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Improving Utilization Efficiencies of CO_2, Water, Electricity, and Light Energy of a Plant Factory
- A Project at Chiba University, Japan -

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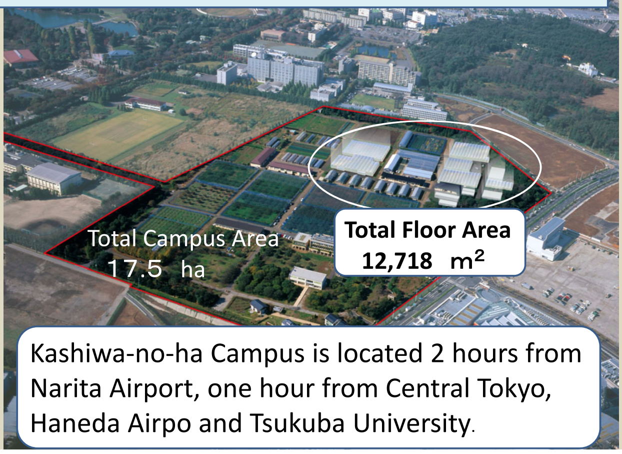
Outline

- Plant Factory Project at Chiba University
- Resource Utilization Efficiency, Type A & Type A
  - CO_2, Water, Inorganic Fertilizer, Light energy and Electric energy
- Closed Plant Production systems (CPPS)
- Estimation and control of state variables
- Integrative Environment Control

Bird Eye's View of Plant Factory at Kashiwa-no-ha Campus



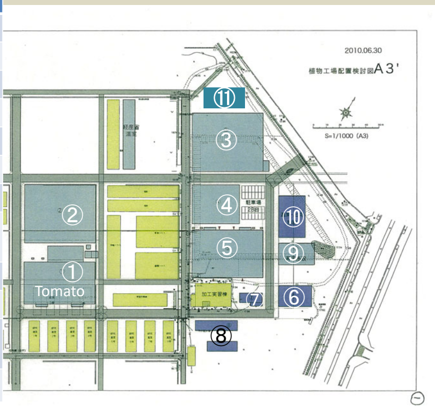
Kashiwa-no-ha Campus is located 2 hours from Narita Airport, one hour from Central Tokyo, Haneda Airpo and Tsukuba University.

Bird eye's view of Plant Factories at Chiba University

March 2, 2011, Under construction

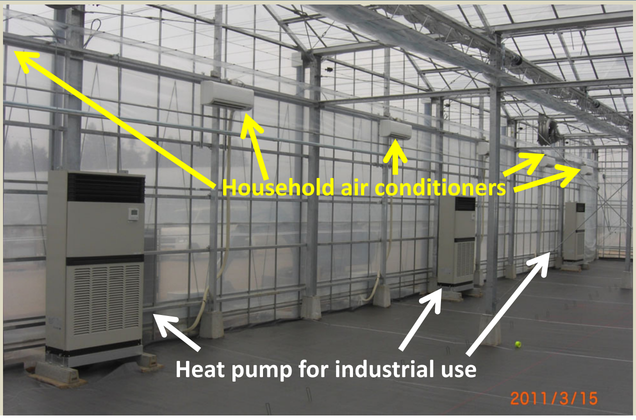
Layout of Plant Factory Compartments

	Crop	Floor Area
①	Tomato	2,151 m^2
②	Tomato	2,430 m^2
③	Tomato	2,412 m^2
④	Tomato	1,080 m^2
⑤	Tomato	1,980 m^2
⑥	Lettuce	406 m^2
⑦	Lettuce	207 m^2
⑧	Meeting Rooms	792m^2
⑨	Packing	640 m^2
⑩	Nursery	476 m^2
⑪	Waste Processing	144 m^2
	Total Area	**12,718 m^2**



Plant Factory Compartment with Solar Light for Tomato Growing

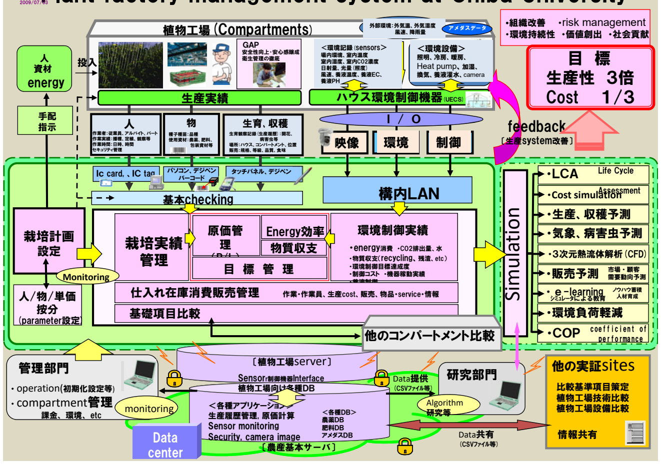
Multi-purpose Heat Pumps for Heating, Cooling, Humidity Control, Water collection and Air Circulation



Plant Factory with Artificial Lighting

Grading and Packing House

Plant factory management system at Chiba University



Goals of our Project is Concurrent Realization of:

- High yield, high quality and high value creation
- Savings of fossil fuel-derived products, water, fertilizers, space, time, and other resources.
- Environmental conservation by minimum emission of pollutants including CO_2 gas, and by producing a number of high quality transplants
- Comfort working environment
- Profit-making and providing job opportunities

Features of our Plant Factory Project

- Open architecture and information disclosure
- **Improvement of resource utilization efficiencies** (RUE)
- Intensive use of multi-purpose heat pumps
- Recycling use of rain and drain water
- Development of Integrative environment control system
- Providing training courses for advanced growers and engineers
- Close collaboration with NPO Plant Factory Association of

  Japan and other organizations in Japan and overseas

Resource Utilization Efficiency (RUE)

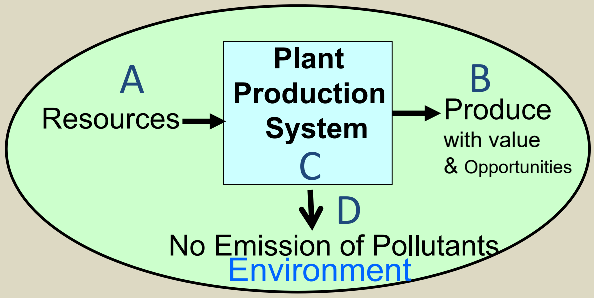
- Type A RUE

$$\frac{\text{Amount of resource utilized in plants}}{\text{Amount of resource supplied to the System}}$$

- Type B RUE

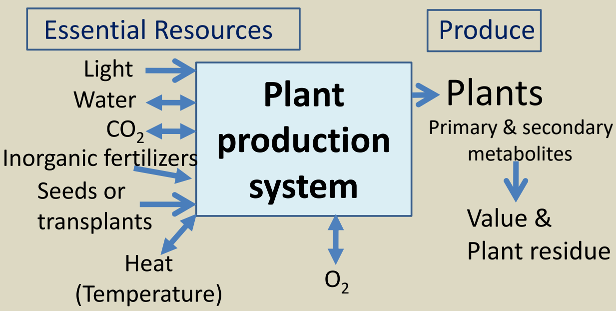
$$\frac{\text{Amount of resource utilized by the system}}{\text{Amount of resource provided to the system}}$$

Type A Resource Utilization Efficiency = B/A,



Concept of CPPS (Closed Plant Production System) : B/A=1
C=D=0

Essential resources needed for photosynthetic growth of green-colored plants



Type A Utilization efficiencies:

CUE: CO_2 fixed by plants divided by CO_2 supplied to the system

WUE: Water held in plants divided by Water supplied to the system

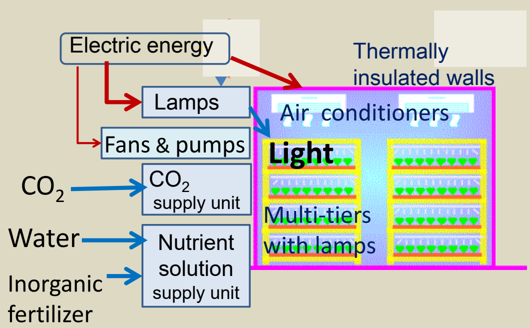
IUE: Inorganic fertilizer (IF) fixed in plants divided by IF supplied

LUE: Light energy fixed as chemical energy in plants divided by light energy supplied

Type B Utilization efficiencies:

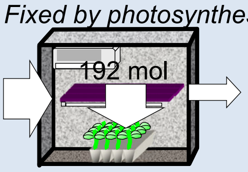
- Light energy emitted by lamps divided by electric energy consumed
- COP of heat pump: Heat generated for heating or cooling divided by electricity consumed
- No. of plants harvested/No. of seeds sown
- Area occupied by plants divided by floor area

Plant factory with artificial light designed based on the concept of **Closed System**



CO_2 utilization efficiency = $\frac{CO_2 \text{ Fixed}}{CO_2 \text{ supplied}}$

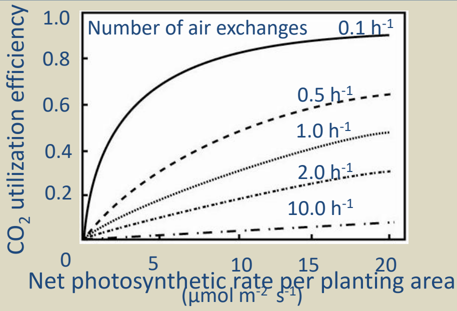
= 192/221= (221-29)/221=0.87



Number of air changes= 0.01 h^{-1}

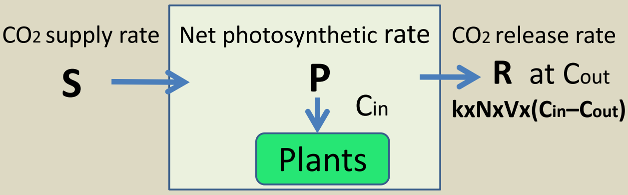
Ohyama et al. (2005)

CO_2 utilization efficiency as affected by net photosynthetic rate & number of air exchanges, N



Floor area and air volume: 1000 m^2 and 3000 m^3; N: 0.1, 0.5, 12 and 10 h^{-1}; CO_2 conc. inside and outside: 1000 and 350 μmol^{-1}; air temperature inside and outside: 27 C; floor is covered with plants; soil respiration is negligible (Yokoi et al., 2005).

Determination of Optimal CO_2 concentration (C_{in}) based on the cost performance



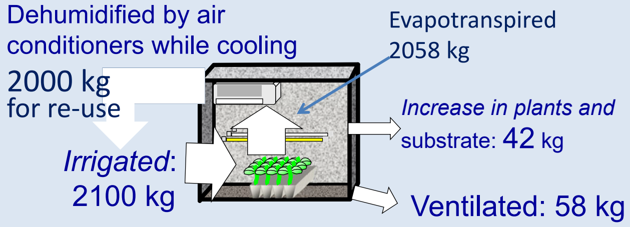
CUE=P/S=(1-R+NxVx(C_{in}-C_{out}))/S

Optimum C_{in} is determined to maximize the cost performance, expressed by

"Benefit of P/(cost of S + a x penalty for R)"

Water utilization efficiency:

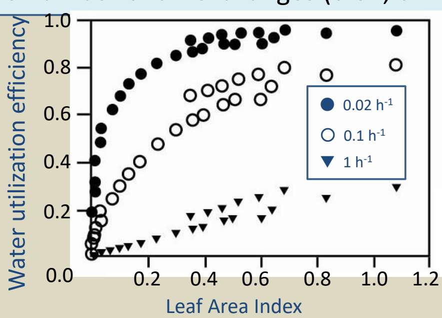
$$\frac{\text{Irrigated – Ventilated}}{\text{Irrigated}} = \frac{2100 – 58}{2100} = 0.97$$



If dehumidified water is not used, the efficiency is 0.02 (=(2100 -58 - 2000)/2100=42/2100) ⇒ the water needed for irrigation in the CPPS is 1/48 (=2/97) of that in a greenhouse.

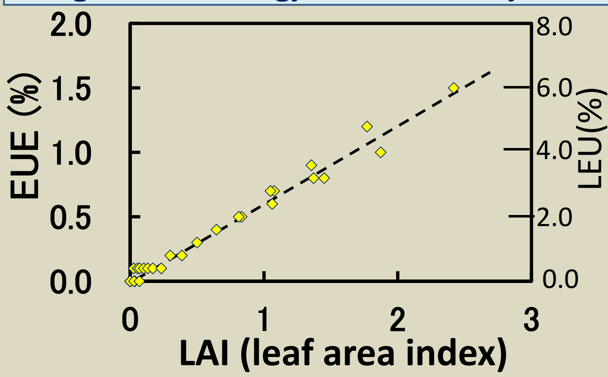
Ohyama et al. (2002).

Water utilization efficiency of the CPPS as affected by the number of air exchanges (0.02, 0.1 and 1 h^{-1})

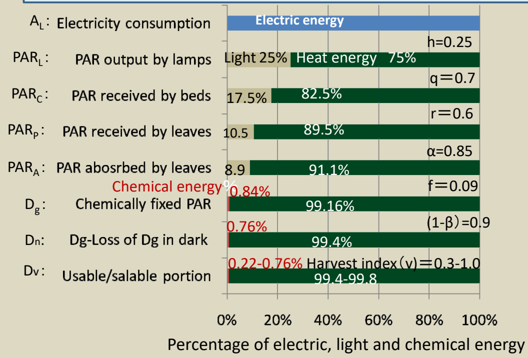


Water vapor density inside and outside the closed system was assumed to be 16 and 6 g m^{-3}, respectively. All values indicate simulated values (Yokoi et al., 2005).

Utilization efficiencies of electric (EUE) and light (LUE) energy as affected by LAI

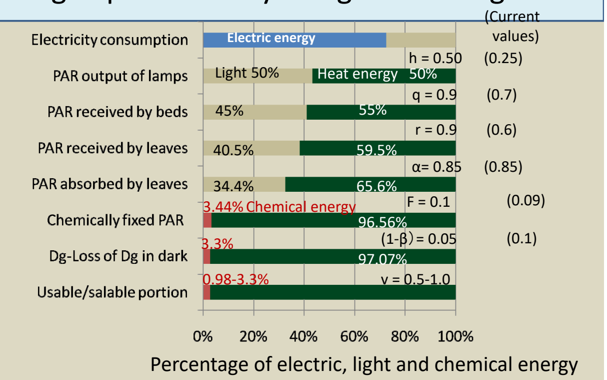


Conversion process of electric energy for lighting with artificial light



(Drawn based on Ohyama et al. (2000), Yokoi et al. (2003, 2005).

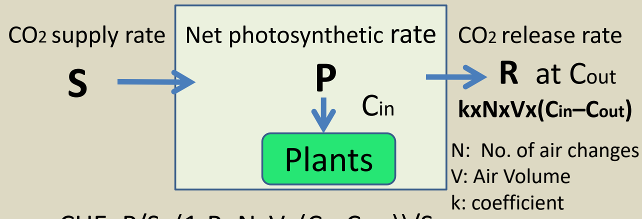
Ideal conversion process of electric energy for lighting in plant factory using artificial light



Applications of RUE concept

- CO_2 enrichment based on null CO_2 balance method, resulting in 100% CO_2 utilization efficiency
- Estimation of rate variables and environmental control based on rate variables
- Integrative environmental control based on RUE and cost(/benefit) performance

Online Estimation of net photosynthetic rate (P) and CO_2 enrichment based on null CO_2 balance



$CUE=P/S=(1-R+N \times V \times (C_{in}-C_{out}))/S$

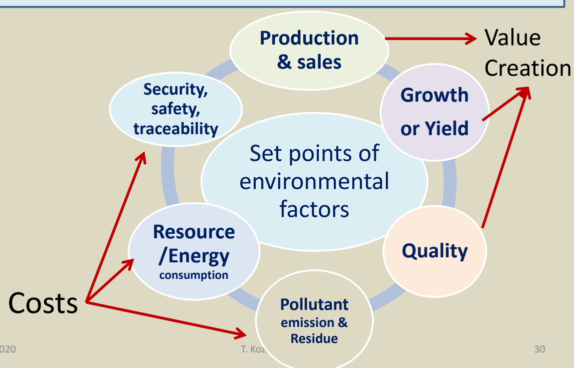
1) If N can be is estimated, P can be estimated by P=S-R
2) If CO2 is supplied to keep (Cin –Cout) being zero, CUE is 100% and S=P

Environmental control based on not only state variables but also rate variables

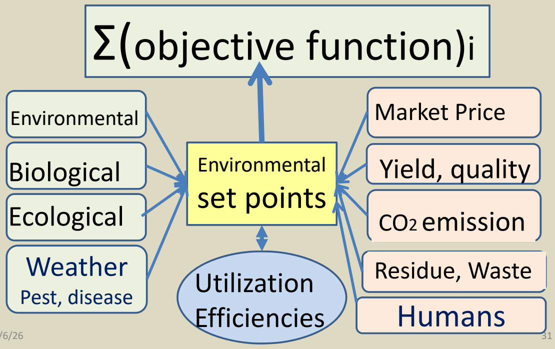
- State variables (without unit of time)
  - Environmental: Temp., humidity, CO_2 conc., pH, EC
  - Ecological: LAI, plant weight & height, color, planting density
  - Biochemical: Vitamin C, Chlorophyll fluorescent,
- Rate variables (with unit of time)
  - Ecological: rates of net photosynthesis, dark respiration, transpiration, water uptake and nutrient uptake
  - Control variables: Supply rates of CO_2, water, light/electric energy, nutrient
  - System parameters: Rates of ventilation, heat transmission

Concept of Integrative Environmental Control

- Determination of set points of environmental factors based on the factors below -



Determination of Set Points of Environmental Factors Based on Multi-purpose Objective Function



Type B Resource Utilization efficiencies

- COP of the heat pump
- Floor area utilization efficiency

COP (coefficient of Performance) of multi-purpose heat pump

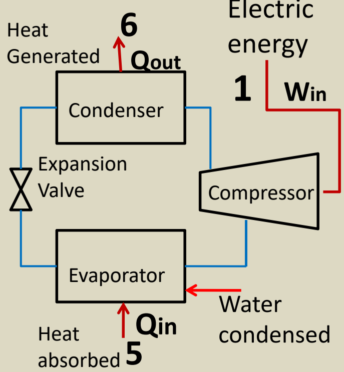
$COP_{heating}=6$

$COP_{cooling}=5$

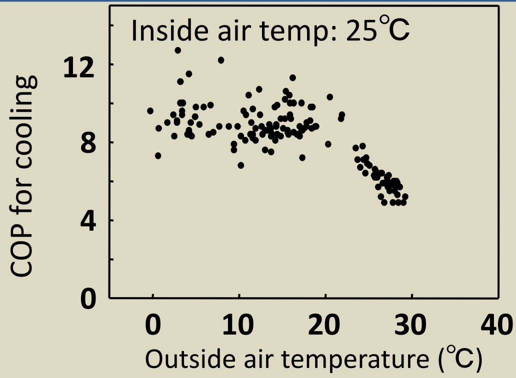
$COP_{multi}=11+\alpha$

$=(Q_{out}+Q_{in}+\alpha)/W_{in}$

α: Dehumidification
water collection
Drying, air circulation
etc.



COP for cooling of room air conditioner (or heat pump) as affected by outside air temperature



(Ohyama et al., 2002)

Percentages of Annual Electricity Consumption by Components (Ohyama and Kozai, 2004)

Purpose	Percentage	Equipment
Lighting	80%	Fluorescent lamps 40W
Cooling	16%	Heat pumps (Air conditioners)
Others	4%	Water Pumps, Fans, etc.

The COP of the heat pump is 5.25 (=(80+4)/16＝5.25).

Application of multi-purpose heat pump
for high yield and quality with minimum consumption of resource and minimum emission of pollutants

- Heating air, water and substrate
- Cooling air, water and substrate
- Dehumidification of the air to control relative humidity/water vapor deficit
- Enhancement of air circulation/movement
- Collection of condensed water while cooling
- Drying, humidifying, warm/cool heat storing

Environmental control equipments to be operated in combination with heat pumps for integrative environmental control of plant factory with solar light

- CO_2 supply unit
- Ventilation unit
- Air circulation fan
- Shading screen
- Thermal insulation screen
- Fog or Pad & fan cooling unit
- Nutrient solution supply unit
- Nutrient solution heating/cooling unit
- Heat storing/release unit

92% reduction in land space and 47% reduction in seedling production period by the CPPS with 4 tiers, compared with the greenhouse for production of tomato seedlings

	Greenhouse	CPPS
Floor Area	1,250 m^2	100 m^2
Production period	28 days	14 days

The seedlings are used in the greenhouse with a floor area of 2.5 ha for growing tomato plants with three-trusses at high density planting

(Data by Taiyo Kogyo Co.)

古在豊樹編著
オーム社
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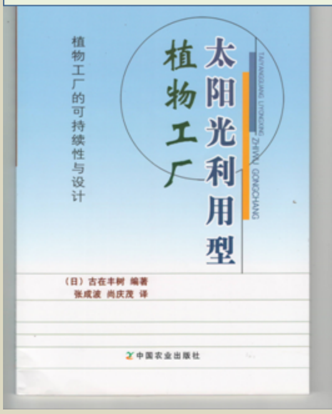
2010年12月　2刷

As for Plant Factory with **Solar Light**, please read this book.



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Conclusion

- Plant Factory Project at Chiba University has started
- Utilization Efficiencies of CO_2, Water, Inorganic Fertilizer, Light energy and Electric energy are useful concepts.
- Closed Plant Production systems (CPPS) is a useful concept to improve the resource utilization efficiencies.
- Estimation and control of state variables is essential to develop an integrative Environment Control

Thank you for your kind attention

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