Role of Plant Factory with Artificial Lighting (PFAL) for sustainable society

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• Why fresh food production in urban areas?
• Current status
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• Advantages and disadvantages
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Four Inter-related global as well as local issues to be solved concurrently

- Decreases in agricultural populations & arable land area
- Quality of Life
  - Nutritious, safe & tasty food
  - Aging society
  - Community
  - Therapeutic space
- Decreases in bio-diversity & green space
- Abnormal weather
  - Environmental pollution
- Shortages of
  - Water, $\text{PO}_4^{3-}$, $\text{K}^+$
  - Fossil fuel
  - Biomass

Food, Agriculture

Climate change

Ecosystem

Environment

Society, Economy

Resource, Energy
Our Mission is:

to develop economically feasible plant production systems which achieve:
a maximum production of highest quality plants with minimum yield variation,
using minimum amounts of resources, leading to highest resource use efficiencies, minimum costs and pollutant emission, for human welfare and global as well as local sustainability.
Why fresh foods in urban areas using PFALs?

• The population in urban areas will keep increasing, and will reach 70% of world population in 2050.
• The population in agricultural areas will keep decreasing, with aged farmers/growers.
• We need to produce and deliver foods with less water, less fossil fuel and less fertilizer.
• Also, we need to reduce the resources to process the foods after harvest, if fresh foods are tasty and good for our health, and environmentally friendly.
By producing fresh foods in urban areas:

• Much fossil fuels for the transportation and refrigeration are saved, with less traffic and less CO$_2$ emission. Traffic jams and accidents are reduced.

• Job opportunities are created, and vacant spaces can be used. Local production for local consumption is achieved,

• Citizens can enjoy ‘fresh’ foods, and growing them.

• Wastes (waste water, garbage, CO$_2$ etc.) can be used as essential resources (water, fertilizer, CO$_2$, etc.) for plant production.

• Nighttime (surplus) electricity can be used for lighting and air conditioning.
Resource in-flows and waste out-flows in urban areas

**Resource in-flows**
- Water
- Fossil Fuel
- Food
- Products
- Materials

**Urban areas**
- Food processing
- Living space
- Factory space
- Amenity space
- Business space
- Public space

**Waste out-flows**
- Heat
- CO2
- Waste water
- Garbage, other wastes

**Resource in-flows**
- Vehicles/Personnel

**Resource out-flows**
Components of Urban agriculture

- Plant factory with artificial lighting (PFAL)
- Greenhouse with/without supplemental artificial lighting (including rooftop one)
- Protected cultivation (mulched, netted screen, tunnel)
- Open fields (including roof top gardens)
Current status of PFALs
A PFAL with LEDs lighting, Mirai Co. Ltd.

Annual production capacity
2,500 lettuce heads/m²
Sales: 2,500 US$/m²

The PFAL with LEDs in Japan by Mirai Co. Ltd.
The largest PFAL in Japan built in 2006, producing 23,000 leaf greens daily

Spread Co. Ltd. Kyoto, Japan
Six main components of PFAL as CPPS

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

① Air conditioners with fans
② Thermally insulated & almost airtight walls
③ Multi-tiers with lamps & hydroponics
④ Nutrient solution supply unit
⑤ CO₂ supply unit
⑥ Control unit

Drained water

Electric energy

Light
Leafy vegetables/herbs currently produced commercially in PFAL

- Grow under low PPFD,
- Short in height,
- High price per weight,
- High % of salable portion,
- High planting density,
- Added value for pesticide-free.

Price (Euro) per kg
- Leaf lettuce 7
- Basil 20
- Coriander 35
- Peppermint 60
- spearmint 60

Low potassium leaf lettuce, rocket (*Eruca sativa*), watercress, parsley 30 Euro
Whole plants of root vegetables and medicinal plants are edible/salable when grown in PFALs.

- Turnip
- Radish
- Angelica acutiloba
- Panax ginseng
- Carrot
- Leaves, petioles and roots of Wasabi

Both shoots with leaves and roots are edible, tasty and nutritious.
Plants which suited to commercial production using PFAL

- **Staple foods**
  - Rice
  - Wheat
  - Corn
  - Potato, etc.

- **Functional foods**
- **Vegetables**
- **Herbs**
- **Medicinal plants, edible flowers**

PFALs cover a small portion of agriculture.

*PFAL* stands for *Plant Derived Functional Ingredients for Agricultural Livelihoods*. This concept focuses on the commercial production of high-value plants using PFALs.
The number of PFALs in Japan by year

Year (2009 – 2016)

No. of PFALs

2009: 34
2011: 64
2012: 106
2013: 125
2014: 165
2015: 185
2016: 191
Initial & production costs by components

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

Consumables, Packing, shipping, transportation 12%
Depreciation 23%
Electricity 28%
Labor 26%

Consumables 3%, Seeds 2%, Repair 2% Supplies 1%, Water 1%, Land rental 1%, Miscellaneous 1%, Land rental 1%

Ohyama (2015)
Is PFAL business profitable in Japan?

- Currently, 30% of PFAKs only is making profits, 50% is break-even, and 20% is loosing money.
- It should be noted, however, the economic profitability will be much higher in 2020-2025 than in 2016.
PFAL business can be profitable only when the PFAL is:

• Well designed,

• Operated by a well-educated, well-trained high-skill manager, with respect to managements of environment, workers and production process

• Almost all produce can be sold because of its quality and delivery as scheduled under reasonable marketing.
Components of PFAL Technology

PFAL Technology

- Energy and material flows
- Communication (Information flow)
- Transportation logistics
- Biosystems-engineering

Market, Social needs
Strength of PFALs (1)

Resource consumptions in the PFAL are reduced considerably, compared with those in the greenhouse

- Pesticide by 100% (clean room),
- Water by 95% (recycling),
- Land area by over 90% (multi-tiers, etc.),
- Fertilizer by 50% (no drainage),
- Labor hours by 50% (small area, etc.),
- Plant residue by 50% (Environ. Control)
- Variations of yield & quality by 50% (CPPS)
Strength of PFAL (2)

• Clean, so that no need to wash before eating fresh
• Longer duration of life due to very low population of microorganisms on leaves
• Plant growth & quality of produce are not affected by weather, soil fertility, pest insects.
• Comfortable working condition,
• Taste, nutrition, flavor & mouth feeling can be modified by environment control.
• Production cost of leaf vegetables can be competitive in price against imported ones
• Almost perfect traceability from seeding to harvesting.
Estimated relative annual productivity of PFAL by its components, compared with those in the open field.

<table>
<thead>
<tr>
<th>No.</th>
<th>Magnification by PFAL compared with the open fields</th>
<th>Component Factor</th>
<th>Multiplied Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15-fold by use of 10 tiers</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>2-fold by shortening the culture period by means of optimal environment control</td>
<td>2</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>2-fold by transplanting seedlings one day after harvest all year round assuring no time loss</td>
<td>2-3</td>
<td>60-90</td>
</tr>
<tr>
<td>4</td>
<td>1.5-fold by increased planting density per cultivation area</td>
<td>1.5</td>
<td>90-135</td>
</tr>
<tr>
<td>5</td>
<td>1.5-fold per cropping by no damage due to abnormal weather &amp; outbreak of pest insects</td>
<td>1.5</td>
<td>135-202</td>
</tr>
<tr>
<td>6</td>
<td>1.3-fold sales price due to improved quality and less loss of produce after harvest</td>
<td>1.3</td>
<td>175-263</td>
</tr>
</tbody>
</table>
Research on quality of vegetables has been conducted intensively from different aspects:

**Quality**

- **Safety** (traceability)
  - Pesticide-free
  - Low CFU
  - Long lifetime
  - No foreign matters

- **Functions**
  - Minerals, essential oils
  - Antioxidants (ORAC value), Vitamins, Carotenoids

- **Delicious-ness**
  - Taste, mouth feeling, color, texture, shape, freshness
Vitamin C (L-ascorbic acid) in leaves as affected by light quality (white, red, red/blue and blue) (Ohashi-Kaneko, 2015)
Essential oil concentration in herbs (Perilla and Coriander) as affected by light quality (Ohashi-Kaneko, 2015)

Perilla

Coriander

![Chart showing essential oil concentration in Perilla and Coriander](chart.png)
An ongoing social experiment in Kashiwa-no-ha smart city with urban agriculture, in corporation with Chiba University and Japan Plant Factory Association.

Towards changes in life style and social infrastructure for sustainable societies.
A smart city with urban agriculture
Kashiwa-no-ha, the suburb of Tokyo

- Organic Community Garden & Restaurant
- Rooftop Farm
- PFAL Vegetables in Supermarket
- Bee Culture Garden
- Small PFAL in Shopping Center
- PFALs
- Power System (Solar, Wind, Storage Battery)
- Greenhouse Cultivation
- Medicinal Plant Cultivation
- Herbal Clinic

Our Campus
Smart city with urban agriculture

- Rooftop farm, organic city farm, organic restaurant
- Mini PFALs at the shopping center, food shop, café restaurant, hotel restaurant,
- PFALs of Mirai, Japan Dome house and Wago
- Household PFAL
- Greenhouses at Chiba Univ.,
- Solar panel & wind power generation, Batteries
- Oriental medicine clinic, acupuncture clinic, herb garden
- Honey bee house
Smart Building with solar panels, wind power generation, and green walls
PFALs in Kashiwa-no-ha town of different sizes for different purposes

10,000 heads/d

3,000 heads/d

700 heads/d

CPPS for Seedling Production

Hotel Restaurant

Home-use
Since 2014
1,400 m²
11-14 layers
10,000 heads/day
PFAL at Chiba University built in 2010.
Floor area of culture room: 338 m², 10 tiers, 9 rows

Operated by Mirai Co. Inc.

Leaf lettuce

3,000 heads/day
One M heads/y

2,800 heads/m²/y
Leaf lettuce grown in PFAL at Chiba Univ. produced by Mirai Co. Ltd. for sale at a supermarket

Romaine lettuce  1.4 Euro/bag (70-80 g)
PFAL technology based on ‘Cloud Computing’

Cloud System

By the courtesy of PLANTX
Visualized daily report of power consumptions by components on the computer display screen for the PFAL manager as a daily report.

- **Menu bar**
- **Equipment type & data**
- **Current time, date & year**
- **Alert & Message**
- **Current power consumption (kW)**
- **Layout of culture room**
- **Percent power consumption by components**
- **Measured numerical data**
- **Power consumption integral (kWh)**
- **Predicted % power consumption this month by components**
- **Time course of power consumption by components**

SaibaiX by Plantx Inc.
Japan Dome House, Inc., Kashiwa
Inside View of PFAL, Japan Dome House, Kashiwa
A CPPS (closed plant production system) for production of transplants with a floor area of 16 m². In 2014, about 300 units of CPPS are in use at 130 different locations in Japan.

Mitsubishi Chemicals Inc.

Four layers, 2 rows, holding 96 plug trays
A household plant factory connected with Internet for SNS by Panasonic Inc.
Household PFAL network for SNS via Internet

- Technical support: MIRAI
- Website: CHIBA UNIVERSITY

Panasonic

Family A
- Mitsui Real Estate Co.
- Smart plant factory network

Family B
- SNS Club
- Party
- Seminar
- Meeting

Family C

Chiba University
- Large-scale plant factory

LalaPort Kashiwa-no-ha shopping center
http://www.miraibatake.ne
Bookshelf-type PFAL at coffee shop in Kashiwa, Chiba

Café Restaurants Agora
Further applications with support of Japan Plant Factory Association and Chiba University
PFAL connected with mushroom factory operated by ‘Japan Dome House’ in Fukushima Pref., Japan
In the lobby of Sakakibara Memorial Hospital
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)
Plant factory for next generation
PFALs for Next Generation (1)

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

- Professional Growers/farmers
- Farming as side-business/2nd job
- Hobby, amateur, volunteer
- Beginners, Children
Distributed (Ubiquitous) network of PFALs

- Large-scale Plant factories
- Medium-scale for Shopping mall, etc.
- Mini-scale for home, school, community center, restaurant, hotel, etc.

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

PFALs

- Mushroom room
- Fish/shell
- Greenhouse, open fields
- Fermentation
- Composting
- Water purification

Natural Energy
- Solar
- Wind
- Biomass
- Hydro Power
Resource inputs and reduce, reuse & recycling of wastes, and minimizing losses in a food chain.
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.
We are just at the entrance of PFAL technology. PFAL networks will grow by being integrated with other biological systems towards sustainable societies.
Improvements of PFALs
How can we overcome the weakness of PFAL

• High initial (building and facilities) costs
  - Improve the cultivation system and its components

• Environmental control & its visualization and analysis
  - Reduce electricity cost
  - Increase the plant growth rate
  - Increase the economic value of produce
  - Increase salable or edible portions of plants

• Human operations
  - Automation and improvements of production process
  - Computer software development, IT, AI and IoT
  - Human resource development

• Marketing, market creation, new life style creation
Methodology for improving resource use efficiency and cost performance in PFALs

- resource use efficiency (RUE)
- cost performance (CP)
  - economic value per weight
  - salable portion of plants
Resource Use Efficiency (RUE) = P/R

Higher the RUE, higher the economic feasibility & sustainability

Resources: water, CO₂, fertilizer, light energy, seeds, labor etc.
• **RUE (Resource Use Efficiency)**
  Resource fixed by produce/Resource supplied

• **CP (Cost Performance)**
  Economic value produced/cost of resource

• **CV (Coefficient of variation)**
  Standard variation of production /Its average

• **CPPS (Closed Plant Production System)**
  PFAL is Perfect CPPS when RUE=1
Breakdown of RUE

1) Water use efficiency (WUE)
2) CO$_2$ 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)
7) Coefficient of performance of heat pumps (COP)
WUE, CUE and LUE are significantly greater in PFAL than in the greenhouse

<table>
<thead>
<tr>
<th>Use Efficiency</th>
<th>PFAL</th>
<th>Greenhouse</th>
</tr>
</thead>
<tbody>
<tr>
<td>WUE (water)</td>
<td>0.96</td>
<td>0.02-0.03</td>
</tr>
<tr>
<td>CUE (CO₂)</td>
<td>0.88</td>
<td>0.4-0.6</td>
</tr>
<tr>
<td>LUE (light energy)</td>
<td>0.027</td>
<td>0.017</td>
</tr>
<tr>
<td>EUE (electricity)</td>
<td>0.007</td>
<td>------</td>
</tr>
</tbody>
</table>

Ohyama et al. (2002; 2005; 2006); Yokoi et al. (2005)
Water use efficiency (WUE)

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

Dehumidified by air conditioners while cooling

- **2,000 kg** for re-use
- **Irrigated**: 2,100 kg
- **Ventilated**: 58 kg
- **Evapotranspired**: 2,058 kg
- **Increase in plants and substrate**: 42 kg

If dehumidified water is not used, the WUE is 0.02

\[=\frac{(2100 - 58 - 2000)}{2100} \Rightarrow \text{the water needed for irrigation in the CPPS is 1/48 (=2/97) of that in the greenhouse.}\]

Ohyama et al. (2002).
Light Energy Use Efficiency (LUE) can be more than doubled in PFAL.

- Electric Energy
- Photosynthetically active radiation (PAR)
  - PAR received by crop leaves
  - PAR fixed by plants as chemical energy

Heat energy:
- About 70%
- About 29%
- Lower than 1%

100%
Current PFAL consumes much electricity for lighting and cooling.

Light source, lighting and culture systems, and new cultivar (by breeding) need to be newly developed. High value crops needed.