History of Controlled Environment Horticulture: Indoor Farming and Its Key Technologies

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Abstract. The most recent platform for protected horticultural crop production, with the shortest history to date, is located entirely indoors, lacking even the benefit of free, natural sunlight. Although this may not sound offhand like a good idea for commercial specialty-crop production, the concept of indoor controlled-environment plant growth started originally for the benefit of researchers—to systematically investigate effects of specific environmental factors on plant growth and development in isolation from environmental factors varying in uncontrolled ways that would confound or change experimental findings. In addition to its value for basic and applied research, it soon was discovered that providing nonlimiting plant-growth environments greatly enhanced crop yield and enabled manipulation of plant development in ways that were never previously possible. As supporting technology for indoor crop production has improved in capability and efficiency, energy requirements have declined substantially for growing crops through entire production cycles in completely controlled environments, and this combination has spawned a new sector of the controlled-environment crop-production industry. This article chronicles the evolution of events, enabling technologies, and entrepreneurial efforts that have brought local, year-round indoor crop production to the forefront of public visibility and the threshold of profitability for a growing number of specialty crops in locations with seasonal climates.

The most recent commercial platform for growing specialty crops under cover does not use sunlight. In fact, all cardinal factors of plant growth (light, temperature, water, nutrients, and atmosphere) must be provided and controlled to grow crops to harvest maturity indoors (Mitchell, 2004). The umbrella term “controlled-environment agriculture” (CEA) covers additional appellations including “indoor agriculture” (IA), “indoor farming” (IF), “vertical farming” (VF), “plant factories” (PF), “container farms” (CF), and more. By controlling all cardinal factors, fresh produce can be grown rapidly and productively indoors year-round, regardless of outside climatic or weather conditions. Complete environmental control has obvious advantages for growing perishable produce with limited shelf life, especially to avoid risk of quality loss and costs associated with long-distance transportation. Local indoor production also accommodates food safety by eliminating abiotic and biotic risks to

crops growing in the field, as well as threats to food security related to global climate change and disruption of international supply chains.

Milestones of Environmental Control

From slow beginnings to accelerating change. Organized plant agriculture began with open-field cultivation of precursor crops in the fertile crescent at least 12,000 years ago (Riehl et al., 2013). Irrigation was the first environmental control. Agrarians quickly learned how to further protect crops from nature’s elements. The semicontrolled environments we now refer to as greenhouses have existed since 30 CE (Paris and Janick, 2008), but the advent of controlled-environment research buildings called *phytotrons* occurred only 71 years ago (Kramer et al., 1970; Went, 1957), enabling understanding of how combinations of environmental factors control plant growth and development. Environmental control has set the stage for the present CEA era of plant agriculture, which has evolved rapidly over the past half century, raising hope that it will contribute to sustainable food production of the 21st century. As well, launch of the “Veggie” plant-growth unit for “pick-and-eat” salad-crop production on the International Space Station (Herridge, 2014) is a precursor to self-sustaining human space habitats (MacElroy et al., 1985). This article highlights important milestones that have enabled the rapid

evolution of indoor agriculture, including vertical farming, as well as future space farming.

Phytotrons and growth chambers. Development of the Earhart Plant Research Laboratory at the California Institute of technology in 1949 was the first significant upgrade from the semicontrolled environments of greenhouses. Many technological innovations to control all aspects of the plant-growth environment, including sole-source electric lighting in specialized growth compartments, enabled useful basic and applied controlled-environment (CE) plant research to take place at Earhart (Went, 1950). Earhart was followed by establishment of several externally funded phytotrons and biotrons at U.S. universities and other institutions (Duke, North Carolina State, Wisconsin, the St. Louis Botanical Gardens), as well as internationally (Australia, France, Japan, New Zealand) during the 1950s and 1960s (Chouard and de Bilderling, 1975; Downs, 1980; Warrington, 1974). The phytotron concept included large, centralized environmental-control facilities serving individual plant-growth compartments involving distributed power, water, and heating/ventilating/air-conditioning (HVAC) subsystems, thereby allowing multiple growth rooms to operate independently of each other with different environmental-control options. Although much valuable basic and applied research has come out of phytotrons, the downside of the original concept was great installation cost and high operational expense. Maintenance costs, especially for electrical power use, were high, and users typically had to bear significant recharge costs for phytotron space or were subsidized. Occupancy rates in phytotron facilities were initially robust but declined gradually over time. Competitive growth-chamber companies advanced concurrently, including Conviron (<https://conviron.com/>), Environmental Growth Chambers (EGC; <https://www.egc.com/>), and Percival (<https://www.geneva-scientific.com/percival-scientific>). (All three companies’ websites were last accessed 20 July 2021.) Many other growth-chamber companies have formed since these initial pioneers. Such companies have collectively developed customized as well as standardized reach-in chambers and walk-in CE rooms for a fraction of the cost of large, centralized phytotron facilities. The phytotron concept has been gradually replaced for a great majority of CE researchers by smaller, decentralized, individual growth-chamber units with more affordable mechanical and electrical operating costs and less daunting maintenance requirements. Research-grade growth-chamber units at many academic institutions throughout the world have improved incrementally and continuously, especially since the 1960s.

Moving CEs toward commercialization. The prudent academic research spirit hesitates to herald commercialization of new technology before it can be validated and

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optimized, before realistic business plans can be developed, before markets can be determined favorable, and prospects for business profitability considered promising. Regardless, the indomitable entrepreneurial spirit typically charges forward to establish a competitive leadership position, to be well postured for anticipated technological advances, and to pursue the promise of untold riches awaiting those who do not hesitate. Such has been the history of IA, long before vertical stacking was even a demonstrated concept. The industry advances with slow but steady input from systematic research, but ambitious business enterprises surge forward, changing things as they need to or can.

Geniponics. One of the first hybrid research/commercial IA enterprises was Geniponics, a synthesis of General Electric and “hydroponics,” which opened in Syracuse, NY, in 1973 (Murphy, 1983). Geniponics initially had R & D funding from the U.S. Department of Defense to grow fresh vegetables for crews of nuclear submarines submerged for months at a time. However, the federal sponsor quickly dropped its funding when it was discovered that submarine space needed to grow fresh vegetables could be used to store more torpedoes instead. General Electric continued to self-fund Geniponics, which also attracted short-term external sponsors. Hot, energy-guzzling high-pressure sodium (HPS) lamps, recirculating hydroponics, CO₂ control, and air-conditioning were combined to grow tomatoes, lettuce, and cucumbers, achieving 5-fold higher vegetable yield than in the field, but it was determined that Geniponics could be profitable only if electricity costs were less than \$0.015/kWh. News releases suggest that Geniponics sold some of their produce commercially. Geniponics also deployed mobile CE units at a military facility in Newfoundland, Canada, as part of U.S. Army Natick Laboratories-sponsored work, demonstrating feasibility of onsite production of fresh vegetables for hundreds of service personnel at remote sites (Ayoub and Rahman, 1982). Control Data Corporation purchased them in 1980 and tried to establish a business, but rising electricity prices led to Geniponics shutting down in 1984.

Phytofarms. Phytofarms of America, initially a General Mills precommercial R & D project, started up in 1978, but the parent company got out when they realized the CE technology of the time was not ready for near-term, significant profit margins. Developer Noel Davis bought Phytofarms back from General Mills and made a private commercial run (Field, 1988) until the early 1990s, when economic factors conspired to also close Phytofarms. However, the enterprise was innovative for its time. It was warehouse-based, used CO₂ control, and was strategically located in DeKalb, IL, from which it could deliver fresh produce daily to the Chicago and Milwaukee markets when hydroponic vegetables were still novel. Phytofarms practiced assembly-line crop production on two warehouse levels (Fig. 1), so it

Fig. 1. Interior layout of Phytofarms of America warehouse including unique technology, materials flow, and crop production on two levels. (Image courtesy of *Discover* magazine.)

already was “vertical” in that sense. Patented innovations included water-cooled, 1000-W high-intensity discharge (HID) lamps, allowing lamp placement only 1.2 m above crop stands. Waste heat was exchanged outside, even during the coldest days of winter. Troughs with recirculating nutrient solution were placed at right angles across worm gears that automatically spaced plants out between rows as they grew in diameter. Side walls of slowly moving benches reflected light from alternating HPS and metal halide (MH) lamps and minimized light gradients (Fig. 2). Phytofarms burned about a megawatt of electricity, which contributed to its commercial demise as off-peak electrical cost crept up over time.

The yield advantage of IA. Because Geniponics and Phytofarms eliminated variables that limit plant growth in the field, their crops achieved higher yields (Mitchell, 2004). Being able to grow crops indoors leverages the advantage of continuous vs. seasonal crop production, and increasing degrees of control only extend that advantage. Thus, annualized yield rates of Geniponics and Phytofarms crops were at least an order of magnitude higher than those of field-grown crops (Table 1; Bates and Bubenheim, 1982). Although the yield advantage of indoor production was obvious, early commercial profitability was elusive due to high costs of production, especially for electric lighting.

Vertical IA in the Netherlands. While Geniponics and Phytofarms were operational in the United States, J. Lestraden in the Netherlands pioneered the concept of stacked layers to grow crops in an industrial factory (Reformatorisch Dagblad, 1984). Lestraden was a mushroom grower before expanding into lettuce, gerbera, tomato, and tulip in seven to 20 vertically stacked layers, requiring the addition of electric lighting. He tried different lamps available at the time, and

found neon lights to work best for him. Crops were cultured in 6-m-high closed cells described as “gigantic test tubes” that were periodically ventilated through air filters for disease control. It is unclear how long this Dutch enterprise lasted, but local critics seemed to wait for its failure, which may reflect loyal commitment to the greenhouse platform prevailing in the Netherlands at that time.

Plant factories. In Japan, precommercial growth-chamber research began in the 1970s (Takakura et al., 1974). TS Farm, developed by the Kewpie Corporation in 1989–90, uses aeroponics and A-frame design and is the oldest PF in continuous operation (Nakamura and Shimizu, 2019). PFs with artificial lighting (PFALs) initially used HPS crop lighting but converted to less hot fluorescent lighting when fluorescence improved in efficiency by the late 1990s, making it feasible to stack plant shelves vertically with lamp-to-shelf separation distances of 40 to 50 cm (Kozai, 2016). Conversion to light-emitting diodes (LEDs) began by 2005. Due to its population density and need to make indoor cropping space as efficient as possible, the Japanese generally are credited with the stacking concept and its annual yield advantage of 100-fold compared with the field on a ground-area footprint basis (Kozai, 2013a, 2013b). Technically, Phytofarms in the United States and Lestraden in the Netherlands also should be recognized for this innovation, although for different stacking concepts. One reason for the longevity of PFAL enterprises in Japan involves government subsidy and participation of academia in the design and testing of subsequently commercialized enterprises. Toyoki Kozai at Chiba University has become known in Japan as the “Father

Fig. 2. View from the harvest end of one slowly-moving Phytofarm bench. (Image by the author.)

of the Plant Factory” (Fig. 3). In addition to conducting much CE research, Kozai coordinated the writing of multiauthored, authoritative reference books on a diversity of PFAL topics (Kozai et al., 2016a, 2016b, 2020).

Global IA summary. Countries where IA is actively under commercial development include the USA, where the players generally are large, private companies with external investors (Agrilyst, 2017; Kubota, 2020); Japan, which probably has the most commercial enterprises, and has been government subsidized (Kozai, 2020); Taiwan, with some subsidized R & D (Fang, 2020); Korea, exporting technology (Chun, 2020); China, importing technology, preparing to take over their local IA industry (Tong and Yang, 2020). The UK and the European Union are interested, with some IA business development, but they also have a well-established greenhouse industry to compete with. Canada is a leader in CEA technology development for seasonal climates; its efforts are currently focused on *Cannabis* production (CEA, 2018). Overall, IA/VF expansion seems to be most rapid in Asian countries but is on the rise globally. The present configuration of the IA industry is uniquely suited for local production of highly perishable vegetables. The entrepreneurial spirit of many IA purveyors is global, but their intent is to expand local operations to a global scale, not to ship produce globally. Becoming profitable and sustainable without overextending capability at any given location is their present challenge.

CE Technical Advancements

Historical technology advancement. Today’s commercial vertical farms and plant factories are a logical spinoff, upgrade, and scaleup from early growth-chamber/phyto-tron technologies. Mechanical and electrical components of CEs have improved continuously since the 1950s, still operating on the same engineering principles but becoming more robust and reliable over time.

Two significant technological advancements that have moved environmental controls beyond initial capabilities include computer-based automation (Jones et al., 1984; Takakura et al., 1974) and adaptation of LED technology for sole-source crop lighting (Massa et al., 2008; Tennessen et al., 1994). Modern computer controls are more sophisticated today than for first-generation growth chambers with mechanical controls. When applied to automation, computer controls enable substantial replacement of manual labor in commercial operations. LEDs have a long lifespan, do not radiate significant thermal energy from photon-emitting surfaces, can be selected for wavelength specificity, continuously improve in efficiency, and lend well to vertical stacking of growth tiers.

CE research enabled by NASA. Early growth-chamber research languished from lack of adequate and consistent funding. By the late 1970s to early 1980s, however, NASA began funding a few academic research projects based on the vision that CE plant growth can sustain bioregenerative human life-support systems in space (MacElroy et al., 1985; Wheeler, 2010). Initial returns indicated that crop plants could indeed generate the O_2 , purify the H_2O , scavenge the CO_2 , and produce the edible biomass needed to nutritionally support human crews living in closed-space habitats (Bugbee and Salisbury, 1988; Goyal and Huffaker, 1986; Knight and Mitchell, 1983; Tibbitts et al., 1994). While NASA was funding early CE plant research, in 1987 it also developed the Biomass Production Chamber (BPC) at the Kennedy Space Center (KSC) in Florida (Corey and Wheeler, 1992; Prince and Knott, 1989). The BPC was converted from a high-altitude simulation chamber for the

Gemini and Apollo programs into a vertically tiered, ground-based growth chamber for conducting food-crop research within materially closed environments (Dreschel et al., 2019) in 20 m² of growth space. Recirculating hydroponics, HPS lighting, CO_2 injection, gas-exchange monitoring, and massive thermal controls and air-moving equipment were arrayed within and around the BPC in an aircraft hangar at KSC. Candidate crop species (wheat, soybean, lettuce, potato, rice, and tomato) were grown hydroponically and monitored continuously for diurnal gas exchange to determine the feasibility of growing food crops while revitalizing atmosphere in closed environments as a model for future space bioregenerative life-support systems (Galston, 1992; Wheeler, 2003). NASA considered the multistoried BPC with crops growing on four levels its own version of a vertical farm (Fig. 4). Precursor closed-system research with plants conducted in Russia (Gitelson et al., 1976, 1989) set the stage for the BPC and NASA’s bioregenerative life-support research program.

The light-source problem. The only electric light source available throughout the 1970s and into the 1980s to provide sufficient light intensity to grow crops productively indoors were HID lamps, which have high energy requirements for lighting and heat rejection. Because this was more energy than NASA could provide for crewed life support in space (Drysedale and Bugbee, 2003; Mitchell et al., 1996), NASA put life-support research involving plants on hold in 2006. Energy costs of HID crop lighting also contributed significantly to the premature closure of early commercial IA ventures such as Geniponics and Phytofarms.

LED lighting. An unexplored alternative to HIDs for sole-source plant-growth lighting until the 1980s was the LED, which was originally developed by General Electric in 1962 (Baldwin, 2012), but at that time was not powerful enough to provide adequate light for photosynthesis. The “high-output” LEDs developed in the late 1980s put out from one to several watts of photon power per diode, which was a considerable upgrade. Because of their individual small size, LEDs could be mounted close together in large arrays to collectively emit substantial, overlapping light beams (Morrow, 2008). LEDs are solid-state light sources that run on low-voltage direct current; have long lifetimes (at least 50,000 h); can be manufactured to emit light of specific wavelengths; do not require hot, bulky ballasts; and emit little waste heat at photon-emitting surfaces when adequately heat-sinked (Bourget, 2008).

Due to the high-energy burden of CE plant lighting holding back commercialization of IA into the 1980s, NASA sponsored the first plant-research project with LEDs at the University of Wisconsin to explore the feasibility of reduced-energy plant-growth lighting, and the outcome was promising (Bula et al., 1991; Hoenecke et al., 1992). Test plants grew adequately under red (R)

Fig. 3. Vertically stacked production systems built at Chiba University in Japan. (A) The seven-tiered system built for research and development in 2000 used fluorescent lighting. (B) The Chiba plant factory with artificial lighting built in 2011 for commercial production of leafy vegetables was converted to LED lighting in 2016. (Images courtesy of Toyoki Kozai.)

Table 1. Yield (pounds/ft²/yr) for three vegetable crops grown in various cropping systems.

Crop ^z	Lettuce	Tomatoes	Cucumbers
Field	0.5–3.0	0.5–3.0	1–5
Greenhouse	4–10	4–11	5–19
Abu Dhabi greenhouse actual	10.2	8.1	19.0
A Dhabi greenhouse potential	13.8	9.0	20.7
Geniponics actual	40.0	21.1	34.1
Geniponics potential	65.0	48.0	50.0
Phytofarms actual	55.0	—	—
Phytofarms potential	75.0	—	—

^zAfter Bates and Bubenheim (1982).

LED light alone, which has the highest relative quantum efficiency of photosynthetically active wavebands (McCree, 1972). Blue (B) light provided originally by fluorescent lamps combined with R LED light promoted pigment formation and stimulated growth and photosynthesis even more than did red light alone. However, at more than a few percent of total radiation, B light powerfully inhibits stem elongation (Cosgrove and Green, 1981). NASA subsequently flew LED arrays lighting plants on the space shuttle to test growth of food crops in microgravity for future space bioregenerative life-support systems (Barta et al., 1992; Croxdale et al., 1997; Morrow et al., 1995; Stankovic et al., 2002; Zhou, 2005). Ground-based research subsequently investigated spectral combinations of LED lighting, including newly available B and far-red (FR) LEDs (Brown et al., 1995; Matsuda et al., 2004; Tennessen et al., 1994; Yanagi et al., 1996). In addition to the desirable effect of stimulated leaf expansion (Li and Kubota, 2009), radiation from FR LEDs synergistically stimulates photosynthetic efficiency when combined with shorter photosynthetic wavebands (Zhen et al., 2018).

When leafy greens were grown under different proportions of R, B, and green (G) LED light, 24% G stimulated leaf expansion and shoot dry weight gain (Kim et al., 2004). Because G light is absorbed by leaves less efficiently than are R and B light (McCree, 1972), G is able to penetrate deeper into leaf canopies and drives photosynthesis of inner leaves. Green light also antagonizes photomorphogenic actions of B light (Folta and Maruhnich, 2007).

Experimentation revealed which plant processes are controlled by specific wavebands but also reinforced the importance of broad-band light. Considerable interest subsequently developed to grow plants with white (W) LEDs, which are actually B LEDs with a phosphor coating that reradiates W light. Phosphor composition determines whether reemissions give cool-W, neutral-W, or warm-W, depending on proportions of B reemitted from the LED. White LEDs giving off a higher proportion of B light result in shorter and smaller plants, from both a stem-elongation and a leaf-expansion perspective (Cope and Bugbee, 2013). As the LED industry has progressed, different chromatic indexes of W

LEDs are substituting for combinations of monochromatic LEDs, depending on species spectral preferences and desired growth outcomes. Three scientists in Japan and the United States shared the 2014 Nobel Prize for physics celebrating their development of the B LED in the early 1990s (Royal Swedish Academy of Sciences, 2014), which enabled important aspects of plant-lighting technology, including W LEDs.

Improving LED efficiency. Early trends in LED technology development suggested a reciprocal pattern of efficiency improvement vs. cost reduction predicting that, for each decade of product development, the electrical efficiency of LED photon output would increase 20-fold while the cost of LED production would decrease 10-fold (Drennen et al., 2001). Although it is unclear whether similar trends extrapolate today, LED electrical efficiencies and photon-flux efficacies have indeed improved over time. By 2006, R LEDs were only 21.5% efficient (meaning that just 21.5% of input electric energy was converted to photon energy), whereas Bs were just 11% efficient (Massa et al., 2006). Two years later, R efficiency had climbed to 25%, B jumped to 20%, and W lagged at 10% efficiency (Bourget, 2008). By 2014, B LEDs climbed to 49% efficiency, followed by cool-W at 33%, and then R at 32% (Nelson and Bugbee, 2014). Photon flux efficacy (PFE) at that time was 1.87 $\mu\text{mol/J}$ for B LEDs, 1.72 $\mu\text{mol/J}$ for R, and 1.52 $\mu\text{mol/J}$ for cool-W. By 2017, B LEDs were 54.8% efficient at a PFE of 2.17 $\mu\text{mol/J}$, R 47.6% efficient at 2.42 $\mu\text{mol/J}$, and W 42.5% efficient with a PFE of 1.94 $\mu\text{mol/J}$ (Cocetta et al., 2017). Green LEDs lagged in efficiency

Fig. 4. NASA Kennedy Space Center Biomass Production Chamber (BPC). (A) Multilevel high-altitude test chamber reconfigured for closed-system plant growth. (B) Hydroponics maintenance system outside the BPC. (C) Taking data for wheat grown in closure. (D) Looking up through four tiers of wheat growing in NASA's BPC "vertical farm." (Images courtesy of NASA.)

at 16.7% to 30.5%, depending on G-waveband-emission range, and their PFEs ranged from 0.73 to 1.46 $\mu\text{mol/J}$. By 2019, OSRAM data sheets (D. Hamby, OSRAM, personal communication) indicated the best B LEDs were 71% efficient at a PFE of 2.42 $\mu\text{mol/J}$, whereas R and FR were 59% each, with PFEs of 3.14 and 3.50, respectively. It is likely that LED electrical efficiency and photon flux efficacy will plateau in the next 10 to 15 years as they approach a practical maximum $\approx 10\%$ below their theoretical maximum (Kusma et al., 2020).

Although manufacturing costs for LED plant-growth arrays have declined as product demand has risen, capital investment for growers started out 3 to 5 times higher for LED arrays than for equivalent-coverage HPS fixtures, which has been an issue preventing commercial growers from investing substantially and frequently upgrading rapidly evolving LED technology. However, recent marketing trends have been for cheaper LED products with shorter lifespans that will allow affordable replacement every few years as LED technology advances. Beyond periodic upgrade of commercial LED efficiency, bringing operational costs of LED lighting down by improving best practices is of ongoing interest because the IA industry is not yet consistently profitable.

Unique LED properties. Leveraging the unique properties of LEDs is an approach with potential to make indoor plant lighting more efficient. Because individual LEDs are point sources of radiation (Bickford and Dunn, 1972), they obey the inverse square law of physics, which describes how radiation intensity decreases exponentially with increasing separation distance between light source (LED chip) and light target (leaf). A large decrease in light intensity with incremental separation between lamps and plants can be mitigated by combining use of optic lenses that restrict beam spreading from LED clusters with appropriate spacing between clusters so that a uniform light beam is emitted from the fixture that minimizes loss of intensity with separation distance. Electrical power and energy can be saved by reducing the separation distance between lamps and plants (Massa et al., 2008). Minimal separation distance is enabled because waste heat is removed from the rear circuitry of heat-sinked diodes (Bourget, 2008). This means that energized LEDs can be located close to plant tissues without scorching them, and with reduced input power to those LEDs, photon intensity at plant surfaces still can be the same as with greater separation distances. LEDs arrayed onto fixtures with overlapping photon beams are no longer point sources, and beam intensity decreases less with increasing separation distance.

Intracanopy lighting. Those energy-saving principles were initially demonstrated for within-canopy crop lighting using low-power fluorescent lamps (Frantz et al., 1998, 2000, 2001). Subsequent lighting improvements included LED “lightsicle” strips that provided “intracanopy” lighting for upright-

growing, self-shading plants (Massa et al., 2005a, 2005b). Light engines containing dimmable LED clusters arrayed along vertical strips could be switched on sequentially to keep pace with growth in crop height so that the interior leaf canopy could be lighted, but not empty spaces above the crop stand. A fan mounted at the top of lightsicle strips pulled cooling air up through the hollow strip across heat sinks behind each light engine and out the top of the light strip (Fig. 5). The small-scale laboratory lightsicle concept has been scaled up into “LED towers” used for intracanopy lighting of greenhouse high-wire tomatoes (Gomez et al., 2013; Gomez and Mitchell, 2016) and vertical “walls” of LEDs used in container farming.

Close-canopy targeted lighting. Similar principles have been adapted for overhead lighting of low-profile crops such as leafy greens. LED fixtures are mounted horizontally on an adjustable-height framework with a switching mechanism that allows clusters of LEDs positioned above individual plants to be energized selectively. Thus, as plants grow in diameter, targeted-lighting circles enlarge until the crop canopy closes, when all LEDs are energized. For lettuce crops grown with targeted vs. full-coverage LED lighting, 50% electrical energy was saved using targeted lighting (Fig. 6; Poulet et al., 2014). Automated plant-size detection, targeted LED switching, and minimizing plant/fixture separation distance will be future technical strategies for smart, energy-efficient overhead lighting in IA.

Efforts to establish LEDs for sole-source crop lighting. Anticipating technology advancements to help establish profitability of the commercial IA sector, members of the ASHS CE Working Group and NCERA-101 Committee on CE Technology and Use organized a workshop at the 2007 ASHS conference titled “LEDs in Horticulture.” Publication of the proceedings in the Dec. 2008 *HortScience* attracted interest from the global plant-research community, and one workshop article, “Plant Productivity in Response to LED Lighting” (Massa et al., 2008), has been highly cited. In 2010, a team of plant scientists, economists, and engineers from academia and industry was awarded a Specialty-Crop Research Initiative (SCRI) grant led by Cary Mitchell at Purdue University entitled “Developing Light-Emitting Diode Technology and Practices for Sustainable Specialty-Crop Production” (Mitchell et al., 2012). That SCRI team published a review article titled “LEDs in Horticulture” (Mitchell et al., 2015) revealing a field of CE research interest expanding worldwide. In 2018, another SCRI project led by Marc van Iersel (2018) at the University of Georgia was funded titled “LAMP: Lighting Approaches to Maximize Profits,” and a third SCRI project led by Erik Runkle at Michigan state University was funded in 2019 titled OptimIA: “Improving the Profitability and Sustainability of Indoor Leafy-Greens Production” (Allen, 2020). These

projects collectively deliver new information and technical innovations helping to advance the IA industry.

Coming full circle from space back to Earth. Adaptation of LED technology for plant growth, originally supported by NASA, has greatly enhanced terrestrial IA over the past two decades. Prospects for successful growth of plants in space for future human life support now benefit from advances in LED technology spinning off from research funded by agencies other than NASA. Two LED-lighted “Veggie” plant-growth units were launched to the International Space Station (ISS) in 2014 as part of a “pick-and-eat” experiment to grow vegetables for supplementation and psychological augmentation of astronaut diets (Massa et al., 2013). Although CO_2 concentration, temperature, and humidity within Veggie vary with ambient ISS cabin levels, light from Veggie LED fixtures is adequate to grow leafy vegetables, and information regarding environmental-control capabilities needed for successful plant growth in space has been obtained growing plants in Veggie (Burgner et al., 2020; Massa et al., 2016). Subsequent installation of an Advanced Plant Habitat (APH) on ISS has enabled more precise control of the plant-growth environment (McAllister, 2018). Veggie and APH are collectively providing historic baseline data regarding unique environmental requirements for plant growth in space.

Public Awareness of IA/VF Crop Production

Popular press. While academic CE research funded by NASA and NIFA was ongoing and being communicated primarily within life science and engineering peer communities, a book titled *The Vertical Farm: Feeding the World in the 21st Century* was published in the popular press (Despommier, 2010). That big-picture book expanded public awareness of VF that federally funded research had not yet communicated extensively to the general public through academic extension and outreach channels. However, the book’s futuristic visions of high-rise indoor urban agriculture prompted push-back from agricultural engineers and CEA experts, raising questions about the reality of where the energy would come from for its utopian visions of indoor urban agriculture (Bugbee, 2015; Shackford, 2014;). Similar questions haunted Geniponics, Phyto farms, and investors seeking early return on investment in the nascent IA/VF industry. Book reviews of the *Vertical Farm* are mixed, but it has contributed to public awareness of the rapidly developing IA/VF industry.

A novel and its movie. Publication of the novel *The Martian* (Weir, 2011) and the 2015 movie based on the book have exploded public enthusiasm about how enclosed food crops can be grown for autonomous life support in space as well as on Earth. Fictional future astronaut Mark Watney is accidentally stranded at a hastily abandoned Mars base

Fig. 5. A crop stand of hydroponic tomato plants growing among air-cooled “lightsicles” with light engines containing red + blue LEDs switching on from the bottom up as plants grow in height. Lack of thermal radiation from the diodes + effective heat sinking within the strips permits close spacing of LEDs and plants. (Image courtesy of Gioia Massa.)

with a food supply limited to a few months, but he needs to survive for hundreds of sols (one sol = one 24-h Earth day + 39 min) longer before rescue is possible. Watney discovers a few live potato tubers among stored food supplies and creatively leverages his dual training as a botanist and mechanical engineer to propagate and successfully grow a potato crop in Mars regolith (oxidized mineral soil) that he hauls into an environmentally controlled, inflatable habitat. After supplementing the regolith with organic matter from freeze-dried astronaut feces, he inoculates the mix with soil bacteria brought from Earth for composting. Then he converts Mars atmospheric CO_2 to O_2 (via oxygenator technology), catalytically converts rocket fuel (hydrazine) to H_2 , and then combusts the H_2 and O_2 together to create H_2O for plant growth. Watney is depicted as successfully growing potato crops that provide him with supplemental energy and nutrition essential for survival until he can be rescued. The book author and movie producer assume that habitat electric lighting powered by external solar collectors is adequate for indoor plant growth on Mars. Ultimately, none of several potential caveats to CE crop growth on Mars would be showstoppers, if adapted with realistic technology applications and energy requirements for plant growth (Bugbee, 2015; Maynard-Casely, 2015). *The Martian* demonstrates that creatively leveraging science and technology together can solve many problems of both human and plant survival in stressful environments. This appealing story

educated the public about the feasibility of CE food-crop production in the entertaining context of a “realistic” space adventure.

Current Trends and Future Directions

IA has an ongoing history of technology convergence. Technologies collectively enabling control of the cardinal factors of plant growth have evolved, developed, and converged over the past 80 years to enable IA to become routinely operational: They include soilless culture, which started in the 1930s (Gericke, 1938; Hoagland and Arnon, 1950); the advent of plastics, which made modern hydroponics feasible (Jensen and Rorabaugh, 2020) in the 1940s; environmental-control systems, evolving out of growth-chamber/phytotron research starting in the 1950s (Went, 1957); computerization and automation of those controls, starting in the 1970s (Jones et al., 1984; Takakura et al., 1974); and the LED era starting in the early 1990s (Bula et al., 1991), which kick-started evolution of the IA industry to where it is today. This history of steady technology convergence, innovation, and adoption has defined present features of an indoor vertical farm as we know it (Kozai and Niu, 2016): an insulated warehouse; vertical tiers of grow racks equipped with overhead LED lighting; HVAC for thermal, humidity, and ventilation control; CO_2 injection and control, especially for large buildings filled with vegetation; soilless drip fertigation, recirculating hydroponics, or aeroponics;

computer-based environmental control; and, increasingly, automation of previously manual operations. Smart environmental systems controlled by artificial intelligence are a next step in technology convergence and advancement.

Container farms. An alternative to traditional, warehouse-based VFs are much smaller, modular, indoor farms, which typically are created from 20- or 40-foot-long shipping containers that have been outfitted for complete environmental control. Greens might grow out of rows of vertical hydroponic panels or towers faced by walls of LED lights illuminating in two directions. Such limited-scope technology convergence typically is deployed in specific locations with niche markets, such as remote arctic cities with limited seasonal supply of fresh produce; in urban food deserts lacking fresh produce; or adjacent to high-end gourmet restaurants whose chefs and customers demand fresh, high-quality, premium produce grown locally.

LED trends for IA growth of leafy vegetables. Currently, LED technology continues to improve in efficiency, and costs are coming down as a function of sales volume but are still significant. In fact, some LED equipment, especially W LEDs with a shorter lifespan, are being marketed at reduced cost, the marketing strategy being that as cheaper lighting equipment approaches the end of its lifetime, it will be replaced by new, still relatively inexpensive equipment with improved performance capability. Turnover of LED lighting equipment every 3 to 4 years is a near-term marketing strategy for the evolving IA lighting industry. The commercial IA industry is moving away from using blends of monochromatic LEDs to either a mix of broadband W LEDs plus a few R LEDs or just warm-white LEDs that are rich in red, which is preferred by red-loving species such as lettuce (Kong et al., 2019). Multichannel LED arrays dimmable by waveband give flexibility for growing more species or cultivars with different spectral preferences but will cost more. Researchers want to retain such flexibility, but commercial growers may opt for cheaper, fixed-spectrum, nondimmable LEDs and specialize in crops best suited for a given, affordable lighting technology. As adjustable-height lamp mounts become available for VFs, trade-offs can be

Fig. 6. (A) Full-coverage close-canopy vs. (B) targeted close-canopy LED lighting of leaf lettuce. Photons of targeted lighting are not wasted striking surfaces not populated by plants while plants grow in diameter. (Images courtesy of Lucie Poulet.)

weighed between the cost of dimmable LED hardware and energy savings offered by close-canopy lighting. Profitability for baby and leafy greens also will be a tradeoff between costs of ever-improving technology and being able to command premium pricing in the market place. Economies of scale may play a role in survivability and profitability of VFs growing greens, most likely favoring larger growers.

Cannabis. With many states legalizing production of recreational and/or medicinal *Cannabis*, consumer demand for cannabinoid floral metabolites has expanded. Although increasing supply is bringing market prices somewhat lower (Durkay and Freeman, 2016), product value still is considerable (Naville, 2019), and potential to grow multiple crops rapidly year-round under sole-source electric lighting is attractive to growers. Although most high-light fruiting crops are grown more profitably in greenhouses with supplemental lighting than indoors under sole-source electric lighting, the market value of *Cannabis* products is high enough to absorb the extra cost of sole-source lighting, and by turning more crops per year by IA than seasonally outdoors or even in greenhouses, IA profits are even higher. In fact, electrical demand for indoor *Cannabis* lighting has become 1% of total demand in the United States (Electricity Plans, n.d.) and as much as 50% of recently added electrical demand in areas of California (Maloney, 2018).

High-intensity discharge lamps initially were used for supplemental lighting of *Cannabis*. Despite interest, indoor growers have been slow to transition to LEDs, in part because cheaper HID work, and high product value justifies the extra electrical cost. Much research is needed to optimize lighting recipes for *Cannabis*. As indoor cultivation of *Cannabis* matures, intracanopy LED lighting will be used increasingly

when *Cannabis* is grown indoors as a tall crop. Horizontal LED Interlights could be placed within the canopy of densely spaced crop stands to supplement overhead lighting and promote vegetative growth while preventing mutual shading or to enhance flower-bud formation under inductive short days. For cultivation of *Cannabis* in vertical tiers (Gayman, 2019), short-statured plants are required. Apical dominance can be broken by pinching, and once short photoperiods induce flower-bud formation, close-canopy overhead lighting can best be achieved using LED arrays, which consume less power and produce much less waste heat than do HIDs. If light spectra can be leveraged to enhance desired amounts or ratios of cannabinoid metabolites of interest, tunable sole-source LED lighting will become the light source of choice for indoor *Cannabis* production in coming years.

Plant-made pharmaceuticals. The metabolites of interest in *Cannabis* production are natural products of gene expression. However, as host plants are engineered genetically to produce plant-made pharmaceuticals (PMPs) including insulin, antibiotics, or vaccines, such as for severe acute respiratory syndrome, Middle East respiratory syndrome, and Ebola (Yao et al., 2015), rapidly and at a fraction the cost of mammalian cell or egg cultures, prescription medications likely will decrease in production cost, perhaps significantly. Of course, PMPs will not be natural plant metabolites because genes needed for their expression will have to be introduced into host plants such as tobacco, maize (Schlüttenhofer et al., 2011), wheat, tomato, mustard, banana, and soybean, possibly involving techniques of gene editing or synthetic biology (Moon et al., 2019). Use of enclosed CEs for their production will be valuable not only for enhanced yield of metabolites of interest, but also for the containment and isolation value that CEs can

provide, given social stigmas associated with genetically modified organisms (GMOs). Indoor production of host crops expressing genes for high-intrinsic-value pharmaceuticals is a logical merger of productive indoor plant agriculture with enabling plant biology, and could occupy a significant share of future IA/VF space. As for *Cannabis*, large-scale indoor PMP culture could be economically lucrative.

IA/VF and the need to increase world food production. It has been projected that 9.6 billion people will inhabit Earth by 2050, and that 70% more food than we grew in 2013 will be needed to meet minimum human nutritional requirements (United Nations, 2013). Can IA/VF play a role addressing those looming sustainable-growth needs? The energy efficiency of CE crop production is improving due to technology advancements and development of innovative best practices, but the substantial capital and operational expenses of IA presently require that it be limited to quick-turning, high-value specialty crops. Among edibles, that translates into production of microgreens, baby greens, leafy greens, and culinary herbs that command premium pricing in upscale urban markets. It also includes nonfood crops such as high-value *Cannabis* and near-future PMPs. Growing macronutrient/calorie crops (wheat, rice, soybean, etc.) affordably, which are needed on a massive, feed-the-world scale, is not the strength of IA/VF, at least not in its present configuration.

CE edible biomass production. Could future CEs be of value growing edible photosynthetic biomass in large-scale liquid cultures? Jacketed, tubular LED arrays could be immersed in aqueous, CO₂-aerated photo-bioreactor cultures of single-celled photosynthetic organisms selected, bred, engineered, or created to synthesize macronutrient-dense biomass that could be readily processed onsite into functional human

Fig. 7. Warehouse-based vertical farm in Newark, NJ. (Image courtesy of AeroFarms.)

foods. Such bioreactors could be located in regions rich in solar, wind, geothermal, tidal, or other sources of renewable energy that could be leveraged to power LED photo-bioreactor systems on a large scale. Such unorthodox CE facilities borrowing specific lighting and environmental-control technologies from IA/VF could be strategically scaled as needed to address future shortfalls in open-field food production or to compensate for agricultural disasters caused by global climate change.

Current trajectory of the IA/VF industry. The largest IA/VF commercial enterprises in the United States recently have been able to attract substantial external investments to enable their expansion into a variety of new capabilities. In 2017 alone, venture-capital funding for VF increased from \$36 M to \$271 M (Clark, 2017). Plenty in San Francisco received \$226 M from investors to expand in size and number of operations. Aerofarms in New Jersey (Fig. 7) raised \$40 M in new funds to a total of \$143 M to increase staff and expand globally. Bowery Farming, in New York, raised \$300 M as of 2021 to continue its national expansion (VerticalFarm Daily, 2021).

A number of large greenhouse companies growing greens as well as fruiting crops, such as Bright Farms and Gotham Greens, also have been able to raise significant capital. All platforms of CE food production are on the rise.

Technology development for the emerging IA/VF industry will continue to evolve in sophistication of automation, artificial intelligence, and labor-saving devices likely favoring large growers and economies of scale, plus some smaller growers with specific, secure niche markets. Young professional urban consumers demand healthy fresh produce grown locally year-round and are willing to pay for it. Given the high capital and operational costs of IA, near-term economic viability typically will occur in upscale urban locations where IA/VF growers command premium pricing year-round. Operational expenditures likely will be less important for indoor production of super-high-value plant-produced pharmaceuticals. Leafy greens and culinary herbs are the current mainstay of the indoor-production industry, but growers have great interest to expand into production of fruiting crops such as strawberries (Samtani et al. 2019; Schatz and Kim, 2021), other berries, and small tomatoes as technology and best practices advance to allow such crops to be consistently profitable. Indoor agriculture is here to stay but will undergo continuous evolution, adopt promising new technologies, target emerging niche markets, and incorporate new crops as IA moves inexorably through the 21st century and deeper into its accumulating history.

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