We developed two types of closed systems with lamps for commercial production of high quality transplants, using minimum electricity, water, CO$_2$ and labor in a reduced floor area.
External View of Closed System A at Chiba Univ.

Internal View of Closed System A
Automatic Transporter in the Middle
Closed System B

- Internal View of Closed System B
  - 3-4 modules/system
  - 4 shelves/module
  - 4 trays/shelf
  - 16 trays/module
  - 48-64 trays/system

A Module

Internal View of Closed System B
Definition of “Closed Transplant Production System”:
1) Covered with opaque thermal insulators,
2) Ventilation is minimized,
3) Artificial light only.

Increase in yearly productivity per floor area of the closed system is about 7 times that of the greenhouse.

- Planting Area: 2-3 Times
- Planting Density: 2 Times
- % Reduction in Production Period: 30%
- % Increase in Salable Plants: 10%
- \(2.5 \times 2.0 \times 1.3 \times 1.1 = 7\)
Increased Production Area per Floor Area
7 Shelves/Module
8 Trays/Shelf
560 Trays
Shelves/Floor
Area Ratio=2.3

High Density Planting Possible
288-Cells/Tray, 144-Cells/Tray
12 Days after Sowing
Tomato Seedlings 14 days after Sowing by Planting Density

Low Density

High Density

Air Flow Pattern in Closed System A

Air conditioner

Fluorescent lamps

Fans

Trays

128-Cell

200-Cell

288-Cell
Moderate and uniform airflow over/within the transplant canopy makes the transplants vigorous and grow fast even at high planting density.

- Uniform environments over the trays
- Reduced relative humidity
- Enhanced CO2 and H20 exchanges
- Light penetration to the bottom due to fluttering of leaves by breathing air

Uniform Distribution of Air Temp.

<table>
<thead>
<tr>
<th>Shelf No.</th>
<th>Light (°C)</th>
<th>Dark (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>26.0 ± 0.1</td>
<td>16.7 ± 0.0</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Ave. ± S.D.

Light: 26.0 ± 0.1°C
Dark: 16.7 ± 0.0°C
Uniform Distribution of PPF

Ave. ± S.D.
241 ± 6
μmol m⁻² s⁻¹

Shelf No.
7
6
5
4
3
2
1

0 100 200 300
PPF (μmol m⁻² s⁻¹)

Uniform Growth of Tomato Seedlings 20 days after Sowing
Rapid Growth: Sweetpotato Transplants 14 days after Transplanting Single Node Cutting

Day 0

Day 14

Uniformity of Growth over Shelves

C. V.: 4.9%

Shelf No.

0 200 400

Dry Weight (mg)
Sweetpotato transplants 14 days after transplanting in the closed system

Rapid Growth

Value-added transplants
1) Pathogen and pest insect free sweetpotato,
2) Tomato, pansy, eggplant with enhanced flower bud development,
3) Spinach with delayed bolting,
4) Vigorous Chinese cabbage,
5) Vigorous grafted tomato, etc.
Uniform/Vigorous Growth of Pansy with High Percent of Salable Transplants

Closed System  Greenhouse

Rapid Growth of Pansy Transplants 29 days after Sowing

Closed system  Greenhouse
Early Flowering of Pansy Transplants at Shipping, Grown in the Closed System

64 Days after Sowing

Closed System Greenhouse

Initial Investment Cost?
Main Components of the Closed System

- A warehouse-like structure covered with opaque thermal insulators,
- Modules each consisting of multi-shelf having fluorescent tubes and their fixtures,
- Air conditioners, fans, and
- A CO₂ supply unit.

Main components of the closed system:

- Mass-produced,
- Recycling system is established,
- 50-80% discount is common by a bulk purchase,
- Steady and significant technical advancement and price-reduction year by year.
Components unnecessary in the closed system, but often necessary in the greenhouse:

- Thermal/shading screens
- Roof/side/fan ventilators
- Heaters, Benches/Beds
- Transparent covers (Glass/Film)
- Evaporative cooling systems

Components Common to the closed system and the greenhouse

- Irrigation unit
- Environmental control unit
- (CO2 supply unit)
After all, the initial investment cost for the closed system which floor area is about 15% of that of the greenhouse can be lower than the cost for the greenhouse.

Costs for Heating, Cooling, Ventilation, CO$_2$ Enrichment, and Irrigation?
Heating cost is almost zero even during the winter in northern countries, because all the walls/roofs of the closed system are covered with 15 cm-thick thermal insulators.

In northern countries, the supplemental artificial light energy over (natural + artificial) light energy in the greenhouse accounts for 30-50% during the winter. To use such natural light, much fuel is used for heating.
Cooling load of the closed system is almost equal to the heat generated by lamps only, because heat enters into the closed system from outside is negligibly small due to its thermally insulated structure.

Cooling cost is 25% of lighting cost even during summer in subtropical countries, because C.O.P. of recent air conditioner is higher than 4 under summer condition.
Percentages of Electric Energy Consumption by the Components of the Closed System A

Lamps : 78 %
Air Conditioner: 17 %
Fans etc. : 5 %

When lamps are ON, air conditioner is also ON for cooling, which results in dehumidification or collection of condensed water at cooling panels of air conditioner.
Thus, relative humidity in the closed system naturally tend to be 60-70% during photoperiod when transplants are grown.

Since ventilation is minimized in the closed system, its initial and operation costs for ventilation is nearly zero.
Utilization efficiencies of water, CO$_2$, electric energy and PAR energy are significantly higher in the closed system than in the greenhouse.

Water utilization efficiency

\[
\text{Irrigated: } 1667 = \frac{\text{Dehumidified + P + S}}{\text{Irrigated}} = 0.985
\]

Dehumidified for Re-use: 2014

P: 42
S: -414

Ventilated: 39 (Unit: kg)

P: Increase in plants
S: Increase in substrate
By recycling the dehumidified or evapotranspirated water for irrigation, net water consumption of the closed system is reduced to a few percents of that in the greenhouse.
**CO₂ utilization efficiency**

\[
\text{utilization efficiency} = \frac{\text{Fixed}}{\text{Supplied}} = \frac{192}{221} = 0.87
\]

**Energy utilization efficiency**

\[
\text{utilization efficiency} = \frac{\text{Chemical Energy Fixed}}{\text{Electric Energy Supplied}} = 0.0038
\]
PAR Energy Utilization Efficiency

\[
\text{Chemical Energy Fixed} = \frac{\text{Chemical Energy Fixed}}{\text{PAR from Lamps}} = 0.029
\]

Supplied: 4000

Released as Heat: 3884

Fixed as Chemical Energy: 116 (Unit: MJ)

PAR and Electric Energy Efficiency as affected by LAI

\[
\begin{align*}
\text{Energy Efficiency, } \% & = 12.0 \\
\text{Leaf Area Index} & = 0, 1, 2, 3 \\
\text{PAR} & = 11\% \\
\text{Electric} & = 1.6\%
\end{align*}
\]
CO₂ and electric energy efficiencies of the closed system are about 2 times those in the greenhouse.

Electric energy required for lighting is small, because

1) PPF is 200-300 µmol m⁻²s⁻¹,
2) Production period is 15-30 days,
3) Planting density is 400-1000 plants m⁻²,
4) Transplants are placed 20-30 cm below fluorescent lamps.
• PPF of 250 mol μm\(^{-2}\)s\(^{-1}\) can be obtained by six 40 W FL tubes 40 cm above the trays. Its integrated PPF over 16 h is 16.4 mol m\(^{-2}\), which is equal to the daily integral of PPF on a fine day in September in Tokyo.

Electricity cost to produce a single node cutting of sweet potato:

\[370 \text{ kJ} = 0.11 \text{ kWh} \]
(or 1 US Cents)

A virus-free transplant of sweet potato is about 1 US $ in Japan
Price of Electricity per KWh by countries in US cents

- Japan: 15-20
- USA: 8-12 ?
- Canada: 5-8 ?

Labor cost can be lowered in the closed system because its working area is 15% of the greenhouse area, and its provide comfortable working environment.
Conclusions

• Quality/productivity of transplants produced in closed systems are high.
• The closed systems is energy and material efficient and environmentally friendly.
• Initial/operation costs of the closed system can be lower than that of the greenhouse, and it will be commercialized.

Acknowledgement

• C. Kubota
• M. Nishimura
• S. Yokoi
• M. Hasegawa
• M. Fujiwara
• Taiyo Kogyo Co.
• Technova Inc.
• Toyota Motor Co.