PLANT-GROWTH LIGHTING FOR SPACE LIFE SUPPORT: A REVIEW

Gioia D. Massa[1], Jeffrey C. Emmerich[2], Robert C. Morrow[2], C. Mike Bourget[2], and Cary A. Mitchell[1]
[1] Department of Horticulture and Landscape Architecture and NASA Specialized Center of Research and Training in Advanced Life Support, Purdue University, West Lafayette, IN 47907
[2] Orbital Technologies Corporation, Madison, WI 53717

ABSTRACT

The lighting system is one of the most important components of a greenhouse or chamber that will be used for plant growth in an Advanced Life-support System (ALSS). Several designs of such lighting systems have been proposed including the use of natural sunlight with supplemental electric lighting. Although electric lighting is energy intensive, it is necessary when balanced against the hazards and limitations of plant growth under natural sunlight on the surface of the moon or Mars. The characteristics of different electric light types are reviewed, and functionality for space application is compared. Different lighting systems used in Earth-based advanced life-support (ALS) simulations are highlighted. A new design using light-emitting diodes (LEDs) for intracanopy lighting, i.e. lighting entire crop canopies for energy savings and crop enhancement, is discussed. When the benefits of LEDs are combined with the advantages of intracanopy lighting, electric lighting for ALS becomes increasingly feasible.

INTRODUCTION

Food crops will have to be grown when it is necessary to support human life off Earth for an extended time period. NASA's (former) Advanced Life Support (ALS) program included research associated with water purification, air revitalization, waste processing, food production and preparation, and system integration using a combination of bioregenerative and physico-chemical technologies. The ultimate goal of life-support research is to support human habitation off Earth for an indefinite period by creating a sustainable life-support system that is open with respect to energy but closed with respect to mass. NASA's ALS program evolved from an earlier Closed Ecological Life-Support System, or CELSS, program. Several other countries or groups have worked on ALS-related topics, including Russia, Japan, Canada, the European Space Agency, and most recently, China. Early work on human life support emphasized synergisms between plants and humans in closed systems, with particular focus on future crop-production systems in space.

The early ALS work in the US, the USSR, and elsewhere focused on use of microalgae such as *Chlorella* sp. for food production as well as for oxygen and water revitalization in an ALSS. The lighting systems used for algae will not be discussed here, as most research moved early on to higher plants, but for an excellent review of those experiments, refer to Gitelson, Lisovsky, and MacElroy (2003).

More recent ALS research includes the design and testing of habitats for plant growth that will be used on the surface or subsurface of the moon or Mars. One such design proposes the use of an inflatable greenhouse that relies on solar photosynthetically active radiation (PAR) to directly irradiate crops. The design of such greenhouses requires transparent films that would have to withstand low external atmospheric pressure, large external temperature gradients and swings, strong UV-C fluxes, micrometeorite impacts, solar particle events, cosmic-galactic radiation, and must address issues associated with the widely varying intensity of solar PAR available to support plant growth (Cockell and Andrady, 1999; Cockell, 2001; Rontó et al., 2003; Horneck et al., 2003). On the moon, the latter relates to extended periods of darkness; on Mars, to global dust storms of unpredictable duration, to diurnal and seasonal light cycles, and to the planet's variable distance from the sun. To deliver solar PAR to plants growing underground or in containment on the moon or Mars, there not only will be the same solar-availability constraints, but additional losses of light as it travels through fiber optics or light pipes (Cuello et al., 1998; Jack et al., 2002). Jack et al. (2002) recently evaluated the efficiency of Fresnel-lens Himawari and parabolic-mirror optical waveguide solar collection and distribution systems for plant growth. The first of these devices consists of a collection of Fresnel lenses that track the sun and focus collected irradiance onto a cable of fiber optics that can be directed into the plant-growth area (Jack et al., 2002). The second device has primary concentrators in the form of rotating parabolic mirrors that focus the light onto a solid quartz secondary concentrator that is then linked to a fiber-optic cable (Jack et al., 2002). Losses of 2.5% - 6.7% per meter were seen as the light was transmitted through the optical fibers (Jack et al., 2002; Nakamura et al., 1998). Although intense light levels over 800 µmol m^{-2} s^{-1} could be obtained in areas of the plant-growth chamber with the optical waveguide concentrator, lack of uniformity and variability of light levels was extremely high (Jack et al., 2002). Cloudy or rainy days reduce the available light and can cause crop loss (Nakamura et al., 1998). On Mars, dust storms of great intensity and long duration occur and limit the already reduced solar radiation that is available. On the moon, night length is about 2 weeks in length at most locations except for the south polar region. Direct or indirect, solar radiation is not reliable enough to

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* *Correspondence to:* Gioia D. Massa
Department of Horticulture and Landscape Architecture
Purdue University
625 Agriculture Mall Drive
West Lafayette, IN 47907-2010
Email: gmassa@purdue.edu
Phone: 765-496-2124; Fax: 765-494-0391

be the primary source of photosynthetic energy for human life support on the moon or Mars.

Since solar energy is not a viable primary option to support crop production, electric lighting must be considered. Characteristics to consider when adapting an electric lighting source for a life-support system away from Earth include the following:

- Conversion efficiency of electrical power to photons of photosynthetically active radiation (PAR)
- Thermal burden (amount and location relative to crop canopy)
- Lifetime of light source
- Durability of light source
- Mass of light source and associated hardware
- Volume (both storage and usage)
- Light output
  - -- Quantity
  - -- Quality
  - --Tunability/dimmability (versatility for a variety of crops)

Electrical conversion efficiency refers to the wattage of electric power that is converted to wattage of light formed, specifically PAR (400 - 700 nm, Sager and McFarlane, 1997). Electrical energy that is not converted to light energy is given off as sensible heat as well as long-wave radiation, both from ballasts (transformers) as well as from light sources (lamps) themselves. That part of the thermal burden generated by lamp surfaces needs to be removed from the plant-growth area and either redirected to some heat-requiring region of an ALSS or be rejected from the habitat. The electrical power required to run the lamps and to remove the heat burden becomes the single most expensive cost factor for crop production in an ALSS. Thus, a primary goal of plant research for ALS is to generate the largest amount of edible biomass possible for the least amount of electrical energy used (i.e., optimize for energy-use efficiency).

Another consideration in adapting an electric lighting source for ALS is the lifetime of the source, which impacts the number, volume, and mass of replacement lamps that must be launched as well as the crew time needed to maintain a lighting system. Durability of the source refers to its structural integrity when subjected to the rigors of launch from Earth to space, including routine handling, and the conditions encountered in microgravity for a duration that might be fairly short (Lunar transit, ISS) or long (Mars Transit). Improved launch, transit, and landing technologies may reduce such stresses, but the nature and composition of the light source will continue to be a factor both for functionality as well as for issues of astronaut safety.

The mass and volume of a light source, including all necessary mounting infrastructure, and accessory equipment, become important in terms of the lift capacity needed to send those materials to the desired location in space. Current estimates of launch costs from the Earth's surface vary depending on vehicle, but can be approximated at $10,000 per Kg to low earth orbit and $300,000 per Kg to the surface of Mars in 2000/2002 dollars, with costs to the lunar surface falling between the two (Futron Corporation, 2002; A. Drysdale, 2005 Pers. Comm.). Related issues include the transport and storage volume of replacement lamps, both in the spacecraft and at the outpost. Another issue in the design is volume of space that the lighting infrastructure will occupy within and above a plant-growth compartment. Larger lighting systems will limit the space available to accommodate plants. Therefore, a design with smaller, less massive lighting systems is desirable.

Other design considerations include a need for flexibility in the output of light quality, quantity, intensity, and positioning of the lighting system. Specifically, design questions to be addressed regarding light quantity include how many plants each light source will support, and how flexible a particular light source is with respect to planting designs? Also, how will photon flux influence lighting configuration and uniformity? The quality factor of light output can be very important as well. Some species have special wavelength requirements for flower initiation in long-day plants, such as barley requiring far-red wavelengths (Deitzer et al., 1979). Intumescence in tomato is eliminated by the presence of UV (Lang and Tibbitts, 1983) or far-red light (Morrow and Tibbitts, 1988). Certain crops, like lettuce and wheat, grow under red light alone (Hoenecke et al., 1992, Goins et al., 1997), but these and other crops have improved biomass production with the addition of small amounts of blue light (Hoenecke et al., 1992, Goins et al., 1997; Brown et al., 1995). Is it better to have one standard white-light source including all wavelengths, allowing increased cropping flexibility? Is it better to have custom light sources designed for each crop, allowing energy conservation? Or, is some middle ground preferable? The issues of tunability (e.g., altering color output by shifting red : blue ratio) and dimmability (altering intensity of emission) also are light-output factors. Some types of crops thrive under light with high blue fluxes, while others grow better under red-enriched light with minimum blue. Certain crops prefer dim light, while others require bright light, or may require it only during certain periods of development. Fluorescent lamp dimming is linear, with little efficiency drop-off as input power is reduced to a lower limit (Osram Sylvania, 2004). High-intensity discharge (HID) lamps have an issue of spectral shift as input power is decreased (Bubenheim et al., 1995). Additionally, minimum power levels required for an arc to fire are still high for both metal halide (MH) and high-pressure sodium (HPS) lamps (Bubenheim et al., 1995). For LEDs, which are current controlled, dimming is linear and continuous, with a correlation between PAR and current that can be greater than 0.99 (Massa et al., 2005b). It would be best to maximize edible biomass output per unit energy input by tuning the light source to suit the crop at different stages of its development, but features such as dimming typically come with associated energy, mass, and volume costs for traditional lamp types.

Another consideration in reducing the energy requirement for crop production in a closed system involves reducing the transpiration rate of crops and thus the amount of energy that will be required to condense transpired water vapor. If HID lamps are used, the area of a closed-canopy crop stand necessary to continuously support the food requirement of one person in an ALSS (~50m^2) will transpire approximately 4 L/ m^2/dayof water vapor, which amounts to 200 L of water transpired per person per day (Wheeler et al., 2003). While this at first may seem like a benefit, in terms of water reclamation, an average person requires only 2.5 L per day of water to satisfy their drinking-water requirement (Hopkins, 1993), and at most 40 L of water per day in an ALSS for all purposes (Mitchell et al., 1996). This leaves an excess of 160 L of water per crewmember, which adds substantially to the energy burden of crop production. The change of phase from liquid to vapor requires 582 cal/g of water at 25˚C, and the reverse phase change back to liquid is similar. Each latent heat draw will add 0.68 KW-h for every liter of water condensed from transpiration (Nobel, 1974), adding to the thermal burden of crop production in an ALS system. If a crop-lighting technology can be developed resulting in a lower thermal load on plants, then this transpiration rate and the concomitant water-condensation burden also can be reduced.

Several excellent articles have been written reviewing the efficiency and usefulness of different types of electric light sources for plant-growth applications. Bickford and Dunn (1972) wrote a definitive reference book on this subject characterizing not only available light sources, but also addressed the specialized lighting requirements of numerous crops. An international workshop organized in 1994 compiled a number of papers on plant and animal lighting in controlled environments with intent for use in a life-support system (Tibbitts et al., 1994a). Sager and McFarlane (1997) reviewed radiation impacts on plant growth and evaluated a wide range of lighting sources for use in controlled environments. The light sources used in terrestrial plant growth chambers, however, are not necessarily a good indicator of what would work best in an ALSS. Traditional light sources, for example, can be hot, fragile, and require large, heavy ballasts. Table 1 compares some characteristics important to an ALSS between different electric light sources.

Table 1. *A comparison of several characteristics of light sources important for an ALSS. These values are averages and may not reflect recent advances in some lamp types.*

		High Intensity Discharge (HID) Lamps			
Parameter	**Cool White Fluorescent**	**High Pressure Sodium**	**Metal Halide**	**Microwave**	**Light-Emitting Diodes**
% Power to PAR	22%[1]	35%[1]	29%[1]	38%[2]	Red, 21.5% Blue, 11%[3]
Lifetime	20,000 hr[1] 70% or less output at 6,000 hr[4]	24,000 hr[1]	12,000-20,000hr[4]	10,000 hr or more[1]	~100,000 hr[5]
Composition	Glass tubes, Hg vapor, phosphor coating[4]	Ceramic alumina arc tube contains Hg, Xe, and Na, glass outer bulb[1, 6]	Quartz tube in glass bulb, metal halides + pressurized Hg[4]	Electrodeless quartz bulb filled with S[1]	Solid state, materials vary with LED color, discrete, or multiple[3, 5]
Light quality	400-700nm[4]	Red shifted, Peak 550-650nm[4]	Blue-biased 400-700nm[4]	400-700nm[1]	Various, use multiple LEDs for desired spectrum
Availability	available	available	available	not available	available

1. MacLennan et al., 1994, 2. Ciolkosz et al., 1998, 3. Mike Bourget, Personal Communication, 2005, 4. Sager and MacFarlane, 1997, 5. Barta et al., 1992, 6. Bickford and Dunn, 1972

LIGHTING IN ALS RESEARCH

Fluorescent light was a standard for controlled plant growth research for many years, and numerous baseline studies were done using this lighting system. With fluorescent light, especially cool-white fluorescent, and often with additional incandescent light, plants grow “normally” and in approximate proportion to growth of plants outdoors (Downs and Hellmers, 1978). However, fluorescent lamps decline gradually in output, do not typically emit high intensities, and have a limited lifetime (Sager and McFarlane, 1997). For physiological studies this may not be an issue, but for crop production, fluorescent lamps lack the sustained photosynthetic photon flux (PPF) capability necessary for high productivity. Most of the lighting sources previously considered for ALS are in the (extremely fragile) HID category of lamps. In the Russian Bios–2 facility, a 4.5 m^2 phytotron was irradiated with four water-cooled 6-kW xenon lamps with an average irradiance of 90-115 W/m^2 of PAR (Gitelson et al, 2003). Bios-3 was an impressive closed life-support system containing two plant-growth compartments, an algae cultivation compartment, and a habitation unit for three crewmembers. Bios-3 was unique in that it was designed for control entirely by crewmembers within the system, as in an off-Earth life-support scenario, and had teams of people enclosed for up to 6 months. In the plant chamber, Bios-3 used the same lamp type as Bios-2, with 20 lamps placed in each of two 31.5 m^2 compartments (Gitelson et al, 2003). To reduce the IR radiation coming from the xenon lamps, the light sources were installed in a quartz jacket. This was then enclosed by a glass jacket, and water for cooling flowed between the two layers to remove heat. In Bios-3, lamp-cooling water was pumped directly from the nearby Siberian Yenisei River since it is both cold and pure (Gitelson et al, 2003). In Bios-3, plant productivity produced oxygen levels greater than required for a three-person crew. Food production from crops ranged from 30% of their food requirements in the first three-person trial to 77.5% in the final two-person, five-month closed trial. Other foods, predominantly animal products, were stored in lyophilized or canned forms. Roughly 21% of crew time for a three-person crew and 19% of crew time for a two-person crew was spent maintaining the operation of plant and algal growth areas. Significant amounts of time were also spent in food preparation, water purification, and other life support-related maintenance tasks. Overall, Bios-3 achieved 78-95% closure of the system and reduction of pre-stored substances that would need to be supplied for human life support (Gitelson et al., 2003).

At Kennedy Space Center (KSC), a different kind of HID lighting was utilized within the closed Biomass Production Chamber (BPC). This large, closed plant-growth chamber was a converted hypobaric test chamber for the Mercury program. Generally, this chamber was lighted by ninety-six 400-W HPS lamps with remote, dimmable ballasts, but occasionally MH lamps were used when crops required it (Wheeler, 1992; Wheeler et al., 2003). The BPC had 20 m^2 of plant growth area within a volume of 113 m^3, and more than twenty tests were performed. Several crops were grown, including potatoes, wheat, soybean, lettuce, tomatoes, and rice, and one test even ran for longer than a year with four successive potato generations grown in the same nutrient solution. Numerous important conclusions were reached during the course of those experiments, and research continues using conventional growth chambers (Wheeler et al., 2003). Such studies demonstrated that, if crops required wide spacing at maturity, productivity and radiation-conversion efficiency could be improved if they are transplanted from smaller areas. Also, a nearly linear response was found between daily PAR and productivity across a range from 15-60 mol m^{-2} day^{-1} for a variety of unrelated crops (Wheeler et al., 2003). Another key result that complements other published research indicates that, in nearly all plant species tested, those grown in a controlled environment have higher protein, and ash levels and lower carbohydrate levels than crops grown in the field (Wheeler et al., 2003).

The Lunar-Mars Life Support Test Project (LMLSTP) at Johnson Space Center (JSC) incorporated an 11.2 m^2 Variable Pressure Growth Chamber (VPGC) to grow a wheat crop for air revitalization (Gitelson et al., 2003). Eight banks of 400 W HPS lamps were used in this chamber and it was demonstrated that wheat growth in this area revitalized 25% of the carbon dioxide produced by a crew of four over the 91 days of Phase III testing (Lawson, 2004). Physico-chemical systems regenerated the remaining 75%. In addition, some food was provided from the wheat as bread, and from a separate small plant growth chamber that used LEDs to produce lettuce (Gitelson et al., 2003; Lawson, 2004). Following these tests, the BIO-Plex facility at JSC was designed to use water-jacketed HPS lamps for crop growth (Tri, 1999). However, the current status and plans for this integrated plant growth and human habitation facility remain unclear (Gitelson et al, 2003).

Lastly, the Closed Ecology Experimental facility, or CEEF, on the northern island of Honshu, Japan, utilizes HPS lamps in four plantation chambers, as the sole PAR source in three of those chambers, and as a supplement to sunlight in the other (Masuda et al., 2005; Nitta, 2005). CEEF has a total cultivation area of 150 m^2, and early experimental results indicated that, without increased productivity, they would need almost 255 m^2 crop growth area per person for a balanced diet. Peanut cultivation for oil accounted for 78% of this estimate, due to the low level of fats available in a typical vegetarian diet (Masuda et al., 2005). Although rice and soybean showed high productivity within the facility, several other crops require further optimization to produce optimum biomass. Currently, only short-term closure experiments have been performed in CEEF, although one-month habitation experiments are scheduled to start in the summer of 2006 (Nitta, 2005).

LED RESEARCH

Light-emitting diodes, LEDs, are a comparatively new light source for plant growth and are being actively investigated for numerous applications. Every week new articles appear in the popular press about advances in LED technology and the potential of this solid-state light source for automotive and home lighting, computing, public works light sources, etc. Red LEDs originally had 15-18% efficiency, but now are up to almost 22%, whereas blue LEDs were only 3-4% efficient and are now at 11%. This increase in efficiency makes LEDs competitive with other sources for plant-growth lighting (Tennessen and Ciolkosz, 1998; M. Bourget, 2005 Pers. Comm.). Another important advance in LED research is the commercial availability of "chip-on-board" LED light engines. Unlike discrete LEDs with plastic lenses, these light engines are small printed-circuit wafers that pack large numbers of small LEDs of selectable emission colors into close proximity. For example, the ORBITEC light engine can array 132 LEDs of five colors in a 6.25 cm^2 square (Massa et al., 2005a). This allows for unprecedented color blending and very bright light levels. LED emissions are current-controlled, and the light output is directly proportional to input current within their operating range, so unlike other types of dimming systems for lighting, dimming of LEDs directly reduces power usage. LEDs have solid-state construction, are extremely durable, and resistant to shock. Transparent coatings on the chips protect them against high humidity and allow for cleaning without reducing light levels. LED chips, like discrete LEDs, have low mass and volume. LEDs generally emit light in a narrow region of the color spectrum. The number of available colors is extremely large, with one of the most efficient being red LEDs emitting at 640 nm, where light has a relative quantum efficiency for photosynthesis of ~96% (Sager and McFarlane, 1997). Experimentation has demonstrated that different species can be grown successfully under LEDs, including spinach (Goins and Yorio, 2000), lettuce (Goins et al., 2001; Kim et al., 2004), radish (Goins et al., 2001), wheat (Goins et al., 1997), and micropropagated potato plantlets (Miyashuta et al., 1995). Generally, about 15% blue light is required for normal growth, and yields have been achieved that are comparable to growth under white light (Yorio et al., 1998). Research has demonstrated that green light also can have beneficial effects for growth and plant assessment, especially within dense foliar canopies (Kim et al., 2004; 2005).

INTRACANOPY LIGHTING FOR CROP GROWTH

Intracanopy (IC) lighting aims to improve lighting efficiency by providing light distribution throughout the canopy of a crop. In planophile crops, where leaves present themselves perpendicular to overhead light and eventually close off their inner canopy to light, mutual shading of lower leaves by those above leads to net carbon loss via respiration, premature leaf drop, and often flower bud and fruit abortion inside the canopy (Ohler et al., 1996). Thus, unshaded top and side leaves end up doing all photosynthetic work for the entire crop stand. If the light sources could instead irradiate from within the canopy, a much greater percentage of available leaf surface could be utilized for photosynthetic work. This should increase biomass output per energy input efficiency. Additionally, light intensity drops off exponentially from a point irradiation source according to the inverse square law, where

$$I = E / d^2$$

with I being the irradiation on a surface at a distance d from the light source emitting radiant energy E (Bickford and Dunn, 1972). Thus, light levels drop off rapidly with increasing increments of distance between lamp and plant, so that with the necessary separation of hot light sources above a crop stand the amount of light incident upon the leaves is highly attenuated, further requiring that the hot source be high-emitting and high power. If a much cooler light source can be maintained in close proximity to or even touching leaves, more light will be available at leaf level for lower power cost. This will lead to a greater energy-use efficiency of the biomass-production system.

IC lighting has been previously examined, either as a supplement to traditional overhead lighting, or as a sole lighting source. Stasiak and colleagues tested soybean grown under microwave lamps and supplemented with side-mounted lighting that was piped into the canopy via glass tubes lined with optical lighting film to levels of at least 150 $\mu mol\ m^{-2}\ s^{-1}$ PAR at 100 mm from the tube surface. When overhead light of 400-1200 $\mu mol\ m^{-2}\ s^{-1}$ PAR was supplemented with inner canopy lighting, productivity increased 23-87% (Stasiak et el., 1998). Also, Tibbitts and Wheeler found that using fluorescent side lights or MH light pipes with overhead-lighted potato crops gave increases in tuber dry weights of 12-16% (Tibbitts et al., 1994b). Sideward lighting systems for production of plants from cuttings was developed to reduce the vertical PAR gradient found in overhead-lighted propagation chambers (Hayashi et al., 1992; Kozai et al.,1992). One system used fluorescent lamps and it was demonstrated that sideward lighting reduced the electricity cost per potato plantlet produced from cuttings (Hayashi et al., 1992). Fluorescent lamps, however, take up a large volume of space, and they release heat that then has to be removed. To counteract these issues, Kozai and others (1992) used diffusive optical fibers as a light source for side lighting. This allows plant containers to be stacked, and also allows placement of containers near the light source, thereby increasing the efficiency of light capture and the vigor of biomass accumulation by plantlets (Kozai et al, 1992).

If low-intensity IC lighting is used as a sole source of PAR starting from the seedling stage, Frantz and others demonstrated that expanding cowpea leaves adapted physiologically to become shade leaves, with lower light-saturation levels and light-compensation points than plants lit with more intense light from above (Frantz et al., 1998). They used short, 15-watt fluorescent tubes suspended within the crop canopy by monofilament and surrounded by transparent Mylar sleeves to prevent leaf scorch (Frantz et al. 1998; 2000; 2001). With IC lighting as a sole source, they found twice as much edible biomass production per unit energy input as in overhead-lit canopies (Frantz et al., 2000). The two lighting architectures combined, however, did not increase overall yield relative to input wattage, probably because the fixed-position overhead lights were underutilized until the plants grew to sufficient height (Frantz et al., 2000). Frantz and colleagues demonstrated that increasing lamp number within the canopy by 38% raised stand productivity by 45%, and that the highest energy-use efficiencies could be obtained by switching lights on higher up in a canopy as the plants increased in height (Frantz et al., 2001). When the data were normalized, plants grown under low-intensity IC lighting produced 50% of the edible biomass of those grown under high-intensity overhead lighting but with only 10% of the total electrical energy input (Frantz et al., 1998). Further increases could not be accomplished, however, due to the volume occupied by the heat-shielded lamps – if more lamps were added to the canopy, the available planting space decreased. Those proof-of-concept studies with fluorescent lamps illustrated the need for a cool, small-volume light source that will allow switching on of lights to keep pace with plant growth. Vertical, linear-arrayed LEDs were found to fit those requirements.

LED RECONFIGURABLE LIGHTING ARRAYS

The NASA Specialized Center of Research and Training in Advanced Life Support (ALS NSCORT) was created to develop technologies to lower the equivalent system mass (ESM) of an advanced life-support system (Drysdale, 1997). The crops focus area of the ALS NSCORT has entered into a collaboration with Orbital Technologies Corporation (ORBITEC, Madison, WI) to develop a reconfigurable LED lighting array that will significantly reduce the power and energy required to grow plants using electric lights. The development and preliminary testing of this lighting-array system has been described in previous publications (Massa et al., 2005a; 2005b). Briefly, the prototype system uses ORBITEC's proprietary light engine, consisting of 100 chip-on-board LEDs set into a 6.25 cm^2 square chip. There are sixty-four 640-nm-emitting (red) LEDs, sixteen 440-nm-emitting (blue) LEDs, and twenty 540-nm-emitting (green) LEDs on each chip. Additionally, there are two photodiodes. The green LEDs and the photodiodes are in place to accommodate future system-upgrade capabilities. The small size and close proximity of the LEDs allows for uniform spectral blending of photon emissions. Since the LEDs are current controlled, with the colors controlled separately, both the red-blue ratio and the light intensity output can be adjusted continuously. Twenty each of these light engines are mounted along a hollow linear support (approximately 3 cm wide x 1.5 cm thick x 65 cm long) that is attached to an electronics enclosure (approximately 5 cm x 12 cm x 10 cm) also containing two fans. Figure 1 shows such a "lightsicle". The hollow design of the lightsicles allows air to be drawn through them from the bottom of the canopy past the circuitry controlling the LEDs and out the top of the enclosure, thus removing electrically generated heat from the vicinity of the plants. Each lighting array presently consists of 16 such lightsicles sized to light a growth area ~0.25 m^2 and a growth volume ~0.15 m^3. These arrays are currently configured to energize light engines from the bottom up, so that the lights can be switched on incrementally to keep pace with changing plant height.

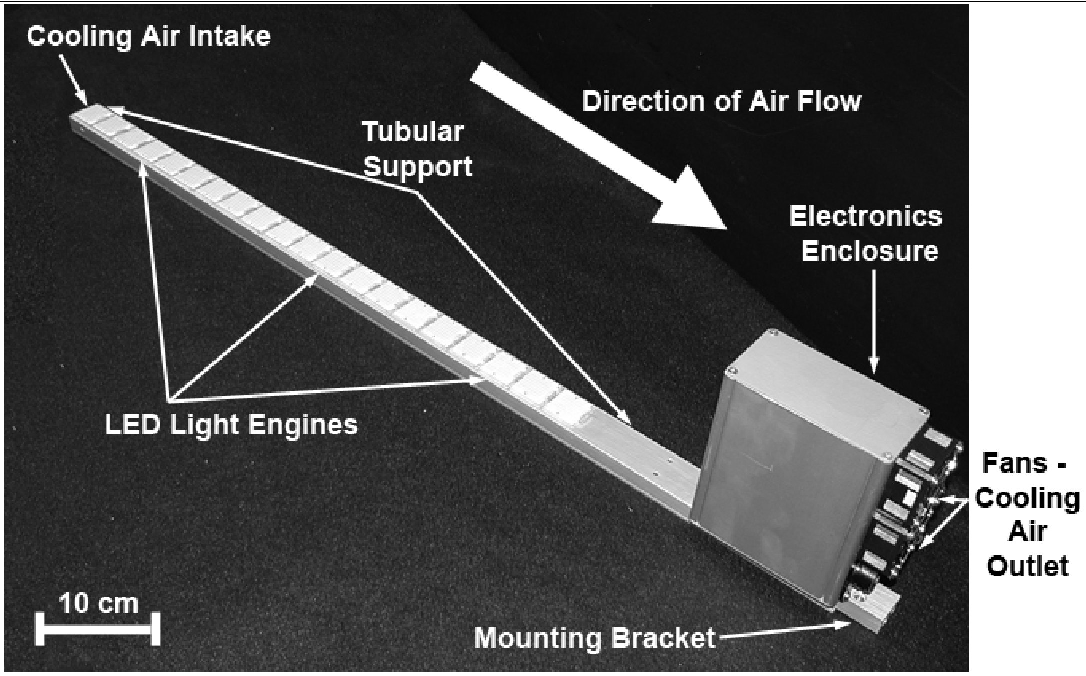

Fig. 1 *A lightsicle for the reconfigurable lighting array with the major external components labeled. Each lightsicle consists of 20 LED light engines mounted to a tubular support, with associated electronics. Cooling air is pulled through the support past the internal electronics by fans mounted on the electronics enclosure.*

The electronics systems within the lightsicles communicate with a control enclosure via a Controller Area Network (CAN) communication system. The control enclosure allows the user to select LED power levels as well as the number of light engines energized to allow manual control that keep pace with plant growth. Red and blue LEDs have independent controls. Photoperiod is controlled by a programmable timer. The control enclosure also houses the system power supply and plugs directly into grounded 110 V power sources.

Each lightsicle can be hung independently in a variety of configurations, allowing for flexibility in the intracanopy plant-growth arrangement. In addition, the lightsicle array can be reconfigured into a rectangular planar array consisting of 20 x 16 light engines for close-canopy, overhead lighting. Figure 2A and B shows lightsicles in intracanopy and overhead configurations, respectively. This close-canopy configuration is ideal for lighting rosette (e.g., lettuce) or erectophile (e.g. dwarf wheat) crops. The light array can be brought in close proximity to crop surfaces without scorching them, and after the development and integration of automated switching protocols, the energized engines will be able to track and mirror plant growth. Light engines positioned directly above each seedling will switch on automatically, and then adjacent engines will illuminate as the leaves of the seedlings are produced and expand until all engines are on. As with the IC lighting, greater efficiency will be achieved by not lighting empty space, but rather targeting lighting only where photosynthesis can occur.

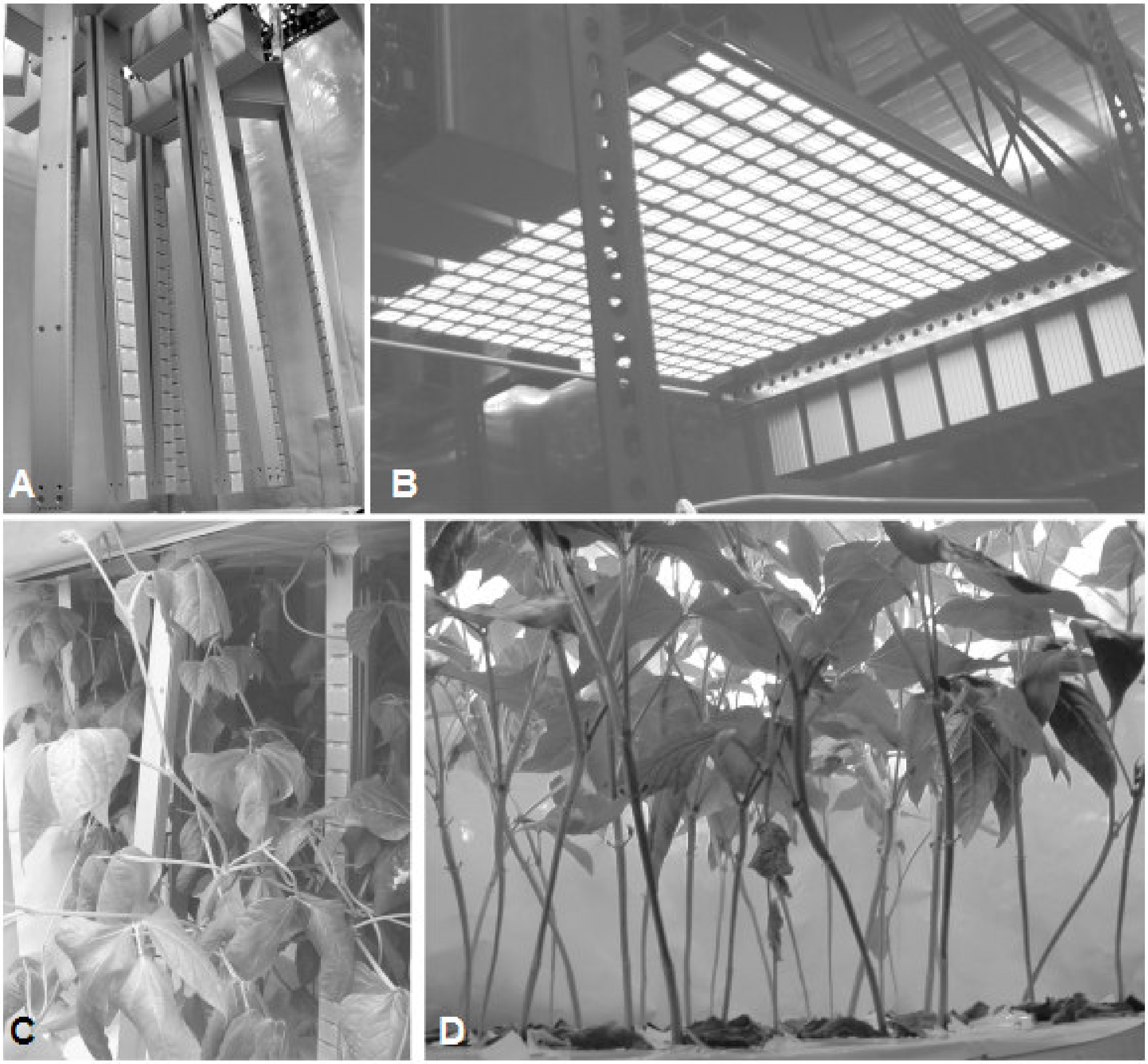

Fig. 2 ***A.*** *Intracanopy LED lightsicle array with LEDs off.* ***B.*** *Overhead LED array with LEDs energized.* ***C.*** *Intracanopy array with closed canopy of cowpea plants. LEDs are not energized.* ***D.*** *Overhead array with closed canopy of cowpea while LEDs are energized. Note senescence of lower leaves. Plants in* ***C.*** *and* ***D.*** *are both 32 days old.*

Five hardware tests were performed with the first prototype lighting array using cowpea crop stands. Modifications to the experimental design were made between trials 1 through 4 with incremental improvements in crop productivity achieved at each successive trial (Massa et al., 2005a). Figure 2C shows an example of an intracanopy-lighted plant canopy prior to harvest. Following intracanopy trial 4, the lighting system was reconfigured into a planar array, and a fifth trial was run using conditions identical to trial 4 but mounting the lights overhead (Fig. 2B.). In the overhead trial, all light engines were energized throughout the trial, while in the intracanopy trials, lights were switched on incrementally to keep pace with plant growth. To normalize the total power usage, the overhead lights were run at a current that was identical to the average daily current of intracanopy trial 4 so that the same total amount of electrical energy (99kW-h) was used during the month-long trial. In the overhead trial, we observed mutual shading and drop of the lowermost leaves, so that 11% of the total biomass senesced prior to the end of the trial. Figure 2D shows the overhead-lighted canopy prior to harvest. Overall, plants grown under overhead lights produced less biomass and had a reduced energy conversion rate than plants grown with intracanopy lights, with overhead-lighted plants averaging 75% of the productivity of intracanopy-lighted plants (data not shown).

These trials were conducted prior to the correction of certain electronic anomalies reported by Massa et al. (2005a). In the first hardware tests, PAR output from the light engines was very low when only lower engines were energized, with a maximum of 100 µmol m^{-2} s^{-1} emitted from a lower engine with 5 engines energized. As more engines on each lightsicle were energized, the light output from each engine increased until more than 700 µmol m^{-2} s^{-1} of PAR were detected from the same lower engine when all 20 engines were energized at the same power level. Thus, when plants were young and only a few light engines were energized, the light emission from that engine was still very low, causing elongate growth and spindly stems of seedlings. This light-output issue has been rectified through a modification of the software controlling the light-engine drivers, and now we are able to obtain uniform irradiation from a given engine regardless of the number of light engines energized along the array. A second set of lightsicles has been constructed by ORBITEC, and tests are underway to examine IC vs. OH irradiation in a side-by-side experiment. An additional feature added to the second prototype array is an extension so that the control box is raised on 8 of the 16 lightsicles. This allows the shorter lightsicle electronics enclosures to nestle under the longer lightsicles, giving a much wider range of possible lighting configurations. Light-engine positions in the longer lightsicles are the same as in the shorter ones.

FUTURE DIRECTIONS

A canopy gas-exchange-measurement system is being developed specifically for IC LED lighting. A custom-made, whole-canopy cuvette will allow real-time photosynthesis and transpiration rate measurements of an entire crop stand growing among the IC lights. Gas exchange will be measured as a function of environmental parameters such as light level, red-blue ratio, CO_2, and temperature. This powerful tool will permit rapid optimization of IC lighting and growth conditions for a variety of ALS candidate crop species.

A second research focus is being developed at ORBITEC under a Phase II SBIR from NASA for “High Efficient Lighting with Integrated Adaptive Control (HELIAC)”. This project focuses on the development of automated plant detection and light-engine switching using green LEDs and photodiodes embedded on individual light engines. Automation of the switching system to energize LEDs only when leaves are in front of light engines will conserve considerable energy by not lighting empty space, will maximize biomass production by keeping pace with plant growth, and will significantly reduce the personnel time involved with light operation. Additionally, these added capabilities will allow development of a close-canopy lighting system for targeted overhead lighting of erectophile and rosette crops.

CONCLUSIONS

When considering a light source for ALS, several important characteristics must be kept in mind: A variety of light sources have been evaluated from this perspective. LEDs, especially the relatively new chip-on-board LED light engines, appear to be optimal lighting systems for ALS crop growth for a variety of reasons. As a rapidly developing technology, electrical efficiency of these light sources continues to increase. In addition, the ability to precisely select a spectrum that is efficient for photosynthesis, growth, and flowering, the durable solid-state nature of LEDs, the relatively cool emitter surface, their long lifetime, tunability of the spectrum and irradiation levels, and ability to easily remove heat all combine to make this lighting type the best contender for ALS crop production. When the benefits of LEDs are coupled with techniques that apply light only where there is photosynthetic capability, the increased lighting efficiency will result in a significant reduction in the power required to maintain desired levels of biomass production, reducing the cost of growing plants in an ALSS, and bringing crop growth on Luna and Mars that much closer to reality.

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