Mini Expo “SMART AGRI DAY 2025” organized by BIOTEC, Thailand.

The next generation plant factories with artificial lighting (PFAL): - from ‘local’ to ‘global’ technologies -

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August 28, 2025

Outline

1. **Local technology (LT) and global technology (GT)**
2. **Environmental control of cultivation room (CR) is a GT**
3. **The reasons why the CR can achieve high resource use efficiency (RUE), resource productivity (P_R) and monetary (P_M) productivity**
4. **Increase in yield and reduction in resource inputs (R_I) of the PFAL, relative to those in the open fields: A rough estimate**
5. **Technology to be introduced to the next generation PFALs**
6. **Contributions of PFALs to solving the 4-way deadlock issue**
7. **Conclusion**

1.1. Local technology (LT)

(1) LT is affected by climate, soil, landscape and/or history at the locality

(2) LT includes technologies of agriculture, food, housing, clothing and crafts at the locality

1.2. Global technology (GT)

(1) GT can be applied anywhere in the world regardless of climate, soil, landscape and history at the locality

(2) Recent GT includes integrated circuits of semiconductors, internet protocols, smartphones, and large language models

(3) Recent GT spreads relatively rapidly worldwide due to its usability and low cost, although its initial development cost is high

2.1. The CR environmental control can be a GT, because the CR environment is unaffected by climate, soil, landscape, and history at the locality.

Since the CR:

(1) is airtight and thermally insulated,

(2) is covered with optically opaque walls,

(3) is free from pathogenic microbes and viruses, and

(4) uses a soilless hydroponic cultivation unit.

3.1. Definition and numerical examples 0f Resource use efficiency (RUE), resource productivity (P_R), and monetary (P_M) productivity

3.2. Definition of RUE

$$RUE = P_O/R_I = (R_I - W_O)/R_I$$

R_I

Resource input rates

Electricity, light energy, water, CO_2, fertilizer, seeds, and other consumables

→ **PFAL** →

P_O

Production rates

Quality and quantity of produce, economic value, O_2, etc. Rates of net photosynthesis, fresh weight increase and transpiration,

W_O

Waste production rates

Wastewater, heat energy, plant residue, used consumables

Time course of RUE for each resource input is estimated automatically

3.3. Definitions of P_R and P_M and their examples

Kozai and Hayashi (2022)

(1)Resource productivity (P_R):

$P_R = S/R_{SP} = RUE \times S/R_{min}$

R_{SP} : Resource supplied to the CR

S: dry or fresh weight of produce harvested

R_{min}: Minimum amount of resource required to produce S

(2)Monetary productivity (P_M)

$P_M = U_P/U_C \times (RUE / R_{min})$

U_P: Unit sales price of produce

U^C: Unit production cost of produce

RUE: Resource use efficiency

3.4. Major units of the CR

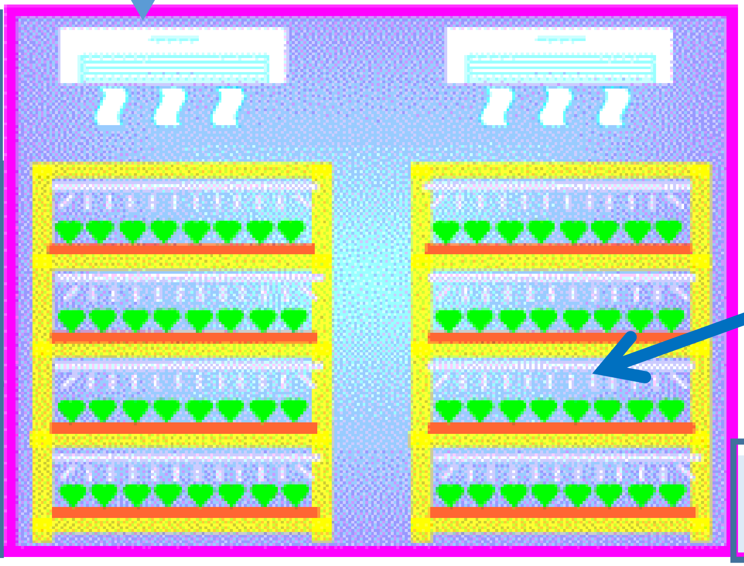
3. Air conditioners and fans

1. Thermally well-insulated, almost airtight cultivation room

4. CO_2 supply unit

5. Nutrient solution supply unit

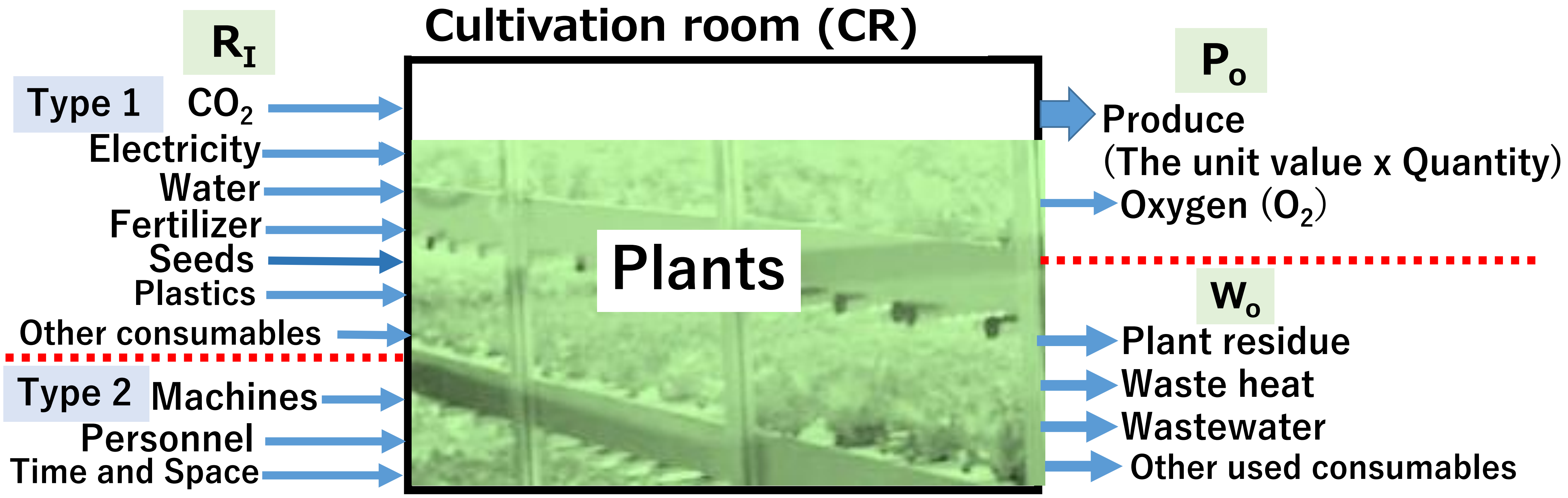
6. Environment control unit



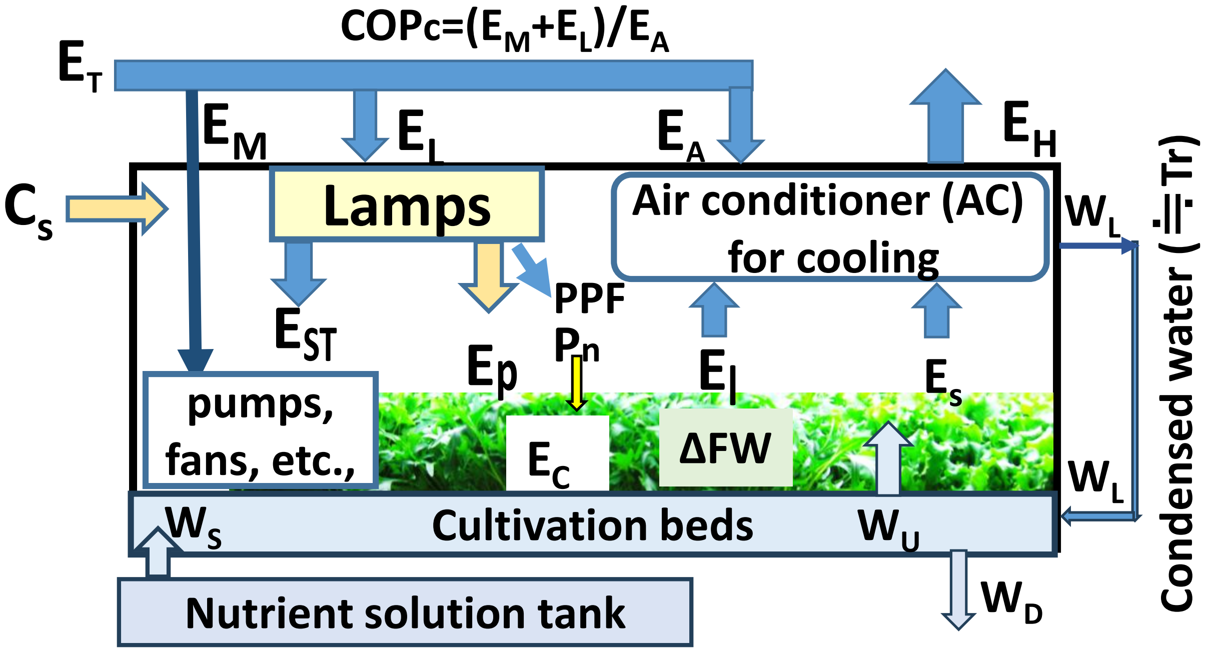
2. Multi-tier cultivation shelves with lighting and soilless hydroponic cultivation units

Air shower room

3.5. Resource inputs (R_I), product outputs (P_o) and waste output (W_o) of the CR can be measured and controlled accurately



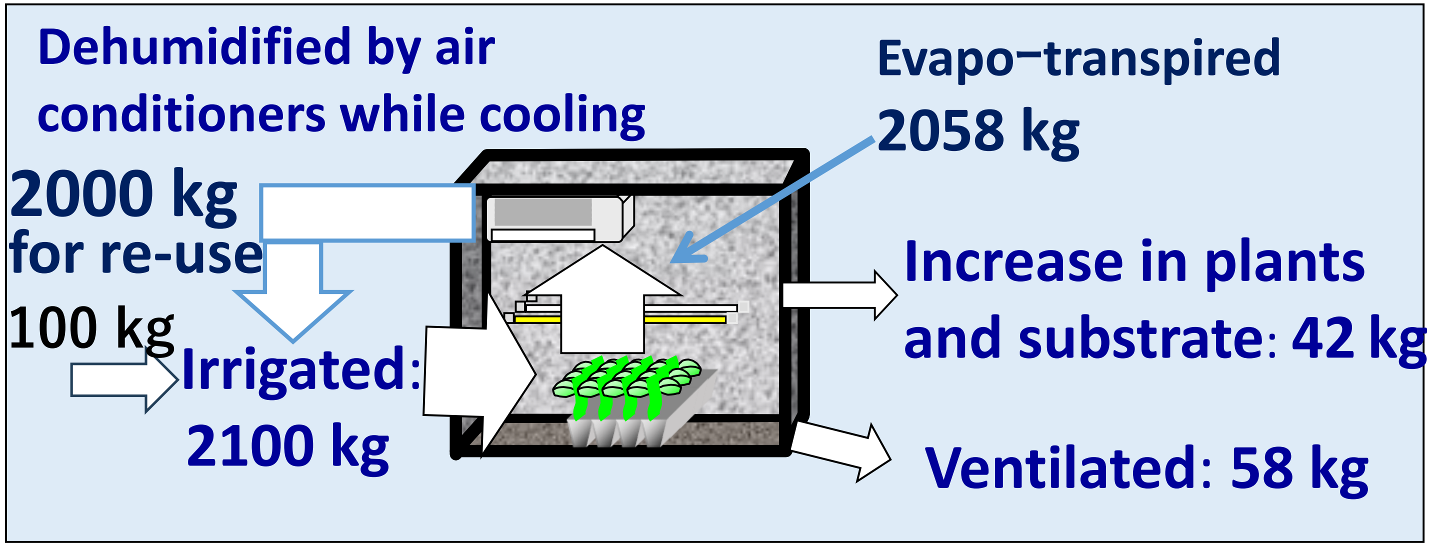
3.6. Conversions of R_l (CO_2, water, and electricity, and transplants) in the CR can be measured accurately



COPc: coefficient of performance of AC for cooling
C_S: CO_2 supplied to the CR
E_A: Electricity for air conditions
E_C: Chemical energy fixed in plants
E_L: Electricity for air conditions
E_l: Latent energy absorbed by AC
E_M: Electricity for pumps, fans
E_S: Sensible energy absorbed by AC for cooling
E_T: $E_A + E_L + E_M = E_H$
E_{ST}: Sensible and radiation energy
E_P: Photosynthetic radiation energy
Pn: Net photosynthetic rate of plants
PPF: Photosynthetic photon flux
W_D: Water drained from the culture bed
W_L: Water condensed at the cooling
W_S: Water supplied to the cultivation bed
W_U: Water untaken by plant roots
ΔFW: Increase in dry weight of plants

3.7. Water use efficiency (WUE):

$$\frac{\text{Irrigated} - \text{Ventilated}}{\text{Irrigated}} = \frac{2100 - 58}{2100} = 0.97$$



Ohyama et al. (2002)

If dehumidified water (2058 kg) is unused, the WUE is (=(2100-2058)/2100 = 42/2100 = 0.02. Thus, the recycling-use of dehumidified water for irrigation is essential for water saving.

3.8. RUEs in PFAL and Greenhouse

RUE	Max. Value	PFAL	Greenhouse
Water	1.0	0.96	0.02-0.03
CO_2	1.0	0.88	0.4-0.6
N, P, K, etc.	1.0	0.8-0.9	0.5-0.7
Seeds	1.0	0.95	0.8-0.9
Light energy	0.11	0.027	0.017
Electric energy	0.06	0.007	-------------

Ohyama et al. (2002; 2005; 2006); Yokoi et al. (2005)

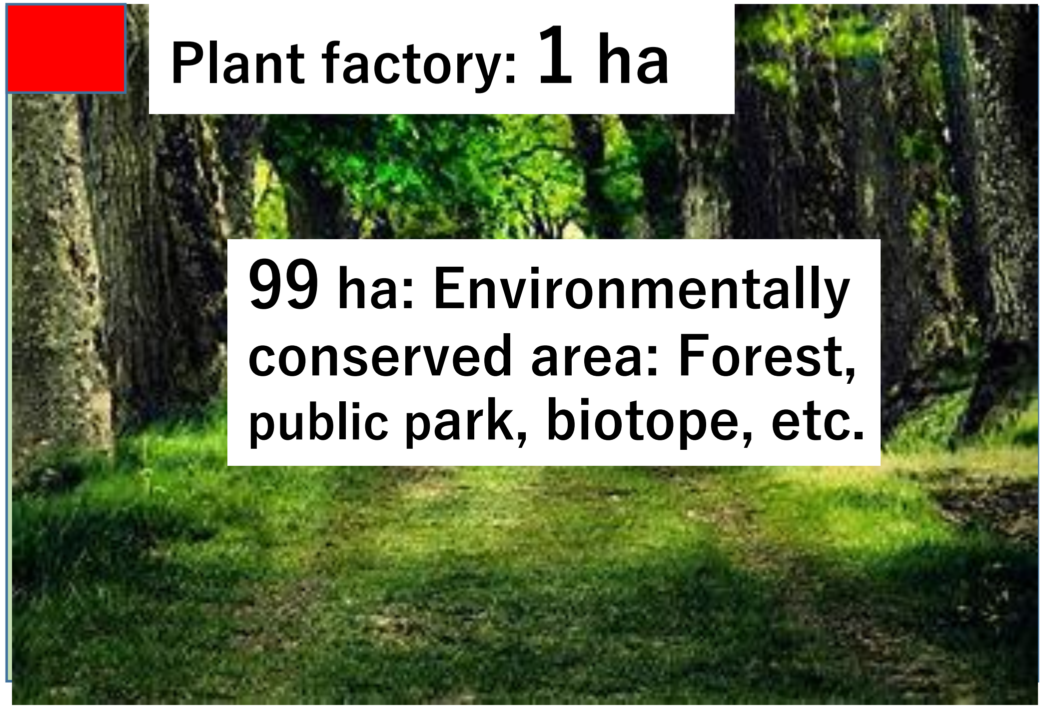
4.1. Increase in yield (production per land area) and reduction in resource inputs (R_I) relative to those in the open fields: A representative example

(1) Number of cultivation shelf layers is 20 : 20 times
(2) Yearly cultivation period is 360 days: 2.6 times
(3) No damage by unfavorable weather: 1.4 times
(4) No damage by pest insects, etc.: 1.4 times

Accumulated magnification (1)x(2)x(3)x(4)
=20 x 2.6 x 1.4 x 1.4 = 101.9

4.2. ‘A’ can be more sustainable than ‘B’ !

A: Plant factory (1 ha) and environ-mentally conserved area (99 ha)



B: Vegetable production in the open field (Land area: 100 ha)

4.3. Percent reduction in R_l relative to the open field production:

1) Land area by about 99%
2) Irrigation water consumption/kg of produce by over 90%
3) Working hours per kg of produce by over 50%
4) Pesticide application by almost 100%
5) Cultivation period for one cropping by about 50%
6) Fertilizer application by about 30%
7) Damage to plants due to harsh weather, pests, etc. by about 40%

Notes: The initial construction cost per land area is 10 times higher in the PFAL than in the greenhouse with environmental control units, while the initial construction cost <u>per yearly</u> production capacity of the PFAL is almost the same as that of the greenhouse.

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4.4. Essential characteristics of CR

1) **High controllability of environmental and sanitary conditions**

2) **High traceability of environment, management/ operations, plant growth and R_I, P_O and W_O**

3) **High reproducibility and predictability of P_O**

4) **Online estimation and successive improvement of RUEs**

5.1. The PFAL technology will be advanced by:

(1) Developing it as a GT with the use of AI and other advanced GTs

(2) Developing energy-, water and fertilizer-autonomous PFALs with the use of natural energy and waste recycling

(3) Getting higher public acceptance of PFALs for their high quality products and environmental friendliness

(4) Automatic determination of environmental variable setpoints

5.2. Technology to be introduced to the next generation PFALs

(1) Almost uniform three-dimensional (3D) distributions of the environment and phenotype in the plant community consisting of leaf canopy and root systems

(2) Phenotype-based automatic control of environmental variables

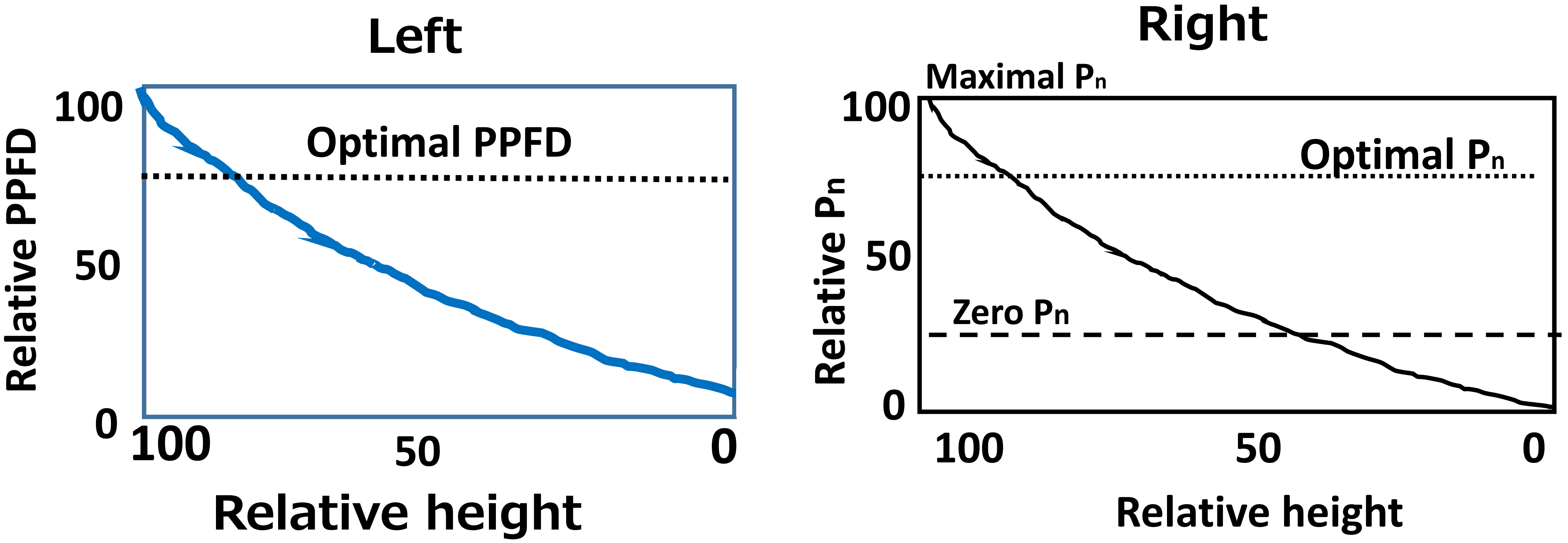
(3) AI-type agent to maximize the multiobjective function

(4) Plants suited to the production in PFALs

(5) Integration of speed breeding, environmental control, phenotyping, management, and CR improvement technologies

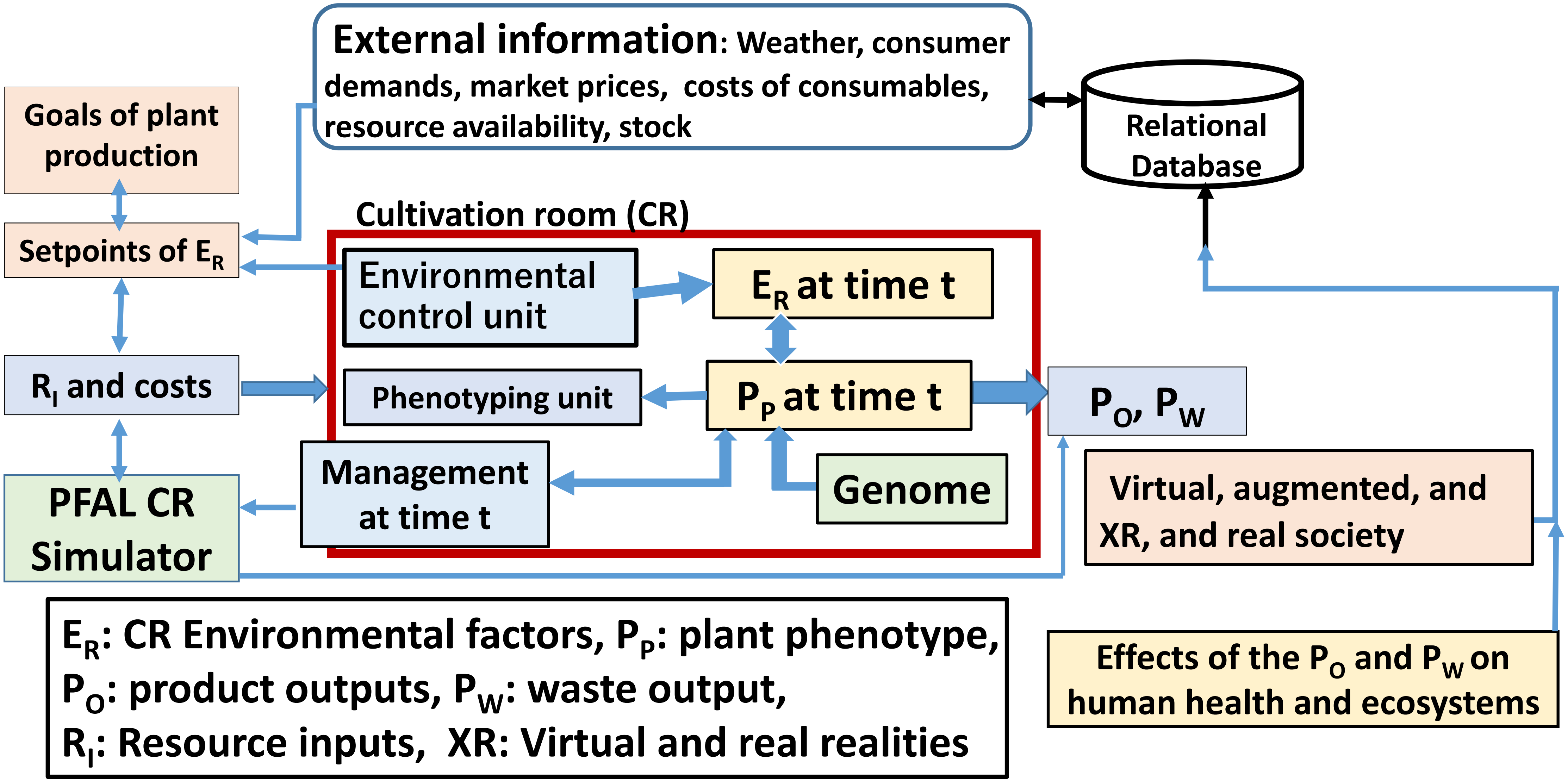
(6) Minimizing global warming gas emissions based on LCA (Life Cycle Assessment)

5.3. Exponential decrease (solid lines) in horizontally averaged PPFD (Left) and P_n (net photosynthetic rate) (Right) with decreasing relative height of a densely populated leaf canopy in the CR. Optimal PPFD and P_n (dotted lines) (Left) would be almost constant regardless of the relative height of canopy. Besides, 3D distributions of air current speed, CO_2 conc., and VPD in the canopy are uneven.

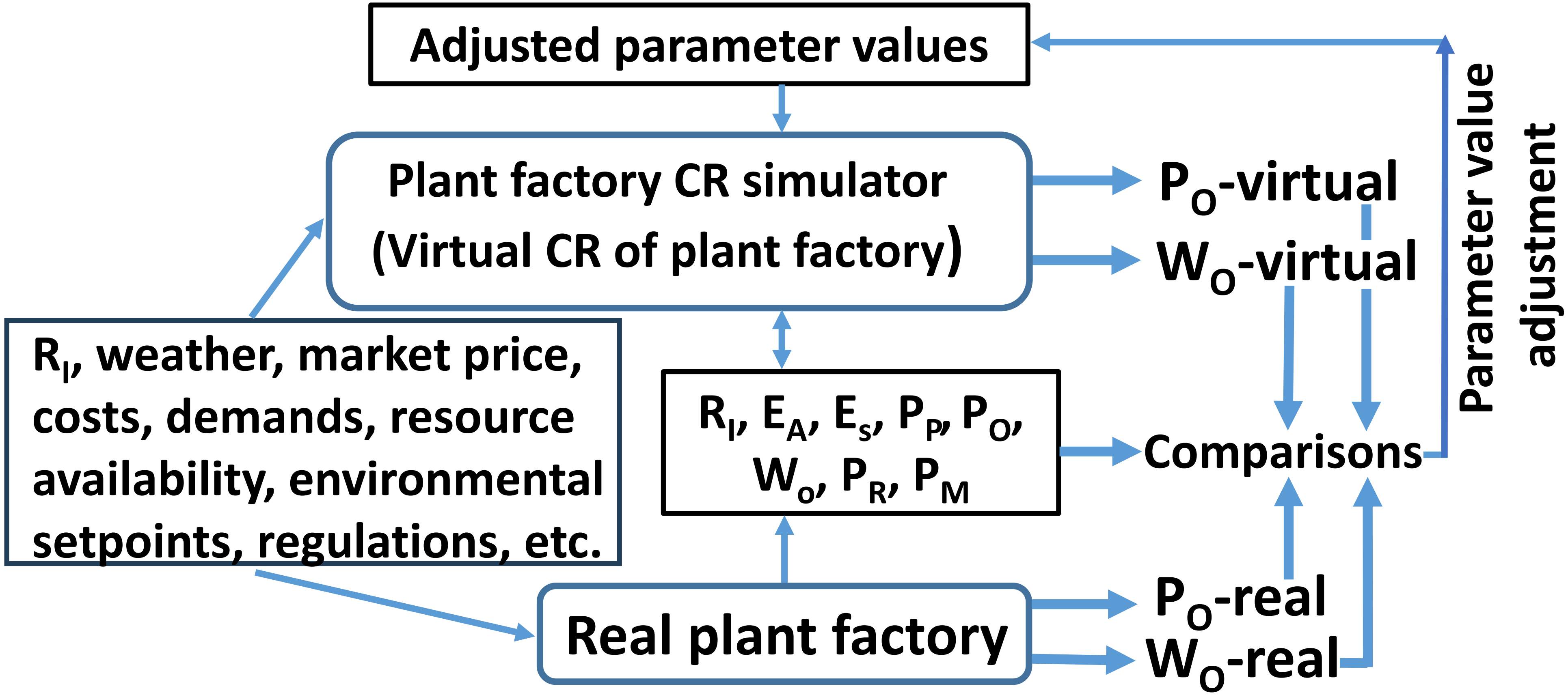


Optimal PPFD and P_n generally appears below the top of leaf canopy and P_n is negative near the bottom of the leaf canopy.

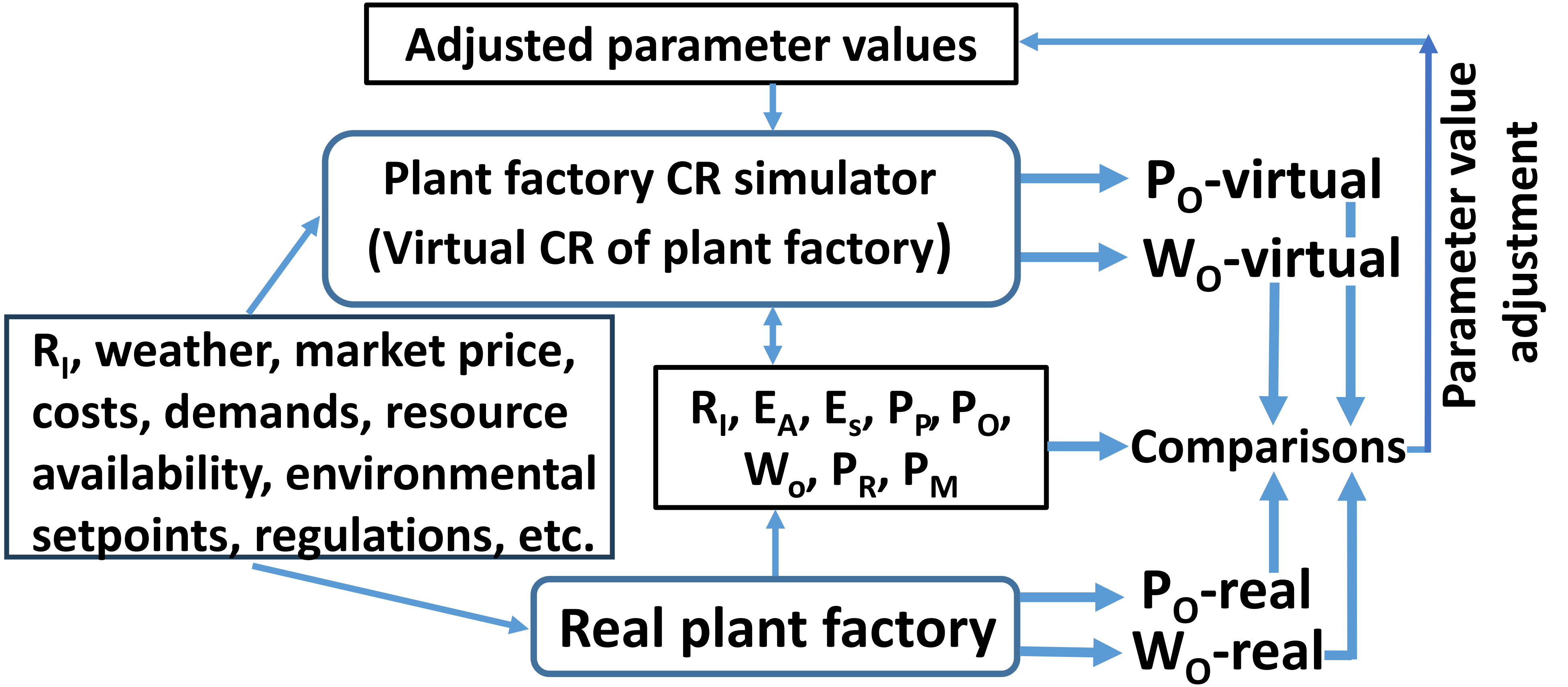
5.4. Phenotype-based determination of environmental variable setpoints with use of PFAL CR simulator and external information



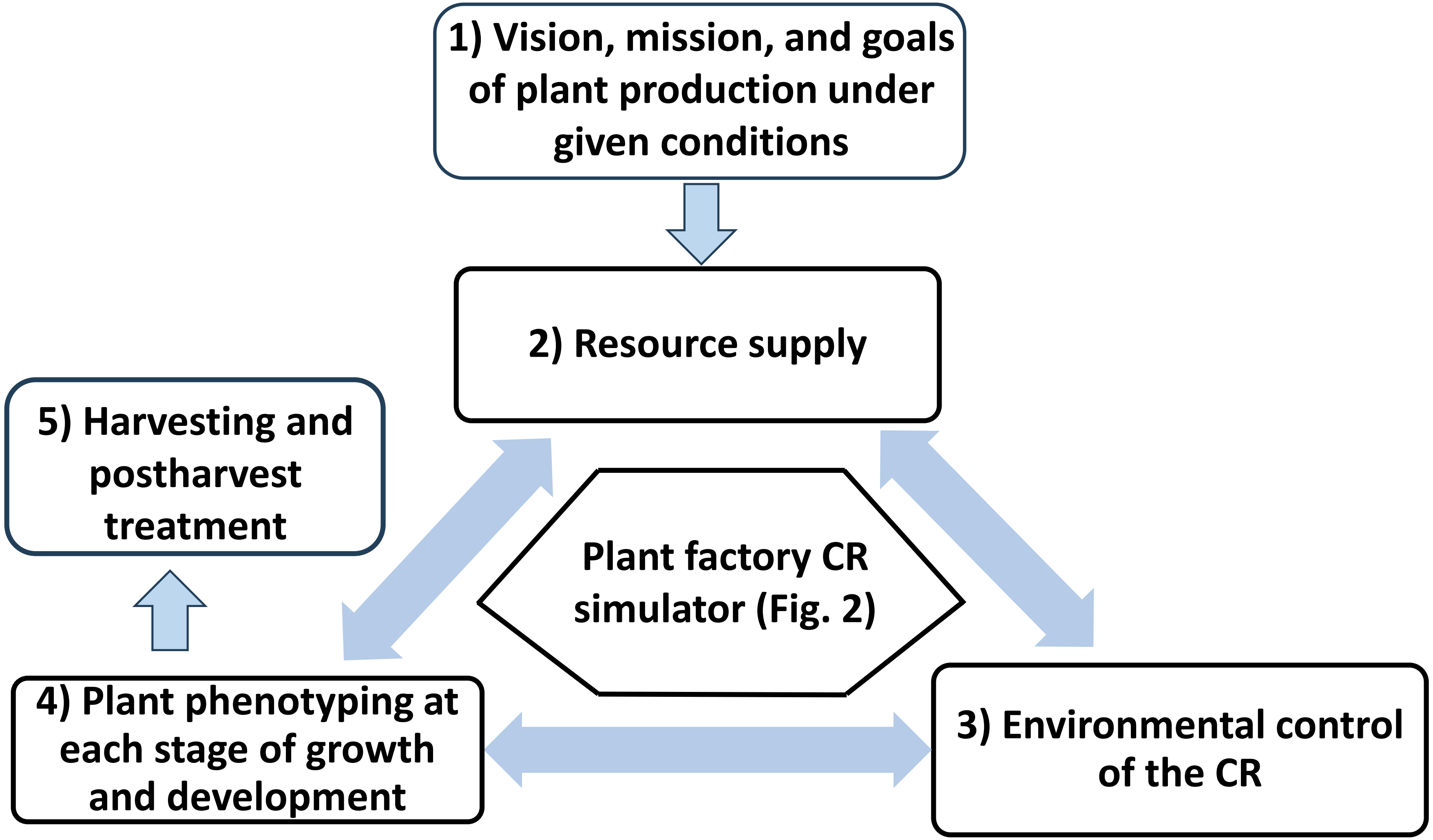
5.5. Online adjustment using the datasets of parameter values of the plant factory CR simulator



5.6. Online adjustment using the datasets of parameter values of the plant factory CR simulator



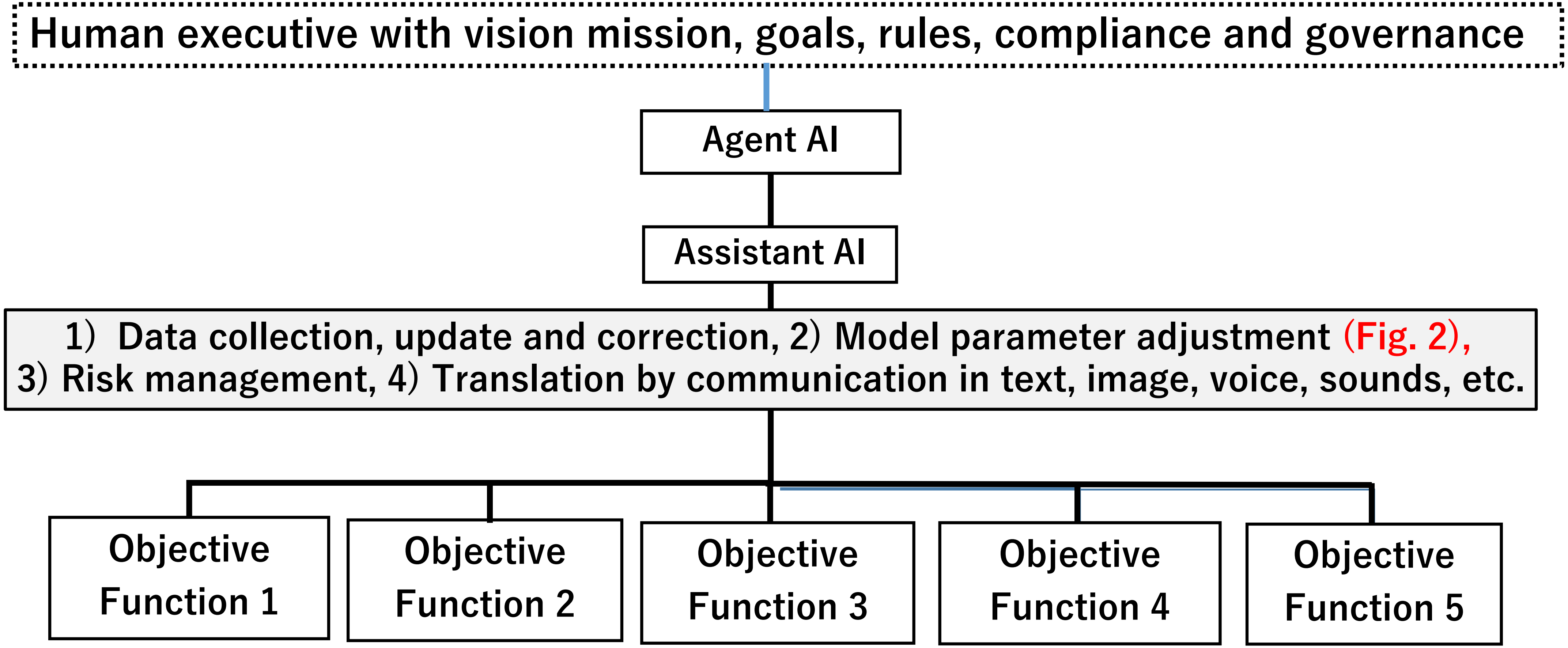
5.7. Dynamic determination of environmental variable setpoints of the CR based on interactive steps 2), 3), and 4), and non-interactive steps 1) and 5) of plant production process



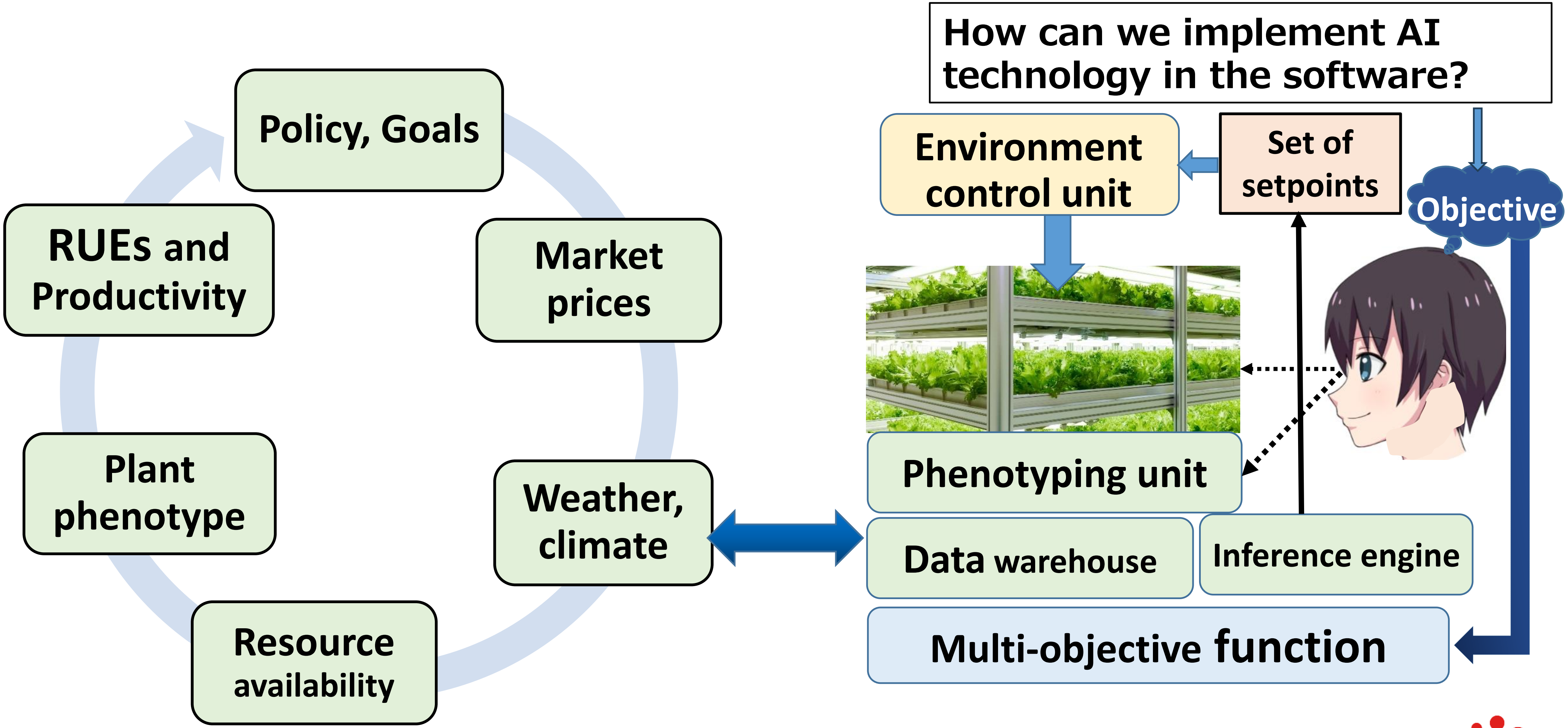
5.8. Examples of plant phenotype (P_P)

	Category	Examples of P_P
1	Leaf surface	Spectral distribution of transmittance and absorptance of leaves, leaf surface gas conductance, stomatal gas conductance, leaf surface structure (rough ness)
2	Leaf blade	Leaf temperature, net photosynthetic rate, transpiration rate, mesophyll gas conductance, chlorophyll fluorescence, RUBISCO activity, tissue /organ structure, the natural frequency of leaves and plants
3	Pigment conc.	Chlorophyll a/b conc., carotenoid conc., conc. of other chemical components
4	Relative growth rate	Relative growth rates of leaf area, leaf blade, root weight, fresh weight, dry weight, plant height, and plant density, germination rate, leaf bud/flower bus emergence rate, shoot/root weight ratio
5	Physiological disorder	Tip-burn, chlorosis, wilting, browning, yellowing, intumescence, texture color, micro-element deficiency
6	Translocation rate	Water uptake rate, translocation rates of water, sugar, ions, phytohormones, etc.

5.9. AI-type agent for assisting human executives to maximize the multiobjective function with help of assistant AI for adjusting the parameters of objective functions 1-5



5.10. Determination of optimal of environmental factor setpoints to maximize the given multi-objective function



Adopted from Kozai (2018)

5.11. Plants suited and unsuited to PFALs:

(1) Plants suited to production in the CR

- Plant height is shorter than about 50 cm for production on the multi-layer shelves
- High photosynthetic and growth rates under low PPFD, high CO_2 conc. and high air current speed to save electricity consumption
- High-quality functional (e.g., horticultural and medicinal) plants
- Disease-free and acclimatized transplants (or seedlings, cuttings and micro-propagated plants) for their growth in the open fields.

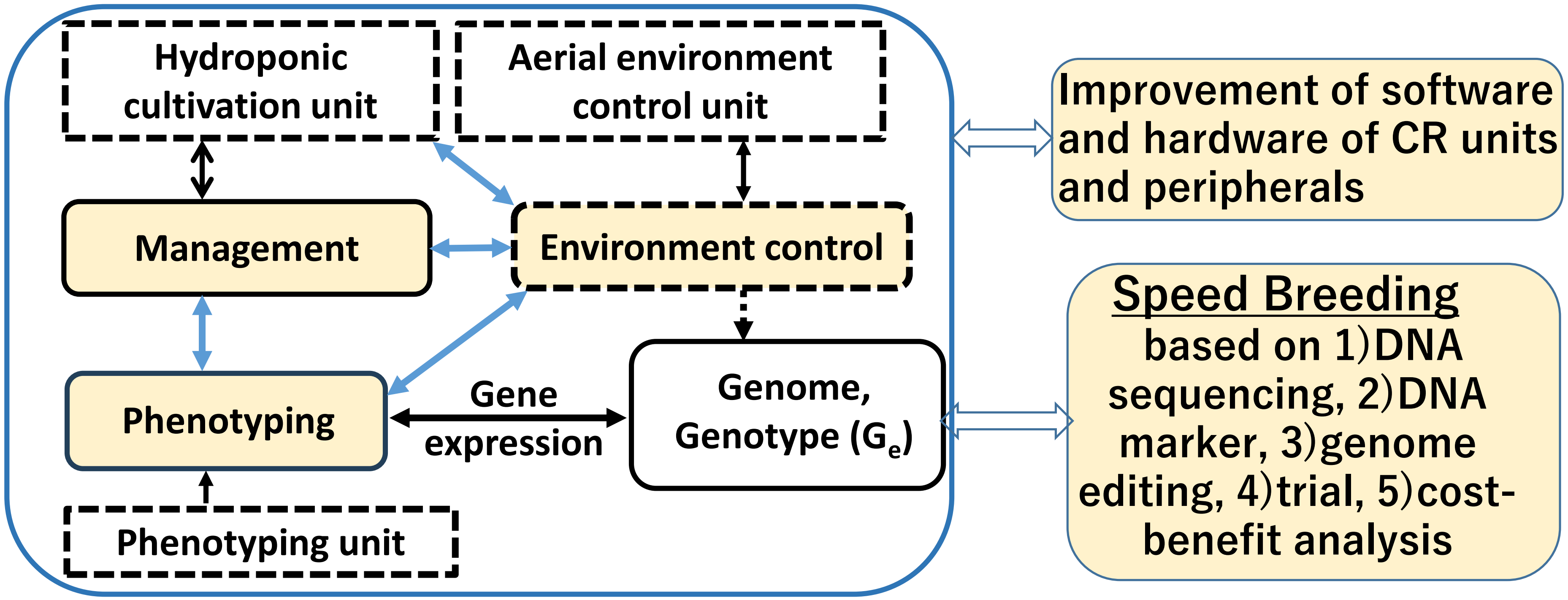
(2) Any types of plants including staple crops, trees, aquatic plants are suited to breeding in the CR

(3) Plants unsuited to production in the CR

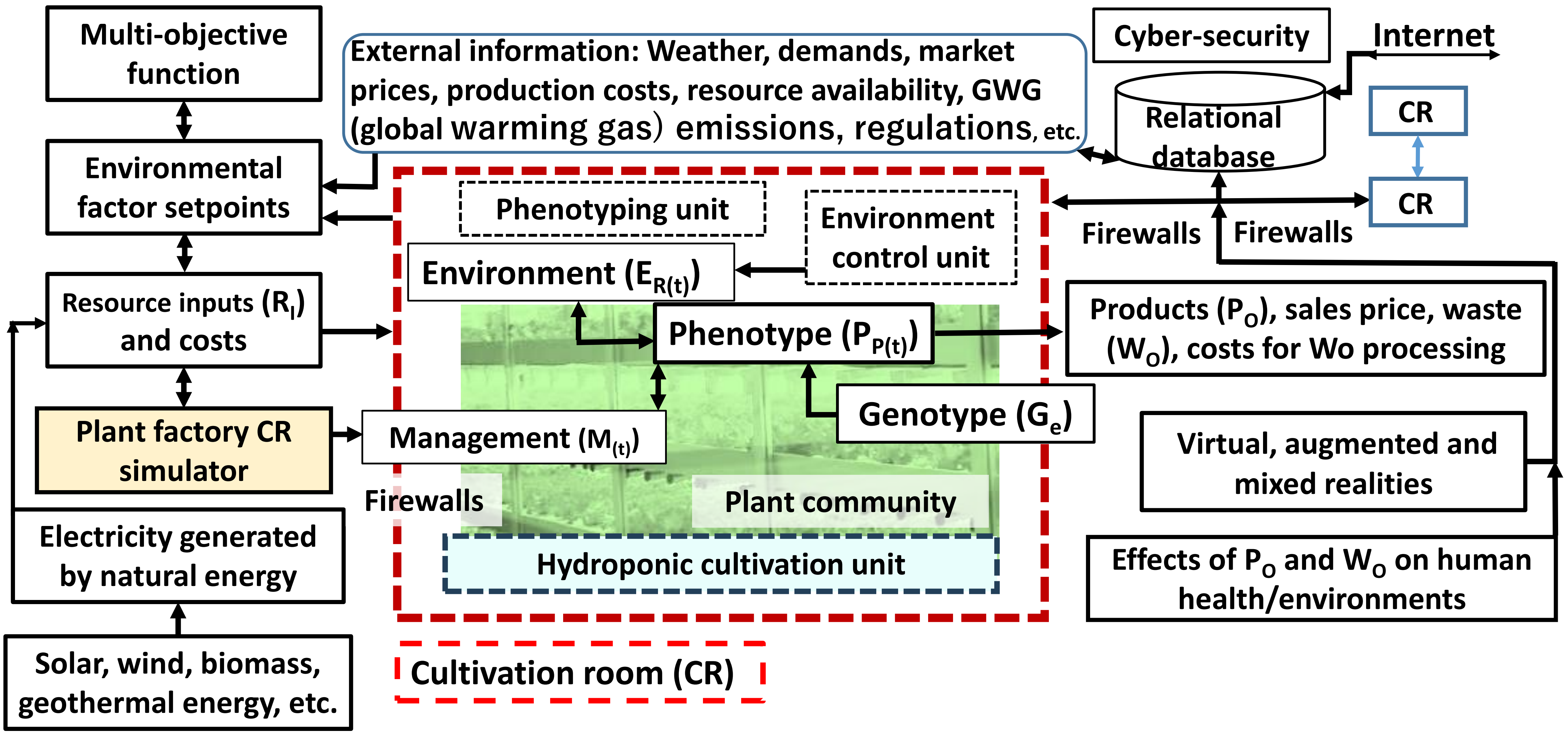
- Crops bred for production in open fields and greenhouses
- Food crops mainly for taking calories (e.g., carbohydrates), not for functional components (vitamins, proteins, minerals, fibers, lipids, etc.)

5.11. Interactive integration of speed breeding, environmental control, phenotyping, management, and CR improvement technologies

CR (cultivation room)



5.12. Scheme for the CR environmental control in the next generation PFALs



6.1. The next generation PFALs contributes to solving the 4-way deadlock by means of :

(1) **Electricity consumed for lighting, air conditioning, etc. is generated by renewable energy such as solar, wind power, geothermal, and biomass energy.**

(2) **Emissions of global warming gases (CO_2, CH_4, N_2O, etc.) and other environmental pollutants are minimal.**

(3) **Resource inputs (R_I) and outputs (R_O), resource use efficiency (RUE), and resource (P_R) and monetary productivity (P_M), and phenotype (P_P) are measured and controlled.**

(4) **The P_R and P_M are controlled based on the multiobjective function consisting of plural objective functions.**

6.2. Contributions of the next generation PFALs to solving the 4-way deadlock

1. Food security, safety, quality/nutrition, loss during cultivation and after harvesting, and shortage

2. Quality of housing, clothing, health, gender gap, racial equality, and social welfare

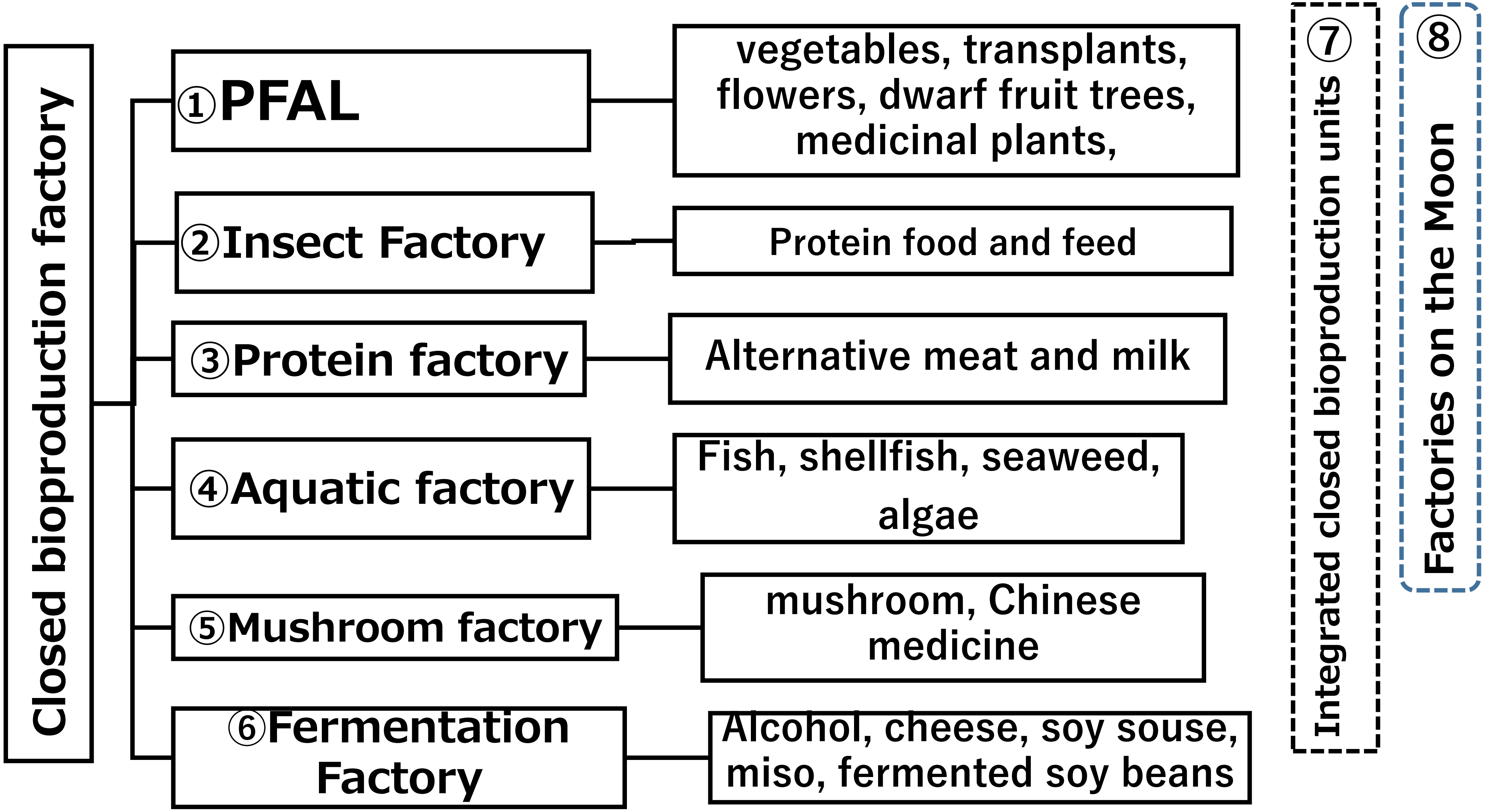
3. Shortages of abiotic resources such as water and fossil fuel

4. Global warming, natural disasters, environmental pollution, reduction in natural ecosystems

6.3. The 4-way deadlock issue needs to be solved under the conditions of :

1) Increasing urban population
2) Decreasing agricultural population with aged farmers
3) Decreasing arable land area for food/plant production
4) Decreasing the fertile soil area for farming
5) Increasing weather disasters (e.g., high temp., heavy rain causing floods, strong winds, drought) and pest insects
6) Increasing demands for reducing emissions of CO_2eq. and environmental pollutants causing global warming and environmental pollution

6.4. Examples of closed bioproduction units



7. Conclusion (Prediction)

The best way to predict the future is to invent it, by Alan C, Kay (1971)

1) **Resource inputs autonomous PFALs are commercialized by 2035**

2) **PFALs are developed as a Global technology (GT) by 2030**

3) **PFALs contribute to solving the 4-way deadlock issue concurrently by integrating the biological with non-biological GTs by 2035**

4) **PFALs are integrated with other closed bioproduction units such as aquatic, insect and mushroom culture units and other CO_2 and heat energy emitting facilities**

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References

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3) Kozai T. (2019) Towards sustainable plant factories with artificial lighting (PFALs) for achieving SDGs. Int. J. Agricultural and Biol. Eng. 12 (5): 28-37.

4) Kozai, T., Niu, G. and Takagaki, M. (eds.) (2020) Plant Factory: An indoor vertical farm for efficient quality food production, 2nd edition. Elsevier, 434 pages

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Thank you for your listening !

5.11. Dynamic determination of environmental variable setpoints of the CR based on interactive steps 2), 3), and 4), and non-interactive steps 1) and 5) of plant production process