

CU-MU Joint Symposium 2018

Plant Factory for Next Generation

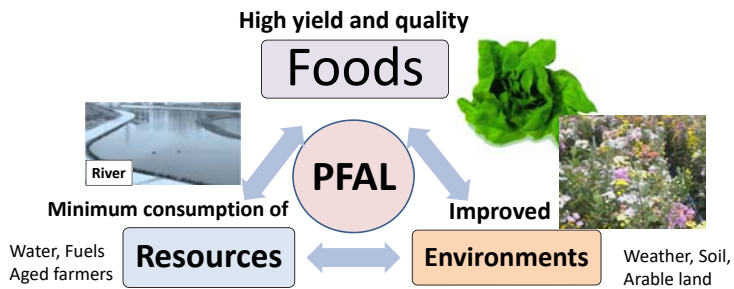
Mahidol University
Satang Monkusuk Conference Room
9:00-9:45, January 26, 2018

Toyoki Kozai Japan Plant Factory Association

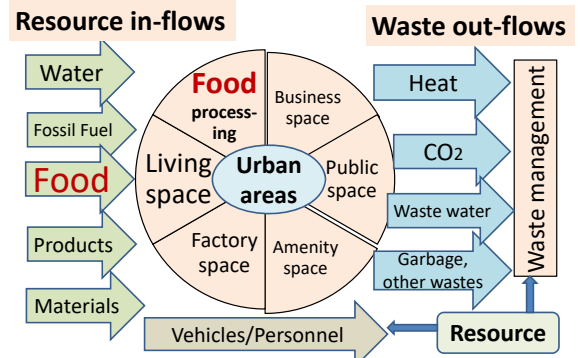
Contents

- Part 1: Social backgrounds, current status and the merits
 - Part 2: Basic technologies, concept and methodology
 - Part 3: Medicinal plant production
 - Part 4 Plant factory for next generation
- Challenges for PFAL to World's Plant Production
- Conclusion

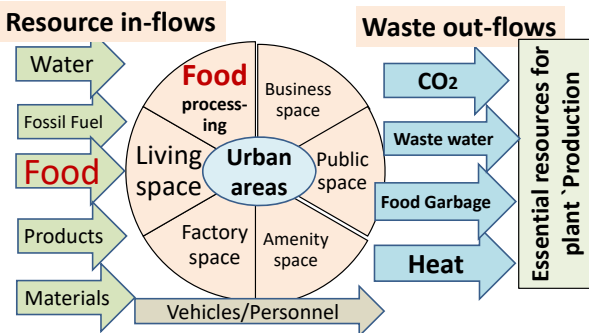
PFALs will play a significant role to solving the food-environment-resource trilemma



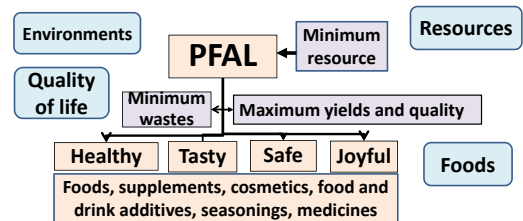
Resource in-flows and waste out-flows in urban areas



Wastes emitted in urban areas can be used as essential resources for plant Production



Mission and goals of plant factory with artificial lighting (PFAL)



PFAL-grown plants do not compete with field- and greenhouse-grown plants, and create a new market.

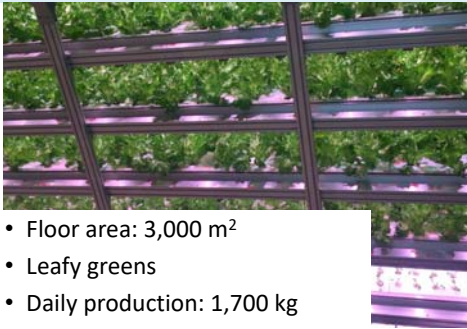
Current status of PFALs for commercial production in the world

Estimated number of PFALs in the world is over 400

Country/area	No.	Country	No.
Japan	200	Russia, Singapore, The Netherlands, United Kingdom	2 or more
Taiwan	100		
China	50	Mongolia, Panama, Vietnam, France, Belgium, Finland, India, Dubai	1 or more
USA	25		
Korea	10		

Japan

808 Plant Factory (Shin-Nippou Co.). Shizuoka



- Floor area: 3,000 m²
- Leafy greens
- Daily production: 1,700 kg

A PFAL with LEDs lights, Mirai Co. Ltd., Japan

Built in 2013



Daily production: 600 kg
 Annual production:
 2,500 lettuce heads/m²
 (200 kg/ m²)
 Sales: 2,500 US\$/m²

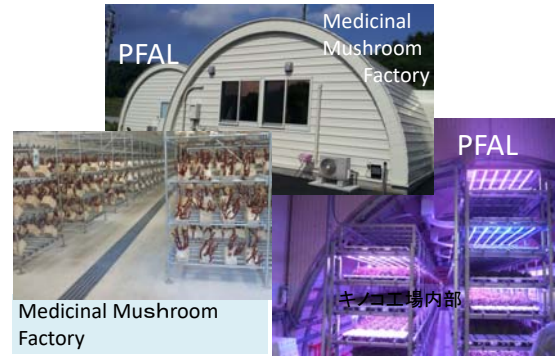
The PFAL first built in 2006, producing 23,000 leaf greens daily



Spread Co. Ltd. Kyoto, Japan

Other applications in Japan

PFAL connected with mushroom factory operated by 'Japan Dome House' in Fukushima Pref., Japan



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In the lobby of Sakakibara Memorial Hospital



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Small PFALs for educational/self-learning purposes, connected each other via Internet with cloud computing system



Iri'hune Junior High School, Urayasu city, Chiba, Japan (Panasonic)

Taiwan

Taipei, Taiwan, Nice Kitchen



Healthcare goods in Nice Kitchen



China

PFAL in Xiamen, China (Jan. 2017) Floor area 9,000 m², 6 layers



USA

Plenty Inc: Vertical farms at San Francisco, USA



SoftBank Vision Fund, the huge tech-investment vehicle helmed by Masayoshi Son, has led a \$200 million investment into indoor farming startup [Plenty](#). Eric Schmidt and Jeff Bezos joined this investment.

 **AeroFarms®**
130 Times More Productive
Than Field Farming



The Netherlands

High-wire cherry tomato production in PFAL Priva Group, 'Seven Steps to Heaven'



A PFAL in Amsterdam, The Netherlands



With vertical farming, we can grow the greens in the center of Amsterdam. So we can provide the city with a sustainable and local food supply, that's as delicious as it is fresh
<https://www.growx.co/our-farm>

Grow Underground, UK

<http://growing-underground.com/whole-foods-launch/>



Why PFALs will become indispensable in Thailand?

Increasing demands of:

- **Healthy, nutritious, safe, tasty, pesticide-free vegetables**
- **Wide applications of PFAL-grown medicinal plants –medicine, cosmetics, food- and drink additives**
- **All year-round and stable production of plants regardless of contaminated, saline, non-fertile and/or gravel soil in shaded/hot humid areas.**
- **Production costs will continue to decrease, the productivity and its economic value/kg will continue to increase during the next several years.**

Merits of PFALs and Technological backgrounds

Merits of PFALS

Consumers side

- Pesticide- and insect-free
- No need to wash before its use
- Stable price
- 2-fold shelf life with freshness
- Local production for local consumption
- Controlled secondary metabolite production

Producers side

- Scheduled production regardless of weather
- Safe and light work under comfortable environments
- **Over 100-fold annual productivity per unit land area (leafy vegetable)**
- **Reduced consumptions of water, fertilizer, etc.**
- LEDs, IoT, AI, biotechnology and natural energy utilization can be fully used.

Estimated relative annual productivity of PFAL by its components, compared with those in the open field

No.	Magnification by PFAL compared with the open fields	Component Factor	Multiplied Factor
1	10-fold by use of 10 tiers	10	10
2	2-fold by shortening the culture period by means of optimal environment control	2	20
3	2-fold by transplanting seedlings one day after harvest all year round assuring no time loss	2-3	40-60
4	1.5-fold by increased planting density	1.5	60-90
5	1.5-fold per cropping by no damage due to abnormal weather & pest insects	1.5	90-135
6	1.3-fold sales price due to improved quality & less loss of produce after harvest	1.3	135-202

Reduction of resource consumption in PFALS in comparison with the greenhouse soil cultivation

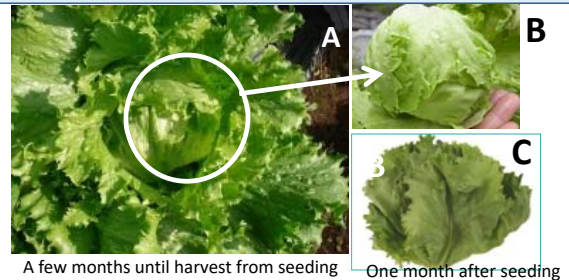
- Pesticide by 100% (clean room),
- Water by 95% (recycling use),
- Land area by over 95% (multi-tiers, etc.),
- Fertilizer by 50% (no drainage),
- Labor hours by 50% (much less distance to walk, etc.),
- Plant residue by 50% (Environmental/sanitary Control)

But, much electric energy is required for lighting and air conditioning.

Which is more resource-saving, environmentally friendly, economical & healthy?
Why use artificial light rather than natural light?

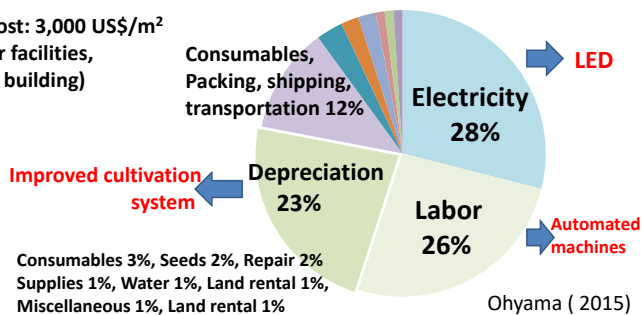
Crisp head lettuce

- A: Whole plant grown in the open filed
- B: Salable part of Photo A, which is about 50% in weight
- C: Whole plant grown in PFAL, all of which is salable



Initial & production costs by components of PFALS with fluorescent lamps in Japan as of 2015

Initial cost: 3,000 US\$/m²
(50% for facilities,
50% for building)



Current demerits

Current demerits	Facts and challenges
High initial investment per land area	Initial investment per production capacity is similar to the greenhouse
High production cost	
Electricity cost	Using LEDs etc., it can be reduced by 50%.
Labor cost	With (semi-) automation etc., it can be reduced by 50%.
Low-value plants such as lettuce	PFALS producing lettuce are making profits recently.
Old-fashioned Cultivation System	High-value plants such as medicinal plants is a next target.

Why artificial light? (1)

Factors below can be controlled precisely in the PFAL

- Photoperiod/lighting cycle, light quality, PPF, lighting direction
- Temp., CO₂ conc., VPD, air current, nutrient solution
- Pest insects/pathogens/hygiene

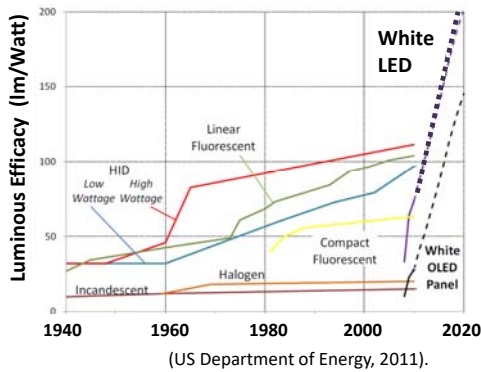
Thus, throughout the year, regardless of weather,

- **3-5 fold light energy use efficiency** for photosynthesis
- Photomorphogenesis and secondary metabolite production
- High-value crop production at high yields

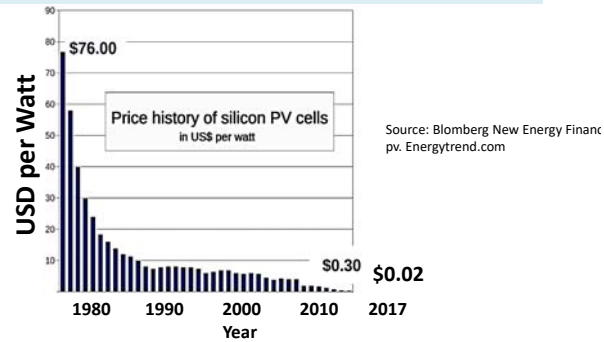
Why artificial light? (2)

- Price of LEDs has been decreasing and its conversion efficiency/efficacy has been increasing.
- The prices of renewable electricity technologies such as solar cells and wind power with batteries, have been decreasing and will continue to decrease.

Historical and predicted luminous efficacy of light sources



Yearly reduction in price of silicon solar cells

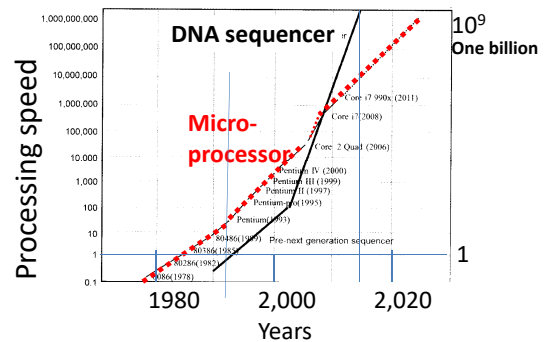


Average battery pack price by year

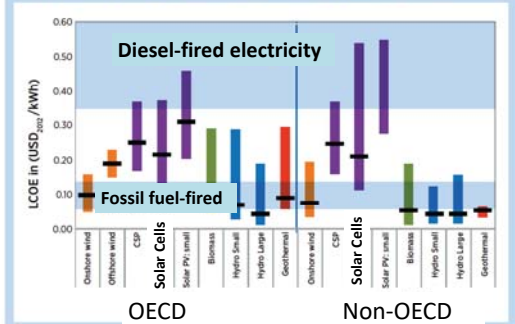


Source: Bloomberg New Energy Finance
 Note: Battery prices are an average of electric vehicle and hybrid electric vehicle packs

Processing speed/US\$ of Computers and DNA sequencers (Wetterstrand, 2011).



Cost of electricity by renewable energy technologies



(International Renewable Energy Agency, 2016 <http://costing.irena.org/>)

Technologies to be implemented in the PFAL

- Energy-efficient and smart LEDs lighting system
- Energy-efficient environment control system for high yield and high quality plants
- Breeding of energy-efficient and high-value health care crops
- Breeding and environment control using AI (artificial intelligence), phenomics, genomics with bioinformatics

Part 2

Basic technologies, concept and methodologies of the PFAL



Published by Elsevier in October 2015

Edited by T. Kozai, G. Niu and M. Takagaki

PLANT FACTORY
An Indoor Vertical Farming System
for Efficient Quality Food Production



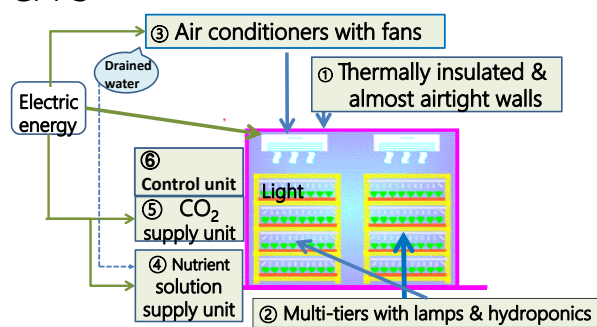
Edited by Toshiaki Kozai, Genhua Niu, Michiko Takagaki

2018/12/14

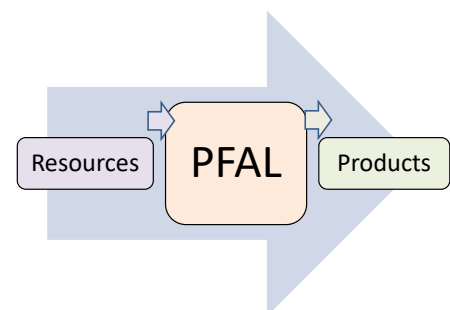
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Six main components of PFAL as in PFAL

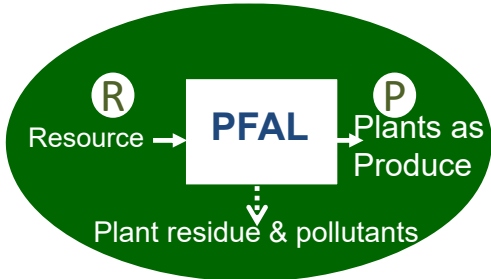
Cost: 3,000 US\$/m² in Japan (50% for facilities)



Scheme for resource supply and product takeout to/from the PFAL



Resource Use Efficiency (RUE) = P/R



Resources: water, CO₂, fertilizer, light energy, seeds, labor etc.

Breakdown of RUE

- 1) Water use efficiency (WUE)
- 2) CO₂ use efficiency (CUE)
- 3) Light energy use efficiency (LUE)
- 4) Electric energy use efficiency (EUE)
- 5) Fertilizer use efficiency (FUE)
- 6) Seed/transplant use efficiency (SUE)

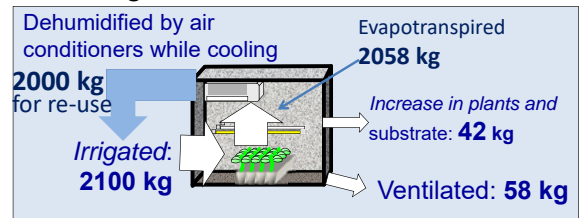
Resource Use Efficiencies (RUE) in the PFAL and greenhouse, and its maximum possible value

Resource	PFAL	Greenhouse	Max. Value
Water	0.96	0.02-0.03	1.0
CO ₂	0.88	0.4-0.6	1.0
Fertilizer	0.80-0.90	0.5-0.7	1.0
Seeds	0.90-0.95	0.8-0.9	1.0
Light energy	0.027	0.017	0.1
Electric energy	0.007	---	0.05

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

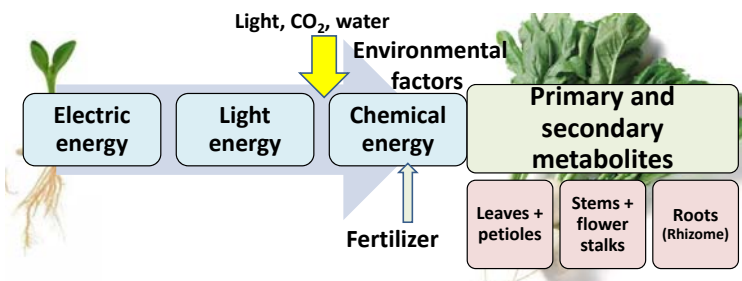
Water utilization efficiency (WUE):

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



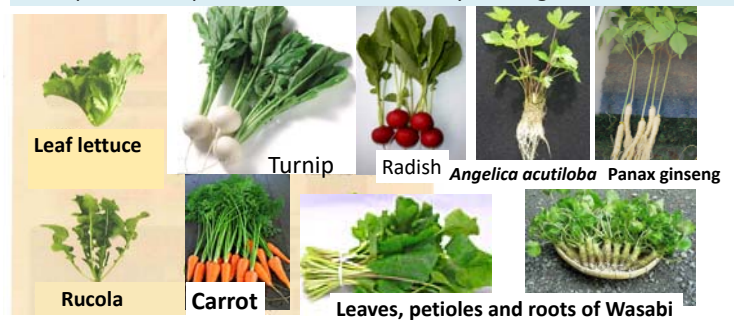
If dehumidified water is not used, the efficiency is 0.02
 (= (2100 - 58 - 2000) / 2100 = 42 / 2100) ⇒ the water needed for irrigation in the CPPS is 1/48 (= 2/97) of that in a greenhouse.
 Ohyama et al. (2002).

Energy and metabolite conversions in the PFAL

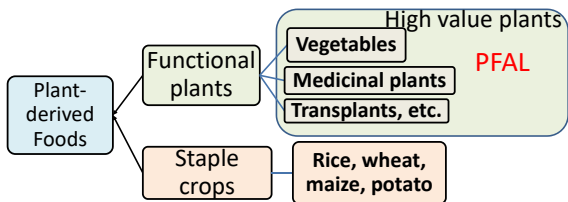


The RUE is the highest when whole plants are marketable.

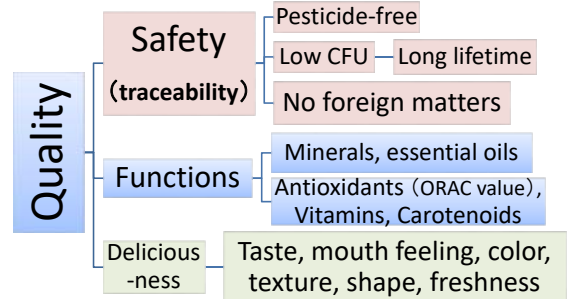
Most part of the plants are marketable only when grown in the PFAL



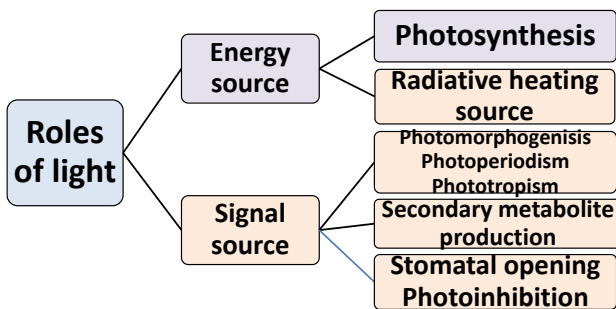
Plants suited to commercial production in the PFAL



Quality of vegetables which can be controlled in the PFAL



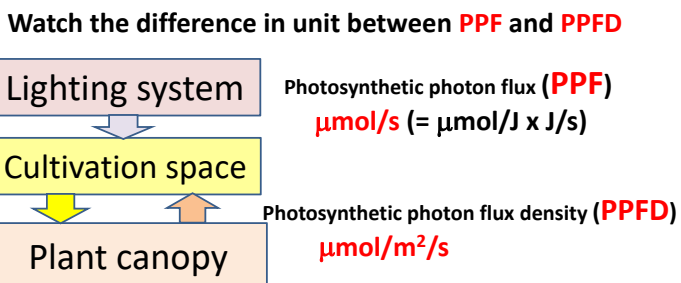
Roles of light for plants



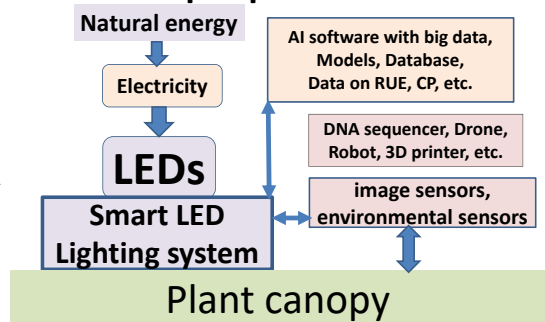
Light environment is characterized by:

- PPFD (photosynthetic photos flux density), Daily integral of PPFD
 - Spectrum (UV, Blue, Green, Red, Far-red, infrared)
 - Lighting cycle (photo-/Dark-periods)
 - Lighting direction (Down-, side- and up-wards)
- and their spatial changes with time

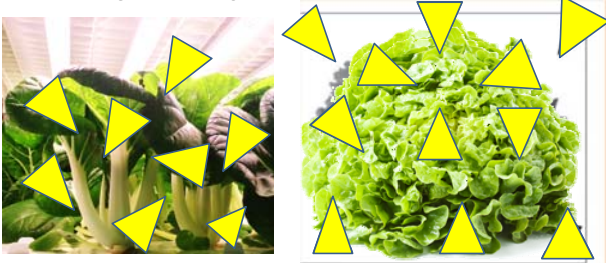
PPFD is affected by optical properties of LEDs, cultivation space and plant canopy



Smart LED lighting system and its peripherals



Photosynthesis of a plant can be maximized by distributing the light energy evenly to all parts of the all leaves



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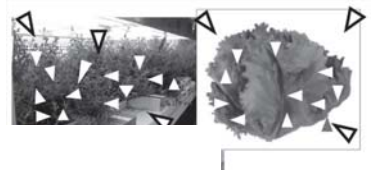
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Light environment inside the plant canopy and headed vegetables, and its effects on chlorophyll synthesis, ascorbic acids, taste, mouth feeling, appearance,

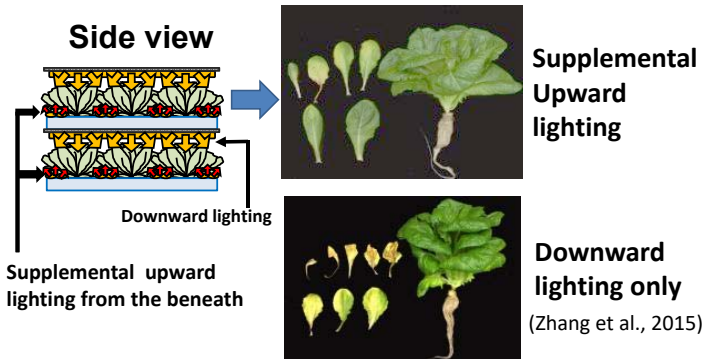
How can we enhance vitamin C synthesis inside the cabbage?



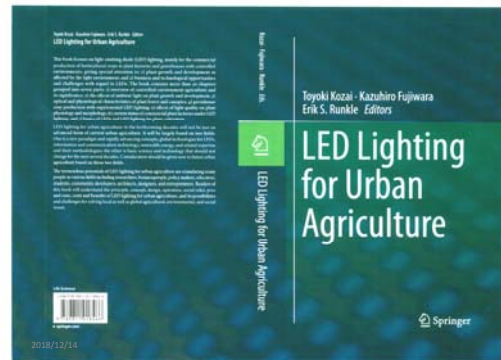
How can we distribute the light energy evenly to all the leaves



Supplemental upward LED lighting in PFAL



LED lighting for Urban Agriculture



Editors
T. Kozai,
K. Fujiwara,
and E. Runkle,
Published in
November 2016
by Springer

2018/12/14

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Part 3
Medicinal plant production

- Oriental medicine
- Healthy vegetables/seasonings
- Healthcare goods/Cosmetics
- Food additives
- Drink additives

CPPS (PFAL) with floor area of 500 m² developed in 2000 at Chiba University, Japan



- Seven tiers with
 - Fluorescent lamps
 - Automatic plug-tray transportation system
 - Automatic precision irrigation system
 - Distributed intelligent control system
 - Total floor area: 500 m²
- Sterilized area (Transfer room, Production room)
Non-sterilized area (Cleaning room, Preparation room, Control room, Research area)

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T. Kozai

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Glycyrrhizia uralensis and St. John's wort (*Hypericum perforartum*)

- Mosaleeyanon, K., S. M. A. Zobayed, F. Afreen and T. Kozai. 2005. Relationships between net photosynthetic rate and secondary metabolite contents in St. Jon's wort, Plant Science (in press)
- Zobayed, S.M.A., F. Afreen, and T. Kozai. 2005. Neccessity and production of medicinal plants under controlled environments, Environ. Control Biol., 43(4): 243-252.
- Zobayed, S. M. A., F. Afreen and T. Kozai. 2005. Temperature stress can alter the photosynthetic efficiency and secondary metabolites concentrations in St.John's wort, Plant Physiology and Biochemistry, 43: 977-984.
- Afreen, F., S.M.A. Zobayed, T. Kozai, 2005. Spectral quality and UB-V stress stimulate glycyrrhizin concentration of *Glycyrrhizia uralensis* in hydroponic and pot system. Plant Physiology and Biochemistry, 43: 1074-1081..
- Couceiro, M.A., F. Afreen, S.M.A. Zobayed, T. Kozai, 2006. Variation in concentrations of major bioactive compounds of St. John's wort: Effects of Harvesting time, temperature and germplasm, Plant Science, 170 (2006) 128-134
- Couceiro, M.A., F. Afreen, SMA Zobayed, and T Kozai, 2006. Enhanced growth and quality of St. John's wort (*Hypericum perforatum* L.) under photoautotrophic *in vitro* conditions. In Vitro Cellular & Developmental Biology – Plant. 42: 1-6.

Glycyrrhizia uralensis and St. John's wort (*Hypericum perforartum*)

- Mosaleeyanon, K., S.M.A. Zobayed, F. Afreen, and T. Kozai., 2006. Enhancement of biomass and secondary metabolite production of St. Jhon's wort (*Hypericum perforatum* L.) under a controlled environment. Environ. Control in Biology. 44(1): 21-30.
- Couceiro, M.A., S.M.A. Zobayed, F. Afreen, E. Goto and T. Kozai. 2006. Optimizing the duration of acclimatization under artificial light for St. John's wort plants grown photoautotrophically and photomixotrophically *in vitro*. Environ. Control in Biology. 44(1): 63-70.
- Zobayed, S.M.A., F. Afreen, E. Goto, and T. Kozai. 2006. Plant-environment interactions: Accumulation of hypericin in dark glands of *Hypericum perforatum*. Annals of Botany. 98, 793-804.
- Afreen, F., S.M.A. Zobayed, and T. Kozai, 2006. Melatonin in *Glycyrrhizia uralensis*: response of plant roots to special quality of light and UV-B radiation, J. Pineal Res., 41(2): 108-115.
- Zobayed, S.M.A., F. Afreen and T. Kozai. 2007. Phytochemical and physiological changes in the leaves of St. John's wort plants under a water stress condition, Environmental and Experimental Botany, 59(2), 109-116.
- Nishimura, T., S.M. Zobayed, T. Kozai, and E. Goto. 2007. Medicinally important secondary metabolites and growth *Hypericum perforatum* L. plants affected by light quality and intensity. Environment Control in Biology, 45(2): 113-120.

Glycyrrhizia uralensis grown for 90 days under colored FL in the CPPS (Afreen, et al., 2005)

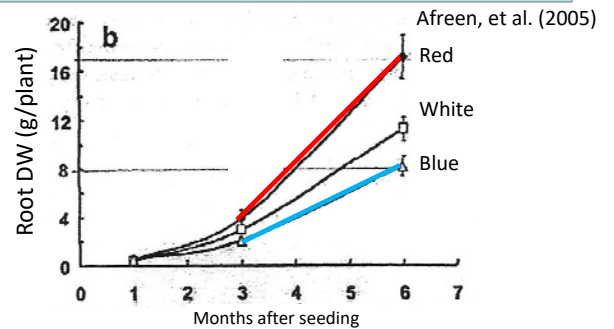
PPF: 300 $\mu\text{mol m}^{-2} \text{s}^{-1}$
RH: 65-70%, CO2 conc. 1000 ppm
Temp. 28/26 C



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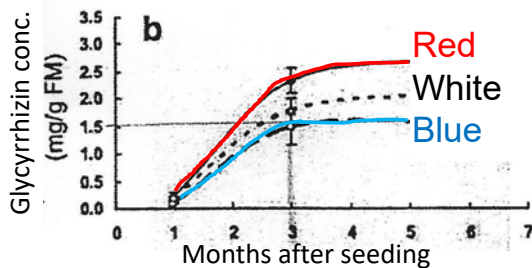
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Root dry weight increase of *Glycyrrhizia uralensis* as affected by red, white (mixed) and blue light



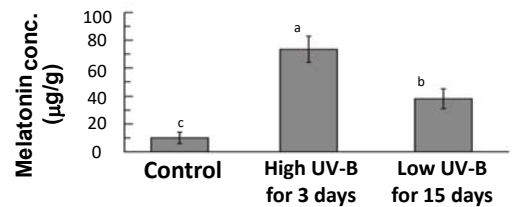
Glycyrrhizin conc. as affected by light quality

Afreen et al (2005)



Melatonin conc. in root of *Glycyrrhizia uralensis* as affected by UV-B irradiation for 3 days at 1.13 W m⁻² and for 15 days at 0.43 W m⁻²

(Zobayed, et al., 2006)



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St. John's wort (*Hypericum perforatum* L.)

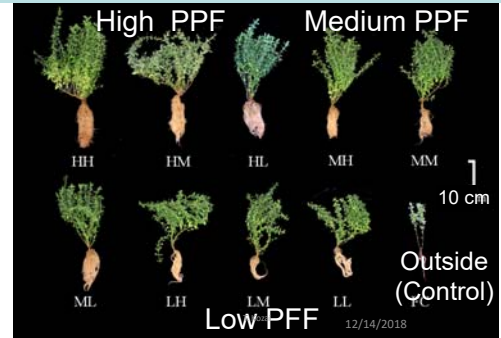
often used as anti-depressant, grown in the CPPS
(Zobayed et al., 2005)



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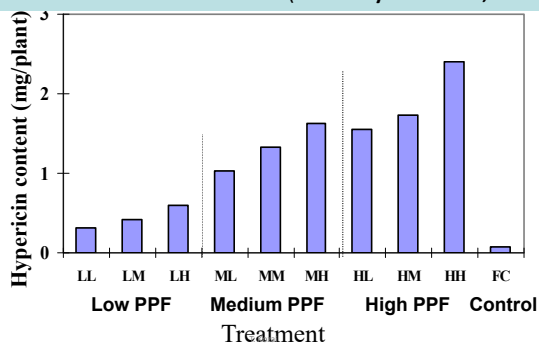
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Hypericum perforatum L. 75 days after sowing as affected by PPF and CO₂ concentration PF: 100, 300 and 600 μmol m⁻²s⁻¹, CO₂ conc.: 500, 1000, 1500 ppm. Mosaleeyanon et al. (2005)



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Hypericin content per plant as affected by PPF and CO₂ concentration (Mosaleeyanon et al., 2005)



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Flower buds of *Hypericum perforatum* L.

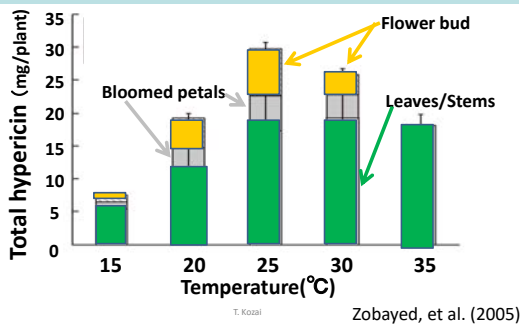


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Flowering *Hypericum perforatum* L.



Total hypericin content per plant in flower bud, bloomed petals and leaves/stems, 85 days after sowing. Temperature treatment was started 70 days after sowing.



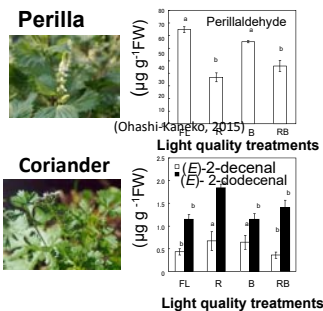
12/14/2018

T. Kobai

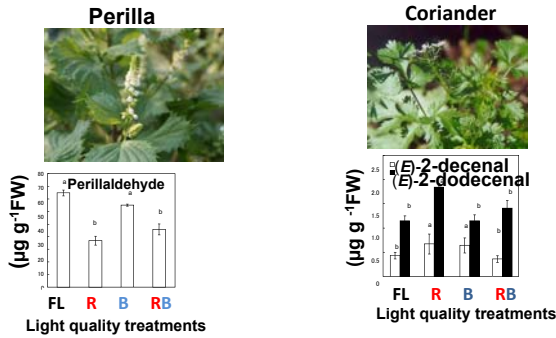
Zobayed, et al. (2005)

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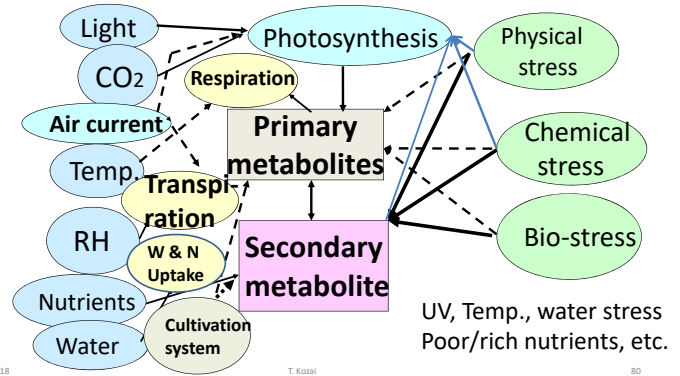
Essential oil concentration in herbs (Perilla and Coriander) as affected by light quality (Ohashi-Kaneko, 2015)



Essential oil concentration in herbs (Perilla and Coriander) as affected by light quality (Ohashi-Kaneko, 2015)

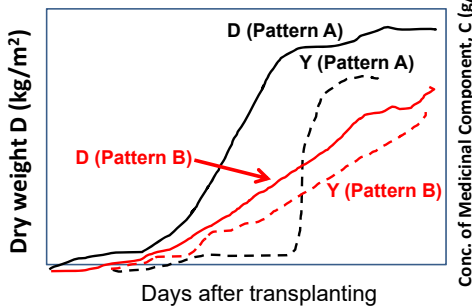


Factors affecting primary and secondary metabolite production



Time courses (Patterns A and B) of dry weight (D) and concentration of medicinal component (C)

Med. Comp. Yield = D x Harvest Index x C



Characteristics of horticultural and medicinal plants/herbs

Factors	Horticultural plants	medicinal plants/herbs
Cultivation methods	Known	Not well-known
Production under CE	Usual	Unusual
Genetic variation of growth	Small (Narrow)	Large (Wide)
Genetic variation of functional components	Small	Large
Market size	Large	Small but will increase

Issues on medicinal transplant production

- **Seedlings**
Large genetic variations of growth and medicinal components
- **(Micro-propagated) cuttings**
Costly ---→ Photoautotrophic (sugar-free medium) micropropagation
- **Issues/benefits common to seedlings and cuttings**
Concentrations of medicinal components and growth rate are affected considerably by the environments
- **Selection of elite plants and breeding are essential.**
- **Plants for PFALS need neither disease nor environmental resistances.**

Glycyrrhiza uralensis transplants grown for 32 days in the CPPS to be transferred to the fields



Angelica acutiloba Kitagawa



Processed roots containing ligustilide as medicinal components



12/14/2018

T. Kozai

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Production of Angelica acutiloba Kitagawa transplants in the CPPS



Germinated seeds are grown for 30 days in plug trays

The plug transplants are further grown for 70 days in pots

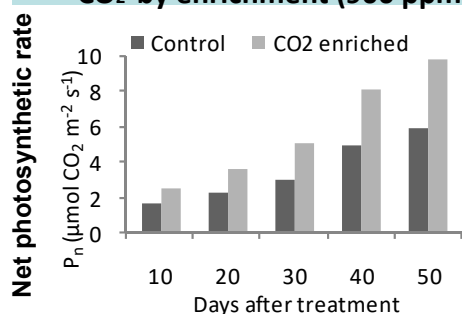
Transplants to be transferred to the fields can be obtained within 105 days after sowing, so that it takes less than one year from sowing to harvesting (after Koyama et al., 2010)

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Promotion of net photosynthesis by CO₂ by enrichment (900 ppm)



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(Koyama et al., 2010)

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Part 4: Next Generation PFAL - Challenges for PFAL to World's Plant Production -

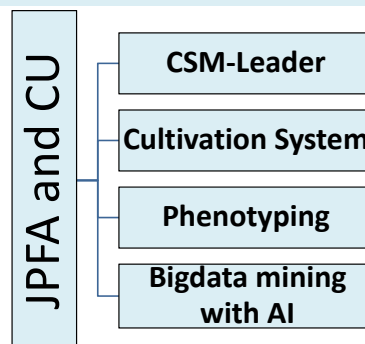
Project started in September 2017: Developments of AI-based phenotyping unit and the basic module for applications in plant factory with artificial lighting (PFAL)

- Japan Plant Factory Association (JPFA)
- Chiba University (CU)
- AIST (National Institute of Advanced Industrial Science and Technology)
- Kajima Corporation

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Cultivation system Module (CSM) Group



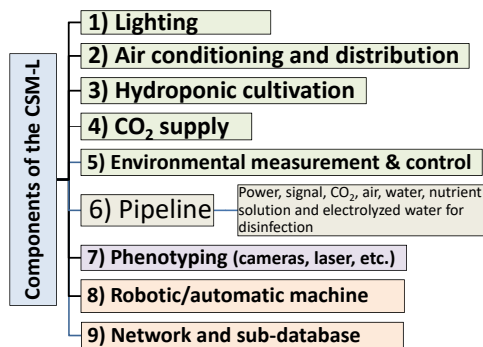
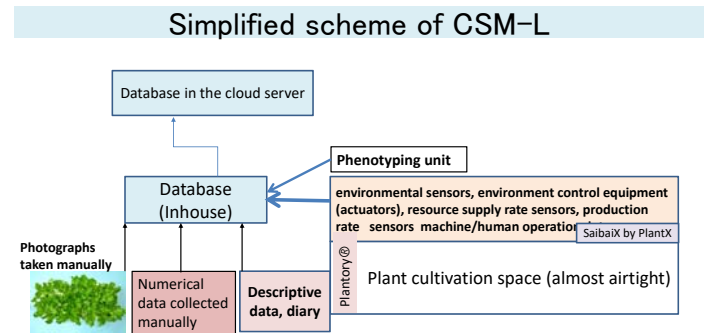
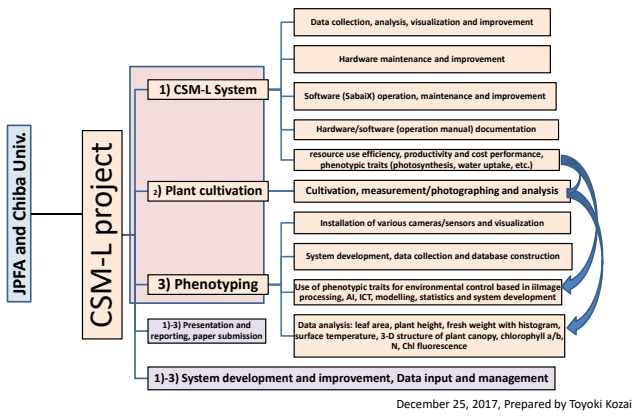


Fig. 4.14 Components installed in the cultivation system module L (CSM-L)

CSM-L: The cultivation rack with 4 tiers is covered with an airtight plastic room, developed by PlantX Corporation.

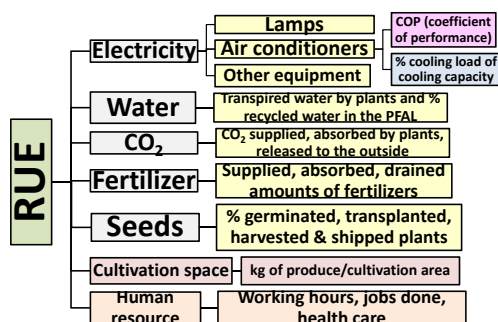
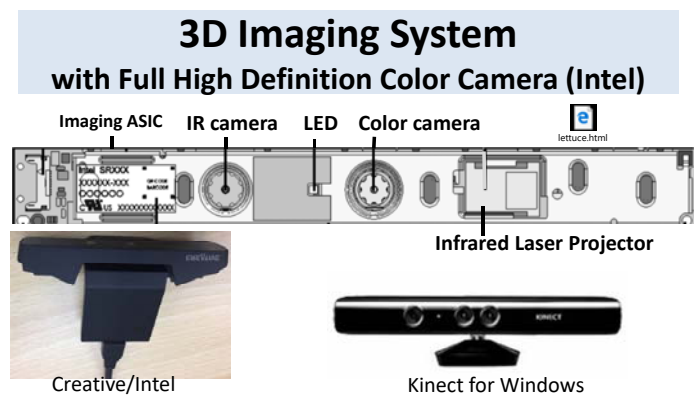
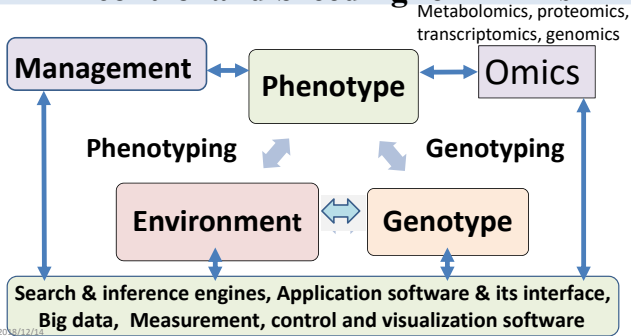


Fig. 20 Resource use efficiencies (RUE) in the CSM-L to be estimated



Phenotyping- and AI-based environmental control and breeding for PFALs



Plant phenotyping is defined as :

Methodologies and protocols to measure a plant specific trait non-invasively (using various kinds of cameras), ranging from the cellular level to canopy level, related to plant structure and function (Ghanem, 2014) .

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Environment control and/or breeding by AI for Function (G, E) using the big dataset of P, G and E

P: **Phenome**, G: Genome, E: Environment

$$P = \text{Function (G, E)}$$

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Typical plant traits for phenotyping

- **3-D plant canopy structure**
 - LAI, leaf angle, projected leaf area, color, No. of leaves spectral reflectance and absorptance
- **Photosynthetic activity**
 - chlorophyll fluorescence (F_m/F_v ; $(F_m - F_m')/F_m'$), stomatal conductance
- **Content/concentration of**
 - water, nitrogen, vitamin C, chlorophyll, N content, etc.

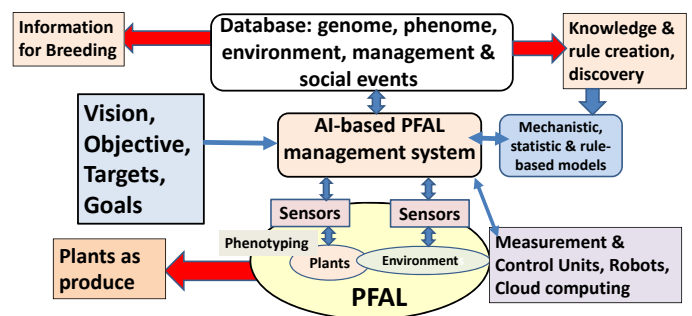
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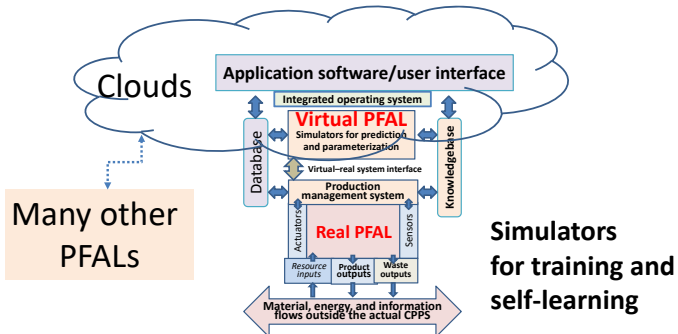
PFALs for Next Generation

- Dual (real/virtual) PFAL
- Multi-layer, ubiquitous PFAL
- PFAL integrated with other biological systems
- Autonomous PFAL with use of natural energy in local, and/or agricultural areas
- Breeding specifically for PFALs with molecular biology
- Integrative bionic sustainable smart city

Image of smart PFAL management system



Dual (Real and Virtual) PFAL and its network



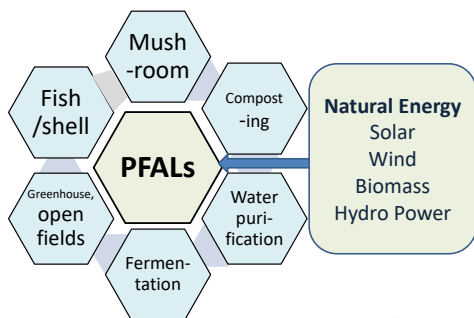
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Multi-layer PFAL users



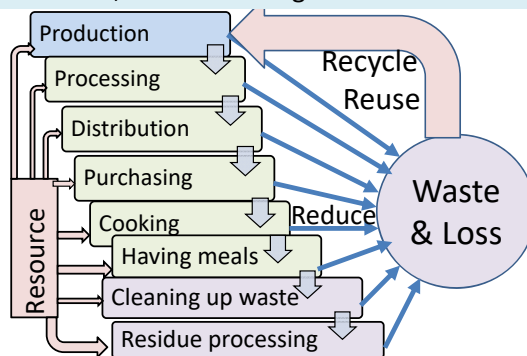
PLALS integrated with other biological systems for sustainable fresh food production in urban areas



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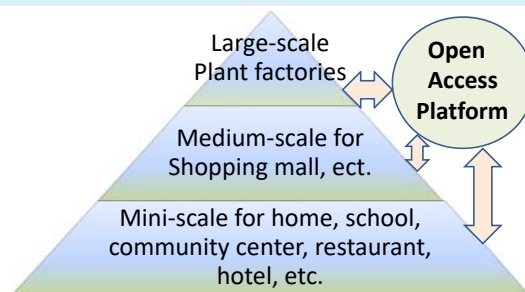
Resource inputs and reduce, reuse & recycling of wastes, and minimizing losses in a food chain



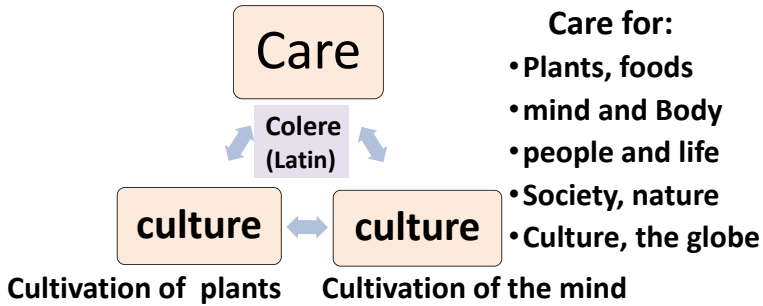
Breeding of plants suited to the production in the PFAL

- Grow fast under low PPFD,
- Grow fast under high CO₂ concentration,
- Easy value-addition by environmental control
- High price per weight,
- High % of marketable portion,
- Short in height,
- High planting density possible,
- Added value for pesticide-free,

Distributed (Ubiquitous) network of PFALs

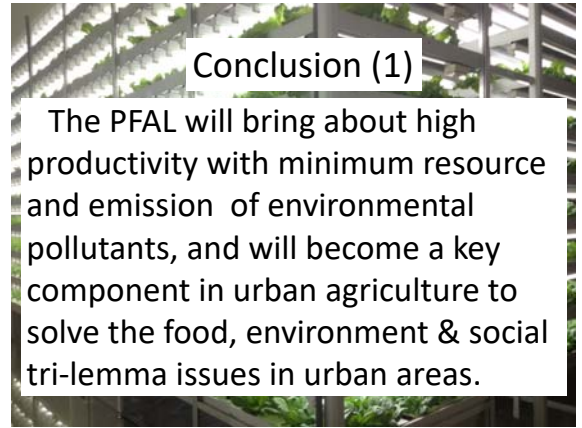


Colele (Latin) as origin of care, culture and culture



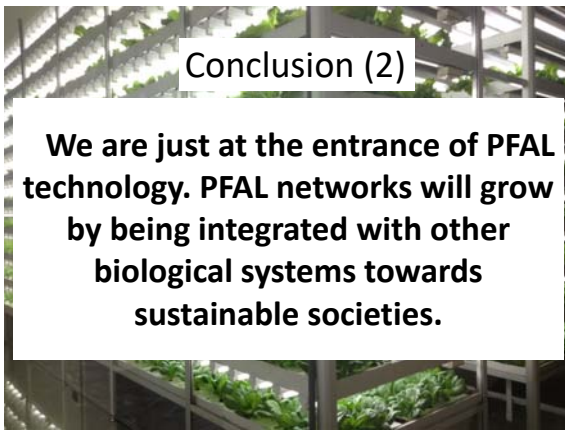
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Conclusion (1)

The PFAL will bring about high productivity with minimum resource and emission of environmental pollutants, and will become a key component in urban agriculture to solve the food, environment & social tri-lemma issues in urban areas.



Conclusion (2)

We are just at the entrance of PFAL technology. PFAL networks will grow by being integrated with other biological systems towards sustainable societies.

Technologies to be introduced in the next-generation smart PFAL

