Current Situations of Korean Strawberry Industry and Strawberry Transplant Propagation Using Plant Factory Technology

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Strawberry industry in Korea (in 2017)

- 209,000 tons (Fruit yield)
- 1.2 billion USD (Production value)
Whole sale price

- Season is critical (earlier and earlier!!) for fruit price.
- Competition with Korean melon & watermelon after March
- Almost 100% in greenhouses

Whole sale price in Seoul

KRW/kg

Nov         Dec          Jan          Feb          Mar          Apr          May

Seolhyang

Akihime

Red pearl

KW/kg

15 USD/kg

15,000

12,000

9,000

6,000

3,000

0
Multi-layered plastic greenhouses for strawberry production

- + Water curtain system
- +/- Heating systems (boilers and/or heat pumps)
Predominant Korean-bred Cultivars

40 domestic cultivars were bred and registered since 2004.

4% in 2004 → 92% in 2018

Foreign cultivars

Akihime 4.8%
Others 3.2%

Seolhyang 83.6%
Jukhyang 5.0%
Maehyang 3.3%
Others 3.3%

(RDA, 2017; KATI, 2018)
Establishment of Propagation and distribution system in Korea

- Operated since 2011, a public-private cooperative system
• It requires ca. 600 million transplants per year.
• It is necessary to establish a rapid propagation and distribution system, especially when new promising cultivars are bred.
Low propagation rate of transplants in the conventional methods (25-30 transplants from a mother plant per year) is a major problem for rapid distribution of newly-bred cultivars.
Structural and functional elements of PFAL (Plant Factory using Artificial Lighting)

- Thermally insulated warehouse-like structure
- Multiple racks (ca. 40 cm between racks vertically) equipped with lighting devices
- Air conditioning facilities
- CO₂ delivery system
- Fans for circulating room air
- Nutrient solution delivery system
PFAL for strawberry transplant production (S-PFAL system)

Seoul National Univ., Korea
S-PFAL for producing elite and pre-basic transplants

- **Nuclear transplants**
  - 1 propagule
  - Breeders

- **Elite transplants**
  - 20 propagules
  - Provincial Ag. Research Centers

- **Pre-basic transplants**
  - 500 propagules

- **Basic transplants**
  - 15,000 propagules
  - Municipal Ag. Extensional Stations / Registered Nurseries

- **Disseminative transplants**
  - 450,000 propagules
  - Growers
Long day condition
(photoperiod of $16 \text{ h d}^{-1}$)

Hancock, 1999
Warm air temperature
(air temperature of 26/23°C, photo- / dark periods)

Hancock, 1999
Light intensity

PPF of 240 μmol·m$^{-2}$·s$^{-1}$

Kim et al. 2010.
### CO₂ Concentration of 900 μmol·mol⁻¹

<table>
<thead>
<tr>
<th>CO₂ (ppm)</th>
<th>Runner number per plant</th>
<th>Total runner length per plant (cm)</th>
<th>Average runner length (cm)</th>
<th>Daily growth of runner length (cm plant⁻¹ d⁻¹)</th>
<th>Daughter plant number per plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>4 ± 1d</td>
<td>164.5 ± 12.8d</td>
<td>45.4 ± 5.1a</td>
<td>3.29 ± 0.26d</td>
<td>2 ± 1b</td>
</tr>
<tr>
<td>450</td>
<td>6 ± 1c</td>
<td>258.1 ± 19.3c</td>
<td>43.5 ± 4.9a</td>
<td>5.16 ± 0.39c</td>
<td>4 ± 1c</td>
</tr>
<tr>
<td>600</td>
<td>8 ± 1b</td>
<td>351.7 ± 15.1b</td>
<td>42.3 ± 1.6a</td>
<td>7.03 ± 0.30b</td>
<td>6 ± 1b</td>
</tr>
<tr>
<td>750</td>
<td>10 ± 2a</td>
<td>419.1 ± 70.6a</td>
<td>43.2 ± 5.3a</td>
<td>8.38 ± 1.41a</td>
<td>8 ± 1a</td>
</tr>
<tr>
<td>900</td>
<td>11 ± 2a</td>
<td>465.4 ± 61.0a</td>
<td>44.9 ± 3.7a</td>
<td>9.31 ± 1.22a</td>
<td>9 ± 2a</td>
</tr>
<tr>
<td>R</td>
<td>0.942</td>
<td>0.942</td>
<td>-0.045</td>
<td>0.942</td>
<td>0.960</td>
</tr>
</tbody>
</table>

Chun et al, 1997
Fertigation

- Sub-irrigation for ca. 10 minutes, twice a day
- Modified Yamazaki’s nutrient solution for strawberry
  \((2 \text{ N}, 1.5 \text{ P}, 3 \text{ K}, 2 \text{ Ca}, 1 \text{ Mg}, \text{ and } 1 \text{ S} \text{ me} \cdot \text{L}^{-1}; 0.7 \text{ mS} \cdot \text{cm}^{-1})\)

Chun et al, 2011
Can a young runner plant autotrophically grow?

Earliest time to separate runner plant from propagule?

- Runner is a passage of carbohydrates, water and nutrients from its mother plant to the runner plant.

- When can the young runner plant autotrophically grow after being separated from its propagule?
Autotrophic growth - Photosynthetic rate of runner plants (1)

Separated from mother plants 15 days after fixing runner tips

![Graph showing photosynthetic rate over time](image)

- **Pn** (μmol m⁻² s⁻¹ / plant)
- **Time after cutting (min)**
Runner plants separated from their mother plants 15 days after fixing runner tips recorded the greater Pn than not separated ones.

Autotrophic growth - Photosynthetic rate of runner plants (2)
Subsequent growth of runner plants

Growth of runner plants as affected by timing of separation from their propagules 15 - 30 days after fixing runner tips.
## Growth and propagation parameters

Growth of runner plants grown until 30 days after fixing runner tips as affected by time separated from their stock plants

<table>
<thead>
<tr>
<th></th>
<th>No. of leaves</th>
<th>No. of runners</th>
<th>Crown diameter (mm)</th>
<th>Leaf area (cm²/plant)</th>
<th>Maximum length of petioles</th>
<th>Dry weight (g/plant)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>leaves</td>
</tr>
<tr>
<td>S15*</td>
<td>4.0a</td>
<td>3.0a</td>
<td>6.7b</td>
<td>160.7a</td>
<td>106.2b</td>
<td>0.93a</td>
</tr>
<tr>
<td>S20</td>
<td>3.5ab</td>
<td>3.0a</td>
<td>7.2ab</td>
<td>150.5a</td>
<td>121.0b</td>
<td>0.90a</td>
</tr>
<tr>
<td>S25</td>
<td>3.3b</td>
<td>3.2a</td>
<td>7.7a</td>
<td>178.2a</td>
<td>146.3a</td>
<td>1.01a</td>
</tr>
<tr>
<td>S30</td>
<td>3.2b</td>
<td>3.2a</td>
<td>7.6a</td>
<td>160.9a</td>
<td>152.7a</td>
<td>0.85a</td>
</tr>
</tbody>
</table>

*Separated X days after fixing runner tips
Accumulated number of runners per propagule

Time course of accumulated number of runners for 36 days as affected by size of propagules.
Propagation cycle

Runner plant separation 15 days after runner tip fixation

Timescales for producing runner plants as affected by size of propagules.
Efficient use of the limited cultivation area of a S-PFAL

- Distance between two adjacent propagules
  - 60, 120, and 180 mm
### Planting density of propagules: 44 propagules/m²

Growth of propagules as affected by planting distance between propagules for 40 days.

<table>
<thead>
<tr>
<th>Planting distance (mm)</th>
<th>No. of leaves (/plant)</th>
<th>No. of runners (/plant)</th>
<th>Crown diameter (mm/plant)</th>
<th>Fresh weight (g/plant)</th>
<th>Dry weight (g/plant)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Leaves</td>
<td>Crown</td>
</tr>
<tr>
<td>60</td>
<td>5.8a</td>
<td>4.2a</td>
<td>10.2b</td>
<td>12.0a</td>
<td>2.1a</td>
</tr>
<tr>
<td>120</td>
<td>6.3a</td>
<td>4.3a</td>
<td>10.9a</td>
<td>13.3a</td>
<td>2.6a</td>
</tr>
<tr>
<td>180</td>
<td>6.2a</td>
<td>4.5a</td>
<td>10.6ab</td>
<td>13.5a</td>
<td>2.7a</td>
</tr>
</tbody>
</table>
Planting density - runner plants (1)

Mutual shading by propagules and runner plants?

- PPF levels above propagules and runner plants
  - 100, 200, and 400 $\mu$mol m$^{-2}$ s$^{-1}$

  
  | 100 $\mu$mol m$^{-2}$ s$^{-1}$ | 100 $\mu$mol m$^{-2}$ s$^{-1}$ |
  | 200 $\mu$mol m$^{-2}$ s$^{-1}$ | 200 $\mu$mol m$^{-2}$ s$^{-1}$ |
  | 400 $\mu$mol m$^{-2}$ s$^{-1}$ | 400 $\mu$mol m$^{-2}$ s$^{-1}$ |

  $\times$
### Planting density of runner plants: 132 runner plants/m²

<table>
<thead>
<tr>
<th>PPF (µmol·m⁻²·s⁻¹)</th>
<th>No. of leaves (/plant)</th>
<th>Crown diameter (mm)</th>
<th>Fresh weight (g / plant)</th>
<th>Dry weight (g / plant)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Shoot</td>
<td>Root</td>
</tr>
<tr>
<td>400 400</td>
<td>5.0a</td>
<td>6.9a</td>
<td>8.23a</td>
<td>2.75a</td>
</tr>
<tr>
<td>200</td>
<td>4.8ab</td>
<td>6.6abc</td>
<td>7.08ab</td>
<td>2.14b</td>
</tr>
<tr>
<td>100</td>
<td>4.3bc</td>
<td>7.0ab</td>
<td>6.95abc</td>
<td>2.09b</td>
</tr>
<tr>
<td>200 400</td>
<td>4.0c</td>
<td>6.4abc</td>
<td>5.79bcd</td>
<td>1.79bc</td>
</tr>
<tr>
<td>200</td>
<td>4.3bc</td>
<td>6.2bc</td>
<td>5.96bcd</td>
<td>2.03bcd</td>
</tr>
<tr>
<td>100</td>
<td>4.8ab</td>
<td>6.5abc</td>
<td>5.66cd</td>
<td>1.68bcd</td>
</tr>
<tr>
<td>100 400</td>
<td>5.0a</td>
<td>5.9cd</td>
<td>4.92d</td>
<td>1.38cde</td>
</tr>
<tr>
<td>200</td>
<td>4.3bc</td>
<td>6.0cd</td>
<td>4.82d</td>
<td>1.49de</td>
</tr>
<tr>
<td>100</td>
<td>4.0c</td>
<td>5.3d</td>
<td>3.49e</td>
<td>0.97e</td>
</tr>
</tbody>
</table>

**Significance**

<table>
<thead>
<tr>
<th></th>
<th>P</th>
<th>R</th>
<th>P X R</th>
</tr>
</thead>
<tbody>
<tr>
<td>**</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
</tbody>
</table>

**PPF levels of propagules**

**PPF levels of runner plants**

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²PPF levels of propagules

YPFP levels of runner plants
Container size for propagules (1)

- Container size (or root volume) of propagules
- 145, 73, 34 and 21 mL
## Container size (root volume) : 21 mL

Growth of runner plants as affected by container size grown for 35 days.

<table>
<thead>
<tr>
<th>Container size (root volume): 21 mL</th>
<th>No. of leaves (/plant)</th>
<th>No. of runners (/plant)</th>
<th>Crown diameter (mmt)</th>
<th>Leaf area (cm²/plant)</th>
<th>Fresh weight (g/plant)</th>
<th>Dry weight (g/plant)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Leaves</td>
<td>Runners</td>
</tr>
<tr>
<td>145 mL</td>
<td>6.4a²</td>
<td>3.0a</td>
<td>9.02a</td>
<td>319.3a</td>
<td>7.69a</td>
<td>9.44a</td>
</tr>
<tr>
<td>73 mL</td>
<td>6.8a</td>
<td>2.8a</td>
<td>9.40a</td>
<td>348.2a</td>
<td>6.98a</td>
<td>7.84a</td>
</tr>
<tr>
<td>34 mL</td>
<td>6.6a</td>
<td>2.6a</td>
<td>9.16a</td>
<td>330.9a</td>
<td>6.97a</td>
<td>7.52a</td>
</tr>
<tr>
<td><strong>21 mL</strong></td>
<td><strong>6.8a</strong></td>
<td><strong>2.4a</strong></td>
<td><strong>9.70a</strong></td>
<td><strong>379.6a</strong></td>
<td><strong>7.85a</strong></td>
<td><strong>4.32a</strong></td>
</tr>
</tbody>
</table>
## Size of propagules (crown diameter, 1)

<table>
<thead>
<tr>
<th>Crown diameter (mm)</th>
<th>Number of leaves (/plant)</th>
<th>Number of runners (/plant)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD 4.1</td>
<td>4.1±0.1</td>
<td>1.7±0.5</td>
</tr>
<tr>
<td>CD 5.0</td>
<td>5.0±0.1</td>
<td>2.0±0.0</td>
</tr>
<tr>
<td>CD 6.0</td>
<td>6.0±0.1</td>
<td>3.0±0.0</td>
</tr>
</tbody>
</table>
Size of propagules (crown diameter, 2)

CD 4.1
CD 5.0
CD 6.0

Time course of accumulated number of runner plants as affected by crown diameter of propagules for 90 days after transplanting propagules
Crown diameter of propagule: 5.0 mm
Yearly production of runner plants

CD 5.0

Accumulated number of runner plants

Days after transplanting

from 9 propagules

cultivation area of 3.6 m²

3,497

365 DAT
Software flowchart for simulating production

Start

- Propagation cycle $i$ th runner plants ($T_{C_{i-3}}, T_{C_{i-2}}, T_{C_{i-1}}$)
- A set point of propagule production period ($T_P$)
- The maximum number of propagules in cultivation area ($N_{MP}$)
- Propagule production period ($T$)
- The number of propagules at start of propagation ($N_{SP}$)
- Age of propagule ($A$)
- The number of propagules in cultivation area ($N_P$)

- Transplanting of propagule in cultivation area ($N_{SP}$)

• Start of propagation

- End of propagation

Yes

$T \geq T_P$

No

$A=TP_{i-x}$

Yes

- Emission of runner plant from cultivation area

No

$A=TP_{i-3}$

Propagule

Yes

Runner plant

No

$N_P < N_{MP}$

Yes

- Supplement of runner plant as propagule into cultivation area

No

- Production of strawberry transplants
Simulation program
Simulation - initial number of propagules

cultivation area of 3.6 m²

Accumulated number of runner plants

- 1 propagule
- 9 propagules
- 90 propagules

Days after transplanting

- 2,990 (100%)
- 3,612 (121%)
- 4,270 (143%)
Simulation - cultivation area

from 9 propagules

Days after transplanting
0 100 200 300 400
Accumulated number of runner plants
0
5000
10000
15000
20000
25000
30000
35000
3.6 m²
18.0 m²
36.0 m²

29,630 (820%)
15,741 (436%)
3,612 (100%)
Operation flow of ATPM in S-PFAL

ca. 40 days to produce THREE propagules and ONE transplants from a propagule

Consignment or Storage
## Electric consumption

Simulated number of runner plants produced from 10 propagules for one year, electric consumption, and electric charge to produce runner plants

<table>
<thead>
<tr>
<th>PPF (μmol m$^{-2}$ s$^{-1}$)</th>
<th>Number of runner plants$^z$</th>
<th>Electric consumption</th>
<th>Electricity cost (KRW)$^w$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>In a CTPS (MWh)$^y$</td>
<td>Per runner plant (kWh)$^x$</td>
</tr>
<tr>
<td>150</td>
<td>10,638</td>
<td>15.8</td>
<td>1.5</td>
</tr>
<tr>
<td>190</td>
<td>11,270</td>
<td>22.3</td>
<td>2.0</td>
</tr>
<tr>
<td>240</td>
<td>12,094</td>
<td>28.9</td>
<td>2.4</td>
</tr>
<tr>
<td>300</td>
<td>13,058</td>
<td>36.0</td>
<td>2.8</td>
</tr>
</tbody>
</table>

$^z$Simulated number of runner plants produced from 10 propagules in the 9 m$^2$ CTPS (cultivation area: 11.52 m$^2$) for a year.

$^y$Electric consumption for operating a CTPS for a year as affected by number of fluorescent lamps.

$^x$Electric consumption to produce a runner plant. Electric consumption of lighting was presumed 75% of total electric consumption to operate a CTPS.

$^w$Electric charge of electric consumption to produce a runner plant, 39.2 won/kWh.
Phosphor types of white LEDs are produced by adding phosphors to the blue LED to convert a portion to green, yellow and red having different correlated color temperatures (CCT)

(Zhao et al., 2002)
Growth of runner plants grown under LEDs having different correlated color temperature (CCT)
Shortened propagation cycle by adapting LEDs

Greater system productivity with reduced electricity cost

<table>
<thead>
<tr>
<th>Propagation cycle (Days)</th>
<th>7000</th>
<th>12000</th>
<th>950000</th>
<th>N/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>bc</td>
<td>b c</td>
<td>b a</td>
<td></td>
</tr>
<tr>
<td>2nd</td>
<td>b b</td>
<td>b b</td>
<td>a</td>
<td></td>
</tr>
<tr>
<td>3rd</td>
<td>c</td>
<td>c</td>
<td>b a</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>b b</td>
<td>b b</td>
<td>a</td>
<td>a</td>
</tr>
</tbody>
</table>

Fluorescent lamps
40 days
35 days

LED, CCT of 12,000°K

Shortened propagation cycle by adapting LEDs
Greater system productivity with reduced electricity cost

Fluorescent lamps
40 days
35 days

LED, CCT of 12,000°K
Storage of transplants produced in a S-PFAL

- Transplanting
- Light acclimation
- Long-term Cold storage at -1.5°C
- Temperature acclimation

Diagram:

- TC1, TC2, TC3
- TP
- Propagule
- Growth & propagation
- Separation
- Propagule production period
- Cold storage or shipping out
Acclimation at 5°C before long-term cold storage

<table>
<thead>
<tr>
<th>Temperature</th>
<th>1 week</th>
<th>2 weeks</th>
<th>3 weeks</th>
<th>4 weeks</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°C</td>
<td><img src="image" alt="Plant" /></td>
<td><img src="image" alt="Plant" /></td>
<td><img src="image" alt="Plant" /></td>
<td><img src="image" alt="Plant" /></td>
</tr>
<tr>
<td>5°C</td>
<td><img src="image" alt="Plant" /></td>
<td><img src="image" alt="Plant" /></td>
<td><img src="image" alt="Plant" /></td>
<td><img src="image" alt="Plant" /></td>
</tr>
<tr>
<td>10°C</td>
<td><img src="image" alt="Plant" /></td>
<td><img src="image" alt="Plant" /></td>
<td><img src="image" alt="Plant" /></td>
<td><img src="image" alt="Plant" /></td>
</tr>
<tr>
<td>15°C</td>
<td><img src="image" alt="Plant" /></td>
<td><img src="image" alt="Plant" /></td>
<td><img src="image" alt="Plant" /></td>
<td><img src="image" alt="Plant" /></td>
</tr>
<tr>
<td>20°C</td>
<td><img src="image" alt="Plant" /></td>
<td><img src="image" alt="Plant" /></td>
<td><img src="image" alt="Plant" /></td>
<td><img src="image" alt="Plant" /></td>
</tr>
<tr>
<td>25°C</td>
<td><img src="image" alt="Plant" /></td>
<td><img src="image" alt="Plant" /></td>
<td><img src="image" alt="Plant" /></td>
<td><img src="image" alt="Plant" /></td>
</tr>
</tbody>
</table>

Acclimation at 5°C in darkness
Light acclimation after long-term cold storage

Light acclimation at 100 $\mu$mol·m$^{-2}$·s$^{-1}$ for 2 days

Survival rate of runner plants 2 days after transplanting as affected by light condition (100 $\mu$mol·m$^{-2}$·s$^{-1}$) after transplanting.
Summaries

- Strawberry transplants could be rapidly produced using ATPM in a S-PFAL year round and proper storage conditions before being transplanted for fruit production or transplant production were determined.

- S-PFALs have been installed on a trial basis at research agencies where nuclear stocks of major domestic cultivars are maintained.

- The trials were satisfactory, and so scaling-up is currently being reviewed for producing elite and pre-basic transplants in ‘the Korean national program for strawberry propagation’.
Special Thanks to;
Prof. Sung Kyeom Kim
Ms. Miseon Jeong
Ms. Hyein Lee

Thank you berry much!
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