Chapter 8
Total Indoor Farming Concepts for Large-Scale Production

Marc Kreuger, Lianne Meeuws, and Gertjan Meeuws

Abstract Indoor farming can contribute to the world food production in the coming decades. Indoor growing would greatly reduce the need for water and pesticides to grow crops and enable the production of safe, clean, nutritious, and affordable food. However, to realize the yields needed, some of the plant's requirements must be met. For this a climate system was designed where light, temperature, and evaporation are controlled independently. In the modular system, a laminar airflow controls evaporation, independent of light levels and without impact of infrared light. Together with crop models, calculations and predictions of yields can be made, which are necessary to define commercial success in advance.

The Plant Balance Model allows to further increase yields and quality by fine-tuning the specific effects of temperature, evaporation, light, and crop management.

In the modular indoor farm, a large variety of crops can be grown. It can consist of a single-layer growing area dedicated for vine crops like tomato, cucumber, and pepper. Alternatively, a multilayer area can produce herbs, lettuce, and other small crops.

Keywords Plant balance · Tomato · Vine crops · Indoor farming

8.1 Introduction

The growing population and the need to provide enough fresh, tasty, healthy, and affordable food urge agriculture to make a dramatic shift in efficiency. Moving from field to greenhouses, including nutrition and artificial lighting, in the last decades marked a great improvement in food production. However, this is not enough to feed the entire population, certainly in the coming decades with the population rising to nine billion and water becoming the limiting factor in many agricultural areas. Additionally, the current supply chain is too inefficient; too many losses occur during production, transportation, storage, and due to a mismatch between supply

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and demand. And even more, today's crops were selected to increase yields and for being tolerant to abiotic stress and resistant against pathogens. Specific benefits related to feeding a world population in terms of nutritional levels are hardly part of the current breeding programs.

Indoor farming can be regarded as the next generation of agriculture and may very well be one of the few solutions to make that shift. Growing crops without daylight enables higher yields, quality, and nutrition. Food can be produced everywhere with low water usage, without pesticides, and at reasonable prices. The reduction in footprint will be dramatic, especially on those places where water, food, and resources are scarce. The impact on infrastructure and environment will be limited, securing a sustainable food supply.

In this chapter is described how a different view on plant growth, combined with integrated technology, offers the opportunity for a scalable indoor farming solution. The creation of a climate, perfectly fit for plants, will secure the high yields that are necessary for both food production and profitability. Only when both are realized can indoor farming deliver on the promise many people feel it has.

8.2 What Makes Plants Grow

Plant production is driven by light, temperature, and evaporation, generally described as the climate. Outdoors these are intimately linked as the sun provides light as well as heat. Conventional greenhouse growers are in a constant battle with the climate, as this is a continuous uncertainty. Good growers handle the climate very well and know how to control its impact on their crop. The ability to grow plants in an indoor farm offers many more control mechanisms than in a greenhouse. The climate in an indoor farm is very stable, with no need to anticipate to the outside situation. Growers can therefore focus more on crop management and maintenance of the technical operation and equipment.

From the plants' points of view, nature can be a horrible place. It can be too hot or too cold; there is too much or too little light; there can be night, too little or too much water, no nutrients, wind, insects, grazing animals, etc. If it were up to plants, they would want a totally different environment: a stable temperature and flow of air and water and enough nutrients and light. They most likely would not prefer sunlight, as 50% of that light is heat that plants need to get rid of through evaporation. This is how leaves keep their temperature constant and is most prevalent in the upper layers of leaves that catch most of the sunlight (Crawford et al. 2012; Medrano et al. 2005). The temperature control mechanism is key to regulate growth and development but makes outdoor plants use a lot of water. As water uptake by the roots is a passive process following nutrient uptake, the balance between uptake and evaporation greatly impacts plant habitat. Low evaporation with high root pressure will result in higher water content. Taller and elongated plants are generally not favorable in agriculture.

In field and greenhouse evaporation of plants is mostly driven by vapor pressure deficit (Turner et al. 1984; Seversike et al. 2013; Yang et al. 2012). This is the difference between the water content in the air, at a certain temperature, and the saturated water vapor pressure. This is strongly depending on temperature and is calculated and visualized in the Mollier diagram. As leaves heat up in sunlight (Tyree and Wilmot 1990), the temperature in the stomata increases, and as a result, the vapor pressure deficit and consequently evaporation increase as well. Diffusion of water to the outside of the leaf, transpiration, will increase and in turn result in cooling of the leaf. So, in sunlight radiation intensity, photosynthesis and evaporation go hand in hand.

8.3 Evaporation of Plants Indoors

The control of evaporation is essentially different in an indoor farm compared to a greenhouse and field. Air quality is therefore critical for optimal growth indoors where evaporation is mostly driven by airflow and vapor pressure deficit (Turner et al. 1984; Seversike et al. 2013; Yang et al. 2012). Mixing air in a closed environment to control air quality will result in differences in temperature and humidity. This will lead to differences in growth and evaporation rates of a growing crop. Consequently, the uniformity within the growing area will decline. Additionally, crop quality may be affected on certain locations in the growing area. Either way, control levels are declining.

From the viewpoint of the plant, the indoor climate design can be radically different from the usual outdoors or greenhouse climate. The understanding of what makes plants grow in an indoor farm is of great importance. The indoor use of light-emitting diodes (LEDs) as light source has a great impact on the plant's responses. The restricted use of only a few wavelengths to target specific receptors and the low levels of infrared result in a totally different light perception by plants. Plants can do with only blue and red light as this is absorbed by chlorophyll, phytochromes, cryptochromes, and other receptors (Kong and Okajima 2016). These are most of the receptors that direct photosynthesis and developmental responses. Growth under blue and red light only has a very broad optimal ratio; more than 15% blue light in general works well (Hogewoning et al. 2010).

Ultimately evaporation and photosynthesis should be controlled independently. For these two things are needed; the light source needs to drive photosynthesis only and not evaporation. Evaporation needs to be controlled by vapor deficit and air speed alone and preferably not by infrared radiation. The first can be achieved by using very efficient LEDs and not placing them close to the crop. Efficient LEDs with a high μmole/Joule value can be placed several meters from the crop. At that distance, virtually no infrared is left at the plant level while sufficient photosynthetically active radiation (PAR) levels are maintained. Crops placed in close vicinity to the LEDs, like in a multilayer system, experience relatively larger amounts of infrared. This will stimulate evaporation and will fundamentally be linked to the

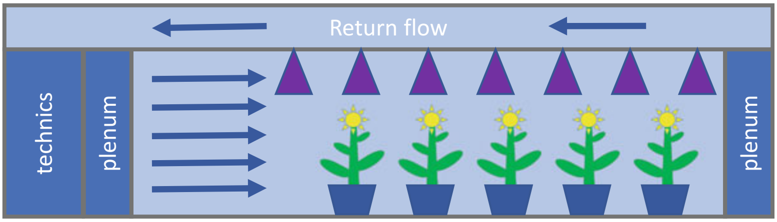

Fig. 8.1 Schematic presentation of an indoor farm with a laminar air flow. Blue arrows indicate the direction of the airflow. Purple triangles represent lighting equipment. The left plenum is the air inlet; the right plenum is the exit. In the technical area is the air treatment system. It also contains the control units and fertigation systems

photosynthesis levels. With increasing efficiencies of LEDs, a decline in infrared light in indoor farms is evident and will continue in the coming years. As a result, leaf heating is declining as well making the control of evaporation increasingly important. In other words, if evaporation drops and the logistic processes of water and nutrient supply are lost, photosynthesis will be inhibited as well.

Following this strategy, a specific climate and associated technology was created to serve best the needs of the plants. The specific construction results in a high refresh rate of approximately 30 h^{-1}. These conditions maintain sufficient evaporation without creating wind stress as a slow moving laminar flow of air moves through the unit. This is realized by an air in and outlet consisting of a plenum space where air is moving through multiple holes. As a result, a large volume of air is conditioned every minute, allowing the incoming and outgoing air to be almost identical to the set point, without creating a high air speed. The uniform distribution of air quality allows every leaf in every position to evaporate equally. The vapor pressure deficit in combination with air speed will determine the loss of water from the plants. Higher deficit and higher air speed both increase evaporation.

In such an environment, light, temperature, and evaporation can be controlled independently which allows full control of plant development. A schematic representation of such a system is shown in Fig. 8.1 but can be scaled to almost any size. A similar principle can be applied in a multilayer system. Dimensions will change then as the heat load per square meter floor area will increase.

8.4 Do We Really Need Far-Red Light in Indoor Farming?

Plants sense different wavelengths of light with several receptors. Each of these receptors results in a specific response of the plant (Kong and Okajima 2016). Purified chlorophyll absorbs red and blue light to drive photosynthesis. Phototropins and cryptochromes absorb blue light. They are involved in circadian rhythms, phototropism, inhibition of hypocotyl elongation, stomatal opening, and various other responses. Phytochromes absorb red (R) and far-red (FR) light and are involved in the shade avoidance response, flower induction, germination, and de-etiolation (Castillon et al. 2007; Cerdan and Chory 2003; Demotes-Mainard et al. 2016; Possart et al. 2014). Outdoors plants experience far-red light every evening (Kasperbauer 1987) when a peak in the ratio FR/R occurs a few minutes before darkness. Plants also use far-red light to sense their surroundings (Jaillias and Chory 2010). In shade, the ratio FR/R is much higher than in bright sunlight. In a response to escape from the lack of light, plants elongate or flower early. Auxin production is induced causing (vascular) tissue to elongate. As a result, plants get taller, reaching the light earlier, but are forced to put more energy in stems. This change in dry matter partitioning will have its impact on the harvest index as a significant higher portion of dry matter must be put in stems (Kasperbauer 1987). Leaves also expand more in far-red light. In general, epidermal cells are larger, but the cell number remains fairly constant. As a result, stomata get diluted over the leaf surface (Chitwood et al. 2015). Whether this has an impact on evaporation is not known.

In some crops, early flowering is induced by high FR/R ratios and/or by end of day far-red light (Cerdan and Chory 2003; Kim et al. 2008). In general, there are many routes and mechanisms that lead to flowering (Simpson et al. 1999), and most plants have the genetic capability to use at least some of them. In most areas plants had to adapt to seasons and local environments. Far too often seasons limit growth, flowering, and seed set as these must be properly timed to secure the next generation. Responses to day length variation (e.g., long-day, day-neutral, and short-day plants) are critical for maintenance of the species. Next to regular seasonality, flower induction can be achieved in multiple ways. “Stress-induced flowering” is considered to be an off-season flowering mechanism induced by “adverse” climate conditions (Roitsch, 1999; Takeno 2016). Obviously, these can be mimicked indoors if the triggers are known. Alternatively, “luxury-induced flowering” is something that almost exclusively can be achieved indoors where plants can be forced to follow different developmental paths. In the described design, the outdoor climate is not meant to be copied, but a new, highly controlled and stable climate is created.

A common factor in flower induction is the formation of the FT protein (Corbesier et al. 2007), also known as the florigen. This is generally accepted as the molecule that triggers the formation of flowers. Additionally, it was shown that a sugar compound, trehalose-6-phosphate (Van Dijken et al. 2004; Wahl et al. 2013), is involved and essential in the process. This compound alone, when present in the shoot meristem, can induce flowering independent of all other signals (Wahl et al. 2013). The same compound is also produced only when sugar is present in abundance (Lastdrager et al. 2014; Stitt and Zeeman 2012). Trehalose-6-phosphate acts as a “sugar sensor” to tell the organism energy is not a limiting factor. Since flowering demands a lot of energy, the sensor may be the lock on the door to ensure plants flower only when enough energy is available. It also shows that at least one alternative route to flowering is driven by sugar and sugar-related compounds, which happens to be under control in an indoor farm environment. The possibility of making plants flower at will may not be too far away since the creation of plants with excess sugar is very well possible.

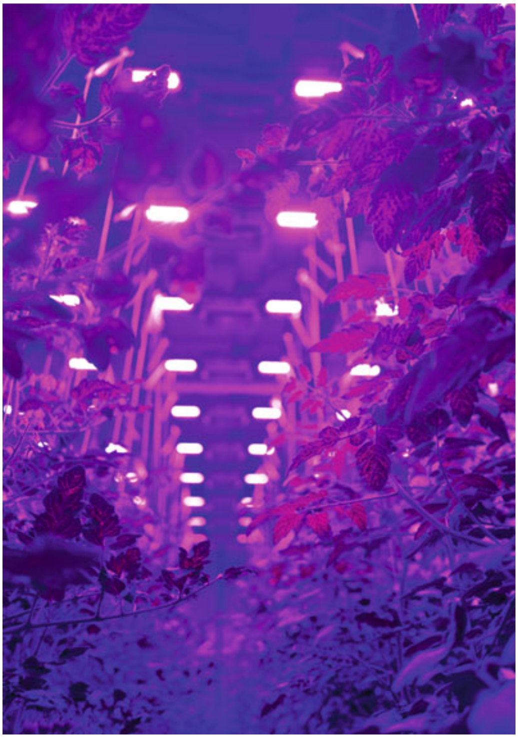

Fig. 8.2 Growing tomato plants in an indoor farm with laminar air flow and LEDs on the ceiling

During fruit set in tomato, far-red light inhibits the synthesis of lycopene (Llorente et al. 2016a; Llorente et al. 2016b). This "self-shading" of fruits ensures lycopene and carotenoids are produced at the right time. Additionally, postharvest treatment of ripe fruits with far-red light reduces lycopene levels (Gupta et al. 2014). Tomato production with only blue and red light may therefore lead to fruits with altered, higher levels of lycopene and carotenoids, though this needs to be proven.

Grown under LED lights, biomass production can be stimulated by red and blue light only, provided the balance between the two is not too far off (Massa et al. 2008; Hogewoning et al. 2010). Growth, from germination till fruit set, therefore should be possible with only the two colors. The absence of far-red light in indoor farms prevents the perception of shadow by plants. Leaves below other leaves will simply receive less light and will not experience shadow. Additionally, flower induction can be achieved in other ways as well, so the need for far-red light is questionable. An example of such culture is shown in Fig. 8.2 where tomato plants are grown under blue and red light only and produce normal fruits.

8.5 The Plant Balance

An indoor farm takes away all the constraints for plants that can be found outdoors. Plants receive what they need in optimal quality and quantity. With their leaves, light, nutrients, water, and CO_2, plants generate energy in the form of carbohydrates, sugar. The sugar is used for basically three things. First in line is maintenance; the energy needed to keep the organs functional and alive. Second in line is growth; any surplus of energy can be used for the formation of new organs (roots, stems, leaves, flowers) and ultimately seeds. This is the delicate balance between source and sinks. Last in line is the secondary metabolism; any energy left over will be used for compounds normally not produced or at very low levels. These are compounds not vital for the plant and often produced in times of stress. Many can have a role in defense against pathogens or adverse conditions. Others are used to attract, like flower colors, fragrances, and tasty compounds. In indoor farms, however, stress is absent, and these compounds can be regarded as luxury compounds.

In field conditions light and temperature are often connected, as 50% of the sunlight is infrared light. More light is mostly resulting in a higher (leaf)temperature with all consequences. Indoors these can be separated as LEDs have much less infrared light. Therefore, the rate of dry matter production through photosynthesis can be uncoupled from the metabolic rate. In practice, this means that dry matter production and content are under control. The ultimate control of the surplus of energy available for the plants allows us to control growth, development, and metabolism. Consequently, essentially different plants can be produced, consistently and scalable. Compared to field conditions and to a lesser extent greenhouses, the energy production in an indoor farm can, in principle, be much higher. This is a key difference between field/greenhouse and indoor farming simply because so much more energy, sugar, can be made (see Fig. 8.3).

In 1989 Gertjan and Lianne Meeuws started Buro Meeuws, a consultancy and research firm in horticulture. They were pioneers in the field of hydroponics,

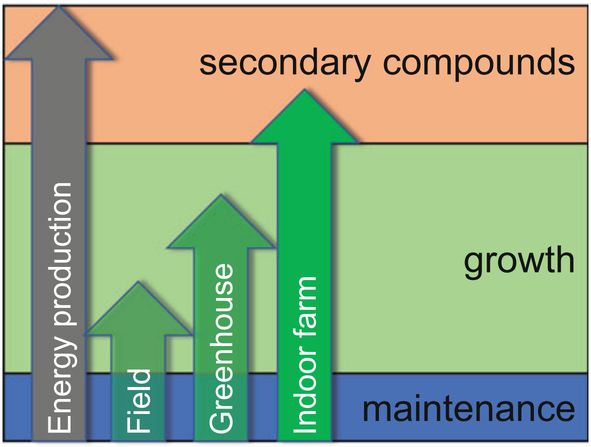

Fig. 8.3 Schematic representation of energy production by plants in the field, greenhouse, or indoor farm. Energy is needed for maintenance, growth, and secondary compounds, in that order

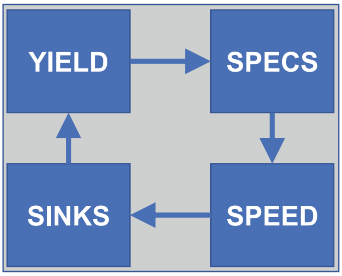

Fig. 8.4 The plant balance model

assimilation lights, and robotics. They have consulted with over 200 leading horticultural companies all over the world. In the 1990s, they worked on a big data project, collecting millions of data over 5 years from 500 measuring fields from different crops and their habitats. The goal of the project was to develop and validate algorithms that help explain and predict the growth of plants; this resulted in the Plant Balance Model.

The Plant Balance Model allows us to calculate biomass production, based on plant characteristics and the environment. Additionally, it enables the prediction of future productivity and/or changes resulting from adaptions in the climate. The model, as shown below, starts at the top left (Fig. 8.4):

Yield is the maximum amount of biomass that can be produced of a certain product, depending on the actual technical equipment of the indoor farm. This is often expressed as dry matter per square meter per year. It is based on the level of photosynthesis and the harvest index (the percentage of produced biomass that we use).

Specs are the actual or desired specifications of the produce grown. It consists of the desired weight of the product and its dry matter content.

Speed is related to temperature and the time it takes to complete a cycle. For instance, how long it takes to produce three leaves and a truss for tomato. This is driven by Growing Degree Units (GDUs) indicating that a raise in temperature will lead to an acceleration of growth. For most crops GDUs are known for each developmental stage.

Sinks is related to the number of sinks needed to produce the desired number and quality of products or fruits. Linked to the previous three items, this can be used to calculate the plant or stem density for instance. It enables the calculation and prediction of yields when the climate parameters like temperature, light intensity, etc. are known.

In theory, this means dry matter production per square meter of growing area can be calculated. Based on a set of assumptions and data gathered over the years (G. Meeuws, L. Meeuws, unpublished data), the maximum amount of dry matter production is 30 $\text{kg.m}^{-2}.\text{year}^{-1}$. One of the assumptions is that 300 $\mu\text{mol.m}^{-2}.\text{s}^{-1}$ of only blue and red light is sufficient for this. In practice, however, this is hardly achieved for a number of reasons (Table 8.1). First, the leaves must absorb the available light. A single layer of leaves will absorb 65% of the light, the next layer

Table 8.1 breakdown of dry matter production per year and reductions due to daylength, harvest index, and planting events

	Unit	DM ($kg.m^{-2}.year^{-1}$)
24/24 hrs. of light	300 $\mu mol.m^{-2}.s^{-1}$	30
Leaf area index = 3	100% light interception	30
Daylength/photoperiod	20 hours	25
Harvest index	70%	18
Planting events, 1x per year	42/52 weeks	14

This is an example of a calculation. For specific crops data will be different. DM is dry matter production

again 65% of the transmitted 35%. Three layers of leaves over a certain area equals a leaf area index (LAI) of 3 and will absorb most of the light (Atwell et al. 1999). As plants grow their LAI will increase, as a result the average LAI may be different. Second the daylength or photoperiod may not be 24 hours. In the example, a daylength of 20 hours is used which is commonly used for most crops. Third is the harvest index. This is the percentage of the product biomass of the total biomass. For example, in tomato this may be 70%, but for lettuce, it can be close to 100%. Finally planting events may result in periods where there is no harvest, in the example 10 weeks. The actual dry matter production of the produce comes down to 15 $kg*m^{-2}*year^{-1}$ in this example. To convert dry matter to food by the addition of water, the dry matter percentage of the crop is a key variable. A high dry matter percentage will lead to less fresh weight produce. A low dry matter percentage will increase yield as simply more water is added to the same amount of dry matter. When calculating and predicting yields starts with dry matter as described, the performance of the indoor farm can be calculated. In the end, the added water determines dry matter percentage and fresh weight produced.

8.6 Large-Scale Production Facility

The first indoor farm dedicated to grow vine crops like tomato, pepper, and cucumber containing the laminar air flow system was realized in Cincinnati, Ohio (OH), United States (USA). It consists of a single-layer growing area of 360 m^2 equipped with the nutrient film technique (NFT) gutters as growing system (see Fig. 8.5). A second similar-sized multilayer area for herbs, lettuce, and other small crops is part of the same building. The two growing areas are separated by a technical aisle containing all air treatment equipment, fertigation units, heat pumps, and control units. The farm is owned and operated by 80 Acres Urban Agriculture limited liability company (LLC).

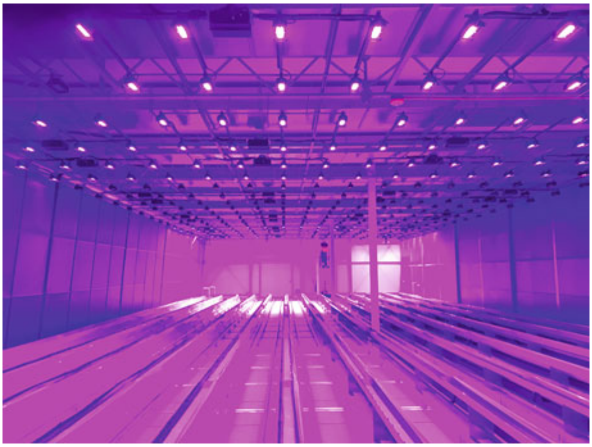

Fig. 8.5 The 80 Acres Urban Agriculture LLC indoor farm in Cincinnati, OH, USA

8.7 Future Developments

The creation of an indoor farm as described will enable the growth of any crop. The Plant Balance Model will calculate and predict yields. Obviously yields must be adequate to justify any investment. All these are needed to make indoor farming viable on any but certainly a larger scale. A contribution to the world food security and production needs to be commercially viable but also scalable.

As developments in LED technology, climate control, and plant science continue, they come together more and more. At the interface, new insights and clever solutions will increase yields even more. Additionally, insight in nutritional values in relation to health and medicine can now become a common platform. The unprecedented control of plant quality offers new opportunities to extend above simply producing food. The combination of technology, genetics, and specific climates can give the term superfood a new meaning.

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