

**DEVELOPMENT OF MICRO-OPTICAL
FURNACE WITH ATMOSPHERIC CONTROL FOR
RESEARCH PURPOSES**

**A Thesis Submitted to
the Graduate School of Engineering and Sciences of
İzmir Institute of Technology
in Partial Fulfillment of the Requirements for the Degree of**

MASTER OF SCIENCE

in Biotechnology

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**December 2018
İZMİR**

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ACKNOWLEDGEMENTS

I would like to express my deepest gratitude and appreciation to my supervisors Asst. Prof. Dr. Engin Karabudak for his guidance, patience and great support and contributions during my M.Sc. period.

I would like to thank all my fellow colleagues whom I have worked within Karabudak Laboratory.

I would like to thank Özge Sevin Keskin, Mert Koç, Ahmet Aytekin, Uğur Soğukkuyu and Emre Göl from Izmir Institute of Technology Karabudak laboratory for helping me a lot and putting up with all my never-ending questions.

I would like to give special thanks and love to my family, who has never stopped supporting me even in hard times, and also to my dear friends who were always there through joy and sadness.

ABSTRACT

DEVELOPMENT OF MICRO-OPTICAL FURNACE WITH ATMOSPHERIC CONTROL FOR RESEARCH PURPOSES

In this thesis, a desktop temperature controlled laboratory type micro-optical chamber system has been developed which can be used for vertical agricultural experiments to observe the development of plants with different wavelengths according to different atmospheric and temperature values using LED light sources. The main purpose of this thesis is to develop a laboratory type easy-to-use device that can control the ideal atmosphere and temperature to perform experimentally the effect of light rays of different wavelength to observe its development of the plant placed in the chamber. In this study, a chamber with rectangular prism geometry was created to prevent the negative effects of harmful insects on plants. Second, a fan system is formed to allow air circulation inside the chamber. Then, a heating unit with electrical resistance system was developed in order to increase or decrease the ambient temperature of the plants. In addition, a control unit with an electronic temperature control circuit is formed to control the atmospheric air circulation and temperature in the chamber. Using the completed system, it was concluded that it is possible to monitor the chamber using LED light sources with different wavelengths to monitor plant growth behaviors in the temperature and atmospheric controlled chamber. In this respect, the changes in the ambient temperature and LED light sources with different wavelengths can be practically used to monitor the growth behavior of the respective plants in chamber.

ÖZET

ARAŞTIRMA AMAÇLI ATMOSFERİK KONTROLLÜ MİKRO-OPTİK FIRIN GELİŞTİRİLMESİ

Bu tezde, farklı atmosfer ve sıcaklık değerlerine göre bitkilerin gelişimini farklı dalgalı ışık kaynakları kullanarak gözlemek için bir masaüstü ısı kontrollü laboratuvar tipi dikey tarım deneyleri için kullanılacak mikro-optik yapı bir fırın sistemi geliştirilmiştir. Bu tezin temel amacı, içerisinde gelişimi gözlemlenmek için yerleştirilen bitki için ideal atmosfer ve sıcaklığı kontrol edebilen ve farklı dalga boyundaki ışık ışınlarının büyüme üzerindeki etkisini deneysel olarak gerçekleştirmeyi sağlayacak olan laboratuvar tipi kolay kullanıma sahip bir düzenek geliştirmektir. Bu çalışmada, ilk olarak ısı yalıtımı sağlayan zararlı haşerelerin bitkilere olumsuz etkilerini engellemeyi sağlayacak olan dikdörtgen prizması geometrisine sahip bir hazne oluşturulmuştur. İkinci olarak, hazne içerisinde hava sirkülasyonunu sağlamak için bir fan sistemi oluşturulmuştur. Daha sonra, bitkilerin içerisinde bulunduğu ortam sıcaklığını arttırıp azaltmak amacıyla elektrikli rezistans sistemine sahip ısıtma birimi geliştirilmiştir. Ayrıca hazne içerisindeki atmosferik hava sirkülasyonunu ve sıcaklığı kontrol etmek için elektronik sıcaklık kontrol devresi içeren kontrol birimi oluşturulmuştur. Tamamlanmış sistemini kullanarak, sıcaklık ve atmosferik kontrollü hazne içerisinde bitki büyüme davranışlarını izlemek için farklı dalga boylarına sahip LED ışık kaynakları kullanarak hazne içerisinde gözlem yapmanın mümkün olduğu sonucuna varılmıştır. Bu doğrultuda, geliştirilen sistem ortam sıcaklığındaki değişiklikler, farklı dalga boyuna sahip LED ışık kaynaklarının kullanıldığı ortamlarda ilgili bitkilerin davranışlarının gözlemlenmesinde pratik olarak kullanılabilir.

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CHAPTER 1

INTRODUCTION

1.1. Properties of Indoor Agriculture Systems

Indoor agriculture systems have gained so much importance in the recent period; because of the increase of the world population, the growth of the metropolises and the decrease of resources. As the cities expand, the gardens and fields are sacrificed to concrete buildings. Migration from rural to urban areas reduces the number of people engaged in farming. As a result, the development of alternative agricultural methods becomes a necessity.

Agricultural production is influenced by many parameters like water scarcity and non-available farming places. Population of world is increasing nearly 9 billion in 2050, and population that live in cities from 3.5 to 6.5 billion, roughly 70% more than current. (Krausmann et al. 2009)

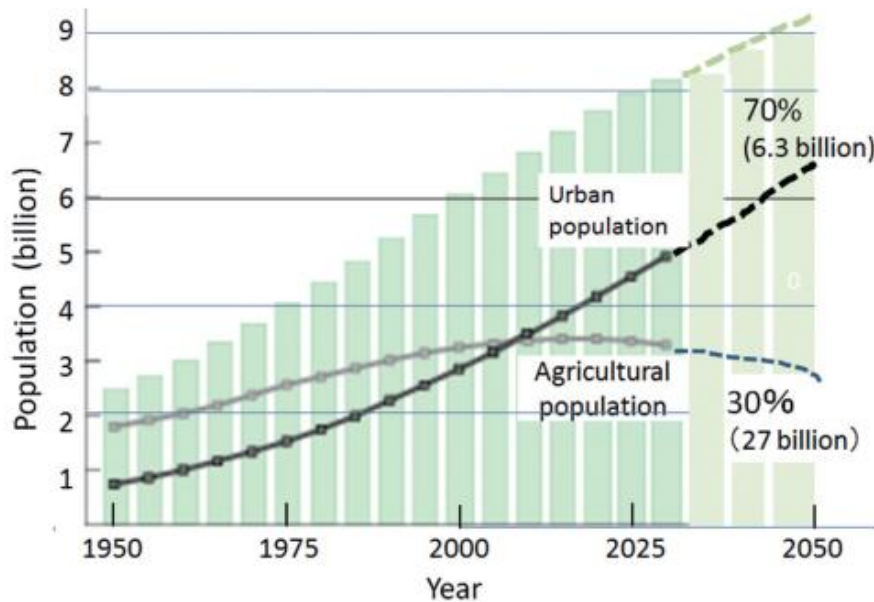


Figure 1.1. World Population Increase (Source: FAO, 2009)

More yields are taken in the indoor farming systems compared to traditional agriculture systems. In the traditional method, you need a lot of manpower and machinery for harvesting. In the vertical farming systems, most of these processes are less needed.

Indoor farming systems supply less water consumption. When production is carried out indoors or in a controlled environment, there is no need to use pesticides as the plant is not exposed to pests. (Watanabe 2009)

Indoor farming does not affect at certain periods of the year due to seasonal changes and climate instead of doing farming on the land. However, you can produce a light-controlled indoor system throughout the year. This means that you will get a lot more products in a shorter period of time more efficient than the traditional agriculture method.

Another important point is water saving. Water turns in a loop, in a closed system, in vertical farming shelves. So there's very little loss of water. But there is a lot of water loss in traditional agriculture.

There are many descriptions of indoor farming. One of them is the term “plant factory with artificial lighting (PFAL)” means to a plant production house with a thermally controlled. (Goto 2012)

Several shelves that have LED light source on each shelf are positioned inside of the chamber. Artificially lighted indoor plant production systems have become alternative for greenhouses or traditional agriculture methods.

Artificially lighted indoor plant production systems have potential for new business opportunities. These systems are in use in many Far East Asian countries. Indoor vertical farms are in use in western developed countries too.

Sun is very essential for plants for making photosynthesis. Spectrum of light has critical influence on plants and each plant need different amount of light and different wavelength of light to grow healthier.

Choosing the type of LED is important for investment costs and productivity of production plant. Generally it is common to use LED or fluorescent light sources in vertical farming system. In this thesis we are mainly focused on LED sources and their wavelength. (Um et al. 2010)



Figure 1.2. Indoor Farm in Japan (Source: Kozai, Niu, and Takagaki 2015)

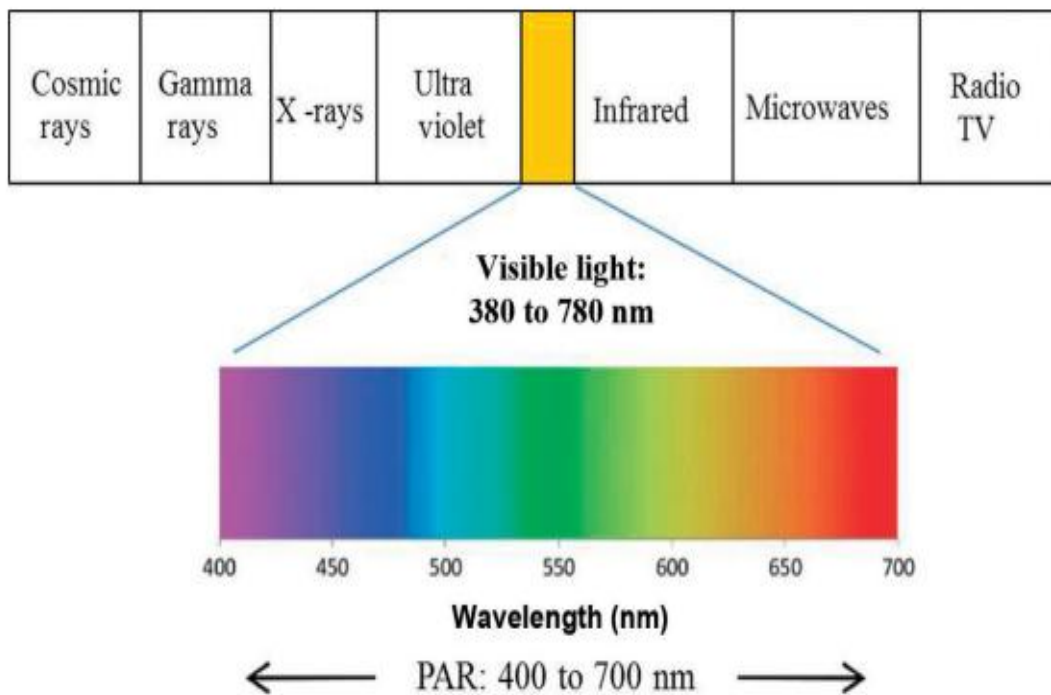


Figure 1.3. Electromagnetic Spectrum (Source: Kozai, Niu, and Takagaki 2015)

The sun is a natural, free, never-ending energy source for plants. Using LED light instead of sun in indoor systems leads to a little more energy consumption. However, if you plan to produce one ton of green leafy plants annually in farmland spreading over hectares, the cost of oil to collect the crop will be much higher than the cost of electricity you will spend on the indoor farming system.

Nearly %50 of electromagnetic spectrum of sunlight is infrared which mainly create heat for plants. Nearly %40 of sun light spectrum is visible range which covers around 400 nm to 700 nm of wavelength. Rest of it is the ultraviolet spectrum.

Table 1.1. Wave Properties of Light

(Source: Kozai, Niu, and Takagaki 2015)

Classification	Wavelength (nm)	Importance
Ultraviolet	100–380	
UV-C	100–280	Disinfecting
UV-B	280–320	Sun burn
UV-A	320–380	
Visible	380–780 (often 400–700)	Photosynthesis and morphology
Far red	700–800 (at the extreme red end of the visible spectrum, between red and infrared light)	Morphology
Near-infrared	780–2500	Heat
Infrared	2500+	Heat

Last ten years, many of the indoor vertical farming systems were installed with fluorescent or high – intensity discharge lamps. But nowadays LED light sources to get more places in plant’s artificial lighting. (Shoji-Kawata et al. 2013)

LED light source mainly has more benefit compare to fluorescent light sources. LED light sources are robust and not affect that much by electric current flow changes.

Also LED's life cycle is longer. Additionally, it is easy for LED light sources to use them with different color of light emitting.

Growing plants in the greenhouse is not energy efficient because the incoming light cannot be controlled. It is very difficult to control the ambient temperature inside the greenhouses depending on the daylight. When necessary, greenhouses should be ventilated in order to reduce the temperature. However, during this ventilation, harmful insects can enter into the greenhouse.

Compare to production costs between traditional farming and indoor farming with artificial lighting; mainly labor cost and risk are higher for traditional method. Below there is a table that shows percentage of production cost for indoor farming with artificial lighting systems. (Morimoto, Torii, and Hashimoto 1995)

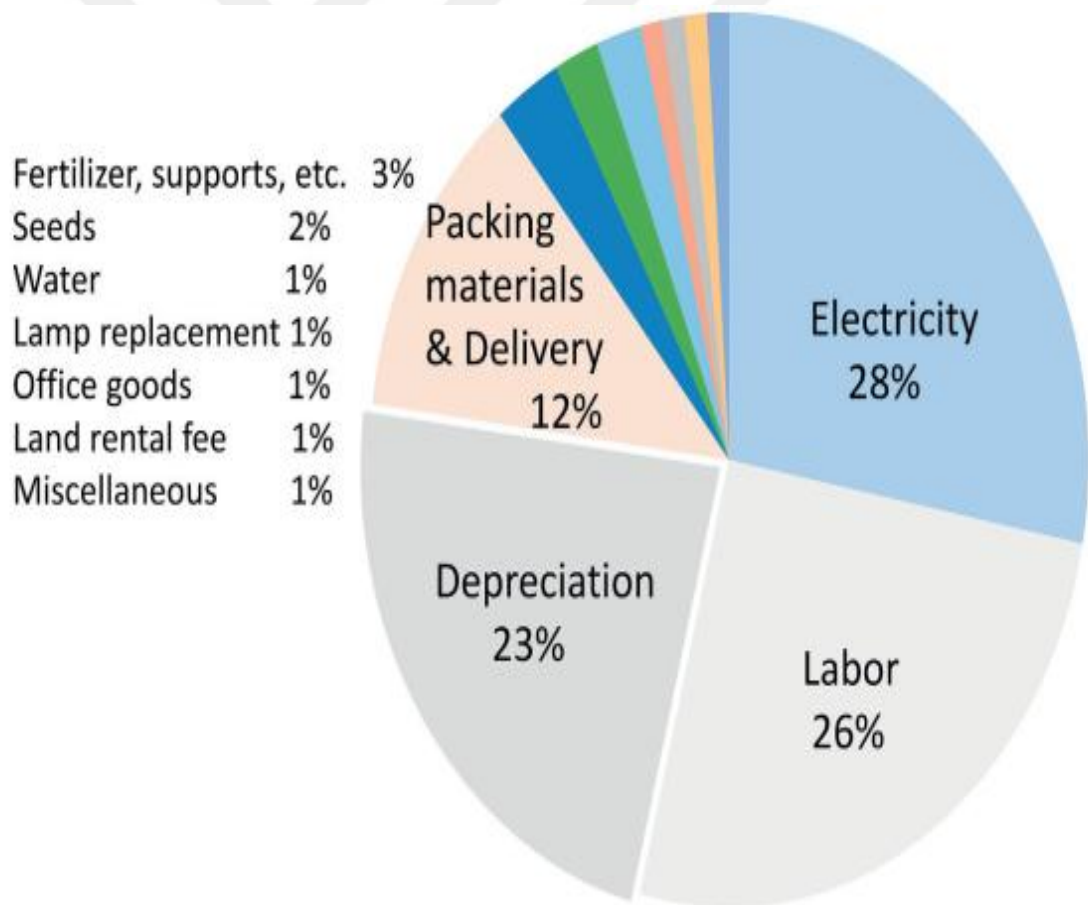


Figure 1.4. Unit Cost Percentage of Indoor Farming with Artificial Lighting

(Source: Kozai, Niu, and Takagaki 2015)

Photosynthetic organisms use light energy to store energy and produce organic compounds. Many plants have chloroplasts mainly located in their leaves. Plants, like other living things, provide the energy needed for their vital activities from the chemical energy of organic matter. For this purpose, by using sunlight, they reduce the carbon dioxide of the air and synthesize their organic foods. In this way, the light energy of the sun is converted into chemical energy and organic material.



Figure 1.5. Desktop PFLD for Home Usage (Source: Kozai, Niu, and Takagaki 2015)

Scattering of light is an optical parameter that affects the absorption characteristics of the plant leaf. The main reason for the light scattering in the leaves is the reflection between the intercellular air gaps and the cells. (Evans et al. 2004)

Possibility of light absorption is determined by path length of light in plant's leaf. Leaves generally are able to absorb 90 percent of blue and red spectrum, 70 percent of green spectrum. (Terashima et al. 2011)

Below these graphs shows absorption spectra of higher plants (a) absorptance spectra of isolated photosynthetic pigments, intact chloroplasts and whole leaf (b) and action spectra for photosynthesis (c)

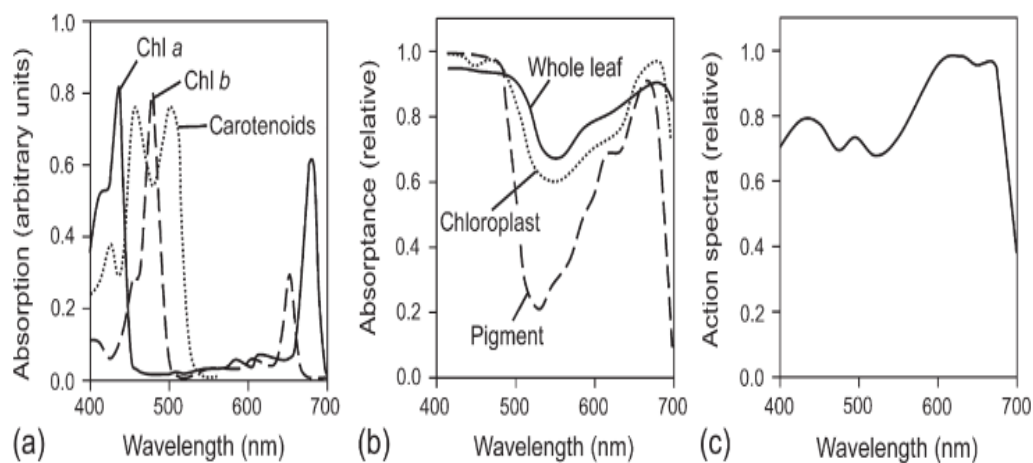


Figure 1.6. Absorption spectra of photosynthetic pigments from higher plants

(Source: Kozai, Niu, and Takagaki 2015)

1.2. Types of Indoor Agriculture Systems

It is possible to divide into three basic groups of indoor agriculture systems: Hydroponic, Aeroponic and Aquaponic.

Aeroponic is the most efficient and advanced system, water is transferred to the plant by spraying method. Because moisture is absorbed rapidly by roots, no more watering is required; up to 90 percent water efficiency is possible. An important point to note here is; that all components supplied to the plant, such as manure or mineral, should not enter the water. Because any particles remain in the spray ducts can cause the system to block. (Borisjuk et al. 1999)

Hydroponic system is much simpler compared to other systems. Plants are grown in hydroponic systems in the interior without sunlight and in soilless

environment. The plant is connected to a channel and a water tank in which certain flow and water flowing. It is illuminated with LEDs at certain times of the day for the plant to grow.

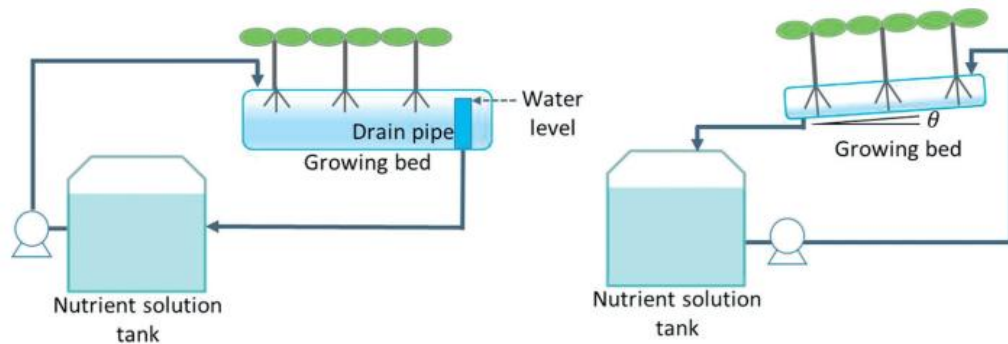


Figure 1.7. Hydroponic System (Source: Kozai, Niu, and Takagaki 2015)

In the aquaponic system, the nutrients required for the plants are supplied from the fish. For this, a fish tank must be connected to the hydroponic system. Fish feces make water rich in minerals and fertilizers. With a pumping system, you transfer water from the fish tank to plants. In order to prevent the fish from dying, the water needs to be circulated in the water with a certain pH and the nutrients required for growing the plant should not kill the fish. Neither the root of the plant is burning nor is the fish dying. They both live in symbiotic equilibrium. (Rakocy, Masser, and Losordo 2006)

Table 1.2. Classification of Four Types of Plant Production Systems

(Source: Kozai, Niu, and Takagaki 2015)

Stability and Controllability	Field	Soil Culture	Hydroponic	Indoor System
Natural stability of aerial zone	Very low	Low	Low	Low
Artificial controllability of aerial zone	Very low	Medium	Medium	Very high
Natural stability of root zone	High	High	Low	Low
Artificial controllability of root zone	Low	Low	High	High
Vulnerability of yield and quality	High	Medium	Relatively Low	Low
Initial investment per unit land area	Low	Medium	High	Extremely high
Yield	Low	Medium	High	Extremely high

In Japan and Singapore, agricultural land is limited, so they use hydroponic systems frequently in use. In America, there is a huge vertical farm established in New Jersey. There, 1 tone of green leafy vegetables can be grown per year with a hydroponics system by using LED illumination. According to traditional agriculture, 75 percent more efficiency per square meter can be obtained. The rate of water use is again reduced by up to 90 percent. (Resh 2016)

1.3. Behaviors Related Temperature Changes

Inside the chamber, we need to supply controlled optimum temperature level for each plant to have better growth rate. Plants can affect negatively about sharp temperature changes. Plants are very sensitive to environmental temperature changes. Even they can die because of temperature changes. Therefore it is very important to control environmental temperature inside of indoor farming systems with artificial lighting.

The most important effect of the temperature factor is the source of energy for the living things on the face of the world. Temperature affects the various physiological activities of living things. That occurrence of temperature, soil formation, genetic soil types, have important roles in the formation of microorganism life, hence humus types is an ecological factor. (Went 1953)

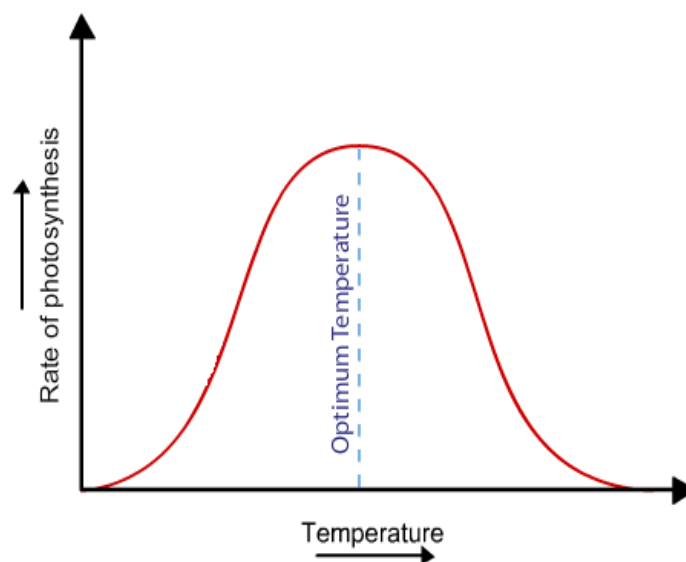


Figure 1.8. Photosynthesis Rate Related With Temperature Changes

Plants at a certain temperature begin to do photosynthesis. As the temperature rises, the intensity also increases parallel to temperature increase and usually reaches the highest amount of photosynthesis at 30 ° C. More than 30 ° C photosynthesis activities begin to decrease. Because of structural deterioration of many enzymes which take role on photosynthesis. As a result; this photosynthesis intensity decreases from 30 ° C and to zero at 40 -45 ° C. (Lyr and HOFFMANN 1967)

The behavior of plants varies depending on the ambient temperature. Phytochromes are light-operated molecular on/off switches. Phytochromes B, which is activated by the red light in sunlight, causes the plant to grow more intensively. Phytochrome was known to be able to switch between active and inactive states regardless of the light conditions. In this process, also known as dark inversion, there are two reactions, one slow and the other fast. The slow reaction ensures that the amount of active Phytochrome B slowly decreases at night time. The other reaction, which is a hundred times faster, competes with the reaction that activates the Phytochromes B under red light, allowing the plant to measure the amount of light in the daytime environment.

Rapid dark reversal reaction is more effective at elevated temperatures. Thus, the plants adapt to the temperature changes in the environment. Phytochrome B integrates light and temperature signals in Arabidopsis plant. (Legris et al. 2016)

1.4. Aim of Design and Construction

The principal aim of this thesis is to develop heat controlled chamber to increase and decrease environmental temperature of plants for observing their behaviors by changing wavelength of light in visible spectrum. In this study, firstly constructed a PID controlled electrical heating system. Then walls of the chamber are constructed by polycarbonate plates to have rectangular prism shape. Inner side of the chamber has two shelves for plant growth observation according to use different type of spectrum of light. Chamber has closed wall structure which has air outlet and air inlet for fan to circulate the inner atmosphere to get fresh air. The design has two equally positioned shelves (carrier plates) where LED sources fixed above to them. Therefore, the distance

between each LED to shelves is equal to supply equal intensity to plants which are located on each shelf. The reason for creating such kind of construction is intensity or brightness of light as a function of the distance from the light source follows an inverse square relationship.

Inverse square relationship is configured in the picture below, which shows the apparent brightness of a source with luminosity L_0 at distances d , $2d$, $3d$, etc. Notice that as the distance increases, the light must spread out over a larger surface and the surface brightness decreases in accordance with a "one over r squared" relationship. The decrease goes as r squared because the area over which the light is spread is proportional to the distance squared.

Light is one of the basic elements of photosynthesis. Green plants, using the energy received from the sun rays with the help of chlorophyll in the leaves of the air CO_2 and the water brought to the leaves produce organic substances. This phenomenon is called photosynthesis. In other words, photosynthesis is the occurrence of carbohydrates by combining groundwater taken by roots with air taken from the air with the help of chlorophyll in the sun rays.

The rays that perform the phenomenon of photosynthesis are in visible beams whose wavelengths are between 400-760 nanometers. In a place of normal temperature and normal CO_2 conditions, photosynthesis increases in proportion to the intensity of light. (Beer and Levy 1983) However, the increase in photosynthesis continues until a certain light intensity, after then the photosynthesis does not increase even if the light increases; remains constant.

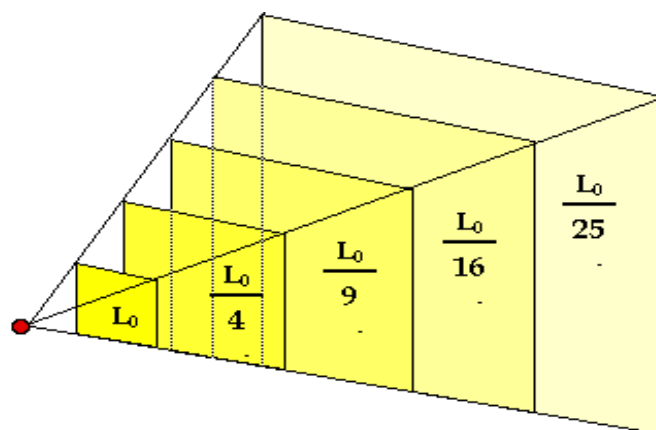


Figure 1.9. Luminosity Changes Related with Distance

(Source: Smale, 2016)

These light intensity limit values vary according to plant species. One of the important relationships between light and plant growth is that some plants want to have full sunlight but some grow better under the shade. The compensation point of light for some plants is 4200 lux, and the shade plants are 27 lux. (Lundegårdh 1957)

We need to create equal light intensity values for each shelves and homogeneous light distribution. Each plant that is growing on the shelves should get equal value of light. For this aim we designed and used different shaped reflectors around the LEDs for each shelves.



CHAPTER 2

METHODS

2.1. Mechanical Design and Construction

Mechanical construction of the system is mainly built by polycarbonate material which is very similar to construction of mini size refrigerator. There are two shelves where we are able to locate plant which we want to observe its growth. Upper shelf has white plastic film which doesn't allow light rays that are emitted by upper LEDs. On the bottom of the chamber there is a heating resistance placed. A fan is also located on the bottom of the chamber. We have opened some circular holes on polycarbonate wall for air inlet and outlet which is suitable for electrical fan. Polycarbonate material is used for forming walls of the chamber which are screwed to four wood poles located on corner of chamber.

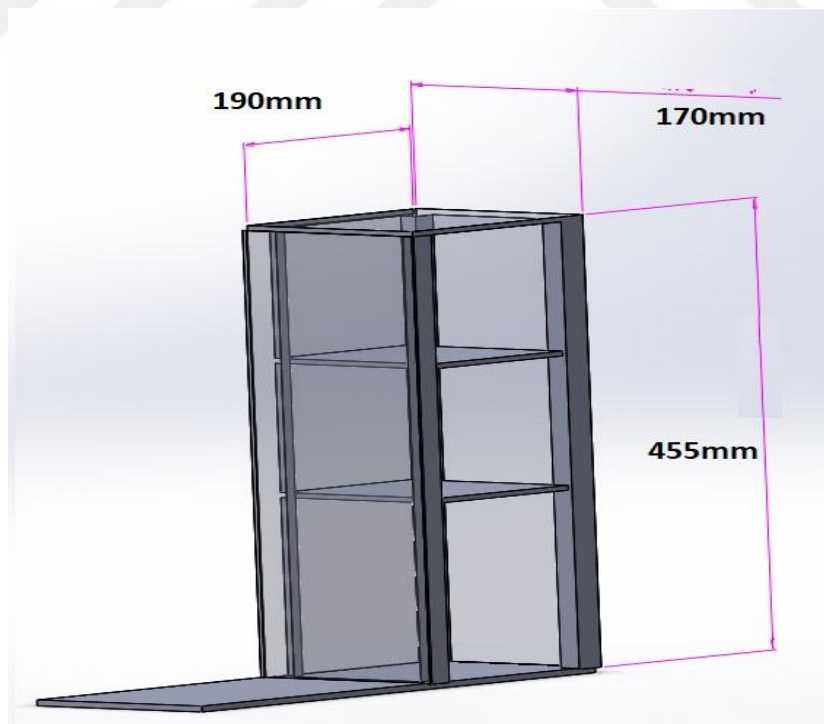


Figure 2.1. Dimensions of the Chamber

Also, there is another circular hole for thermocouple to fix it. Position of thermocouple is close to center of chamber and electrical heating resistance. We used Nichrome alloy type resistance to create heat inside of the chamber. Moreover, we cover the wire resistances with aluminum sigma profiles that are used for conduct the heat to inner atmosphere of chamber. We have design 3D drawings of the system by using SolidWorks CAD software.

Figure 2.4 shows the electrical connections between the PID controller (9), resistance (11), fan (10) and power supply (8). We have 220V alternative current from the mains electricity. Our power supply (8) have 220V AC input (8b) and 12V DC output. PID controller is connected to resistance (11) and thermocouple (7). By PID controller we are able to keep temperature at a constant level inside of the chamber.

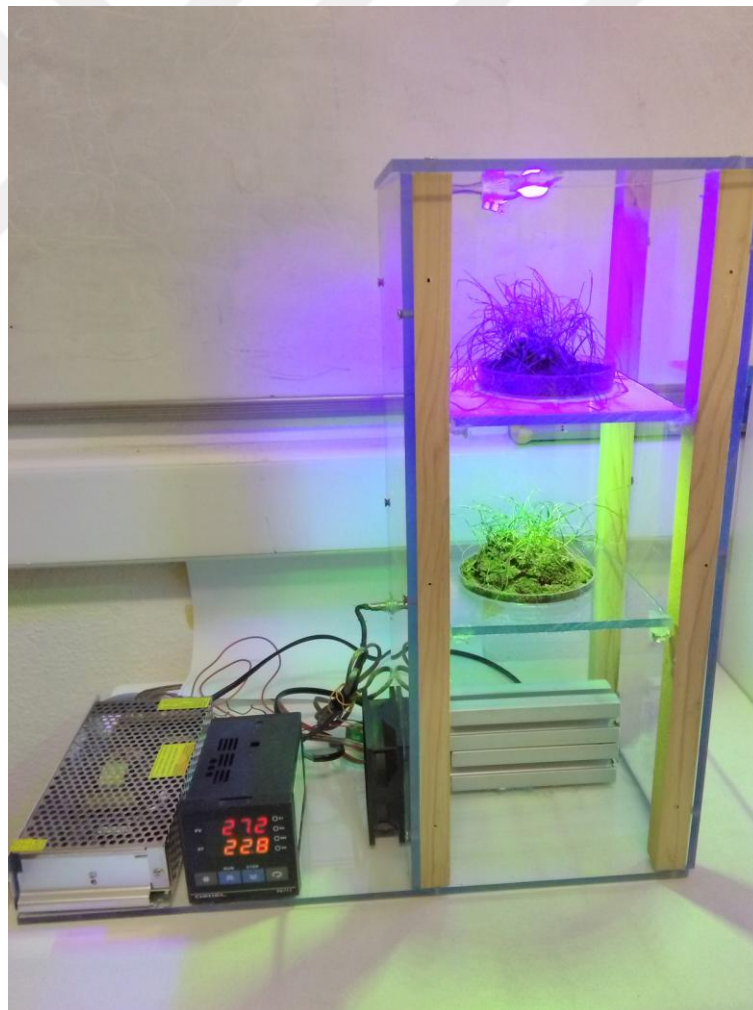


Figure 2.2. Prototype of the System

Below there is a simple demonstration at Picture 2.3. for chamber's subparts and elements. Number (1) shows the whole system. Four pieces wood poles (2) supporting the construction. Polycarbonate transparent walls (3) are covering whole body and making possible to observe inside of chamber. There is same size upper (5a) and bottom (5b) shelves are located inside of the chamber.

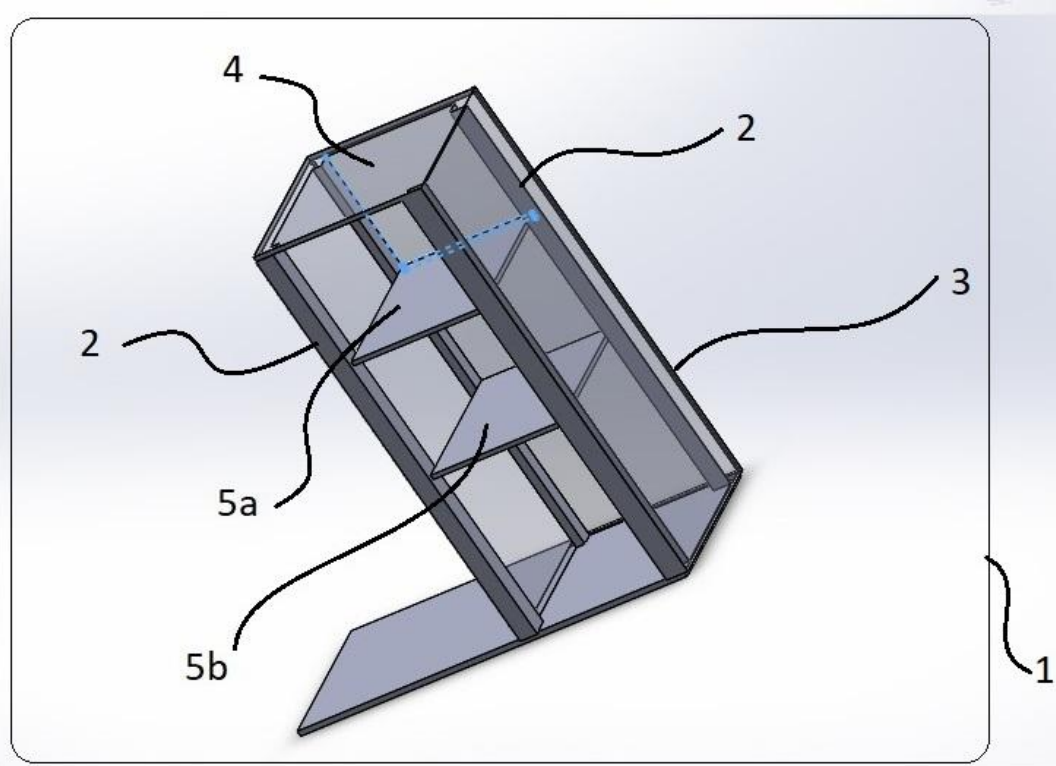


Figure 2.3. Main Construction of System

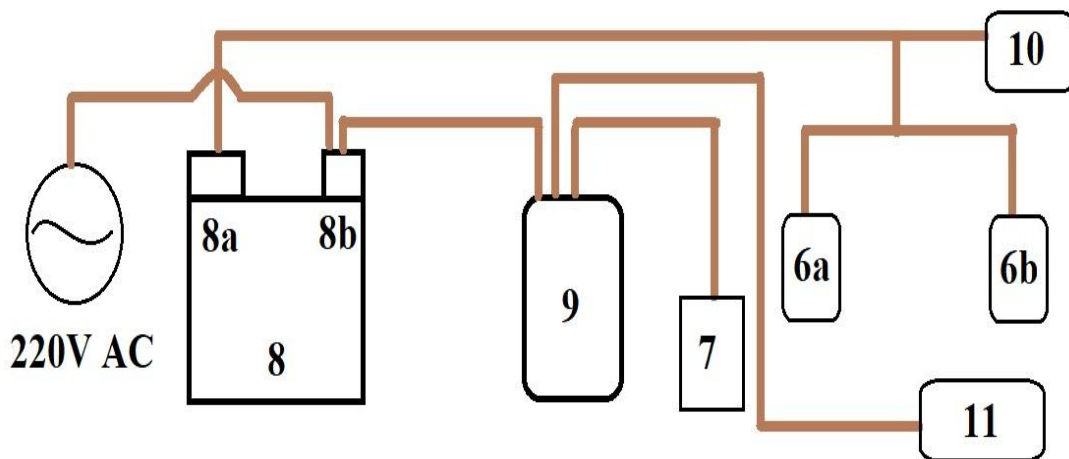


Figure 2.4. Electrical Connections of System

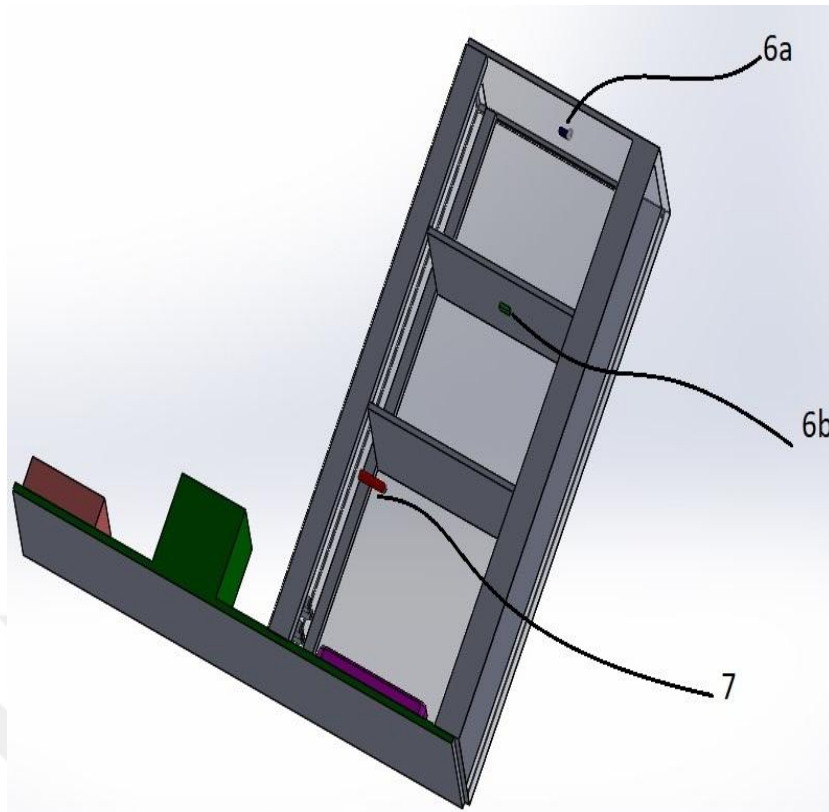


Figure 2.5. Temperature Sensors and Light Emitters

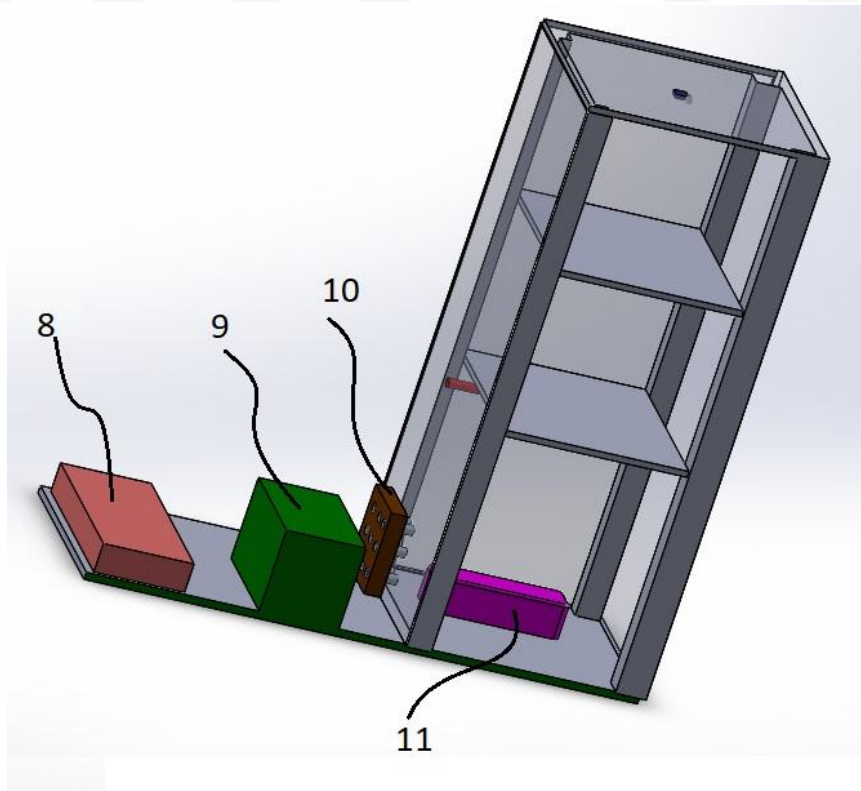


Figure 2.6. Electrical and Electronic Parts

Above, figure 2.5. shows K-type thermocouple(7) which is sending temperature data to PID controller(9). Also, there are two Osram Topled LA T676 model LEDs are located upper side of each shelf. Each LED(6a,6b) has equal distance to its target area to works at different spectrum range. That makes possible for us to compare the plant growth rate with different light spectrum range at curtain controlled environment. Figure 2.6. shows 220V AC and 12V DC power supply(8) which is compensated electrical energy needs of Ordell brand PC771 model PID Controller(9) and electrical fan(10) for ventilation.

2.2. Heating and Temperature Control System

In our system, heating system allows controls the temperature of inner environment of the chamber. Electrical heating resistance system requires a flat one side white painted glass surface with an integrated resistive heating element, a high current power supply and PID controller to control the current supplied to resistance to maintain the desired temperature. Temperature control units commonly use relays which open and close depending on the plate temperature. Relays generally result in considerable temperature overshoot/undershoot because the current is either completely on when the relay is closed or completely off when it is open. The high current relays also tend to be expensive. Also, we used K type thermocouple to measure environmental temperature inside of the chamber.

Continuous control types enable control by generating a signal to the output according to the error difference via feedback. If we look at the expansion of PID;

▶ P (Proportional)

▶ I (Integral)

▶ D (Derivative)

These continuous inspection types consist of P controller, I controller, D controller, and several of these controls consist of PID controller supervision bodies.

PID controllers are a form of control commonly used in industrial control systems. Its structure is very simple; it is very preferred because of the low number of variables to be set and the ease of physical implementation. As mentioned above, the

PID control method includes three separate parameters. P (proportional), I (integral) and D (derivative) parameters are available. (Ang, Chong, and Li 2005)

We used Nichrome heating elements which are made of a non-magnetic alloy composed primarily of nickel, chromium, and iron. Nichrome is characterized by its high resistivity and good oxidation resistance. Most of nichrome heating element producers use numbers as example Nichrome 20 or Nichrome 40. The reason is Nichrome 40 has 40% of Nickel in its composition. Ohmic resistance of our Nichrome 40 heating element is $5k\Omega$. We are supplying 220V AC voltage on the heating element which creates power of 9.68Watt.

A PID controller outputs feedback from the output and compares the signal with the input signal. Based on this error, the PID controller performs an effect by minimizing the error and sends it to the output. In this way, errors are determined with continuous feedback from the output to the input until the error is minimized and the error is reduced by sending the controller effect to the output. PID controllers can be applied to linear systems more easily. The system makes it easier to have a single feedback loop. (Bonivento, Castaldi, and Mirotta 2001)

To summarize the duty in our chamber of the PID controller again; the signal from the output through the input signal to the input signal (reference) compares with the input signal and the difference creates the error. This error is sent to the PID controller and the controller will multiply this signal with a coefficient and take its derivative and integral. Then it is sent to the exit again. In this way, the process continues until the error is minimized in a loop.

In other words, the smallest error at the output of the system should be at least in time and at least oscillating. (Khare and Singh 2010)

2.3. Building LED Lighting System

An artificial light source fed by electrical energy was used to support the growth of the plant by emitting an ideal light for photosynthesis. LED light sources are used to provide the necessary growth instead of sunlight. For example, in the winter months

when sunlight is insufficient for plant growth, artificial light sources are used to extend the time for the plants to continue their photosynthesis. If plants do not receive the desired level of light, they cannot grow healthy.

An artificial light source has been used to provide a light spectrum similar to sunlight. The choice of specific regions of the visible spectrum should be determined according to the type of plant grown, the growing stage and the light yield and color temperature depending on the amount of light needed by the plants.

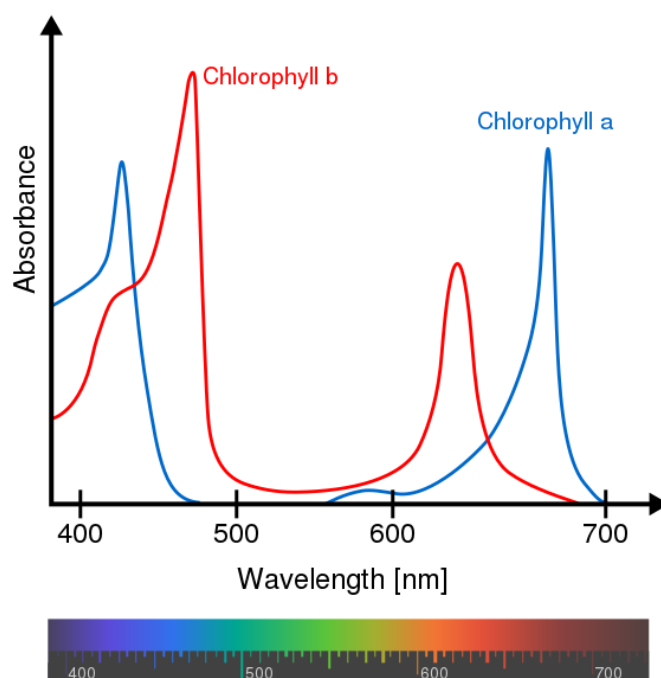


Figure 2.7. Absorbance Spectra of Free Chlorophyll

(Source: Pugliesi 2018)

Above in the graph; action spectra of chlorophyll molecules are slightly modified in vivo depending on specific pigment-protein interactions. Luminous intensity is the number of photons emitted by a source per unit time. The unit is candela (cd). The number of photons emitted by the source depends on the power of the light source. As the power of the light source increases, the number of photons it emits increases. Light intensity only depends on the characteristics of the source.

Luminous flux is the number of photons that hit a surface. The unit is lumen (lm). If the number of photons that come from source per second is 100, these 100 photons will be distributed to the target surface. Even if the radius of the sphere is increased, there is no change in the total number of photons that hit the inner surface of the sphere. If you think a source is attached to a small room, the total number of photons that hit the surfaces of the room will be as high as the number of photons that the lamp produces in one second.

If the same light source is installed in a larger chamber, the surface area of the chamber will be increased, but the number of photons that hit the surface of the chamber will be as much as the lamp produces. Therefore, the luminous flux will not depend on the size of the surface or the distance of the surface from the source.

We have used TracePro optical design software to trace rays and simulate light distribution on each shelf where plants are located. TracePro is one of the most effective illumination system design software in market. Below Figure 2.8 shows ray tracing simulation of rays that are emitted by LED light source which is positioned on top of the each shelf. Below Figure 2.9 shows total luminance map for incident flux on each shelf inside of the chamber.

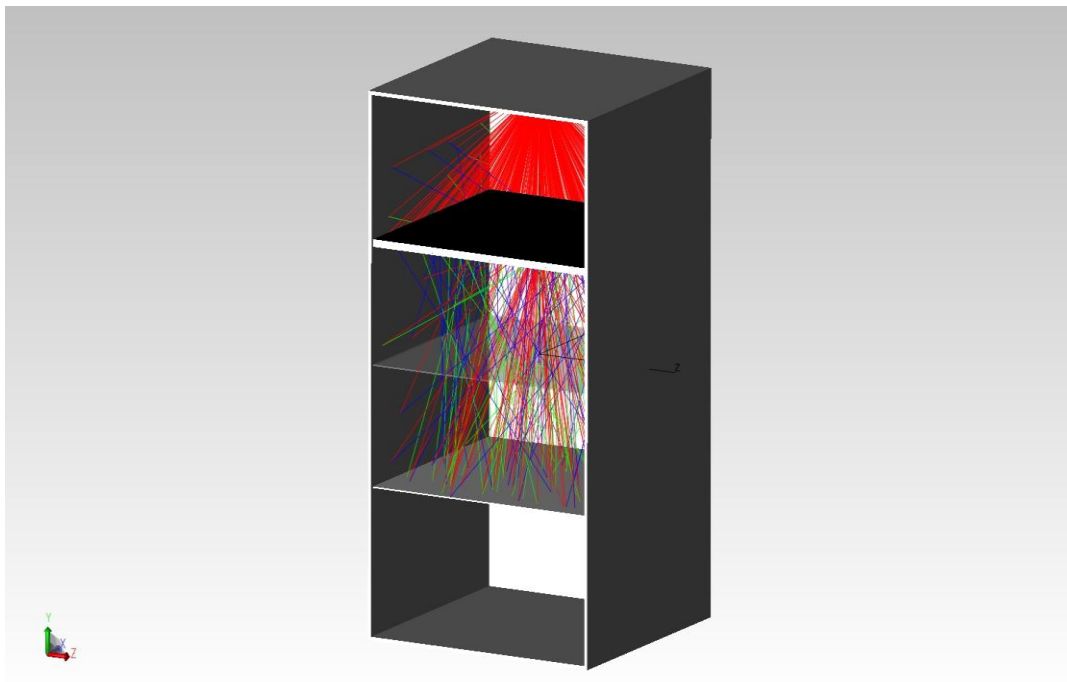


Figure 2.8. Ray Tracing Simulation by TracePro Software

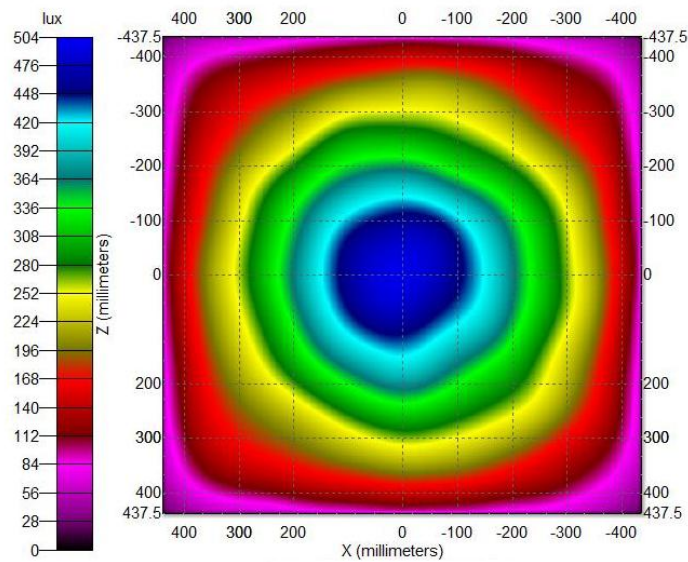


Figure 2.9. Light Distribution Simulation Example by TracePro Software

We have used OSRAM LT 696 model LED source to create light distribution simulation for shelves where plants grow. We tried to find out how we can send as much as possible more photons we can send to plants. Because we use electricity for LEDs and electricity is one of the most expensive costs of indoor plant production.

Therefore, we tried some combination to have more effective use of light rays. Firstly, we tried LEDs without using any additional system to collimate rays. Then we tried to design a reflector, lens and reflector diffuser combination which assists the light rays to be directed to the target shelves surfaces.

2.4. Air Circulation Design

It is very important for plants to have fresh air inside the chamber that they are living in. Air circulation plays a critical role in the perfect indoor environment for indoor farming. Fresh air circulation prevents it and in addition, produces stronger stems to ensure a better harvest. Green plants need constant inlet and outlet of fresh air and CO₂ to maintain its growth. Normal fresh air has CO₂ at the rate of around 330 parts per million (ppm). Especially for indoor farming systems, it is necessary to control the air flow to minimize common issues that affect the harvest. (Rogers, Heck, and Heagle 1983)

We built the power supply and air inlet-outlet. Power supply system is able to give regulated electrical energy for light sources, heating resistances and electronic circuits. Gas inlet and outlet valves are located sidewise of the chamber.

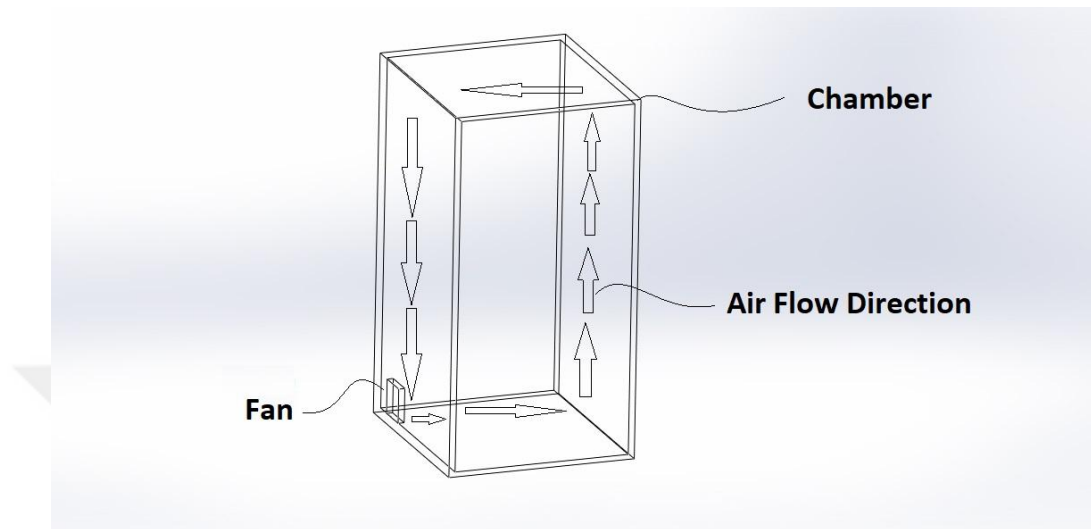


Figure 2.10. Air Flow Direction Inside of the Chamber

In front of the air inlet-outlet on the polycarbonate wall, there is a 12V DC powered electrical fan located. The fan supply fresh air for inner part of the chamber. There are also air circulation spaces on each side of bottom and up shelves.

CHAPTER 3

RESULTS AND DISCUSSION

3.1. Chamber Heating Quality Test

In this study, we used electronic PID controller to have stable and optimum environmental level of temperature. Therefore it is critical to have optimum environmental temperature for better plant growth rate. To verify homogenous temperature distribution in chamber, we used another mobile K-type thermocouple which is located different positions of inner surface of chamber according to test process.



Figure 3.1. Thermocouple Connected Electronic Multimeter

Initially, we need to verify the permanent thermocouple that works well or need calibration. Therefore we located the thermocouple at exactly the same level of permanent thermocouple. Temperature output difference between permanent thermocouple and mobile test thermocouple is nearly 0.1°C degree. It means permanent thermocouple measures the temperature level correctly and calibrated.

One of the difficulties to create homogenous temperature distribution inside of the chamber is warm air goes higher and cold air goes down because it is heavier than warm air. To test homogenous temperature distribution in chamber, we located mobile thermocouple with different height levels inside of the chamber. The temperature difference between the lowest level and highest level is 0.3 °C degree.

3.2. Results of Simulations

As an alternative form of traditional agricultural production, indoor agriculture systems will play an important role in the agricultural policies of the future. It is expected that indoor agriculture systems will have a significant role in urban life in the future. It is very important to locate LED light sources inside of the chamber to get homogenized distributed light on plants. Experiments on each plant and for each plant different spectral wavelength are still continuing to choose better growth rate.

Our aim is to build a system to find out better growth rate for each plant by changing spectra of light and light distribution. To have homogeneous light distribution is important for plants which are growing on the shelves of the system.

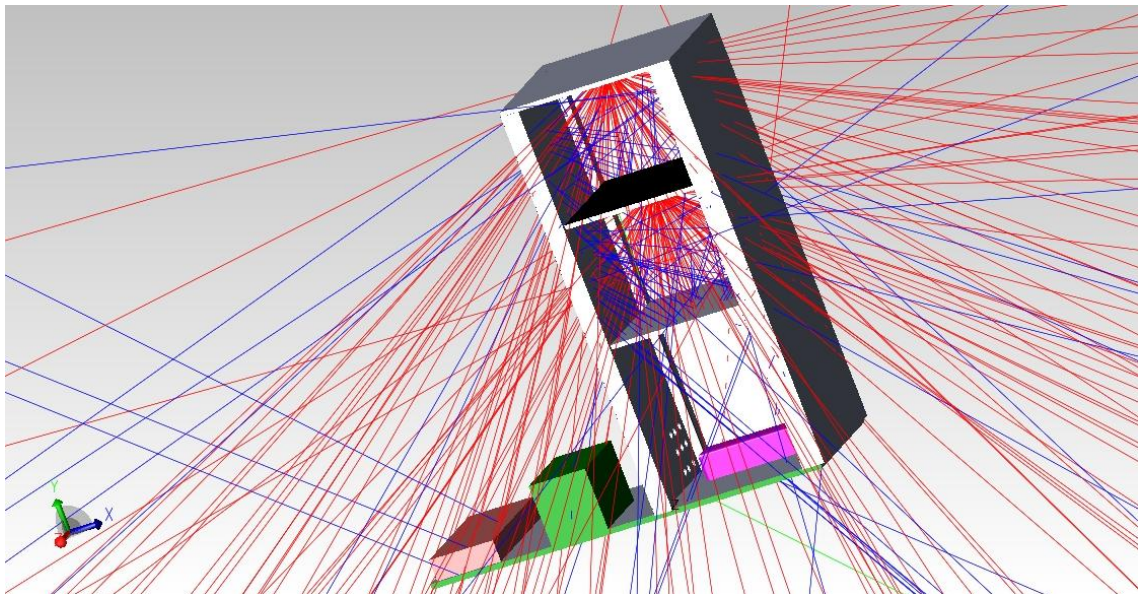


Figure 3.2. TracePro Ray Tracing Simulation with OSRAM LED for Each Shelf

As it is shown above, rays that are coming from LEDs not mainly focused to target surface. Most of the rays go out of the chamber by passing toward the

polycarbonate walls. We should keep light ray inside of the chamber for plant to have better growth rates.

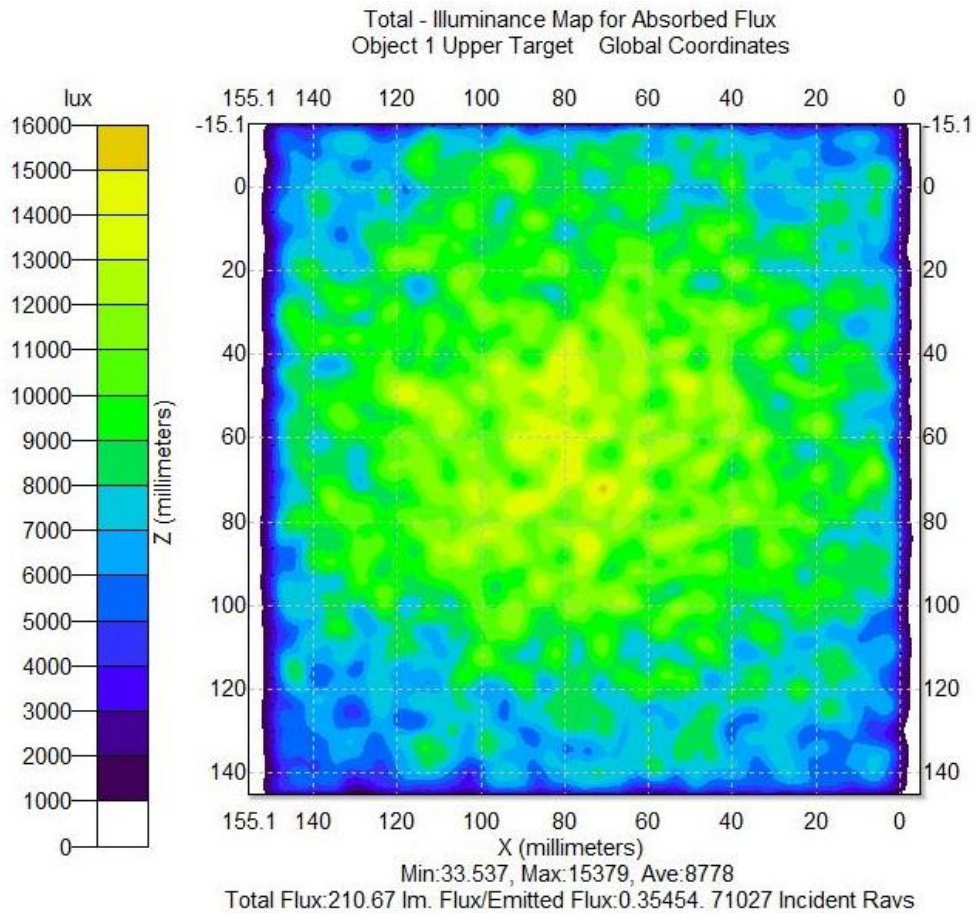


Figure 3.3. Light Distribution Simulation on Upper Shelf Surface with OSRAM LED

According to light distribution map, there is too much difference on lux values between center of target surface and corners of target surface. On the center of the target we are able to observe 12000 lux as average but at corners, it is around 2000 lux. It means 6 times less amount of light on the corners. Also, only %35 of total rays are hitting to target surface and rest of %65 are hitting out of shelf surface. It is not working energy efficient.

The graph below gives an idea that we have better homogenously distributed light at central area but for corners, the lux values go down very rapidly. According to these result, we need an additional optical component which creates more focused light beam for upper and bottom shelf's surface.

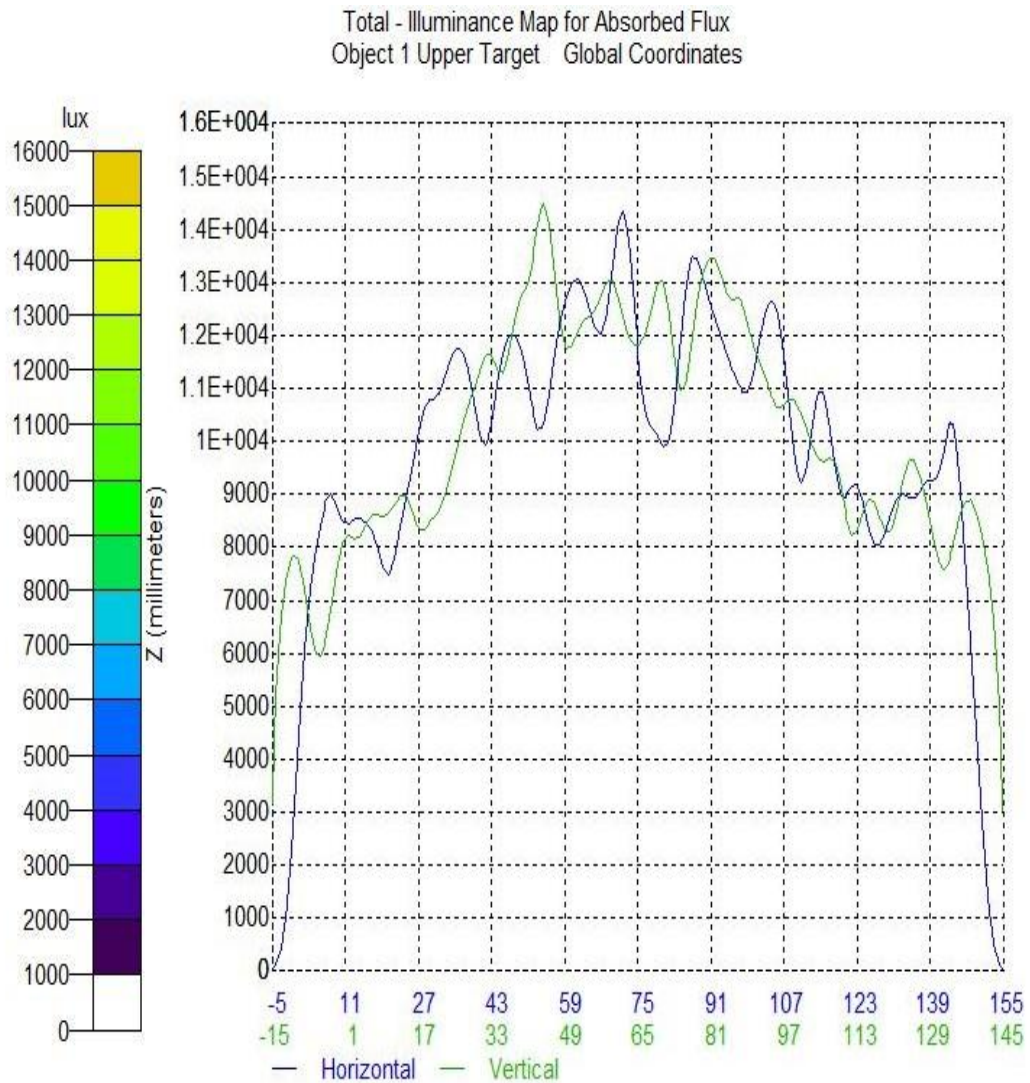


Figure 3.4. Light Distribution Graph on Upper Shelf Target Surface with OSRAM LED

After these results, we decided to design a simple reflector in TracePro software. Design includes circular shaped and inner surfaces of reflector which is covered by 99% reflective material. Reflector has bottom circular LED entrance with diameter of 16mm. Also, reflector has 28mm height and 20.12mm upper radius.

As easily observed from Figure 3.6 ray tracing simulation upper shelf has more collimated light beam by the help of the reflector compare to bottom shelf which reflector is not positioned around of the LED. Because reflector has aluminum coated reflected surface where rays are hitting that surface and then redirected to target surface that the plants are growing up.

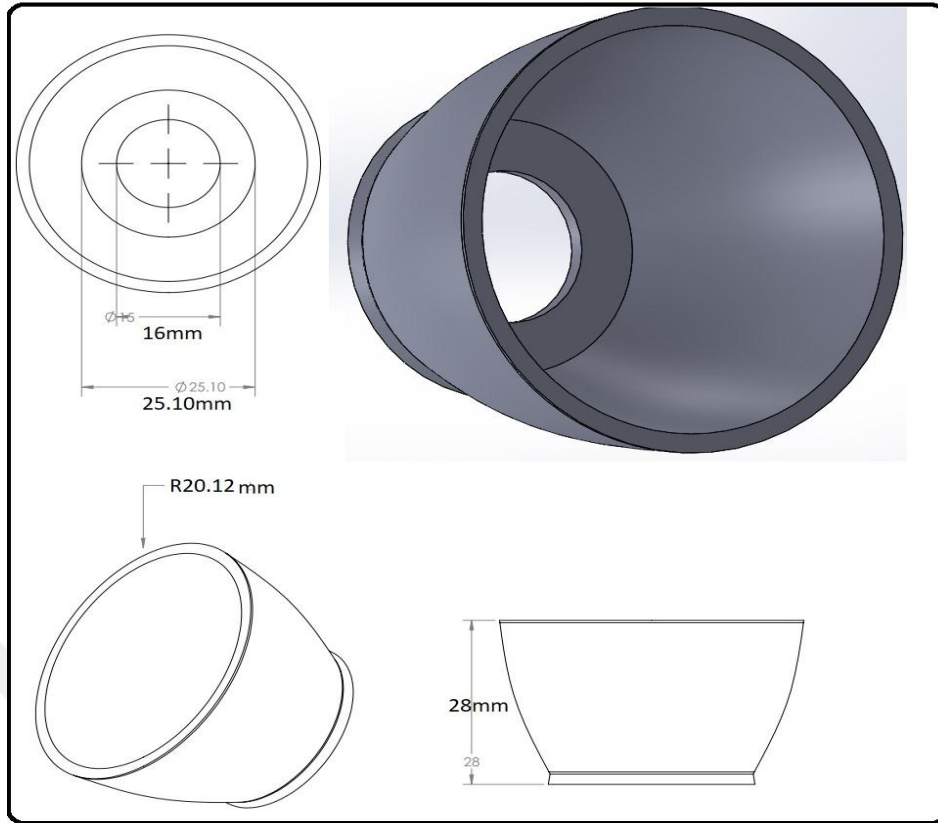


Figure 3.5. The Reflector Design for Collecting More Light to Target Surface

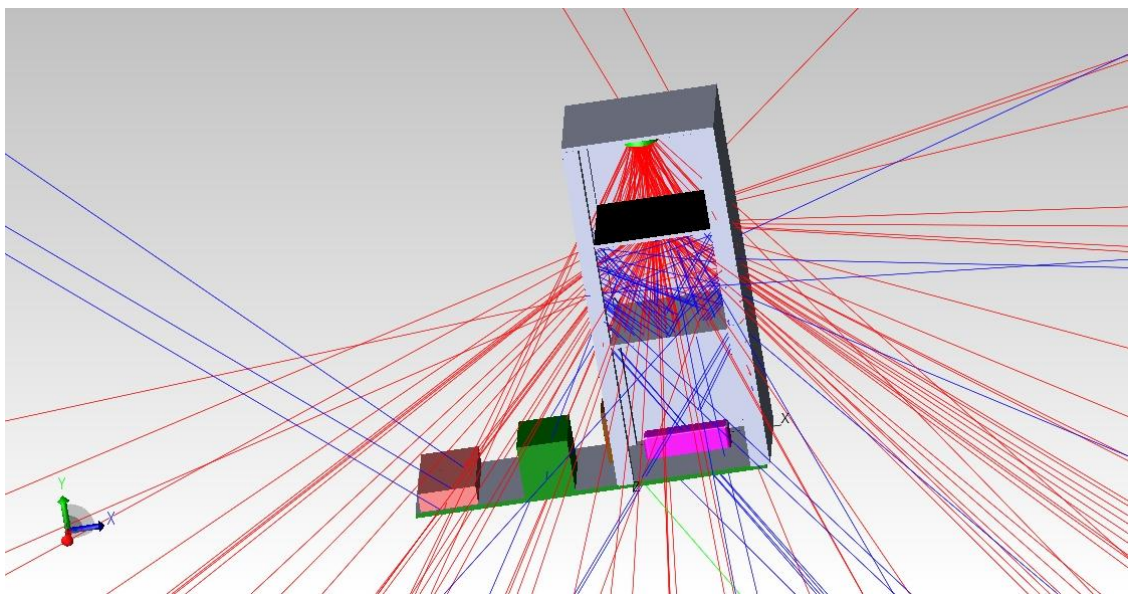


Figure 3.6. TracePro Ray Tracing Simulation with OSRAM LED and Reflector
Combination

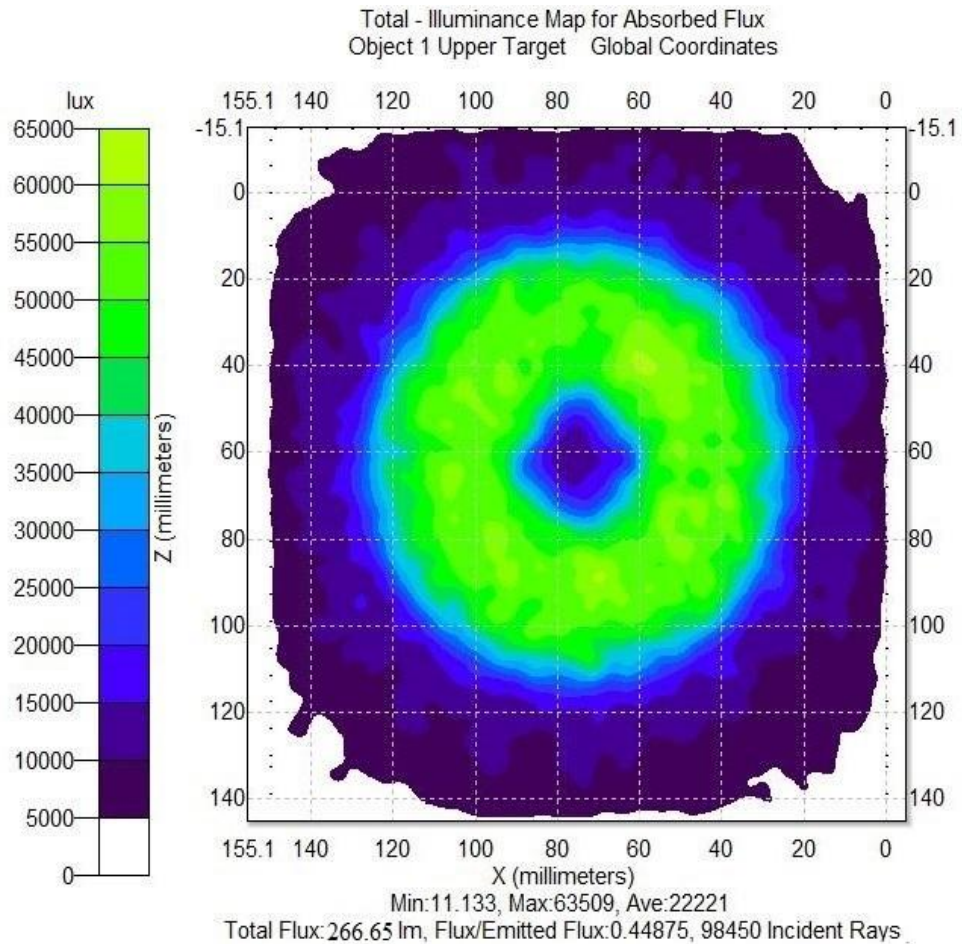


Figure 3.7. Light Distribution Simulation on Upper Shelf Target Surface with OSRAM LED and Reflector Combination

According to light distribution map of Figure 3.7. there is too much difference on lux values between center of target surface and corners of target surface. On the center of the target we are able to observe around 40000 lux but at corners, it goes down around 6500 lux. It means 6 times less amount of light on the corners. Also, only %44 of total rays are hitting to target surface and rest of %56 are hitting out of shelf surface.

Figure 3.8. gives an idea that we don't have better homogeneously distributed light nor at central area neither for corners the lux values go down very rapidly. Additionally, at the center of target there is an area where light distribution values are lower than its rounded area. According to these result, we need to design additional optical component which creates more focused and homogeneously distributed light beam for upper and bottom shelf's surface.

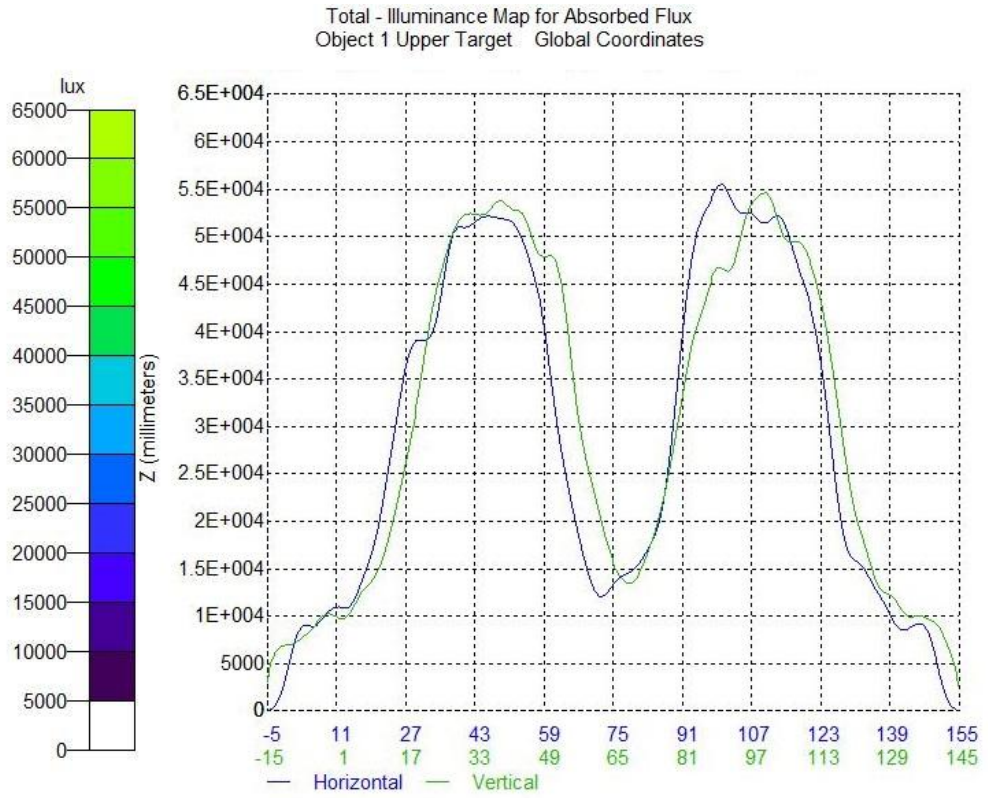


Figure 3.8. Light Distribution Graph on Upper Shelf Target Surface with OSRAM LED and Reflector Combination

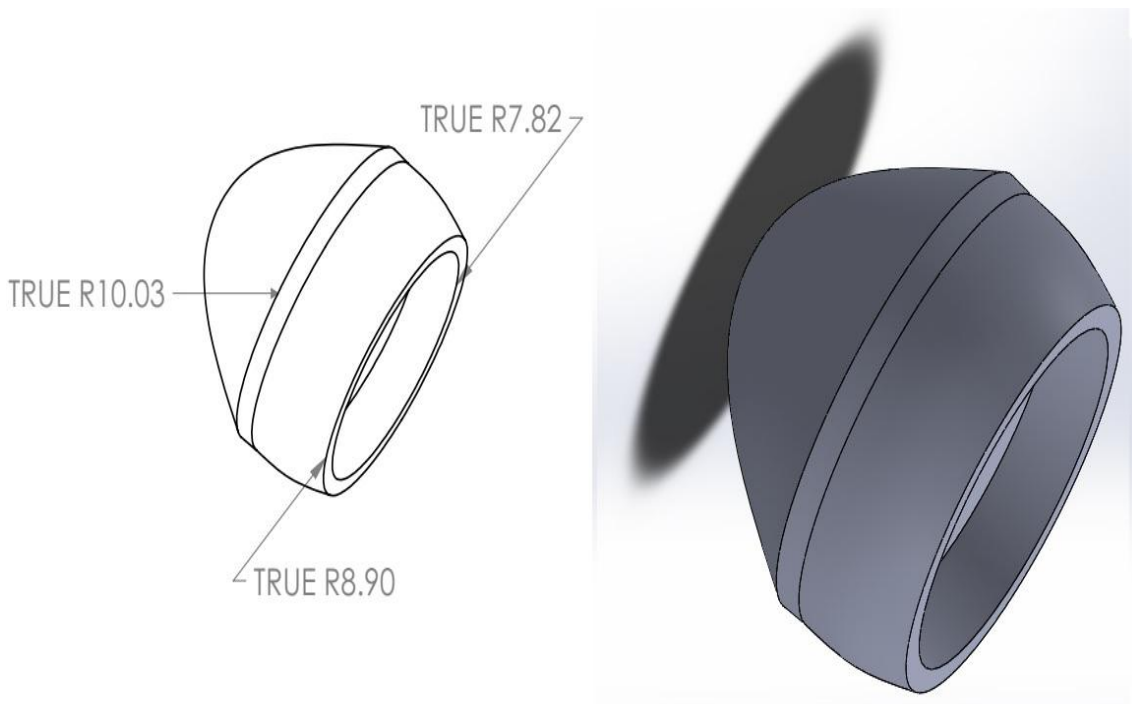


Figure 3.9. The Lens Design for Collecting More Light to Target Surface

After LED and reflector combination results, we decided to design additional simple lens in TracePro software. Design includes circular shaped and made by PMMA which has transmittance of light around 94%. Lens has bottom circular LED entrance with radius of 7.82mm. Also, lens has 10.03mm maximum radius.

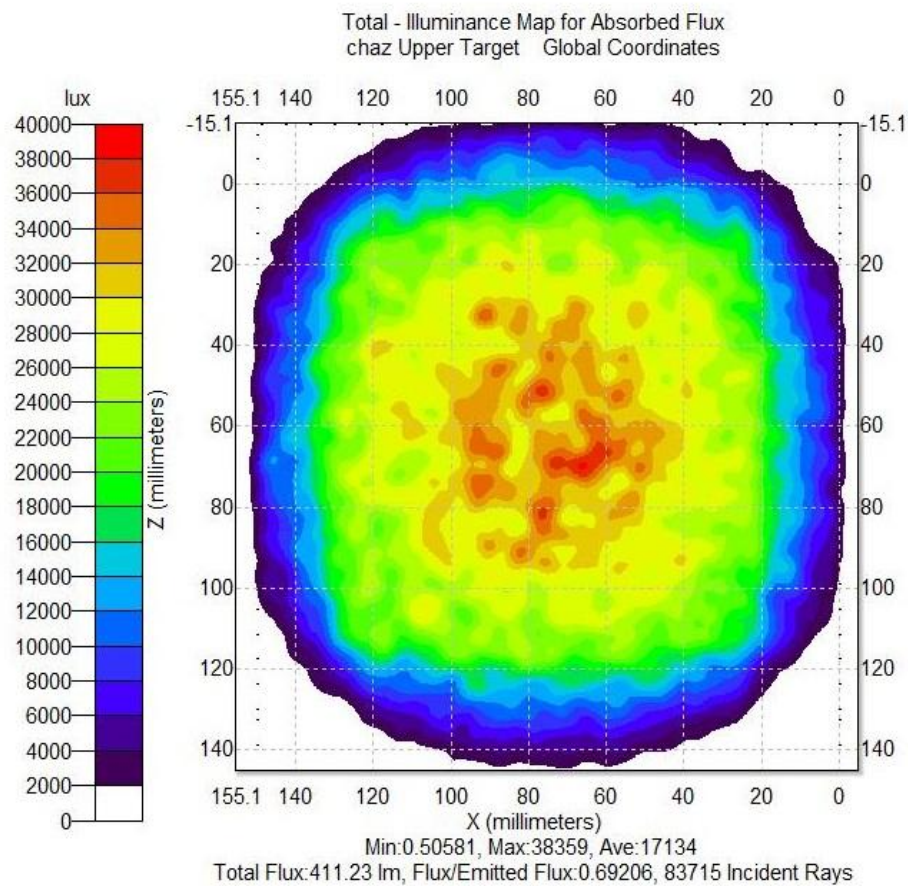


Figure 3.10. Light Distribution Simulation on Upper Shelf Target Surface with OSRAM LED and Lens Combination

According to light distribution map of Figure 3.10, there is not too much difference on lux values between center of target surface and around of the target surface. At the center of the target, we are able to observe around 40000 lux. It is decreasing to around 4000 lux when we look at close to target borders. For 120mm x 120mm central area of the target surface, we have max 40000lux and minimum 15000lux. It means there is not too much luminous intensity difference at that region. Also, %70 of total rays is hitting to target surface and only the rest of %30 are hitting out of shelf surface.

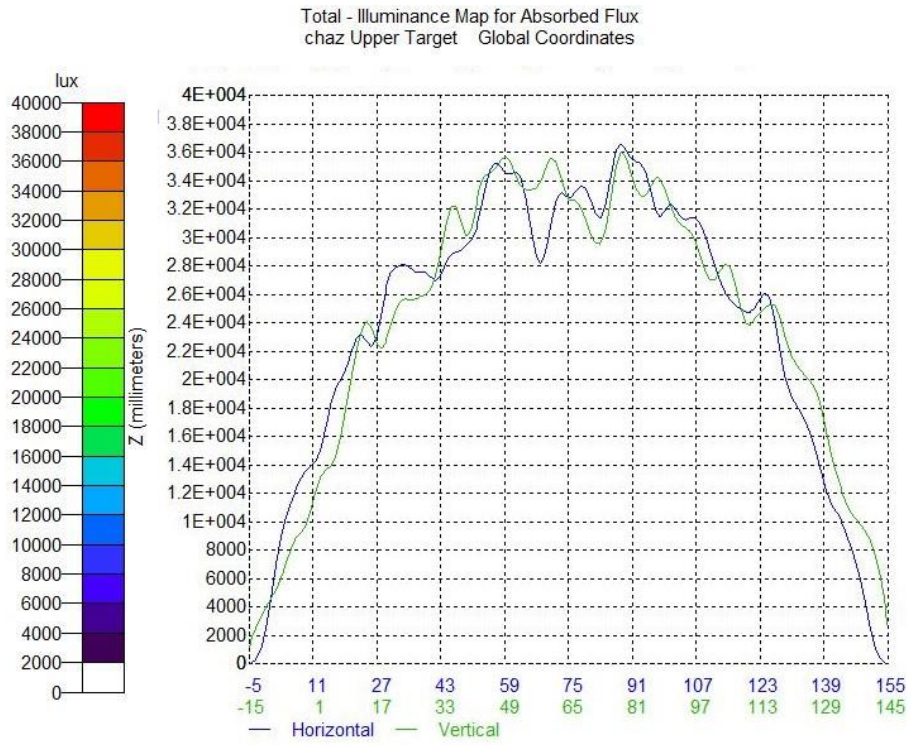


Figure 3.11. Light Distribution Graph on Upper Shelf Target Surface with OSRAM LED and Lens Combination

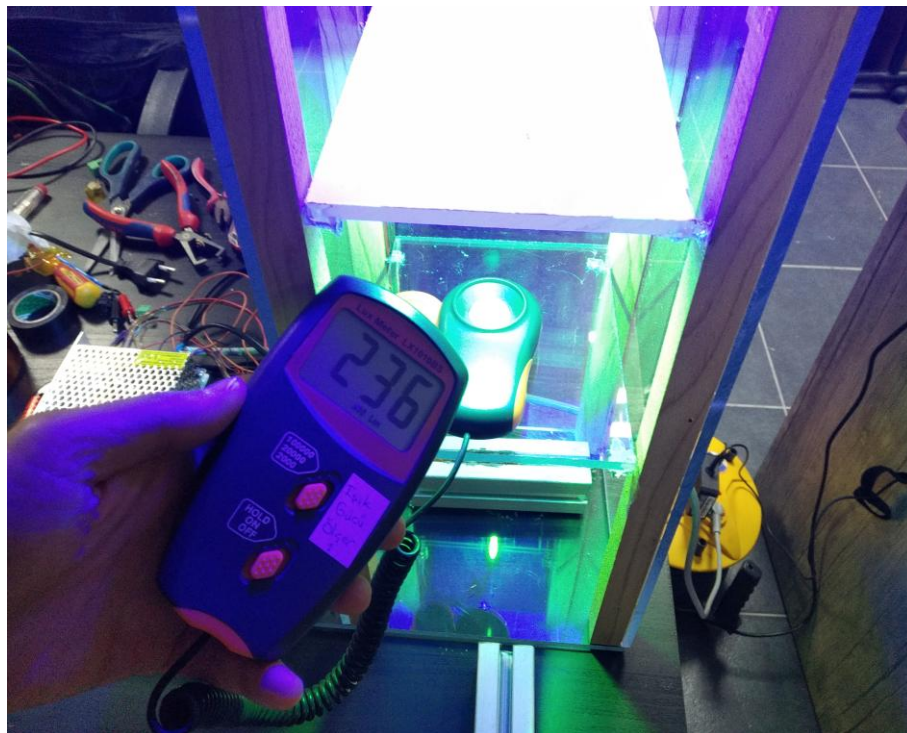


Figure 3.12. Luminous Intensity Measurement at the Bottom Shelf Target

The map and graph shown at figures 3.10 and 3.11 give an idea that we have better homogenously distributed light on target compared to LED-Reflector combination. Additionally, at the center of target area, there is an area where light distribution is less than its rounded area.

We have used simple light meter for measuring illuminance with the help of a lux meter modeled LX1010BS. LX1010BS is designed to measure light intensity in industries, workshops, high schools, and photographic studios. LX1010BS Illuminometer can be used for high power lights, such as sunlight, headlights and streetlamps. LX1010BS has a special sensitivity for the certification and approval application, such as the measurement of emergency lighting. The current measurement value should be set with the Hold key on measurement tool. For both shelves, we have made measurements. At the bottom shelf, we have read the luminous intensity value of 2360lux. It is shown in Figure 3.12. At the upper shelf, we have read the luminous intensity value of 2370lux. It is shown in Figure 3.13.

To equalize the value of luminous intensity on each shelf we changed the level of screws which are holding the bottom shelf. After fixing the bottom shelf with newly positioned screws, we made new measurement with Lux meter. According to new positions, each of the shelves has luminous intensity value of 2360lux.

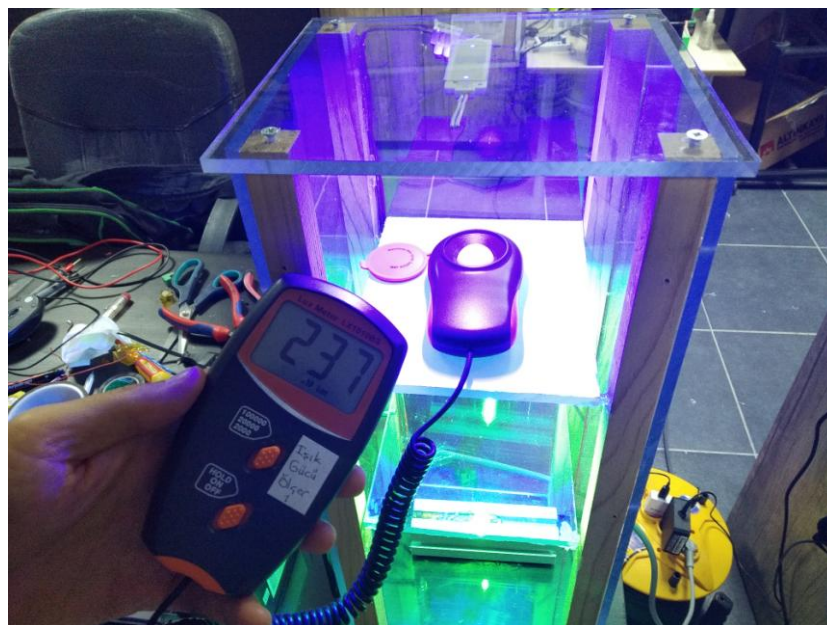


Figure 3.13. Luminous Intensity Measurement at Upper Shelf Target

3.3. Analysis of Simulations

For artificial lighted indoor farming system is critical to have homogenous temperature distribution and optimum temperature level for each specific plant type. Also, LED light sources that we used in the chamber shelves should be positioned downwards to give homogeneously distributed light for plants. According to simulation results, we should not use LED light sources solitarily to have better yield of energy. Because after making a simple comparison with LED-reflector and LED-lens combination, we have better focusing of light beam to target.

Table 3.1 Percentage Comparison of Targeted Rays

Combination	Only LED	LED - Reflector	LED - Lens
Percentage of Targeted Rays	35	44	70
Percentage of Non-Targeted Rays	65	56	30

According to our simulation results, it is better to use LED-lens combination for artificial lighted plant growth systems. By using lens design, we have increased the percentage of targeted ray from %35 to %70. We made it doubled. It is possible to optimize the lens geometry by using free-form optimization tools to have rectangular shaped illumination map on target surfaces.

CHAPTER 4

CONCLUSION

People will prefer to grow their own plants and foods at home at near future probably in next 30 years. Many people will use these indoor plant growth systems somehow at home like refrigerator or microwave heaters. Newly designed indoor agricultural system will be an integral part of our home. These systems will not be affected by climate changes, less rain or thunders which affect traditional land farming related to this risk indoor farming systems with artificial lighting will be more inside in our routine life in near future. According to our study, we tried to developed micro scaled laboratory size indoor farming test system which allows researchers to grow plants with different wavelength of light and observe the effects on plants. In our study we gave importance for creating homogeneous temperature distribution inside of the chamber by using fan, thermocouple and heat conductive aluminum metal profiles. Also, another important criterion for developing such system is using light sources more efficiently. We increased light efficiency two times by designing and using optical component like reflector and lenses. Using light rays efficiently can directly decrease electric consumption which is one of the biggest costs to run indoor farming system. Future aspects of the system is developing the another optical apparatus which allow us to use %100 of photons which can be directed to the plants. It can be possible by optimization of our lens design and combination of LED-reflector-lens addition to mechanically downwards and upwards moving shelves which are able to change distance between plants and light sources.

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