Increasing Profits in Vertical Farming

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Introduction

The world's population is expected to grow from 7.6 billion to 9.3 billion by 2050, with 68.4% living in urban areas (United Nations, 2018). The rapid increase in urban population demands the availability of fresh, nutritious, and safe produce for consumption. Relying solely on outdoor agriculture production may not be the right approach to meet the increasing demand in urban areas. Outdoor agriculture is already experiencing increasing droughts and heat stress from global warming and climate change. There is uncertainty about a regular and sufficient supply of fresh produce from outdoor agriculture. Moreover, a majority of produce from outdoor agriculture comes from California and Arizona. The average food miles (distance between food production and consumption sites) in the U.S. are close to 1,800 for leafy greens (Source: Leopold Center for Sustainable Agriculture). Long-distance food transport decreases the shelf life and increases food wastage.

Given this scenario, alternative and innovative systems, such as vertical farms, can play a vital role in providing fresh produce to the increasing population in the future. In vertical farming, crops are less exposed to the outside environment as they are grown inside confined facilities, such as warehouses and containers using artificial environmental conditions. Vertical farms are successfully producing food even in regions with harsh climatic conditions (McCartney and Lefsrud, 2018; Mir et al., 2022), suggesting their resilience to climate change in the future. Usually, the facilities are located close to urban centers which allows for quick transport from production to consumption sites. Moreover, crops are grown at multiple vertically stacked levels to maximize productivity in limited available space. Water and fertilizers are recycled to reduce their wastage in production (Barbosa et al., 2015; AlShrouf, 2017). Many startup companies have invested in this industry. The U.S. vertical farming industry's market value is projected at $3 billion in 2024 (Qiu et al., 2020).

Vertical farming requires high capital expenditures for investment in production systems, automation, lighting, HVAC, and fertigation systems. Moreover, operational costs are high in vertical farming due to increased energy consumption for artificial lighting and temperature control (Kozai et al., 2019). Given this, vertical farming has an increased level of investment risk compared to conventional outdoor farming. The return on investment should be quick and high for economic sustainability. Not only should crop yield be high but the crop sales should fetch premium prices to remain profitable in vertical farming.

Yield is affected by crop productivity and total production area. Light is one of the most important factors affecting crop productivity. Light-emitting diode (LED) fixtures are commonly used in vertical farming due to their low thermal (heat) emission, high energy efficiency, and customizable light quality (or percentage of different colors of light). In general, narrow (consisting of blue and red wavebands) and broadband (consisting of blue, green, red and sometimes far-red wavebands) lighting is used. There is no clear indication whether dual or broadband lighting increases crop productivity.

Consumers pay a premium price if the produce from vertical farming offers more to their liking, such as freshness, taste, color and nutritional quality. Research found that traits such as nutritional quality and food safety add more value and were rated high for liking by consumers (Jolly et al., 1989; Seong et al., 2023). The artificial light quality used to grow crops in vertical farming contains a small percentage of blue light and does not contain ultraviolet light — both important factors for increasing color, flavor, and nutritional quality of produce (Khare et al., 2020; Kong and Nemali; 2023).

Moreover, consumers expect the produce grown in vertical farms to be completely safe as they are less exposed to outside environment. Food safety is an increasing concern in vertical farming. Factors such as high plant numbers, warm temperatures, closed-loop irrigation and humid conditions make it congenial for bacterial contamination and multiplication. In this article, we describe some of the applied research conducted on increasing crop productivity and enhancing traits that add value to lettuce, including nutritional quality and food safety.

Increasing crop productivity. The intensity of light provided by LEDs in vertical farming is much lower than what crops are exposed to in conventional outdoor farming. At low light intensities, the quality of light provided to plants can greatly affect photosynthesis and growth. This concept can be used to customize the light quality provided to plants using different combinations of LEDs in vertical farming, to increase crop productivity. Colors of light in commercial LED fixtures are produced by a process called phosphor conversion. This involves coating blue LEDs with a chemical, phosphor, that absorbs blue light and re-emits light of lower energy. such as red and green. Based on the quality of light output, the light fixtures used in vertical farming can be categorized into broadband white light and narrowband purple light. The percentages of red, green, and blue components can vary slightly in both narrow and broadband lights, depending on the manufacturer. The broadband white light is considered warm-white light due to a large percentage of red light in the total light emitted by the fixture.

We studied how these two types of light fixtures with differences in light quality can affect the crop productivity of lettuce. In our study, we grew four lettuce varieties belonging to red leaf (Redina), green leaf (Black Seeded Simpson), butterhead (Rex), and romaine (Organic Rouge d'Hiver) groups.

The seeds were germinated in 1.5-inch rockwool starter plugs and transferred to a custom-built vertical farm after seedling emergence (two-leaf stage). The vertical farm was built using 2′×4′ and 0.4″ deep hydroponic trays, 320 gph submersible pumps, 40 gallon reservoirs, 2′×4′×6.5′ metal shelving units, and two types of LED lights. Each level was 1.5 feet apart within a shelf. The fertilizer solution was continuously recycled (closed-loop) during the study between the trays and reservoirs.

We combined two water-soluble fertilizers (N-P-K percentages of 15-2.2-12.5 and 21-2.2-16.6) in a 3:1 ratio to prepare the fertilizer solution. The electrical conductivity (EC, a measure of total concentration of fertilizer salts dissolved in the solution) of the fertilizer solution was maintained close to 1.8 mS/cm (or 1800 μS/cm), and the pH ranged between 5.8 and 6.2. We used a dilute phosphoric acid to lower the pH periodically during the study.

The artificial lights (both narrow and broadband) remained on for the entire duration of the study (4 weeks). We measured power consumption (W/ft2), light intensity (μmol/m2/s), and percentage of blue, green, and red light from each fixture. Four plants of each variety were harvested from the center of each tray after 28 days of growth to measure average fresh weight.

The electric power requirement was similar between the two fixtures used in our study (Table 1). These fixtures consumed a kilowatt of power per square foot of area when turned on continuously for approximately 63 hours. The average light intensity was lower in the narrow band treatment for the given wattage; however, it was not different between the two fixtures when variability in light levels across different locations was considered. There were differences in the quality of light emitted by the fixtures. Higher percentages of red light in the narrow band and blue and green light in the broadband were present in the total light emitted by the fixtures.

We found that crop productivity was highest when plants were provided with purple or narrow band

Table 1. Power consumption, light intensity, light quality, and crop productivity of light fixtures

Light	Power	Light Intensity	Blue	Green	Red	Crop Productivity
	W/ft²/hr	μmol/m²/s	(%)	(%)	(%)	lb/ft²
White	16.5	290	20	45	35	0.58
Purple	16.3	247	15	21	64	0.70

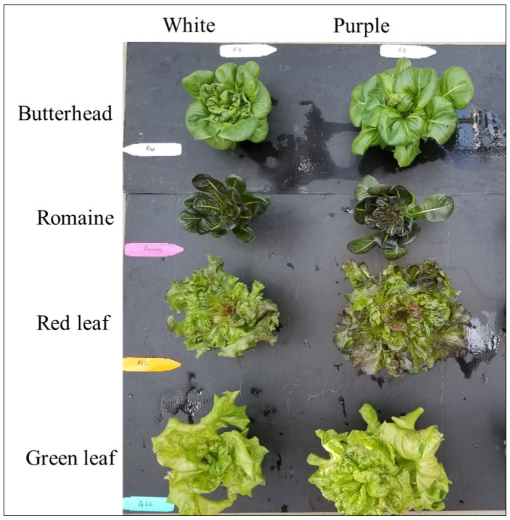

***Figure 1.** Growth differences among lettuce varieties provided with white and purple light quality.*

light quality (see Table 1 and Figure 1). The result was similar among all four varieties of lettuce. The observed differences in crop productivity are likely associated with differences in light quality between the two fixtures. It is well established that red light carries the right level of energy for photosynthesis in plants, followed by green and blue light (McCree, 1971). A lower percentage of blue and green light, and a higher percentage of red light, likely resulted in higher photosynthesis and shoot growth — higher fresh weight of lettuce varieties provided with narrow, compared to broadband, light. Our study indicates that light quality can be an important determinant of crop productivity in vertical farming. Moreover, light fixtures with a higher percentage of red light in the total light will increase the crop productivity of lettuce.

Enhancing nutritional quality. Nutrients consumed through plant-based foods are regarded as superior to those consumed through pills or supplements (Martin and Li, 2017). Health-promoting phytochemicals such as beta-carotene (precursor of vitamin A biosynthesis) and anthocyanins (aid in reducing inflammation and blood pressure, Karlsen et al., 2007; Jennings et al., 2012) are present in leafy greens. However, the levels of these nutrients are generally low in plants (Lako et al., 2007; Thoma et al., 2020). For example, a salad bowl of lettuce (approximately 60 g) can provide only a third of the recommended daily allowance of vitamin A (Institute of Medicine US Panel on Micronutrients, 2001; USDA, 2019). Biosynthesis of human health-promoting phytochemicals is stimulated when plants are exposed to stress (Gillman, 2018). However, plants in a vertical farm are generally not exposed to stressful environments such as high salinity, heavy metals and ultraviolet (UV) radiation, because the plant-growth environment is optimally controlled (Sharath Kumar et al., 2020). The lack of exposure to stress may potentially lower the nutritional quality of produce grown in vertical farming compared to natural outdoor field production (Rowley, 2019).

It is well-known that the addition of high-energy blue light is usually associated with an increased accumulation of phytochemicals, such as carotenoids and anthocyanins (Li and Kubota, 2009; Ouzounis et al., 2015; Amoozgar et al., 2017). The light fixtures used in vertical farming can be customized to provide a high percentage of blue light. However, blue light is less efficient at driving photosynthesis than green and red light (McCree, 1971). Plants exposed to excess levels of blue light show decreased vegetative growth (Hernandez and Kubota, 2016; Craver et al., 2020; Kusuma et al., 2020; Kang et al., 2016). This poses a challenge to increase nutritional quality without compensating for yield.

As opposed to continuously exposing plants to a high percentage of blue light, a variable lighting strategy may be used in vertical farming. This strategy involves changing the light quality provided to plants by the growth stage. This method may allow for more control of plant growth and biosynthesis of phytochemicals during production. As the light quality effect on the synthesis of phytochemicals was reported to be more pronounced at mature growth stages (Sng et al., 2021), a high percentage of blue light can be provided toward the end of the crop cycle to enhance phytochemical biosynthesis. The growth rate of plants is usually slow during the end of crop cycle. Thus, a high percentage of blue light may have a minimal (negative) impact on vegetative growth when provided at the end of a crop cycle.

We tested the usefulness of a variable lighting strategy for green (Amadeus) romaine lettuce. Generally, green varieties show increased vegetative growth and low levels of phytochemicals. We grew romaine lettuce

Table 2. Vegetative growth and phytochemical levels in fixed and variable lighting treatments

Light Quality	Fresh Weight	beta-Carotene	Anthocyanin
	(g)	(mg/100g)	(ΔOD/g)
Fixed-low blue	54	4.08	0.000
Fixed-high blue	20	4.89	0.018
Variable-low followed by high blue	44	5.54	0.002

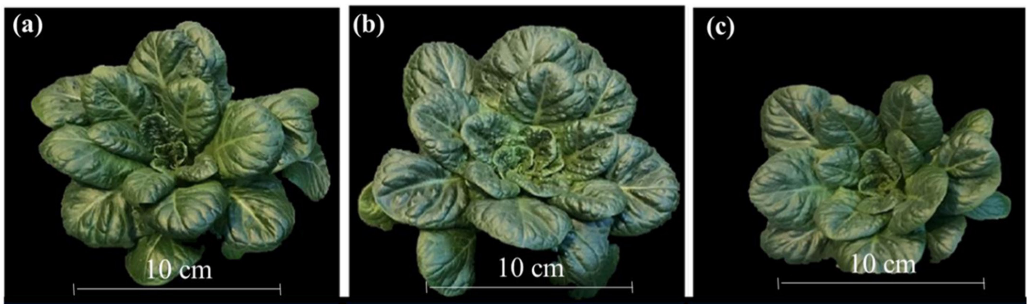

Figure 2. Growth differences in green romaine lettuce provided with fixed and low blue (a), variable with low followed by high blue (b), and fixed and high blue (c) light quality during growth.

plants similar to the method used in the previous study that compared two light fixtures using the custom-built vertical farm. The plants were tested using both fixed and variable lighting methods. The fixed lighting strategy included both low (10% of total) and high (50% of total) levels of blue light provided continuously during crop growth, with remaining light as red light. The variable lighting strategy used low level (10% of total) of blue light initially for 21 days followed by a high level (50% of total) of blue during the last 10 days of growth. The two fixed light quality treatments were used as controls for comparing vegetative growth (low blue) and phytochemical levels (high blue) with the variable lighting strategy. The total light intensity was similar in all three light quality treatments.

We found that the variable lighting method slightly reduced the fresh weight of green romaine lettuce compared to fixed lighting with low blue light level (Table 2, Figure 2). This is mostly because the plants in the variable light treatment were exposed to a high percentage of blue light during the last 10 days. However, the reduction in vegetative growth was small as overall growth generally slows during the last 10 days of a crop cycle. One reason for slow vegetative growth during the last week of a crop cycle is the shading and competition for light among neighboring plants.

The interesting observation was that the level of beta-carotene was higher when plants were grown using the variable than both the fixed lighting strategies. This suggests that plants increased biosynthesis of carotenoids even during the final 10 days of growth, likely as a stress response. We did not observe an increase in the level of anthocyanins in plants grown using the variable lighting strategy. As expected, the fresh weight was lowest and the anthocyanin level was highest in the fixed and high blue light quality treatment. Our study indicates that it is possible to increase the levels of health-promoting phytochemicals such as beta-carotene in lettuce with a minimal negative impact on vegetative growth using a variable lighting strategy in vertical farming.

Maximizing food safety. Food safety has been an important issue worldwide, especially for fresh produce (Redmond et al., 2004). It has been reported that nearly 46% of foodborne illnesses were associated with fresh fruits and vegetables (Painter et al., 2013). Leafy greens generally fall into the class of foods described as ready-to-eat, which means the product will usually be consumed raw. Foods that do not get cooked before consumption can lead to a greater food safety risk (Barnhart et al., 2015). Based on a report from the Interagency (CDC, FDA, and USDA), leafy vegetables were attributed 21.5, 3.9, and 62.1 percent of foodborne illnesses caused by Listeria, Salmonella, and E. coli O157 respectively in the US (IFSAC, 2023).

Although vertical farming involves food production in confined spaces that are isolated from outdoor contamination, it is not realistically possible to completely prevent the occurrence of pathogen contamination. The introduction of pathogens into vertical farms can occur through accidental contamination via workers, seeds, media, harvest equipment and water (Avgoustaki and

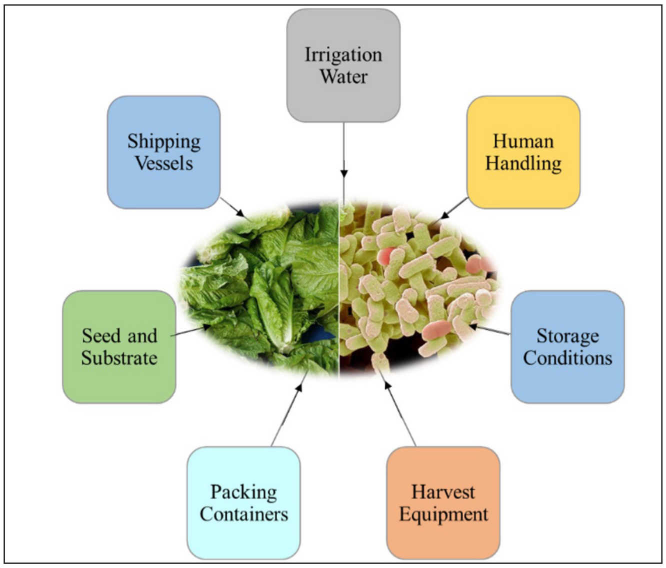

Figure 3. *Potential sources of contamination from food-borne pathogens in a vertical farm.*

Xydis, 2020; Roberts et al., 2020). Once a pathogen is introduced into a vertical farm, it can easily multiply and spread throughout the entire production system due to warm temperatures and closed-loop air and water recirculation. Vertical farms benefit from consumers' perception that the food is generally safe for consumption. However, reports show that small- to medium-size vertical farms may find it difficult to maintain consistent food-safety practices due to additional costs, limited time, and lack of knowledge and resources (Behnke et al., 2012; Harrison et al., 2013; Chen et al., 2021). Food safety-related issues can potentially change consumer preferences away from vertical farms.

The bacterium *E. coli* O157:H7 is commonly associated with human diseases in the U.S. (Lim et al., 2010). Multistate outbreaks of *E. coli* O157: H7 were reported in 2017-2018 in the U.S. and linked to the consumption of leafy greens, especially romaine lettuce (CDC). In 2017-18, *E. coli* O157: H7 contamination resulted in 272 infections, 121 hospitalizations and five deaths (CDC). Plants can be good alternate hosts for human pathogens such as *E. coli* O157:H7 (Melotto et al., 2014; Jang and Matthews, 2018). When in contact with leaves, pathogenic bacteria can produce molecules to attach and form a biofilm matrix on plants (Yaron and Römling, 2014). It has been reported that human pathogens such as *E. coli* O157:H7 can internalize, colonize, and survive on plant tissues for several days (Brandl, 2006; Brandl and Amundson, 2008; Deering et al., 2012). The ability of *E. coli* O157:H7 to survive on the plant is largely affected by leaf traits (Jacob and Melotto, 2020). For instance, the persistence of *E. coli* O157:H7 on spinach.

Collectively, increased vegetative growth and enhanced value-added traits, such as nutritional quality and food safety, can attract customers and increase their willingness to pay a premium for produce grown in vertical farms. This can potentially increase wholesale value and profits.

References

Additional details about the content, data, and other research references used in this publication can be found in the following open-access scientific articles:

1. Kong, Y., A. Nemali, C.A. Mitchell, and K. Nemali. 2019. Spectral Quality of Light Can Affect Energy Consumption and Energy-Use Efficiency of Electrical Lighting in Indoor Lettuce Farming. HortScience. https://doi.org/https://doi.org/10.21273/HORTSCI13834-18.
2. Kong, Y., and K. Nemali. 2023. Fixed vs. Variable Light Quality in Vertical Farming: Impacts on Vegetative Growth and Nutritional Quality of Lettuce. PLoS ONE. https://doi.org/10.1371/journal.pone.0285180
3. Kong, Y., A. Deering, and K. Nemali. 2024. Reducing *Escherichia coli* O157:H7 Contamination in Indoor Farming: Effects of Cultivar-Type and Ultra-Violet Light Quality. Journal of the Science of Food and Agriculture. https://doi.org/10.1002/jsfa.13303.
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