Performance of Various Salad Crops Grown under Candidate Lighting Technologies

NRA98-HEDs-01-067

Gregory D. Goins

Dynamac Corporation
Mail Code: DYN-3
Kennedy Space Center, Florida, USA 32899
Electric Plant Lighting Systems

System Design
- Power Requirements
- Thermal Exchange/Removal
- Mass and Volume
- Modularity

Source Lamp
- Safety
- Conversion Efficiency
- Spectral Quality
- Spectral Distribution
- Longevity

Crop
- Quantum Efficiency
- Spectral Absorption
- Light Interception
- Photoperiod
- Light Pollution

Conversion Efficiency
mol photons/J

Delivery & PS Efficiency
g/mol photons

\[ E = \frac{hc}{\lambda} \]
Why Salad-Type Crops?

- Low growth habit with defined shape
- Adaptable to confined controlled environment cultivation
- Short life cycle allows multiple harvests in defined time periods
- Simple post-harvest processing
- Fresh vegetable source with supplemental minerals, vitamins, and fiber
Light-emitting diodes (LEDs)

• Small mass and volume
• Limited thermal radiation projection to plant canopy
• Plants safely grown in close proximity to arrays
• Particularly suited for space transit vehicles
Sulfur-Microwave Lamp

- Good electrical to visible light conversion efficiency
- High visible light output for remote “light pipe” applications
- Uniform broad-spectrum visible light emission
- Output can be dimmed without significant spectral shift
Past experiments with LED lighting at KSC

Wheat grown under Red LEDs alone (no blue light)
- Net positive CER, dry matter, & grain yield decreased
- In leaves during vegetative and pre-anthesis stages
  - sucrose levels decreased
  - Decreased SPS & cytosolic Frc 1,6 Bpase activities
  - starch levels elevated
  - Increased ADP-G activity
  - Given supplemental blue light, plants grown under red LEDs similar to those under broad-spectrum sources

Arabidopsis grown under Red LEDs alone (no blue light)
- Abnormal leaf development under red LEDs alone (without supplemental blue light)
- Promotion of vegetative growth and delayed flowering under red LEDs alone
- Fewer seed (but viable) produced under red LEDs alone

Spectral distribution of light (300-1100nm) from lamp sources in salad crop experiments at KSC

Narrow-spectrum LED arrays
10 rows red + 5 rows blue
Red LEDs: 660, 670, 680, 690, 700, and 725 nm
Each integrated with Blue LEDs: 470 nm

Broad-spectrum
Cool-white Fluorescent (CWF): F15T12
High-Pressure Sodium (HPS): 250-watt lamp
Sulfur-Microwave: Solar 1000W lamp
Spectral scans (300-1100nm) of light sources

Spectral distribution of light from various light sources. Spectral scans were taken at the top of the plant canopy with a spectroradiometer. Total PPF was approximately 250 µmol·m^{-2}·s^{-1} for all light sources.
# Spectral Characteristics of Lighting Sources

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>μWave</th>
<th>CWF</th>
<th>HPS</th>
<th>660</th>
<th>670</th>
<th>680</th>
<th>690</th>
<th>700</th>
<th>725</th>
</tr>
</thead>
<tbody>
<tr>
<td>300-400</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>400-500</td>
<td>66</td>
<td>54</td>
<td>16</td>
<td>22</td>
<td>22</td>
<td>22</td>
<td>21</td>
<td>23</td>
<td>25</td>
</tr>
<tr>
<td>500-600</td>
<td>113</td>
<td>130</td>
<td>129</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>600-700</td>
<td>72</td>
<td>66</td>
<td>106</td>
<td>227</td>
<td>227</td>
<td>230</td>
<td>228</td>
<td>130</td>
<td>18</td>
</tr>
<tr>
<td>700-800</td>
<td>35</td>
<td>7</td>
<td>28</td>
<td>1</td>
<td>3</td>
<td>11</td>
<td>47</td>
<td>188</td>
<td>319</td>
</tr>
<tr>
<td>800-900</td>
<td>16</td>
<td>4</td>
<td>100</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>31</td>
<td>0</td>
</tr>
<tr>
<td>900-1000</td>
<td>11</td>
<td>2</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>13</td>
<td>18</td>
</tr>
<tr>
<td>1000-1100</td>
<td>11</td>
<td>5</td>
<td>14</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Photon flux (300-1100)</td>
<td>324</td>
<td>272</td>
<td>401</td>
<td>251</td>
<td>253</td>
<td>264</td>
<td>296</td>
<td>378</td>
<td>413</td>
</tr>
<tr>
<td>PPF (400-700)</td>
<td>250</td>
<td>250</td>
<td>250</td>
<td>250</td>
<td>250</td>
<td>253</td>
<td>249</td>
<td>154</td>
<td>45</td>
</tr>
<tr>
<td>YPF</td>
<td>209</td>
<td>218</td>
<td>229</td>
<td>225</td>
<td>221</td>
<td>212</td>
<td>196</td>
<td>150</td>
<td>82</td>
</tr>
<tr>
<td>Blue</td>
<td>66</td>
<td>54</td>
<td>16</td>
<td>22</td>
<td>22</td>
<td>22</td>
<td>21</td>
<td>23</td>
<td>25</td>
</tr>
<tr>
<td>R</td>
<td>72</td>
<td>66</td>
<td>106</td>
<td>227</td>
<td>227</td>
<td>230</td>
<td>228</td>
<td>130</td>
<td>18</td>
</tr>
<tr>
<td>FR</td>
<td>28</td>
<td>4</td>
<td>15</td>
<td>1</td>
<td>2</td>
<td>7</td>
<td>30</td>
<td>94</td>
<td>160</td>
</tr>
</tbody>
</table>
Spinach at 26 dap under different lamp banks
Experimental Details

- Lighting treatments located in 3 Conviron PGW-36 chambers
- 16 (spinach) 18 (lettuce, radish) hour light photoperiod
- Instantaneous irradiance $250 \, \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ PAR
- Daily average irradiance $14-16 \, \text{mol}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$
- Distance lamp bank to root-shoot barrier: 25 cm
- Plant Trays: 52 cm W x 59 cm L x 10 cm H
- Root-shoot barrier: 52 cm W x 59 cm L (Growth area: 0.3 m$^2$)
- Harvest 6 plants at 14, 21, and 28 DAP
Spectral Photon Flux ($\mu$mol m$^{-2}$ s$^{-1}$ nm$^{-1}$)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>CWF</th>
<th>HPS</th>
<th>660</th>
<th>670</th>
<th>680</th>
<th>690</th>
</tr>
</thead>
<tbody>
<tr>
<td>300-400</td>
<td>5</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>400-500</td>
<td>54</td>
<td>16</td>
<td>22</td>
<td>22</td>
<td>22</td>
<td>21</td>
</tr>
<tr>
<td>500-600</td>
<td>130</td>
<td>129</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>600-700</td>
<td>66</td>
<td>106</td>
<td>227</td>
<td>227</td>
<td>230</td>
<td>228</td>
</tr>
<tr>
<td>700-800</td>
<td>7</td>
<td>28</td>
<td>1</td>
<td>3</td>
<td>11</td>
<td>47</td>
</tr>
<tr>
<td>800-900</td>
<td>4</td>
<td>100</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>900-1000</td>
<td>2</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1000-1100</td>
<td>5</td>
<td>14</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Photon flux (300-1100)</td>
<td>272</td>
<td>401</td>
<td>251</td>
<td>253</td>
<td>264</td>
<td>296</td>
</tr>
<tr>
<td>PP F (400-700)</td>
<td>250</td>
<td>250</td>
<td>250</td>
<td>250</td>
<td>253</td>
<td>249</td>
</tr>
<tr>
<td>Y PF</td>
<td>218</td>
<td>229</td>
<td>225</td>
<td>221</td>
<td>212</td>
<td>196</td>
</tr>
<tr>
<td>Blue</td>
<td>54</td>
<td>16</td>
<td>22</td>
<td>22</td>
<td>22</td>
<td>21</td>
</tr>
<tr>
<td>R</td>
<td>66</td>
<td>106</td>
<td>227</td>
<td>227</td>
<td>230</td>
<td>228</td>
</tr>
<tr>
<td>F R</td>
<td>4</td>
<td>15</td>
<td>1</td>
<td>2</td>
<td>7</td>
<td>30</td>
</tr>
<tr>
<td>PSS</td>
<td>0.84</td>
<td>0.85</td>
<td>0.88</td>
<td>0.87</td>
<td>0.84</td>
<td>0.76</td>
</tr>
</tbody>
</table>
Shoot and root dry mass yield of “Waldmann’s Green” lettuce at 28 DAP.

Different letters above bars indicate significant difference based on ANOVA and Tukey's HSD mean procedure test (P<0.05).
Leaf area index (LAI), net assimilation rates, and crop growth rates of “Waldmann’s Green” lettuce plants over 28 day crop cycles in the presence of LED, CWF, or HPS lighting (see appendices for curve fit functions).
Lettuce Head Ground Cover (%)

Days After Planting

Specific Leaf Area (m² kg⁻¹)

Different letters above bars indicate significant difference based on ANOVA and Tukey’s HSD mean procedure test (P<0.05)
Water use efficiency (WUE), transpiration, and carbon exchange rates of 28 day-old “Waldmann’s Green lettuce plants grown in the presence of LED, CWF, or HPS lighting. Different letters above bars indicate significant difference based on ANOVA and Tukey’s HSD mean procedure test (P<0.05)
Spectral Characteristics Comparison

**Total photon flux**

**Phytochrome photostationary state**

**PAR and YPF**

**Red:Far-Red**

- **PAR and YPF**
  - Units: (µmol·m⁻²·s⁻¹)
  - Comparison of CWF and HPS across different wavelengths.

- **Phytochrome photostationary state (PSS)**
  - Units: 0.00 to 1.00
  - Comparison of PSS across different wavelengths.

- **Red:Far-Red**
  - Units: 0 to 250
  - Comparison of Red:Far-Red ratio across different wavelengths.
Spinach Leaf Measurements

Total leaf area (top) and specific leaf area (bottom) for spinach plants grown under various lighting sources for 28 days.

Average shoot diameter for spinach plants grown under various lighting sources for 14, 21, or 28 days after planting.
Spinach edible biomass and net leaf photosynthesis

Edible fresh biomass (leaves + stems) for spinach plants grown 28 days under various lighting sources.

Net rate of leaf photosynthesis for spinach plants (21 DAP) grown under various lighting sources (error bars indicated standard deviation of the treatment mean).
Summary

- Successfully implemented 8 separate light treatments
- Completed spinach growth experiments
- Given equal PAR (with 660-690 nm red LEDs) biomass yields similar
- Shoot diameter tends to increase with red LED wavelength, especially beyond 690 nm
- Many measurements yet to be complete
  - Plant physiological assays
  - Lamp bank electrical power consumption
Supplemental Lighting Strategy for Greenhouse Strawberry Production

Joshua S. Gottdenker – Graduate Student
Gene A. Giacomelli – Professor
Bioresource Engineering
Rutgers University  Cook College
New Jersey
USA
Objectives

• To test the effects of different Daily Light Integrals (DLIs)

• To compare the treatment effects:
  – Productivity (grams of fresh fruit / plant)
  – Economically = ($ / plant)
  • Value of Supplemental Light (SL)
Cultural Practices (cont.)

- Conditioned plug plants are transplanted into the greenhouse. (September 1, 1999)
Incandescent Lamps

HPS Lamps

Polyethylene Film
Measured Daily Light Integral

moles PAR

SLS12
NL
CO$_2$ AND MARS GREENHOUSES

Raymond M. Wheeler
NASA Biomedical Office
Kennedy Space Center
Why worry about CO\textsubscript{2} for Mars Greenhouses?

- CO\textsubscript{2} is required for plant photosynthesis
- CO\textsubscript{2} affects stomatal opening and transpiration
- CO\textsubscript{2} can affect respiration
- CO\textsubscript{2} is available from the Martian atmosphere and could serve as a pressurizing gas
Plant Responses to CO\(_2\):

- Photosynthesis increases with increased CO\(_2\)*
  
  \[ \text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{CH}_2\text{O} + \text{O}_2 \]

- Transpiration decreases with increased CO\(_2\)*
  
  *Stomata Close and Water Use Drops*

- Respiration decreases with increased CO\(_2\)*

* Typical responses as CO\(_2\) is increased from 0.04 kPa to 0.10 kPa
### Composition of Mars Atmosphere

<table>
<thead>
<tr>
<th>Gas</th>
<th>Percent (%)</th>
<th>~Pressure (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$</td>
<td>95.3</td>
<td>0.67</td>
</tr>
<tr>
<td>N$_2$</td>
<td>2.7</td>
<td>0.019</td>
</tr>
<tr>
<td>Ar</td>
<td>1.6</td>
<td>0.011</td>
</tr>
<tr>
<td>O$_2$</td>
<td>0.13</td>
<td>0.0009</td>
</tr>
<tr>
<td>CO</td>
<td>0.07</td>
<td>0.0004</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>0.03</td>
<td>0.0002</td>
</tr>
</tbody>
</table>


** Assuming a total pressure of 0.7 kPa
Potatoes
CO$_2$ and Mars Greenhouses

Sweetpotatoes
CO$_2$ and Mars Greenhouses

CO$_2$ Injury to Leaves

Radish

Soybean
Radish

CO2 Concentration (ppm)
Total DW (g/plant)

CO2 and Mars Greenhouses