainable production*. Improvement of the cultivation system and its operation to reduce, recycle and reuse resources, and use natural energy is essential. Energy-autonomous PFALs need to be designed, operated, and commercialized. The area of solar panels necessary for supplying all the electricity to the PFAL is currently estimated in Japan to be about eightfold that of the flat roof area of a PFAL with ten tiers, when a battery is installed at the PFAL. The necessary area of solar panels would be significantly lower in arid regions than in Japan. In addition, the solar panel area will decrease steadily year by year due to the technological advancements of solar panels and LEDs.

(3) *Advanced technologies* including artificial intelligence (AI), big data, the Internet of Things (IoT), bioinformatics, genomics, and phenomics need to be introduced to improve the resource use efficiency and cost performance of the PFAL (Fig. 2.1). Phenomics is an emerging research field along with the methodologies and protocols for the noninvasive measurement of cellular- to canopy-level plant-specific traits related to plant structure and function.

(4) *Robotics and flexible automation* need to be introduced to reduce the amount of heavy, dangerous, simple, and/or troublesome manual work.

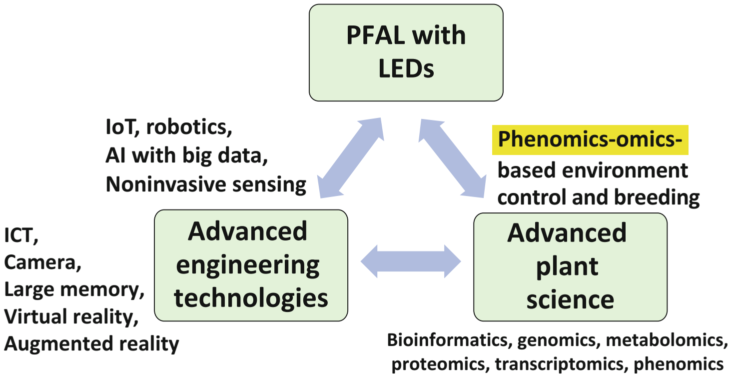

Fig. 2.1 Recent advanced technologies to be introduced in the next-generation smart PFAL. *AI* artificial intelligence, *ICT* information and communication technology, and *IoT* Internet of Things

(5) *Medicinal plants* for high-quality health care and cosmetics products need to be produced at low cost. Genetically engineered plants for production of *pharmaceuticals* such as vaccines for influenza and other viruses need to be produced in a specially designed PFAL.
(6) *Worldwide active organizations* of plant factory industries and academics need to be established for better global communication and information sharing.
(7) *Organic hydroponic systems* for PFALs that are easy to handle and economically viable need to be developed. Symbiosis of plants with microorganisms will benefit plant growth in the PFAL. Organic fertilizer can be produced from fish waste, vegetable garbage, mushroom waste, and other types of biomass.

2.3.2 Some Specific Technical Problems

(1) *Efficient use of white LEDs*, which emit a significant amount of *green light* (20–40% of total light energy). The optimal spectral distribution of white LEDs to meet a specific requirement is still unknown.
(2) *Green light effect* on photosynthesis, growth, development, secondary metabolite production, disease resistance, and human health in the PFAL has become an emerging research topic in relation to white LEDs.
(3) *Net photosynthesis, transpiration, and dark respiration* of plants in the PFAL can be continuously measured. Efficient methods for utilizing this data need to be developed.
(4) *Energy and mass (substance) balance* in the PFAL can be continuously measured. Efficient methods for utilizing this data need to be developed.
(5) *Resource use efficiency (RUE) and cost performance* of the PFAL can be measured, visualized, and controlled (Fig. 2.2). Efficient methods for utilizing this data need to be developed.

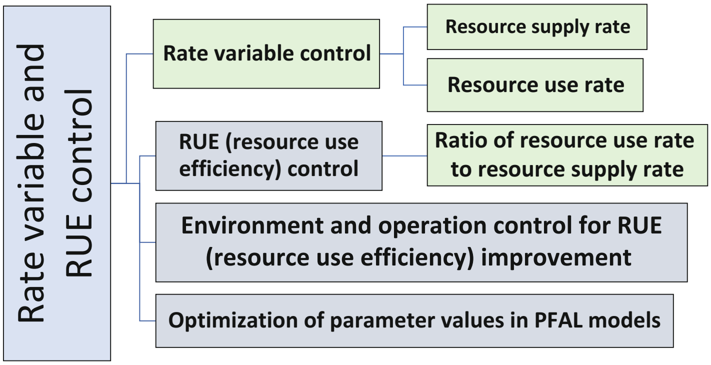

Fig. 2.2 Online measurement and control of rate variables and resource use efficiencies (RUEs)

(6) *Algae growth inhibition* in hydroponics. Also, the occurrence of *intumescence* (or edema) and *tip burn* symptoms on the leaves of leafy vegetables needs to be inhibited by proper environmental control and cultivar selection.
(7) *Microbiological ecosystems* in the culture beds are currently unknown and uncontrolled. Organic acids produced by plant roots, dead roots, dead and living algae, and many kinds of microorganisms including pathogens should be present in the culture beds. Beneficial and stable microbiological ecosystems need to be established.

2.4 Actions Required for Enhancing PFAL R&D and Business

(1) *Rational, powerful, and clear messages on the vision, mission, and goals of the PFAL.* People are increasingly interested in the potential benefits of the PFAL and are expecting further progress in R&D on smart PFALs.
(2) *Open database and open-source business planning and management system.*
(3) *Human resource development for PFAL managers and workers.* Human resource development programs for capacity building of PFAL managers are crucially needed. Well-edited books, manuals, and guidelines need to be published. Software/hardware systems for managing the complicated cause-and-effect relationships in the PFAL need to be developed.
(4) *Tools, facilities, and guidelines* for worker safety, labor saving, and quality operations. Compact and safe systems for efficient seeding, transplanting, harvesting, transporting, and packaging.
(5) *Software with database for minimizing the electricity costs* for lighting and air conditioning under a given lighting schedule.
(6) *Software with database for "smart" environmental control* for production of targeted functional components of a plant species under economic, botanical,

and engineering constraints. A computer-assisted support system for sensing, data analysis, control, visualization, and decision-making needs to be developed.

(7) *Well-designed floor plan and equipment layout* to maximize labor and space productivity.

(8) *Marketing* for creating new markets for health care. New products that do not compete with currently used products are necessary.

(9) *Understanding and anticipation* by local residents regarding the potential of the PFAL. Actual working/virtual models showing people the future are necessary.

(10) *Breeding the plant cultivars for the PFAL.* The characteristics of plants suited to cultivation in the PFAL are (1) fast growth under relatively low PPFD, high CO_2 concentration, and high planting density; (2) fast growth under low stresses of water, temperature, and pest insects/pathogens; (3) fast growth without physiological disorders; (4) secondary metabolite production sensitive to environmental conditions or stresses; (5) dwarf fruit venetagles and medicinal plants, and (6) high economic value per kg of produce due to qualitative plant traits. Molecular breeding can be a powerful tool.

At present, the plant cultivars grown in the PFAL are bred to suit open-field and greenhouse conditions where the environment varies greatly with time. Basically, the genetic characteristics of these cultivars are not suited to the environment in the PFAL. New cultivars bred for the PFAL environment are expected to significantly change the cost performance of the PFAL business.

(11) *Guidelines and manuals* for sanitary control, food and worker safety, and LED lighting.

(12) *Standardization of terminology and units* for the basic properties of light, lamps, and nutrient solution.

(13) *Standardization of PFAL components.* The design and method of operation of current PFALs are diverse, and the specifications of each component are not standardized. This diversity is a result of the creative and tireless efforts by many researchers and developers in the past several decades. The diversity of hardware and software, on the other hand, may delay domestic/international standardization of safety, salinity, and hardware and software parts. The diversity may also delay collaborative research and development with public institutions. It is also causing the high cost of each component, lack of a standard cultivation system, and lack of information and opinion exchange in the industry. On the other hand, the standardization should not restrict creative challenges.

2.5 Challenges for the Smart PFAL

Challenges for developing the software/hardware units or systems to be implemented in the smart PFAL as the next-generation PFAL include:

(1) The PFAL as *an essential unit to be integrated with other biological systems to improve the sustainability* of a building or a city.
(2) The PFAL for *large-scale production and breeding* of high-wire tomatoes and other fruit vegetables and berries such as strawberry and blueberry.
(3) *Cultivation system module* (or unit) as a minimum component of the plant cultivation space in the PFAL, which is easily connected to other basic module units to make a larger PFAL.
(4) *Hydroponic system without the use of substrate (supports) and a nutrient solution circulation unit without the drainage of nutrient solution* from the culture beds. Then, the total volume of nutrient solution in the culture beds, piping, and nutrient solution unit is greatly reduced. Also, the structure of the hydroponic system is simplified, and the physical weight of the system containing the nutrient solution is reduced. However, such a hydroponic system for widespread commercial use in the PFAL does not exist.
(5) *Phenotyping unit* for continuous and nondestructive (or noninvasive) measurement of plant traits such as fresh weight, leaf area, number of leaves, leaf angle, three-dimensional plant community architecture, leaf surface temperature, optical properties and chemical components of the plants, and physiological disorders such as tip burn and intumescence (or edema) of the leaves. The measured data on plant traits is used as input data for the phenome-genome-environment model to determine the set points of environmental factors and/or the selection of elite plants for breeding (Fig. 2.3). A small and inexpensive

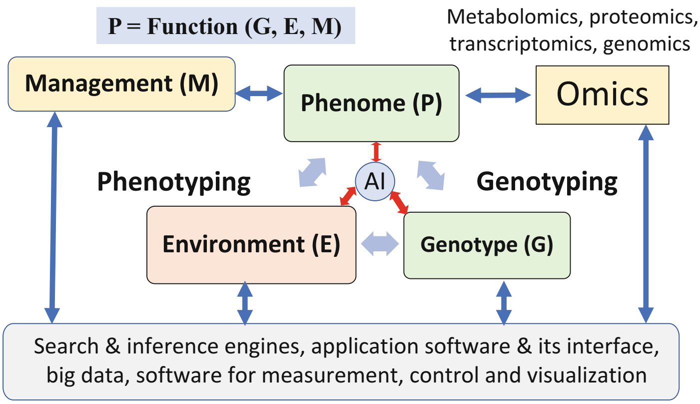

Fig. 2.3 Scheme showing phenotyping- and AI (artificial intelligence)-based environmental control and breeding for PFALs

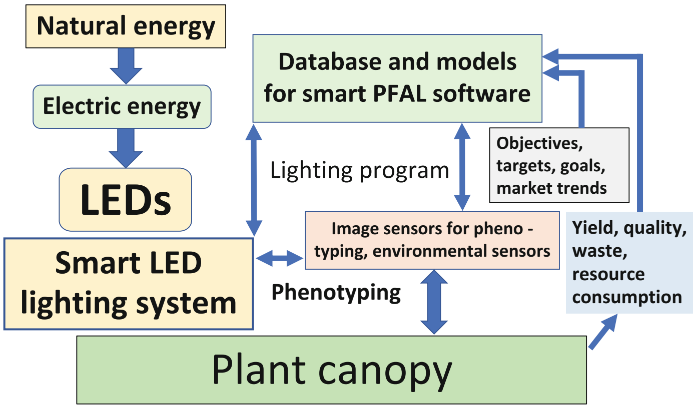

Fig. 2.4 Scheme showing smart LED lighting system and its peripherals

phenotyping unit that can be placed adjacent (1–50 cm) to the plants is preferable.

(6) *Periodic movement of plants* due to circadian rhythms (biological clock), water stress, air current patterns, etc. and their effects on hormonal balance, photosynthesis, transpiration, and growth of plants.

(7) *Smart LED lighting unit* for maximizing the cost performance (product of the unit economic value and the yield of produce divided by the operating cost) by time-dependent control of light environment factors such as light quality, photosynthetic photon flux density (PPFD), lighting cycle (photo-/dark period), and lighting direction (Fig. 2.4).

(8) *Ion concentration control unit* for the hydroponic system. The concentration of each major ion type (NO_3^-, K^+, Mg^{2+}, Ca^{2+}, Na^+, NH_4^+, Mg^{2+}, Cl^-, PO_4^{3-}, and SO_4^{2-}) in the nutrient solution is separately measured or estimated and controlled.

(9) Software unit for *discriminating the effects of spatial variations of the environment* on the spatial variations of individual plant growth from the effects of genetic variations among the plants on the spatial variations of individual plant growth. The spatial variation of plant growth is obtained from the data measured by the phenotyping unit.

(10) *Hardware/software unit for minimizing the spatial variations* of the air temperature, vapor pressure deficit (VPD), and air current speed by controlling the spatial distributions of PPFD and air current speed under the given LED lighting system and three-dimensional plant canopy architecture. The spatial variations of the environment are obtained from the distributed environmental sensors.

(11) *Software unit for automatically determining the set points of environmental factors* to meet the objectives of PFAL operation under the given constraints, using the phenome data and other data.

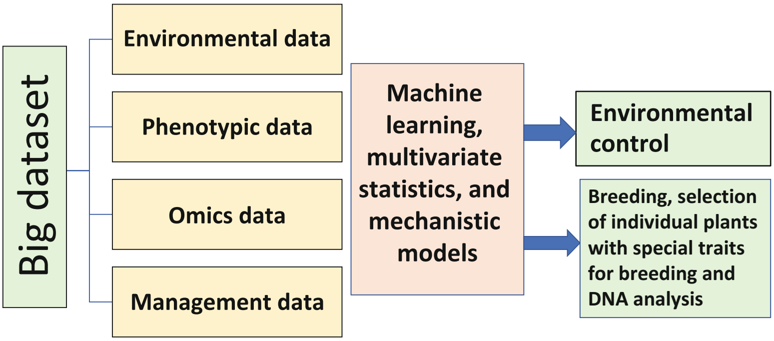

Fig. 2.5 Big dataset with low noise obtained in the PFAL is useful for machine learning, multivariate statistics and mechanistic models

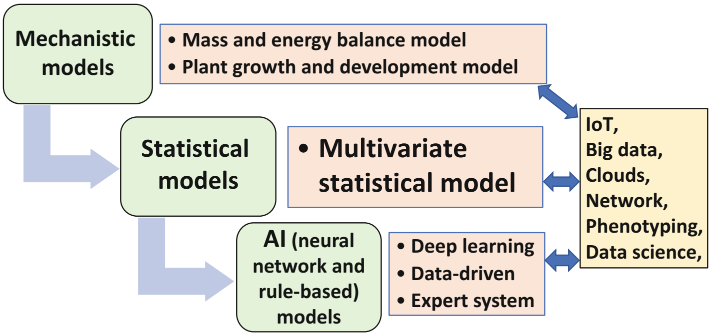

Fig. 2.6 Three types of models for PFAL environment control

(12) *Deep learning unit for searching for a function (G, E, M)* or relationship among the phenome, genome, and environment datasets. P = function (G, E, M) where P is phenome data, G is genome data, E is environment data, and M is management data. Using the big datasets of P, G, E, and M, the function (G, E, M) is found by deep learning. In the PFAL with a controlled environment, the datasets of P, E, and M can be collected relatively accurately and easily. Thus, the genome dataset is known, and the function (G, E, M) can be found relatively easily by deep learning. Figure 2.5 is a scheme showing the phenotyping-, AI-, and big dataset-based environmental control and breeding.

(13) Software/hardware unit for searching for *DNA expressions/markers* driven by environmental changes, using the genome, phenome, and environment datasets, and for determining the set points of environmental factors using the above dataset. Deep learning unit using the phenome, genome, and environment datasets would become a powerful breeding tool.

(14) *Integration of the deep learning model with mechanistic, multivariate statistical, and behavior (or surrogate) models*. Figure 2.6 is a scheme showing three types of models to be used for the PFAL environment control. Figure 2.7 is the

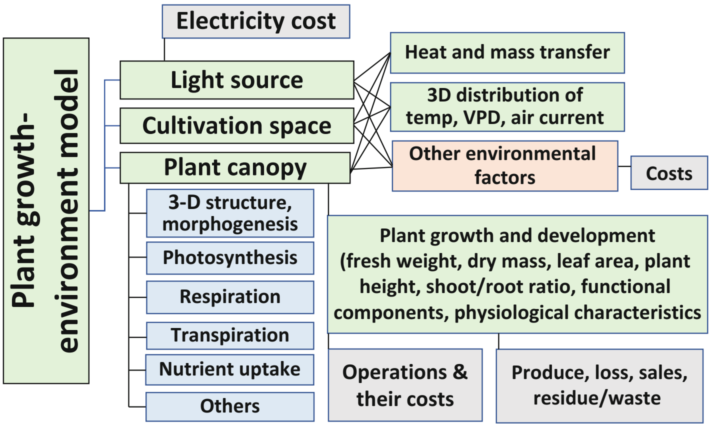

Fig. 2.7 General scheme of plant growth-environment model for maximizing the cost performance (CP)

general scheme of a plant-environment model for maximizing the cost performance of the PFAL.

(15) *Speed breeding*. Watson et al. (2018) proposed a method of "speed breeding" which greatly shortens generation time and accelerates breeding and research programs. They envisage great potential for integration speed breeding with other crop breeding technologies, including high-throughput genotyping, genome editing, and genomic selection, for accelerating the rate of crop improvement.

(16) *Dual (virtual/actual) PFAL*, a pair of virtual and actual PFALs. *The virtual PFAL* placed in the cloud is used to simulate the actual PFAL output using the data input to the actual PFAL. The parameter values in the virtual PFAL are adjusted automatically by using the input and output data of the actual PFAL (Figs. 2.8 and 2.9). The virtual PFAL can be used for training, self-learning, education, fun, and research and development of the PFAL.

2.6 Conclusion

To actualize the potential benefits of the PFAL, a considerable amount of systematic research, development, and marketing with the appropriate vision, mission, strategy, and methodologies are necessary. On the other hand, actualization of the potential benefits is relatively easy, because the energy and material balance and the plant-environment relationship in the PFAL are much simpler than in the greenhouse. Thus, the methods for actualizing the benefits are relatively straightforward. The issues described in this chapter are discussed in more detail in the following chapters of this book.

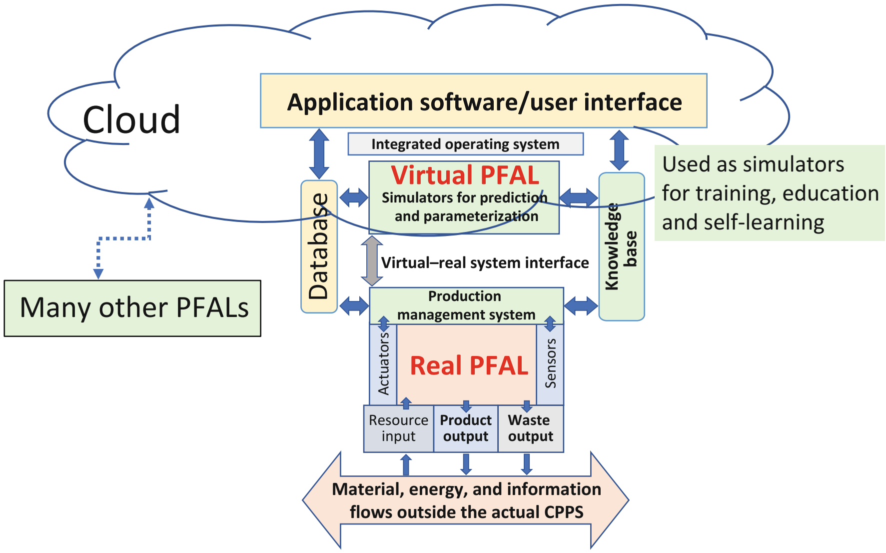

Fig. 2.8 Scheme showing dual (real and virtual) PFAL and its network. (Revised from Kozai et al. 2016)

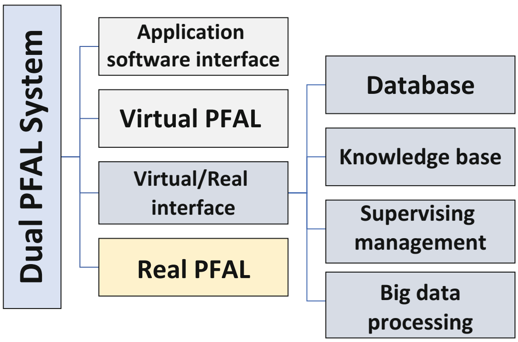

Fig. 2.9 Software configuration of the dual PFAL

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