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Controlled Environment Food Production for Urban Agriculture

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Abstract**. The recent increased market demand for locally grown produce is generating interest in the application of techniques developed for controlled environment agriculture (CEA) to urban agriculture (UA). Controlled environments have great potential to revolutionize urban food systems, as they offer unique opportunities for year-round production, optimizing resource-use efficiency, and for helping to overcome significant challenges associated with the high costs of production in urban settings. For urban growers to benefit from CEA, results from studies evaluating the application of controlled environments for commercial food production should be considered. This review includes a discussion of current and potential applications of CEA for UA, references discussing appropriate methods for selecting and controlling the physical plant production environment, resource management strategies, considerations to improve economic viability, opportunities to address food safety concerns, and the potential social benefits from applying CEA techniques to UA. Author's viewpoints about the future of CEA for urban food production are presented at the end of this review.**

The term controlled-environment agriculture (CEA) was first introduced in the 1960s and refers to an intensive approach for controlling plant growth and development by capitalizing on advanced horticultural techniques and innovations in technology (Hodges et al., 1968). Controlled environments (CEs) provide advantages to predict plant responses to their environment and increase production efficiency, optimize plant yield, and improve product quality. They play a key role in the commercial production of ornamental plants and vegetable crops and in the production of young plant material from seed, cuttings, or tissue-culture (Jensen, 2002; Kozai and Niu, 2016a). The recent increase in market demand for locally grown produce is generating interest in applying CEA practices to urban agriculture (UA), including small- (e.g., in-home production or indoor gardens), medium- (e.g., community gardens), or large-scale commercial operations [e.g., rooftop greenhouses or warehouse-based indoor "plant factories" (PFs), sometimes referred to as vertical, warehouse, or container farms] (Eaves and Eaves, 2018; Jansen et al., 2016).

Before land and labor shortages prompted by the Industrial Revolution forced food production to move away from cities, agriculture was central to urban environments and their planning (Vitiello and Brinkley, 2014). Although some efforts were made to promote UA by documenting health, educational, and social benefits, urban food production was viewed mostly as a strategy to reduce pressure on the public food supply during hardships such as war (Hynes and Howe, 2004; Lawson, 2005). However, recent shifts in consumption patterns are allowing UA to make a comeback through its concerted efforts to address sustainability issues in our food system (e.g., reduced dependence on fossil fuels, increased food security) and promote social and environmental cohesion (Peterson et al., 2015). CEs have tremendous potential for commercial urban food production. The high plant density and year-round production attainable with CEA optimize space use and can help overcome challenges associated with costs and availability of land in urban settings. Moreover, soilless culture systems allow plants to grow in nonconventional spaces, as opposed to fertile soil, while maximizing use of available resources (e.g., water and nutrients). For a comprehensive review of the benefits from CEA in UA, see Kozai and Niu (2016b) and Takagaki et al. (2016).

For UA producers to benefit from CEA, results from studies evaluating the applicability of CEs for commercial food production should be considered. Although profitability will typically depend on the local demand and supply of food, location, population density, facility design, and crops produced, preliminary research suggests that economic sustainability for commercial CEA requires careful consideration of capital investment and operating costs, production volume, product quality and consistency, and local market trends (Al-Kodmany, 2018; Kozai et al., 2016). A review of key studies, followed by a discussion of current and potential applications regarding opportunities and limitations of commercial CEA for urban food production follows.

Physical Environment

Production environment. A key benefit of CEA is the ability to modify production environments to maximize plant quality and yield, extend growing seasons, and enable crop production in unfavorable climatic conditions (e.g., wind, rain, extreme temperature, and limited light). Greenhouses and PFs are the most common types of CEs used in UA. Following the construction of an efficient transportation system after World War II, most commercial greenhouses in the United States settled in rural locations with favorable climates (e.g., high-light, moderate temperatures) or near large markets to improve economic viability (Nelson, 2012). Therefore, it is not uncommon for greenhouse-grown food crops to travel long distances before reaching consumers (Weber and Matthews, 2008). However, increasing interest in local food systems is bringing attention to the impact that greenhouse gas emissions associated with food production against long-distance distribution channels (i.e., "food miles") have on our food chain. Although some argue that reducing "food miles" is necessary to improve the sustainability of our food chain (Morgan, 2009; Paxton, 1994), others call attention to the fact that several key transportation factors (e.g., vehicle efficiency, infrastructure, alternative fuels) affect the sustainability of many CEs typically used in UA (Coley et al., 2009; Mundler and Rumpus, 2012). However, the potential for reducing environmental impacts from UA needs to be assessed from a broad perspective, including evaluating the life cycle assessment (LCA) of a product and incorporating socioeconomic factors (Edwards-Jones et al., 2008).

Greenhouses built on vacant rooftops of city buildings have become popular in recent years as they capitalize on sunlight to produce plant products in close proximity to consumers. In addition, because rooftops represent close to one fourth of residential and nonresidential urban areas, they have significant potential to contribute to the expansion of UA (Getter and Rowe, 2006). Nonetheless, important economic aspects of producing in rooftop greenhouses should be considered, as they may require special construction materials, components, and structural support to satisfy building codes and withstand strong wind loads and substantial sun exposure (Meier et al., 2013). Numerous studies assess the impact of building rooftop greenhouses in urban settings from an economic (Benis et al., 2018; Sanyé-Mengual et al., 2015), environmental (Jones and Gilbert, 2018; Nadal et al., 2017; Sanjuan-Delmás et al., 2018; Sanyé-Mengual et al., 2018), social (Davis, 2011), and educational (Nadal et al., 2017; Sanyé-Mengual et al., 2014) perspective. In addition, a number of commercial operations have demonstrated the economic viability of rooftop greenhouses for urban food production (e.g., Gotham Green Farms, Lufa Farms). Furthermore, rooftop greenhouse designs can include photovoltaic systems and rainwater harvesting strategies, increasing their potential to expand sustainable UA production practices.

In contrast, the economic sustainability of indoor PFs has demonstrated to be more challenging, in part due to their dependence on electricity to run all systems (Banerjee and Adenaeuer, 2014). Indoor PFs are widely used in Asia and are gaining popularity in the United States and European countries for producing high-value crops such as leafy greens (Kozai et al., 2016). However, most countries successfully adopting PFs for fresh food production have land and/or environmental limitations, which, coupled with food-safety concerns, justify the high production costs. However, preliminary research suggests that some U.S. consumers are not willing to pay higher prices for indoor-grown produce (Coyle and Ellison, 2017; Short et al., 2018).

Production systems. Production systems for CEA typically consist of soilless culture, with or without the use of an organic or inorganic substrate and with active application of water and fertilizer, typically provided with a dilute nutrient solution. Hydroponic production is a type of soilless culture in which plant roots are suspended in either a static, continuously aerated nutrient solution, or in a continuous flow or mist (Jones, 2014). The terms "soilless culture" and "hydroponics" often are used interchangeably, especially when using substrates that are chemically inert and provide little nutrient supply or retention.

Crop production using soilless culture or hydroponics has several potential benefits compared with traditional field production, including isolation from soil or water-borne issues (e.g., nematodes, salinity, or heavy metals) and an improved ability to control water and nutrient uptake. For comprehensive reviews about the benefits of using soilless culture in CEA, see Raviv et al. (2019) and Jones (2014). Crops produced using soilless culture often are grown in containers, troughs, or bags with a limited volume, allowing for efficient root-zone management. Argo and Fisher (2002), Bunt (1988), and Raviv et al. (2019) list common sources of nutrients in soilless culture, which include the raw irrigation water, fertilizers either dissolved in the irrigation water or incorporated into a substrate, substrate components, and amendments used to adjust substrate pH. Raviv et al. (2019) also discuss common irrigation and fertilization equipment used for container production systems, including overhead, drip, and subirrigation systems. Nelson (2012) provides a detailed review of management strategies across soilless culture systems, including strategies on system design, substrates, water and fertilizer, production environment, and marketing and business planning.

Substrate selection is a critical aspect of soilless culture. Primary substrate components (i.e., >40% of the substrate volume) often consist of organic materials with low bulk density and high water holding capacity, such as peatmoss and coconut coir fiber (Argo and Fisher, 2002). Conversely, secondary components (i.e., <40% substrate volume) often include materials such as expanded minerals (e.g., perlite and vermiculite), clays, sand, and composts that increase drainage and cation exchange capacity to increase aeration and nutrient retention. Several authors have reviewed the most common organic and inorganic components of substrates, manufacturing, and cultural plant production advantages and disadvantages to using different materials (Bunt, 1988; Burnett et al., 2016; Raviv et al., 2019).

Hydroponic systems commonly used in UA differ in their design and suitability for certain crops and production scenarios. The most common hydroponic systems include nutrient-film technique (NFT), deep-water culture (DWC; also known as deep-flow technique, raft, raceway, or floating hydroponics, among others), and aggregate culture. NFT consist of crops grown in sloped troughs where a thin film of nutrient solution flows (either continuously or intermittently) over the roots, whereas DWC systems consist of crops grown with their roots continuously submerged in a nutrient solution. Aggregate culture consists of growing crops in bagged substrates (e.g., rockwool or coconut coir slabs) or containers (e.g., Dutch/Bato buckets) with the nutrient solution applied using drip emitters. Typically, NFT and DWC systems are used for short-term, non-fruiting crops such as leafy greens and herbs, whereas long-term fruiting crops such as tomato (*Lycopersicon esculentum*), cucumber (*Cucumis sativus*), sweet pepper (*Capsicum annuum*), and strawberry (*Fragaria ×ananassa*) are usually grown in aggregate culture. Several authors have reviewed specific plant species, water and nutrient management, structural design, and economic considerations for producing crops in NFT and DWC (Blok et al., 2017; Walters and Currey, 2015), and aggregate culture (Raviv et al., 2019; Sonneveld and Voogt, 2009).

Soilless culture and hydroponic systems used in CEs also provide opportunities for producing medicinal and pharmaceutical crops with high quality, purity, consistency, bioactivity, and biomass (Hayden, 2006; Lopez and Runkle, 2017; Papadopoulos et al., 2001; Potter, 2014). Hayden (2006)

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and Maggini et al. (2014) discuss the advantages of using hydroponic systems for producing medicinal crops commonly grown in CEs. Moreover, despite being regulated as an illicit crop in many countries, production of cannabis (*Cannabis sativa*) using soilless culture in CEs has increased and gained significant public attention in recent years, particularly in Europe and North America. Cultivation, processing, and regulation of cannabis for medicinal use is reviewed by Potter (2014).

Aquaponic production, integrating hydroponic systems with aquaculture (i.e., fish production), recently has increased in popularity for UA (dos Santos, 2016). Aquaponics involves converting water and organic waste produced by cultivated fish or crustaceans into nutrient solutions used for hydroponic plant production. Potential benefits of aquaponics include the ability to increase resource-use efficiency (e.g., shared startup, operating, and infrastructure costs) and improve sustainability (e.g., reduced water use and waste discharge to the environment) while simultaneously producing fish and food crop commodities (Tyson et al., 2011). Recirculating the nutrient solution between the hydroponic and aquaculture production components, essentially forming a completely closed system, is termed "coupled" aquaponics. Due to the technical challenges with maintaining appropriate chemical and biological properties in a recirculating solution, "decoupled" aquaponics has been proposed as a more efficient alternative to "coupled" aquaponics. In "decoupled" aquaponics, the aquaculture effluent is collected and supplemented with specific nutrients for higher yield of fish and hydroponic food crops (Kloas et al., 2015). However, commercial applications of "decoupled" aquaponics are still under development. Although integrated aquaponic production systems have been used for over 30 years, the commercial application of aquaponics is relatively new to UA. For a comprehensive review on the history of aquaponics see Palm et al. (2018).

For appropriate functioning, aquaponic systems require balancing multiple factors, including solution pH (Wongkiew et al., 2017a; Zou et al., 2016), plant and animal density (Buzby and Lin, 2014; Hussain et al., 2014, 2015), solution flow rates (Hussain et al., 2015; Khater and Ali, 2015; Wongkiew et al., 2017b), economics (Quagrainie et al., 2018; Tokunaga et al., 2015), system configuration (Klemencic and Bulc, 2015; Monsees et al., 2017), and food safety considerations (Elumalai et al., 2017; Pantanella et al., 2015). Several authors have reviewed system types, management, and potential profitability of aquaponic production systems (Blidariu and Grozea, 2011; Lewis et al., 1978; Love et al., 2015).

Leaf chlorosis and/or reduced yields are reported for some crops grown in aquaponics, such as tomato (unpublished data) and eggplant (*Solanum melongena*) (Roosta and Mohsenian, 2015). However, supplementing aquaponic solutions with potassium, sulfur, iron, and manganese may alleviate crop growth and yield losses associated with nutritional deficiencies (Rakocy et al., 2004, 2006; Roosta and Hamidpour, 2011).

Technologies

Electric lighting. The daily light integral (DLI) requirement of food crops commonly grown in CEs typically ranges from 12 to 30 $mol \cdot m^{-2} \cdot d^{-1}$ (Dorais et al., 2017). Greenhouse production located in regions with considerable seasonal variation in solar radiation typically relies on supplemental lighting to increase DLI (Faust and Logan, 2018). Furthermore, solar spectrum can vary depending on location, season, and time of day; however, in general, it is composed of 0.1% ultraviolet-B (280–315 nm), 5% ultraviolet-A (315–400 nm), 19% blue (400–500 nm), 25% green (500–600 nm), 26% red (600–700 nm), 25% far-red (700–800 nm) (extracted from Kotilainen et al., 2018). High-pressure sodium (HPS) lamps are the most common type of electric light source used in commercial greenhouses, whereas metal halide lamps are used occasionally because of their higher blue light output (Menard et al., 2006; Nelson and Bugbee, 2014). However, the use of light-emitting diodes (LEDs) in CEs has substantially increased in recent years (Lopez and Runkle, 2017; Mitchell et al., 2015).

Research comparing LED and HPS lamps as supplemental lighting sources mainly focuses on: 1) evaluating potential reductions in energy consumption; and 2) understanding the effects of light spectra on plant growth, morphology, and quality. Although HPS lamps have a set spectrum that typically is composed of approx. 5% blue, 49% green, 39% red, and 7% far-red (measurements from a 600-W HPS fixture; P.L. Light Systems Inc., Beamsville, ON, Canada), LED fixtures can have different color diodes to achieve customized spectra. However, the most common LED fixtures available for plant lighting contain mainly red and blue diodes (10% to 25% blue diodes), with some fixtures including a small number of far-red and/or white diodes. For a review of different uses, fixture characteristics, and application of LEDs for supplemental lighting in CEA see Lopez and Runkle (2017) and Mitchell et al. (2015).

Although initial efforts to produce high-value food crops in warehouse-based PFs used water-cooled HPS lamps, challenges associated with their economic and thermal management negate the application of these lamps for sole-source lighting in multitiered PFs (Mitchell and Stutte, 2015). Fluorescent lamps have been commonly used for indoor CEA for many years. However, with increasing light efficacy ($\mu mol \cdot J^{-1}$), capital cost reductions, and widespread availability, LEDs are becoming the light source of choice for PFs. In fact, introducing commercial LEDs as plant lighting sources was a major contributing factor to the renewed interest in CEA for urban food production. This is because LED fixtures typically have lower electric power requirements per unit of growing area ($kW \cdot m^{-2}$) and deliver high light intensities with small amounts of radiant heat delivered to crops, theoretically resulting in significant savings for energy-intensive indoor food production. In addition, by maximizing photon capture efficiency using "precision" or "smart" lighting" such as targeted (Poulet et al., 2014), intracanopy (Dueck et al., 2012; Gómez and Mitchell, 2016; Massa et al., 2005), or dynamic (Clausen et al., 2015; Pinho et al., 2012; van Iersel, 2017; van Iersel and Gianino, 2017; van Iersel et al., 2016; Weaver et al., 2019) LED lighting, efficiency of production systems can significantly increase. For a comprehensive review of the adoption of LEDs in UA see Gupta (2017).

Carbon dioxide (CO2) enrichment. In closed environments with high planting densities (typical for greenhouses and PFs), the CO_2 concentration can rapidly drop below the ambient concentration (approx. 400 $\mu mol \cdot mol^{-1}$), requiring supplemental CO_2 injection to avoid limiting photosynthesis and plant growth. Enrichment up to 800 $\mu mol \cdot mol^{-1}$ is typically cost-effective to promote photosynthesis and growth of most plants grown in CEs (Both et al., 2017). However, enrichment strategies and benefits depend on, among others: plant species, target CO_2 concentration, environmental control strategies for light, ambient temperature, and humidity, and the cost and source of CO_2 injection (e.g., equipment and electricity) (Both et al., 2017). Indoor CO_2 concentration can be increased by releasing pure gas or by producing CO_2 from fuel combustion. When using the latter approach, carbon monoxide and ethylene production are also important factors to consider with CO_2 enrichment, as they can be toxic to plants at relatively low concentrations and may result from inefficient fuel combustion or by improperly adjusted burners (Nelson, 2012).

Several studies report responses of different food crops to CO_2 enrichment. Generally, studies suggest that doubling ambient CO_2 levels increases lettuce yield by $\approx$25 to 60% (Chagvardieff et al., 1994; Pérez-López et al., 2015). Conversely, some report small or nonsignificant differences in lettuce fresh and dry mass grown under elevated CO_2 (>800 ppm) compared with ambient levels (Fu et al., 2015; Mortensen, 1994; Park and Lee, 2001). Yield (kg per plant) of strawberry plants grown in CEs significantly increases by doubling the ambient CO_2 concentration (Enoch et al., 1976; Sun et al., 2012). For cucumber, supplemental nitrate enhances the positive effects of CO_2 enrichment on fruit yield (Dong et al., 2017; Enoch et al., 1976). However, Peet (1986) found no response to cucumber production under an elevated CO_2 concentration. Similarly, although some studies report tomato yield increases with CO_2 enrichment (Calvert and Slack, 1975), others have reported increased individual fruit mass and number of high-rated fruits, but no increase in total yield (Peet and Willits, 1984).

Heuvelink and Kierkels (2015) reported that in general, CO_2 enrichment from 400 to 1000 µmol·mol^{-1} in CEs can increase total yield by 35 to 50%. For comparison, yield increases with higher DLIs are often linear, as commonly observed in yield differences between greenhouse crops produced during spring-to-summer vs. fall-to-winter seasons (Acock et al., 1971; Cockshull, 1992; Kubota et al., 2016). Also, responses to CO_2 enrichment are species-specific and concentrations above 1000 µmol·mol^{-1} are not typical for commercial production, since several studies have shown little or no additional benefit at higher concentrations (Calvert and Slack 1975; Enoch et al., 1976; Peet and Willits, 1984). Furthermore, crops with high harvest indices (dry mass of harvestable organs/total plant biomass of plant) such as leafy greens benefit most from CO_2 enrichment, as increases in photosynthesis directly affect the harvestable portion of the plant (i.e., leaves). In contrast, benefits from CO_2 supplementation are less significant with fruiting crops because increased photosynthesis does not directly translate into increased fruit yield.

Humidity control. In CEs, the areal humidity (both absolute and relative) is affected by several factors, such as plant transpiration rate, irrigation strategy, infiltration and ventilation, and active systems used to humidify or dehumidify the air (von Caemmerer and Baker, 2007). Managing humidity is essential for optimal plant growth and development, but it is often the hardest environmental parameter to fully control in CEs. Although relative humidity is the most common measure of humidity, it is not indicative of the plant's relationship to humidity. Vapor pressure deficit (VPD) is the driving force of water loss from a leaf, and therefore, it is a more accurate measure of humidity in CEs. A review of the thermodynamic properties of moist air and their effect on plant growth in CEs can be found in Hanan (1997) and Kozai et al. (2016).

Plant transpiration generally increases linearly with increasing VPD, radiation, and air speed. Therefore, all factors indirectly affect nutrient uptake, leaf temperature, and overall plant growth and development. For leafy greens and culinary herbs grown in CEs, high VPDs are desirable to prevent calcium deficiencies such as tipburn (Frantz et al., 2004; Goto and Takakura, 1992). For CE-grown tomato, VPDs in the range of 0.5 to 1.0 kPa are positively correlated with increases in fruit yield and stomatal conductance, and reductions of blossom-end rot and fungal diseases (Barker, 1990; Guichard et al., 2005; Leonardi et al., 1999; Shamshiri et al., 2018; Zhang et al., 2017). Studies also report that low nighttime VPDs enhance calcium uptake of young and inner strawberry leaves (Bradfield and Guttridge, 1979; Choi et al., 1997), whereas VPDs <0.1 kPa for at least 3 h each night help prevent calcium deficiencies in strawberries produced under environments with high daytime VPD (Kroggel and Kubota, 2017).

Under high-humidity conditions in CEs, water vapor has to be removed from the air to maintain desirable humidity levels. The lowest-cost, lowest-energy method of dehumidification is ventilation, which is the exchange of indoor air with outdoor air, either with fans or vents (Wang et al., 2016). Ventilation works best when outside air is dry and cool. Therefore, in northern climates during winter conditions, ventilation is mainly used for dehumidification. However, if the outside air is too cold, simultaneous heating is needed to maintain the desired air temperature. Alternatively, if the outside air is too hot, cooling will be needed, usually with an air conditioner (common practice for PFs) (Kozai et al., 2016). Growers typically make economic decisions to balance the cost of temperature control with the benefits of lower humidity obtained by ventilation. Kubota et al. (2006) reports that under typical semiarid midday weather, humidity control inside the greenhouse is very efficient. In contrast, humidity control in greenhouses located in continental climates is challenging in the winter months when using ventilation (Kubota et al., 2006). Therefore, the common humidity set point in greenhouses located in continental climates is 80 to 85% relative humidity (Körner and Challa, 2003).

Ventilation is not desirable in PF operations due to reductions in CO_2-use-efficiency from venting out supplemental CO_2 and the potential introduction of pests from the outdoors (Kozai, 2013). For that reason, dehumidification with air conditioning is typically used in PFs, as opposed to ventilation in greenhouses. However, reports using an internal dehumidification system in the greenhouse (dehumidifier or heat pump) indicate reductions in energy consumption compared with the venting-heating technique (de Zwart, 2014; Vallières et al., 2014). Furthermore, several studies have evaluated night-time greenhouse dehumidification using a heat pump to prevent condensation on foliage (Boulard et al., 1989; Campen et al., 2003; Chassériaux and Gaschet, 2011; Migeon et al., 2012), preventing venting the greenhouse during the night to reduce the consumption of energy by conditioning (reheating) the air. In some instances, night-time heat-pump dehumidification requires up to five times less energy than the common venting-heating technique (Chassériaux et al., 2014). Furthermore, proof-of-concept studies demonstrate the feasibility of using desiccant-based systems to absorb moisture from the greenhouse environment during periods with high humidity (Davies, 2005; Lychnos and Davies, 2012; Mei and Dai, 2008).

Transpiration increases the amount of water in the air and increases the energy content (i.e., enthalpy) of the air. Heating, ventilation, and air conditioning systems are able to cool the air (remove energy) while lowering the humidity (dehumidification). In PFs, it is not uncommon for the energy input from transpiration (i.e., latent heat) to be larger than the energy input from electric equipment (i.e., sensible heat) (Graamans et al., 2017). When sizing a heating, ventilation, and air conditioning system, it is important to consider 1) the increase in humidity in the air from plant transpiration; 2) the evaporative cooling effect of plant transpiration; and 3) the resulting increase in latent and decrease in sensible heat that has to be removed from the growing environment.

Resource Management

Resource cycling and environmental footprint of CEA in UA. Recent LCA studies in urban settings provide insights in the carbon footprint of several CE systems. Sanyé-Mengual et al. (2015) report that the environmental impact of a rooftop greenhouse in a city is higher at the construction stage and lower during the cultivation and transportation stages compared with a multispan greenhouse in a rural area. Goldstein et al. (2016) concludes that the overall environmental impact of urban CEA depends on the local energy costs and production materials, and suggest that CEA for urban food production might be better-adapted to mild climates. While results from these projects cannot be extrapolated to all locations or CEA structures, they underline the importance of breaking down environmental footprint and costs by processes in the supply chain and location.

CEA is energy intensive. Some studies conclude that the establishment and infrastructure of CEA in cities can have a high environmental and economic footprint (Coley et al., 2009; de Villiers et al., 2011; Mundler and Rumpus, 2012). In addition, the energy requirement for heating in northern climates can be high. Therefore, some debate whether reducing distance from source to consumer justifies the high-energy footprint of CEA in urban settings (Goldstein et al., 2016; Sanyé-Mengual et al., 2015; Weber and Matthews, 2008). Alternative energy resources, such as geothermal, solar, wind, and hydropower, can be an improvement over traditional carbon-based energy sources. Nonetheless, local land and infrastructure design need to be considered in the overall footprint of a production system.

Soilless culture requires less water than soil-based agriculture. However, environmental gains from the overall net effect of water consumption in UA remain to be determined, considering that the irrigation efficiency (kg·m^{-3}) and indirect water use (e.g., for cooling and heating) depends on the system infrastructure, irrigation design, and location, among other production factors. The multidimensional concept of water footprint considers the whole supply chain, as well as geographical and temporal parameters. Hoekstra et al. (2011) define water footprint of a product as "the total volume of fresh water that is used directly or indirectly to produce the product." In urban CEs, the water footprint of the whole system must be considered to measure the true impact on water resources. Rainwater and wastewater are potential water sources for the production system. However, it is unknown how capturing rainwater in urban environments may affect the entire water system (Goldstein et al., 2016; Hoekstra et al., 2011). In addition, wastewater must be treated to reduce human health risks from pathogens, pharmaceuticals, or excess salts, which can be energy-intensive. Goldstein et al. (2016) show that the total amount of water and nutrient use per crop for production in CEA can be lower compared with conventional agriculture. Nonetheless, until indirect effects on the overall water system are accounted for, the net effect on water consumption in urban setting is unknown.

Fertilizer applications in CEA are more efficient compared with field production because of targeted applications (in time and space) and the physical ease of recirculating nutrient solutions (Goldstein et al., 2016). In urban environments, human food waste could be used as fertilizer sources for plant production (Chiew et al., 2015; Spångberg et al., 2014). However, while integrating solid and liquid waste to supply nutrients for UA is technically feasible, its implementation and technology requires maximum integration to make it economically feasible (Villarroel Walker et al., 2014).

Economic Environment

Although buying local food products may not be economically cost-effective in terms of comparative advantages, consumer groups endorse UA for a number of reasons, such as to support local economies, promote environmental sustainability, and reduce food insecurity by providing access to local, fresh food in inner-city food deserts (Ikerd, 2017; Peterson et al., 2015; Scharber and Dancs, 2015; Steele, 2017). Although interest in UA is growing, few studies evaluate its cost effectiveness. For example, studies compare rooftop greenhouses with other rooftop production systems, but not to the cost of greenhouse production in rural areas (Quagrainie et al., 2018; Tokunaga et al., 2015). There is a need for research that accurately assesses the return on investment and LCA of various types and sizes of CE systems for UA (Al-Kodmany, 2018).

The number of urban farms is currently low due to the many challenges faced by urban growers, such as tight regulations, zoning restrictions, limitations to water access, and high capital and operating costs (e.g., land and electricity), among others (Reisman, 2012; Steele, 2017). In addition, shade from tall buildings and skyscrapers is particularly problematic with growing plants in cities, partly explaining the increasing interest in rooftop greenhouses in urban settings. However, rooftop greenhouses have higher capital costs compared with standard ground-based greenhouses. An alternative to overcoming issues associated with shade is to produce in PFs, but this increases production costs even further because of the need for adequate environmental control (Banerjee and Adenaeuer, 2014). These high costs have kept the number of urban farms small. For UA to be viable, CEs must derive profits from extending the economic benefit to the local community, or by focusing on targeted sales to markets that can pay high prices (Brumfield and Singer, 2018; Singer and Brumfield, 2017).

UA can bring value to local communities by providing opportunities for strengthening social bonds, expressing and maintaining cultural heritage, and engaging in activities promoting social and political change (Steele, 2017). A social business model offers opportunities for alternate funding sources from schools, governmental programs, or donors particularly interested in education, research, or community development. Some businesses have reduced labor costs through the assistance or use of volunteers (Reisman, 2012). In addition, commercial CE businesses with an integrated educational component offer the social benefit of providing job training and skill development for individuals. For example, CEA offers students opportunities to learn about food systems, nutrition, technology, and environmental sustainability, as well as teaching skills in customer service, leadership, marketing, and fundraising (Steele, 2017).

Consumer sociodemographic background typically drives preferences and willingness to pay for local food products. Yue and Tong (2009) show that urban consumers are more likely to buy locally grown produce compared with rural consumers. Therefore, due to the high costs associated with CEs for urban food production, some urban growers target high-value niche products (e.g., microgreens and heirloom tomatoes), charging premium prices to cover the added costs of operating in the city. To increase profitability, urban growers also target high-end restaurants and supermarkets, whose customers are prepared to pay a premium price for locally-grown produce (Sace and Natividad, 2015).

Potential Improvement of Product Quality in CEA

Increasing awareness of health and wellness has generated significant interest in the nutritional composition and health-promoting compounds of fruits and vegetables. The contribution of UA to human health can be significant because urban settings may provide easier access to fresh food (Orsini et al., 2013). Fruits and vegetables are excellent sources of selected minerals, vitamins, and antioxidants, and their impacts on human health are affected by environmental and cultural factors (Bian et al., 2015; Bjorkman et al., 2011). In contrast, harmful substances such as nitrate also can accumulate in these commodities, negatively affecting product quality (Colla et al., 2018). Environmental and cultural factors influencing mineral and phytochemical content of fruits and vegetables include light (intensity, quality, and duration), CO_2 concentration, water availability, fertilization, and pH, as well as plant species, cultivar, and plant developmental stage (Bjorkman et al., 2011; Kopsell and Kopsell, 2008; Vicente et al., 2009). Using CEs provide opportunities for improving the quality of horticultural commodities through precise control and manipulation of these factors. For example, plant phytochemicals serve functional roles in response to environmental stress, and many of the compounds protecting plant cells also protect human cells (Demmig-Adams and Adams, 2002). Thus, environments inducing plant protection can stimulate accumulation of nutritional compounds of interest to consumers.

Although high light intensities are associated with phytochemical accumulation, maintaining high light with sole-source or supplemental lighting in CEs increases operating costs and may induce photoinhibition (Bian et al., 2015). Therefore, optimum light intensities should be considered to avoid these issues while maximizing phytochemical accumulation. Increasing light intensity across the range of 100 to 400 $\mu mol \cdot m^{-2} \cdot s^{-1}$ increases accumulation of lutein and β-carotene in kale (*Brassica oleracea*) (Lefsrud et al., 2006) and spinach (*Spinacea oleracea*) (Li et al., 2011) grown indoor with LEDs. Similarly, increasing light intensity with supplemental HPS lamps increases nutritional quality of vegetables grown in the greenhouse. For example, increasing light intensity increases sugar content in tomato (Dorais and Gosselin, 2002) and soluble sugars in lettuce (Fu et al., 2012). Additionally, chicory (*Cichorium endivium*), lettuce, mizuna (*Brassica rapa* var. *niposinica*), and chard (*Beta vulgaris* subsp. *vulgaris*) grown at a high light intensity contain higher total phenolic content compared with those grown at lower intensities (Colonna et al., 2016).

Manipulating light spectra also affects the quality of plant products, even at low light intensities. Although various light sources are used to grow plants in CEs, the narrow-band light output produced by LEDs offer the opportunity to manipulate spectra to control flavor, pigmentation, and other consumer-desired traits in CE-grown plants. While promising, there are inconsistent results on the effects of light spectra on crop quality, partly due to the complex interactions of multiple factors, including plant genetics and environmental conditions (e.g., temperature, light intensity). For a review on the application of light spectra to manipulate product quality of key crop species see Bian et al. (2015), Carvalho and Folta (2014), Mitchell et al., (2015), and Samuolienė et al. (2017).

High CO_2 concentration can also impact plant phytochemical and nutritional compounds. Based on a meta-analysis using published literature, Dong et al. (2018) surveyed the effect of elevated CO_2 on the nutritional quality of vegetables. The authors concluded that in general, elevated CO_2 has potential to improve the quality of vegetable crops by increasing fructose, glucose, total soluble sugar, total antioxidant capacity, total phenols, total flavonoids, ascorbic acid, and calcium (Dong et al., 2018). Water and nutrient availability also affect the quality of plant products. Crops grown under water deficit tend to have higher nutrient content than those grown under abundant water, although this may partly be due to an increase in concentration per unit dry mass (Bjorkman et al., 2011). Reducing irrigation increases glucosinolate content and total carotenoids in cabbage (*Brassica oleracea*) and pak choi (*Brassica rapa* subsp. *chinensis*), respectively, compared with well-watered plants (Hanson et al., 2009; Radovich et al., 2005). In addition, manipulating the nutrient solution in soilless culture can help regulate secondary metabolite production in fruits and vegetables (Borgognone et al., 2016; Colla et al., 2013; Fallovo et al., 2009). Similarly, controlling the EC of the nutrient solution affects the composition and concentration of fruit phytochemicals (Colla et al., 2013; Rouphael et al., 2012; Wu and Kubota, 2008).

Food Safety

Food safety risks for urban food production are triggered by microbiological, chemical, or external contaminants within the system. All of these risks can be prevented, minimized or reduced through proper training, documentation, policies, and resources. The Centers for Disease Control and Prevention reported that an estimated 48 million people (one in six U.S. residents) suffer from a food-borne illness each year (Scallan et al., 2011); 128,000 are hospitalized, and 3000 die each year from foodborne diseases. Between 1998 and 2008, 46% of all food-borne illnesses reported were associated with fruits, vegetables, and nuts (Painter et al., 2013). Contamination of fruits and vegetables produced in the United States is one of the most important issues for the food industry sector (Centers for Disease Control and Prevention, 2011). After recent high-profile outbreaks associated with fresh-cut produce (Centers for Disease Control and Prevention, 2011; Food and Drug Administration, 2018), widespread scrutiny of the U.S. fruit and vegetable supply underscores a growing concern regarding the awareness of and adherence to best practices by growers and processors.

Typically, fruits and vegetables grown in CEs are perceived to have fewer potential food safety concerns than field-grown produce due to their isolation from the soil and wild animals. However, human pathogens can still be introduced into CE production systems from various sources including water, substrates, and human contact (Olaimat and Holley, 2012; Shaw et al., 2016). In addition, because CEA often uses recirculating nutrient solutions, human pathogens can be introduced into the solutions (i.e., agricultural water or nutrients) and rapidly spread throughout the production system. Research in hydroponic systems show if *Escherichia coli* O157:H7, *E.coli* non-O157 STEC, and *Salmonella* are introduced into systems over a short period of time (48 h), these microorganisms can survive and multiply (Shaw et al., 2016). Orozco et al. (2008) reported that 2.8% of tomatoes harvested from a greenhouse were contaminated with *Salmonella* and 0.7% with *E. coli*, whereas other environments and materials within the greenhouse tested positive for *Salmonella* included puddles, soil, cleaning cloths, and sponges.

Food safety–relevant contamination of produce can occur during production, harvest, processing, wholesale storage, distribution, retail, and preparation (i.e., food service or in-home). Contamination also can be caused by physical aspects (i.e., substrate, water, air, harvesting/processing equipment), animals (i.e., wild or domesticated), or human handlers (Food and Drug Administration, 2018). All growing materials (e.g., substrates, seeds, fertilizers) should be obtained from vendors who can provide evidence of following Good Manufacturing Practices, including careful monitoring of personnel, physical plant and grounds maintenance, sanitary operations, equipment and utensils, processing controls, warehouse and distribution, and holding and distribution of human food for use in animal food (Food and Drug Administration, 2017).

Pathogens of greatest concern in produce include viruses (*Hepatitis A* and *norovirus*), parasites (*Cryptosporidium*), and bacteria including *Bacillus cereus*, *Clostridium* spp., *E. coli* STEC, *Listeria monocytogenes*, *Salmonella* spp., *Yersinia enterocolitica*, *Shigella* spp., and *Campylobacter* spp. (Beuchat 2002; Harris et al., 2003; Olaimat and Holley, 2012). It is important to note that *Salmonella* spp. and *E. coli* O157:H7 are consistently associated with outbreaks of food-borne illness, and *Listeria monocytogenes* has been implicated in fewer, but particularly large, produce-related outbreaks (Olaimat and Holley, 2012). In addition to microbiological food safety concerns, chemical and heavy metal concerns must be considered for urban food production. These contaminants can be introduced in the water throughout the growing cycle and can cause harm to consumers if ingested in large amounts (United States Geological Survey, 2013).

Water is an essential component in all production systems and many foodborne outbreaks are associated with water contaminated with *E.coli* O157:H7, *Salmonella*, and *Cyclospora* (Hedberg and Osterholm, 1993). Furthermore, water sources can be categorized as low risk or high risk. While municipal water sources are considered low-risk due to daily testing by cities and municipalities for *E. coli*, surface water sources (e.g., ponds, streams) are high-risk since they are not regularly tested by a government body. Therefore, the end user is responsible for testing and results are more easily influenced by watershed activities and seasonal variation. Lopez-Galvez et al. (2014) showed that the prevalence of *Salmonella* spp. was 7.7% in irrigation water samples and 62.5% in reclaimed water sources for tomatoes grown hydroponically in greenhouses.

Social Environment

Humans and social systems are an important component of the horticultural industry (Lohr and Relf, 2000; Relf and Lohr, 2003). However in 2012, there were slightly more than three million growers in the United States, which accounted for less than 2% of the population (United States Department of Agriculture, 2014). This relatively recent disconnect from food production presents questions concerning the role of horticultural systems in human well-being, particularly involving the role of UA to provide services which promote public health and other social benefits (Brown and Jameton, 2000; Relf, 1992).

CEA is an important field with many unique facets. However, to date, the role of humans, social benefits, and communities with access to CE systems has not been thoroughly studied. Although we understand that urban food production can increase food access in cities, questions remain as to what extent CEA may alter social connections, community capitals, and education in both positive and negative ways (Eigenbrod and Gruda, 2015). By extrapolating from the available literature about urban horticultural production, we hypothesize that urban CE systems can have benefits for community food security, agricultural education, and horticultural therapy. For example, integrating CEA and UA has great potential to serve extreme-poverty areas by providing job opportunities and access to fresh food that can support a healthy diet (Bohm, 2017; Specht et al., 2014). In addition, hands-on teaching tools, facilitated through demonstrations of CE systems within schools and classrooms, allow students direct access to understand the process of food crop production. Previous research has shown that school gardens positively impact student attitude toward vegetables (Lineberger and Zajicek, 2000). Furthermore, students experiencing hands-on gardening opportunities in school exhibit more positive outlooks toward school (Waliczek et al., 2001). In addition, CEA may hold benefits to increase access to horticultural therapy. In settings such as prisons (Rice and Remy, 1994) and rehabilitation centers (Wichrowski et al., 2005), horticultural therapy facilitates both psychological and physiological healing and recovery (Lewis, 1994; Simson and Straus, 1997). By incorporating CE technologies into social institutions such as prisons, hospitals, or nursing homes, we may realize additional social benefits beyond the individual connection to plants. Furthermore, increasing rehabilitation time reduce taxpayer burden for social systems and promote overall human health and wellbeing in society.

Author's Viewpoints

Long-term success and economic viability of CEs used for food production largely will depend on future trends in consumer preferences and market demand for agricultural products produced in urban settings.

The efficiency of most urban CE systems will be improved by optimizing resources to maximize crop production and quality. For example, as LED technologies continue to increase in efficacy and decrease in cost, more CE operations will adopt the technology to reduce electrical costs and/or to improve product quality. Horticultural-grade LED fixtures are expected to be classified in two main groups: 1) relatively affordable fixtures with fixed spectra, often fixed emission rate (light output), high efficacy, and simple on/off controllers; and 2) custom-made fixtures with advanced controllers to manipulate emission rate, spectral control, and/or with sensor integration. The economic value to end-users will determine fixture applicability. Nonetheless, HPS lamps will continue to be widely used for greenhouse supplemental lighting due to their lower initial capital cost and acceptable efficacy compared with LEDs (approx. 1.7 to 1.9 vs. 2.4 to 3.0 $\mu mol \cdot J^{-1}$ for some LEDs).

Future research evaluating "dynamic" control of CO_2 enrichment will help reduce the long-term adaptation to high CO_2 concentration, which over time, diminishes the positive impacts of CO_2 enrichment in CEs. Studies focused on changing concentration levels during the daytime and/or manipulating the environment to increase CO_2 uptake during specific times of the day will be helpful in furthering our understanding about the potential benefits of using CO_2 enrichment in CEs. Further studies focusing on breeding or sink-source relationships may elucidate ways in which CO_2 enrichment can increase yield by ensuring translocation of photoassimilates to the harvestable portion of plants. Humidity control will continue to be an important challenge in CE production. However, with the continued technological development of dehumidification systems (e.g., heat pumps and desiccants), mainly driven by their use in commercial buildings, their adoption in CEs is expected to increase, especially with the worldwide expansion of PFs and potential adoption by some greenhouse facilities.

The applicability of CEA in urban settings as a solution to current challenges in our food-supply chain will be context-dependent. For example, from a food safety perspective, CEs provide more physical and environmental control compared with field-based production systems. Therefore, given the risks associated with foodborne illness outbreaks coming from large-scale outdoor farms, production in CEs may offer consumers peace of mind in their produce purchases.

Although few studies have evaluated food safety risk factors that could cause a foodborne illness in CEs, food safety should be a priority in all production systems growing edible products. Education about proper fresh produce handling from farm to fork can help prevent food safety contamination within CEA systems. Considering the wide variations in production systems, food safety programs for CEA could focus on four main areas: substrate, water and nutrient solutions, facilities, and people. Prevention of foodborne microorganisms, chemicals, and contaminants from entering into a CE system should be the focus of training and protocols. Employees within production facilities should be trained on how to properly sanitize the facilities, tools, and equipment, along with personal health and hygiene (i.e., washing stations, restrooms, clothing, sickness and injury policies). Strict visitor policies minimizing introductions of food safety risks to the crops (e.g., hand washing, disposable booties, no-touching policies) should also be implemented.

Regarding the sustainability of CEA, local and regional limitations and resource availability must determine the net environmental and economic impacts of CEs in urban environments. The integration of water, energy, nutrients, and plant production in cities could help promote the local food movement (e.g., eliminate food deserts, fresh produce with large carbon-footprints) by delivering a neutral net carbon and water footprint. However, the footprint for crop production will depend on the crop and location, factors that are not commonly considered when assessing the environmental and economic benefits of CEA for urban food production. Consideration should be given to the fact that goods already flow in and out of cities; limiting these flows may result in negative side-effects for UA. Although scientists have advanced our understanding in CEA and many discuss the potential of integrating resources in built settings, few have investigated a truly integrated system in which waste is captured and processed in situ to supply water, nutrients, and energy to local CE operations. Engineers and horticulturists must work together to improve system performance at the establishment and production stages, and design truly integrated and efficient systems. Potential areas of work include infrastructure design and materials, energy production, storage and usage, and closing water, energy, and nutrient loops.

Specific outcomes from CEA to human wellbeing, social systems, and urban communities remain to be determined. As described above, research suggests many potential benefits from integrating CEA and UA. For example, non-commercial, small-scale CE systems may become available for display and hands-on teaching in classrooms and community centers. However, to incorporate CEA into social systems, plant scientists should be actively engaged in understanding and assessing human issues in our food chain. This allows an important unanswered gap in advancing interdisciplinary social sciences and may provide research opportunities to increase urban CEA for social sustainability and community resilience. Urban areas involve a diversity of interacting human components and the future of CEA for food production must consider these important social environments.

Conclusions

UA will continue to increase in importance as populations move into cities and the demand for local food increases. Although currently it is not uncommon for UA to take place on relatively inexpensive land in the urban core (e.g., public land or city-owned properties that are economically rented to reduce the municipal maintenance burden), CE food production for UA is expected to expand to land that is significantly more expensive than rural farming land. Therefore, one of our goals as CEA researchers will be to continue exploring how to make UA as economically, socially, and environmentally sustainable as possible. For example, we will try to recommend the most effective lighting sources available as we continue to explore ways to improve the efficiency of implementing LED lighting. We will also assist growers in managing available resources to reduce negative impacts of agriculture on the urban environment. We may do this by helping growers select irrigation systems and fertilizers that will result in less leaching and runoff. This is particularly important in an urban setting so that UA does not contribute to storm-water management issues. We also hope to identify crops that are economically viable to grow in an urban environment, considering external competition and market trends. Furthermore, our research efforts should consider all energy inputs to ensure that local products truly have a lower carbon footprint compared with crops produced outdoors and shipped to the city. Lastly, we must consider that UA creates green spaces in areas with very few plants, allowing city-dwellers to connect with how their produce is grown. This human connection to plants and food is a major benefit of UA that warrants our support so that urban producers can benefit from CEA.

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