11-2018

Growth And Development of Lettuce (Lactuca sativa L.) In A Hydroponic System with Different Lighting Sources

Ghada Mohammed Ali Hamuda

UAEU

جامعة الإمارات العربية المتحدة
United Arab Emirates University

United Arab Emirates University

College of Food and Agriculture

Department of Aridland Agriculture

GROWTH AND DEVELOPMENT OF LETTUCE *(Lactuca sativa L.)* IN A HYDROPONIC SYSTEM WITH DIFFERENT LIGHTING SOURCES

Ghada Mohammed Ali Hamuda

This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Science in Horticultural

Under the Supervision of Dr. Moustafa Amin Fadel

November 2018

Declaration of Original Work

I, Ghada Mohammed Ali Hamuda, the undersigned, a graduate student at the United Arab Emirates University (UAEU), and the author of this thesis entitled "*Growth and Development of Lettuce (Lactuca sativa L.) in a Hydroponic System with Different Lighting Sources*", hereby, solemnly declare that this thesis is my own original research work that has been done and prepared by me under the supervision of Dr. Moustafa Amin Fadel, in the College of Food and Agriculture at UAEU. This work has not previously been presented or published, or formed the basis for the award of any academic degree, diploma or a similar title at this or any other university. Any materials borrowed from other sources (whether published or unpublished) and relied upon or included in my thesis have been properly cited and acknowledged in accordance with appropriate academic conventions. I further declare that there is no potential conflict of interest with respect to the research, data collection, authorship, presentation and/or publication of this thesis.

Student's Signature: ____________ Date: 5/12/2018

Advisory Committee

1) Advisor: Dr. Moustafa Amin Fadel

Title: Associate Professor

Department of Aridland Agriculture

College of Food and Agriculture

2) Co-advisor: Dr. Shyam S. Kurup

Title: Associate Professor

Department of Aridland Agriculture

College of Food and Agriculture

Approval of the Master Thesis

This Master Thesis is approved by the following Examining Committee Members:

1) Advisor (Committee Chair): Dr. Moustafa Amin Fadel
Title: Associate Professor
Department of Arid Land Agriculture
College of Food and Agriculture

Signature ____________________ Date 12-11.2018

2) Internal Examiner : Mohamed Abdul Mohsen Salem Al-Yafei
Title: Associate Professor
Department of Arid Land Agriculture
College of Food and Agriculture

Signature ____________________ Date 12. 11. 2018

3) External Examiner: Prof. Ali El-Keblawy
Department of Applied Biology,
Faculty of Science, Sharjah University

Signature ____________________ Date 15/11/2.18

This Master Thesis is accepted by:

Dean of the College of Food and Agricultre: Professor Bhanu Chowdhary

Signature Bhanu P. Chowdhary Date 11/12/2018

Acting Dean of the College of Graduate Studies: Professor Ali Al-Marzouqi

Signature Ali Hassan Date 17/12/2018

Copy 5 of 6

Advisory Committee

1) Advisor: Dr. Moustafa Amin Fadel

Title: Associate Professor

Department of Aridland Agriculture

College of Food and Agriculture

2) Co-advisor: Dr. Shyam S. Kurup

Title: Associate Professor

Department of Aridland Agriculture

College of Food and Agriculture

Abstract

The goal of this study was to investigate the influences of different light systems, on growth parameters (fresh and dry weight, height and width, number of leaves and leaf area) and accumulation of chlorophylls and carotenoids of the lettuce. The marketable sensory characteristics (shape, and color) of fresh plants were also evaluated.

(*Lactuca sativa crispa. "Lollo bionda"*) lettuce were cultured in three levels of vertical hydroponically for 45 days under different light sources of natural light in the upper level, 60% shade light in the middle level and red (R), green (G) blue (B), provided by light-emitting diodes (LEDs) was 12/12 (day/night) in the lower level. Three levels of vertical hydroponics were also prepared in the same levels of three treatments, while were exposed to natural light as a control group.

For treatments, lettuces exposed to natural light, with high light intensity, showed the highest values in all growth parameters as well as pigments, while lettuce under the 60% shade, the result showed all pigments and growth parameters were low, except the length was similar to the length of the natural light treatment. As for the lettuce exposed to the (RGB) LED which recorded lowest light intensity, was a significantly lowest value at all growth parameters, while pigments not detectable.

As for the control group, all of which were exposed to natural light, where the light quality was equal, while the light intensity was decreased gradually from top to bottom. The values of the parameters were high at all levels. With noted that, the leaf area was the highest in the middle level, while the fresh and dry weight were highest at the upper level. As for the pigment values, where all were high and no significant difference.

Lettuce Plants under natural light looked large, vigorous, most compact morphology with dark green leaves, while those under 60% Shade and (RGB) LED treatments looked small, weak, sparse and fragile.

The overall results indicate that, all levels of treatments and control group obtained the same qualities of light in terms of spectra radiation, which the required for plant growth, but the different quantities of light spectra radiation were the main

parameter in the greenhouse in the experiment, which led to significantly different results.

These new strategy to exploit the quality and quantity of solar natural light in the vertical hydroponics system should be conveyed for vegetable production in UAE.

Keywords: Lollo bionda lettuce, natural light, 60% shade, (RGB) Light-emitting diode (LED), photosynthetically active radiation (PAR), vertical hydroponic system.

Title and Abstract (in Arabic)

نمو وتطور الخس (.Lactuca sativa L) في نظام مائي مع مصادر إضاءة مختلفة

الملخص

الهدف من هذه الدراسة هو التحقيق في تأثيرات أنظمة الضوء المختلفة، على معايير النمو (الوزن الطازج والجاف، الطول والعرض، عدد الأوراق ومنطقة الورقة) وتراكم الكلوروفيل والكاروتينات في نبات الخس. كما تم تقييم الخصائص الحسية القابلة للتسويق (الشكل، واللون) للنباتات الطازجة.

تمت زراعة الخس نوع لاكتوكا ساتيفا كريسبا (لولو بيوندا) في الزراعة المائية الرأسية لمدة 45 يومًا تحت مصادر ضوء مختلفة، كان المستوى العلوي معرض للضوء الطبيعي،بينما المستوى المتوسط مغطى بشبك الضل بمعدل 60%، في حين المستوى السفلي كان مغلق بأحكام من جميع الجوانب و كان معرض للضوء الأحمر و الأخضر و الأزرق التي توفرها لوح من الثنائيات الباعثة للضوء (ليد) 12/12 (نهار / ليل). كما تم إعداد ثلاثة مستويات من الزراعة المائية العمودية كمجموعة تحكم، و كانت في نفس مستويات المعالجات الثلاث، و قد تم تعريضها للضوء الطبيعي.

بالنسبة للمعالجات، أظهرنبات الخس المعرض للضوء الطبيعي في المستوى العلوي، حيث كثافة الضوءعالية، أعلى القيم في جميع معلمات النمو وكذلك الأصباغ، في حين أن الخس تحت ظل 60% في المستوى المتوسط، أظهرت النتائج أن جميع معايير النمو كانت منخفضة كثيرآ باستثناء الطول كان قريباً من قيمة الطول للمعالجة بالضوء الطبيعي، كذلك قيم الصبغات كانت منخفضة. أما بالنسبة إلى الخس المعرض لـلوح الضوء الصناعي المستوى السفلي والذي سجل أدنى كثافة للضوء، فقد كانت قيم جميع معلمات النمو الآقل على الإطلاق. في حين لا توجد قيم لأصباغ الكلوروفيل و الكاروتينات.

أما مجموعة التحكم، فكانت جميعها معرضة للضوء الطبيعي، حيث كان نوع الطيف الضوئي متساوي، ولكن كثافة الضوء تنخفض تدريجيآ من الأعلى إلى الأسفل. و كانت النتيجة أن قيم معلمات النمو عالية في جميع المستويات، مع ملاحضة أن مساحة الورقة كانت أعلى بقليل في المستوى المتوسط، في حين أن قيم الوزن الطازج والجاف كانت مرتفعة في المستوى العلوي.

أما بالنسبة لقيم صبغات الكلوروفيل و الكاريتونيد فكانت عالية وتقريباً متساوية في مستويات التحكم.

كما أن نبات الخس تحت الضوء الطبيعي بدت مورفولوجيا كبيرة وزاهية مع الأوراق الخضراء الداكنة، في حين تلك التي تحت شبك الظل 60% و لوح الضوء الصناعي، بدت صغيرة وضعيفة وأوراقها متفرقة وهشة.

تشير النتائج الإجمالية إلى أن جميع مستويات المعالجات ومجموعة التحكم حصلت على نفس نوع الأطوال الموجية من حيث الإشعاع الطيفي، وهو المطلوب لنمو النبات. في حين كانت الكميات من إشعاع الضوء الطيفي مختلفة و كانت هيا المعلمة الرئيسية داخل الصوبة في التجربة التي أدت إلى نتائج مختلفة من حيث النمو وكمية الأصباغ في نبات الخس.

يجب نقل هذه الاستراتيجية الجديدة لاستغلال نوعية وكثافة الضوء الطبيعي الشمسي في نظام الزراعة المائية العمودي لإنتاج الخضار في الإمارات العربية المتحدة.

مفاهيم البحث الرئيسية: خس لولو بيوندا، ضوء طبيعي، شبك 60 %، الصمام الثنائي الباعث للضوء، الأشعاع النشط الضوئي (بار)، نظام الزراعة المائية العمودي.

Acknowledgements

I would like to express my deepest appreciation to Dr. Moustafa Fadel for been my supervisor and guide me during my research. Without his continual encouragement, guidance, valuable comments and support this dissertation would not has been possible. Likewise, I would like to express my special thanks and deepest appreciation to Dr. Shyam S. Kurup, Associate Professor, for his valuable critical suggestions and valuable comments on my work.

I also would like to express my sincere gratitude to the Dean Faculty of Food and Agriculture, to the staff members of the Lab of UAE University, and to the Manager, Engineers and workers of Al Foah Experimental Farm for providing me the precious opportunity to utilize the necessary research equipment and facilities to conduct my research experiments at Al Foah Experimental Farm.

I would like to say how grateful I am to my husband and my family for their continuous support, advice, and encouragement throughout my academic studies and research.

Dedication

To my beloved parents and family

Table of Contents

List of Tables

List of Figures

List of Abbreviations

B	Blue color
B	Boron
C1	Control upper level
C2	Control middle level
C3	Control lower level
Car	Carotenoid
Chl a	Chlorophyll a
Chl b	Chlorophyll b
Cl	Chlorine
Cm	Centimeter
Cm^2	Square centimeter
Cu	Copper
$CuSO_4$	Copper (II) sulfate
DW	Dry weight
FW	Fresh weight
G	Green color
H_3BO_3	Boric acid
K	Potassium
Kcl	Potassium chloride
KH_2PO_4	Monopotassium phosphate
KNO_3	Potassium nitrate
LAI	Leaf area index
LED	Light emitting diode
LUX	Lumen per square meter
Mg	Magnesium
µM	Micrometer
µmol	Micromole

mg	Milligram
$MgSO_4$	Magnesium sulfate
mM	Millimeter
Mn	Manganese
$MnCl_2$	Manganese (II) chloride
Mo	Molybdenum
mW	MilliWatt
N	Nitrogen
Na_2MoO_3	Sodium molybdate
Na_2SiO_3	Sodium silicate
NH_4NO_3	Ammonium nitrate
Ni	Nickel
$NiSO_4$	Nickel (II) sulfate
NL	Natural light
nm	Nanometer
P	Phosphorus
PAR	Photosynthetically active radiation
PFFD	Photosynthetic photon flux density
R	Red color
S	Sulphur
Si	Silicon
Zn	Zinc
$ZnSO_4$	Zinc sulfate

Chapter 1: Introduction

1.1 Overview

Light is an important factor in determining plant growth and development as light is necessary for photosynthesis. Light quality shows much more complex effects on plant morphology and physiology compared with light intensity and photoperiod (Chen et al., 2017). The intensity, quality and duration of light effect plant growth and development and spectral quality is an important factor enhancing the growth of the plant (Chung et al., 2010).

Because of the importance of light to the plant, many types of industrial light sources have been used to increase plant productivity and improve quality, such as fluorescent and others, while the best source of light was (light emitting diode) LED light, due to its many advantages. Compared to traditional light sources, LED lighting systems have many unique advantages, including the ability to control spectral composition, small mass and size, durability, long operating life, wavelength specificity, narrow band width, relatively cool and minimal heating, and photon output which is linear with current voltage.

From this point of view, we used LED light source with specific wavelengths to compare with natural light of the sun and natural light with 60% Shade and the effect of the three light sources mentioned above on the growth and development of lettuce *(Lactuca sativa. L).* Lettuce is a major crop grown in greenhouses around the world. Lettuce is used almost every year as there are a number of varieties that are successfully grown in early spring, during summer and winter. There are many kinds of lettuce such as butter, iceberg, loose leaves, romaine and others. In the experiment we used the type loose leaf lettuce *(Lactuca sativa crispa. "Lollo bionda").* It is the easiest kind of lettuces to grow, and as the name indicates, green color with tight curly leaves. It can be harvested leaf by leaf or by the whole plant, it takes 45-50 days to be mature, Height: 15 cm (6"). Spread: 25 cm (10").

Lettuce (Lactuca sativa) is found to be the most cultured vegetable in hydroponic system. This is due to its easy adaptation to this system, which has been showing high productivity in cycle compared with the soil cultivation (Cometti et al., 2013), therefore seedlings of loose leaf were planted in hydroponic system under different light spectra from the following three lights: natural light, 60% Shade, LED (RGB). This research is an attempt to undertake lettuce production in a vertical hydroponic system under three different light resources with same photoperiod in a greenhouse.

1.2 Background of the study

Lettuce (*Lactuca sativa*) is one of the most frequently demanded commodities depending on the increasing popularity of salad recipes containing lettuces (Allende et al., 2007). The lettuce, also known as *Lactuca sativa* L, belongs to the Compositae family. It contains high percentage of water (90-95%), as well as folates, provitamin A or β-carotene and appreciable amounts of vitamin C, these last two with antioxidant action, related to the prevention of cardiovascular diseases and even cancer (Anderson et al., 2017). Several environmental factors are responsible for growth and development of lettuce (Dufault et al., 2009; Gruda, 2005).

Light, in addition to being an indispensable source of energy for the plants, is also an important factor for its growth and development. Plants have three systems of primary perception of light signals, like photosynthetic pigments, special photoreceptors and light-dependent biochemical processes of photosynthetic pigment biosynthesis and DNA reparation (Berkovich et al., 2017). Light quality determine the accumulation of leaf photosynthetic pigments (Carvalho et al., 2011; Lillo and Appenroth, 2001; Giliberto et al., 2005).

Due to this lighting systems of production in a controlled environment are very important as well as the technological advances that may arise in this area. Recently the LED light has become an alternative for the cultivation of plants for the benefits that this system of lighting provides such as the firm control of the spectral composition, production of high levels of light with a low heat radiation index, its small size and a long productive life that allows them to keep working for years without needing replacement (Anderson et al., 2017). The selected LED lights differentially affected the metabolic system of the investigated vegetables. The most sensitive response was in sugars, the main photosynthesis product, and their accumulation in leaves (Lefsrud et al., 2008). Li and Kubota (2009), investigated different LED light quality effect on phytochemicals of leaf lettuce. Light quality determines the efficiency and productiveness of photosynthesis (Swatz et al., 2001; Massa et al., 2008; Johkan et al., 2010; Abidi et al., 2013; Li et al., 2013).

Plants grown in the Shade tend to have a larger leaf area due to high rate of expansion of leaf cells and ultimately there is chance of pigment elevation than in control plants (Fu et al., 2012).

1.3 Purpose of the study

In the growth of Lettuce, the light is not only the source of energy but also a significant environmental input for the development and growth and their physiological and morphological adaptations which can be mediated with the help of morphogenetic reactions and through light-reliant adjustments in the process of photosynthesis.

The quality of light demonstrates much more complex level of impacts on physiology and morphology of plant compared with the intensity of light. The main purpose of the study is to compare lettuce growth parameters under LED light with Shade and natural light as light treatments to satisfy requirements of growth at diverse phases. The reactions of growth and development example plant biomass, leaf area, shoot growth, leaf number, chlorophyll content, carotenoid, that will be evaluated to determine the effect of different light resources on "loose leaf" lettuce in a vertical hydroponic system inside greenhouse.

1.4 Research aim and objectives

The aim of the research is to explore and investigate the growth and development of loose leaf lettuce under different lighting systems in vertical hydroponics system.

1.5 The research will test the following hypothesis

There is no significant difference of growing lettuce *(Lactuca sativa crispa. “Lollo bionda”)* in different light set up.

1.6 Research significance

Investigating the growth of lettuce under different lighting set ups carries a lot of significance. The main goal of the research is to know the impact of diverse lighting types on the quality and productivity of lettuce leaf that can contribute to make further research work and investigations and opens new dimensions to research projects to maintain the plant quality and enhance its growth and productivity through the lighting type and the level of control. On the other hand, growth of shaded plants would help to design vertical hydroponic system with maximum tiers.

In order to conduct the research, particular parameters were monitored. These parameters included length, width, number of leaves, leaf area, fresh weight, dry weight, pigment values, and different micro climatic parameters included light intensity, temperature, relative humidity, and Light quality also were measurement, that included PAR and light spectrum parameters.

Chapter 2: Review of Literature

Cometti et al. (2013) stated that light plays a very important role in the life of plants. Their photosynthetic activity is very conditioned by the quality and quantity of solar radiation they receive. The global radiation spectrum is very broad, however, only a small portion, called Photosynthetically Active Radiation (PAR), is used by plants to perform photosynthesis. (Choosria et al., 2017) reported that, photosynthetically active radiation (PAR) forms one part of the solar spectrum with a wavelength range of 400–700 nm (Fig. 1).

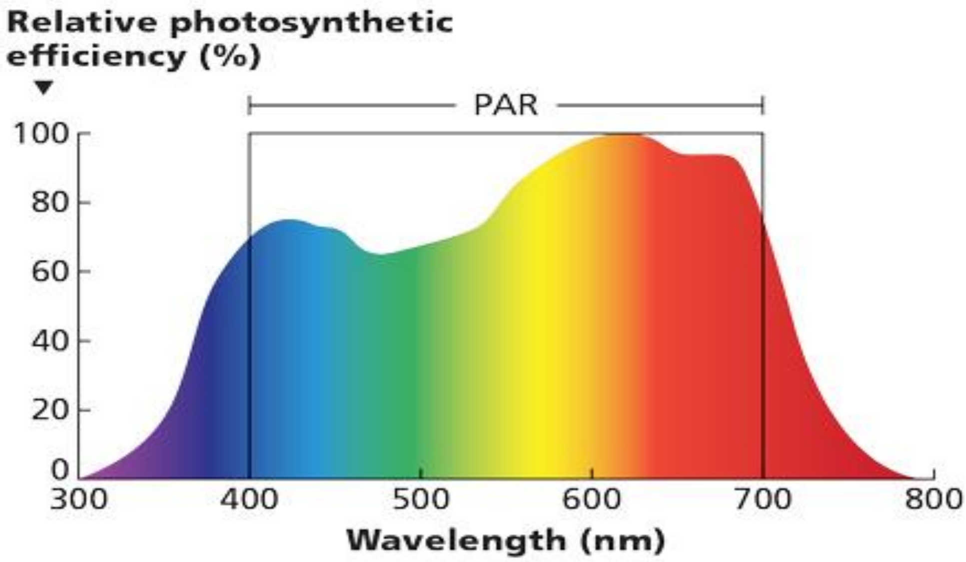


Figure 1: Photo synthetically active radiation

Different pigments are responsible for the capturing or absorption of different light spectrum, like chlorophyll A and B for absorption bands in the red (650–700 nm) and blue (420–460 nm) (Dey and Harborne, 1997). According to Theiler et al. (2016), in the visible light spectrum, the wavelength of green perceived by plant photoreceptors and pigments is 500–600 nm. A small fraction of near-infrared radiation, i.e., far-red light perceived by phytochromes with a sensitivity peak at 730 nm, is also essential to plant development. A summary of the effect of light wavelength on the plant growth is given in Table 1 (Deram et al., 2014).

Table 1: The effect of light wavelength on plant growth

Optical wavelength (nm)	The influence on the growth of plants
280–315	Minimal impact on morphological and physiological process
315–400	Chlorophyll absorbs less, photoperiod effect, tissue and stem elongation
400–520	Chlorophyll and carotenoid absorption proportion is the largest, the biggest influence on photosynthesis
520–610	The pigment absorption rate is not high
610–720	Chlorophyll absorption rate is high, have significant effects on photosynthesis and light cycle effect
720–1000	Absorption rate is low, stimulate cell extended, affecting flowering and seed germination
>1000	Convert into heat

(Source: Xu et al., 2016)

Many studies are available in the literature to estimate PAR from the more routinely measured parameters of solar radiation (e.g. Alados et al., 1996, Jacovides et al., 2004, Escobedo et al., 2009).

Specifically, there are three systems of light signals and primary perception. These are special photoreceptors involved in plant photo regulatory systems and affecting most processes in plants, and light-reliant biochemical procedures of photosynthetic pigment biosynthesis and photosynthetic pigments and DNA reparation that are connected to the transformation of photochemical energy in the (electron transport chain) ETC of the (photosynthetic apparatus) PSA (Berkovich et al., 2017).

It is necessary to consider that there are three major global problems of which it is a priority to find solutions, the need to reduce the emission of greenhouse gases, linked to climate change and natural disasters, as well as the continuous increase in the demand for energy and food (Pinho et al., 2012). It is estimated that by 2050 it will be necessary to increase food production by 50% in order to avoid a food disaster in the future (Murchie et al., 2008). Therefore, it is necessary to use technological advances to face these problems, such as feeding future generations. Due to this, the production of vegetables in controlled environments is a possibility to consider (Pinho et al., 2012) and this has started to grow rapidly all over the world (Liu, 2012).

The use of artificial lighting systems for production in a controlled environment is an opportunity to increase crop yields. High intensity LED light could be a viable alternative to be used for these purposes. However, it is necessary to achieve a better understanding of the processes and mechanisms under which plants respond to light (Pinho et al., 2012). This suggests that it is inescapable to continue carrying out research related to the effects of treatment with type of light, for the production of vegetables in controlled environments. According to lot of researchers such as Okamoto et al. (1996); Drozdova et al. (2001); Chung et al. (2010), different types of lights are used extensively to investigate the effects of spectral quality on the growth of plant and it has been proved that more fine growth of plants can be achieved by making adjustments of the spectral quality. According to Carvalho et al. (2011), the quality of light affects the accumulation and formation of pigments of leaf photosynthetic which may either enhance light harvest under conditions of low-light, or act as free-radical scavengers and screening pigments under high-light conditions. Besides, the quality of light imparts a significant impact on the expression of gene of plants through originating the signaling cascade of photoreceptors like cryptochromes, phototropins and phytochromes (Giliberto et al., 2005; Lillo and Appenroth, 2001).

In Japan, in 2013, LED-based lighting sources illuminated 27% of crop area in vertical farms, which is inferior only to fluorescent lamps (60%); while in 2003, only lamp-based lighting was used in vertical farms (Kozai et al., 2016). Artificial lighting applied to greenhouses has historically been linked exclusively to installations located in areas with few hours of sunshine per year, or to the modification of the photoperiod to induce the flowering of ornamental crops at times of the year that have the highest commercial value. This paradigm may be changing due to the advancement of lighting technology and the decrease in the installation and energy consumption costs of modern lighting systems, which could facilitate its incorporation, not only for the production of flowers, but also for the production of fruit and vegetable, especially in certain farms such as nurseries; in which clearly the supplementary lighting is necessary in the production of grafted plant. In horticultural production it can sometimes be advantageous to provide artificial lighting, or simply regulate natural lighting, for different reasons: to increase net assimilation by forcing a higher rate of photosynthesis, to increase the length of the day in places where required, or in long day plants that would not flower in another way during autumn-winter.

According to Dufault et al. (2009), day by day technology overcomes the limits and shows how far it is able to reach to surprise the senses of men; and agriculture, being one of the primary activities for man to survive, cannot be left behind. In this sense, in recent years LED lamps have meant one of the most important advances in artificial lighting for horticulture. There are several methods to offer plants supplementary light, however, LED lighting systems are considered today the most effective, there are currently specific developments for use in agriculture. These are powerful and efficient in the emission spectra that cover the entire range of PAR radiation, making it possible, in addition, its regulation in various lighting regimes depending on the type of crop and its phenological development. As early as 1966, Hardh suggested that the artificial lighting used for plants should be adapted to the spectra of photosynthetic function sensitivity, and in 1972, McCree offered a proposal for a generalized spectrum of action for photosynthesis. With light sources based on LED technology, it is possible to adapt the spectral composition of light in a way that is not possible with conventional lighting systems. Therefore, it has been suggested that the use of LED-based light sources, which are consistent with the spectral response curve to light from photosynthesis, could improve growth and reduce the energy needed for assimilation illumination.

Hahn et al. (2000) further posit that this new technology offers the possibility of establishing ranges of suitable spectra, which at present are not only used as a primary source of energy for the growth of plants, but also provide physiological regulation information in the various growth processes of plants. In recent years, intensive research is being carried out to clarify the impact of the quality of light on the physiological benefits it causes to plants. In this sense, LEDs are increasingly used as lighting systems in greenhouses, as they allow to study the response of the plants based on the wavelength of the radiation incident on them, in a simple way. The quality of the light under conditions of controlled cultivation can modify the growth, fresh weight and the quality of many horticultural crops and, therefore, can considerably affect its market value. That is why, the study of the effects of LED lighting on plant growth and fruit production, is currently a very important line of research in intensive horticulture. All this without forgetting the traditional use of artificial lighting of the production of ornamental crops, all technology requires an initial investment and LEDs are no exception.

Research results showed that, particular LED lights differentially impacted the metabolic system of the examined vegetables. The subtlest response was in sugars, the major photosynthesis product, and their increase in leaves (Lefsrud et al., 2008). According to Nhut et al. (2003), LED has turned out to be an encouraging source of light used in physiology of plant research in surrounded facilities, and several researches on photobiological research comprising formation of chlorophyll, morphogenesis and photosynthesis which have been carried out by applying LED to numerous plants in which fluorescent lamps are always used as the controller. While examining diverse quality of LED light, Li and Kubota (2009) demonstrated imperative enhance of phenolics compounds under fluorescent lighting supplemented with red LEDs and did not notice supplemental green or blue LEDs influence on the accumulation of phenolics. According to Abidi et al. (2013), in terms of the quality of the light, the impacts of red and blue light on the growth and development of plant appeal most of the considerations as these wavelengths are mainly absorbed by photosynthetic pigments and have the major effect on plant development and architecture.

2.1 Light quality

Light quality refers to the spectral distribution of the radiation. For photosynthesis, plants respond strongest to red and blue light (Singh et al., 2015). Plants can absorb any wavelength; they are very selective in absorbing the proper wavelength according to their requirements. According to Theiler et al. (2016), in the visible light spectrum (400–700 nm), the major wavelengths perceived by plant photoreceptors and pigments are those corresponding to blue (400–500 nm) and red (600–700 nm) and, to a lesser extent, green (500–600 nm). As shown in Fig. 2.

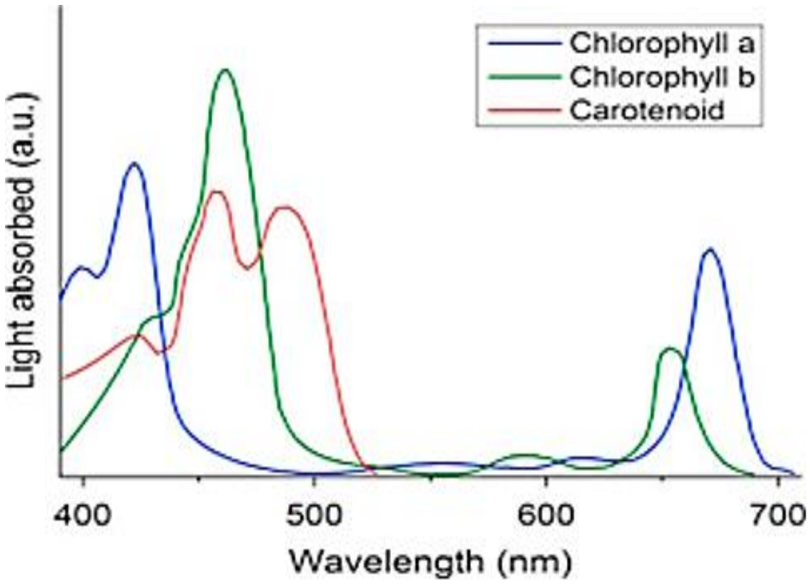


Figure 2: Absorption spectrum of chlorophyll and carotenoid pigments

As a vital segment of the light range for normal development of plant, R affects plant morphogenesis by tempting changes in phytochrome, and is also vital for the growth and development of the photosynthetic apparatus along with controlling the synthesis of phytochemicals such as oxalate and phenolics (Qi et al., 2007; Choi et al., 2015). In addition, according to Hogewoning et al. (2010), blue light is significant for chloroplast development, photosynthesis; chemical composition of plants and chlorophyll formation, but the reaction extremely relies on the quantity of blue light. The researchers further posited that combined red and blue LEDs resulted in enhanced shoot biomass and Pn compared to monochromatic red or blue (Brown et al., 1995; Ohashi-Kaneko et al., 2006; Hogewoning et al., 2010; Nanya et al., 2012; Li et al., 2013). The effect of green light is similar to blue light in plant metabolism (Swatz et al., 2001; Baroli et al., 2008; Hogewoning et al., 2010; Sun et al., 1998).

2.2 Advantages of LED lighting

According to Lazcano et al. (2009), LED lamps can last from 50 to 100 thousand hours without reducing their energy efficiency, having a much lower energy consumption compared to other lamps. Nowadays it is possible to modify the quality of the emitted light, which allows us to carry out a greater experimentation, until we find the optimal values of ideal intensity for our concrete crop. They become a fixed and controllable tool of artificial light in plants. The lowering of installation costs facilitates the profitability of the system. With technological advances and research, it is possible by LED technology to "mold" the ornamental plants according to the preferences of the consumers.

The use of LED technology has emerged as an attractive option for the growth of plants in a controlled environment. A lower energy consumption (cost savings of 40%), longer device life compared to other lighting systems, higher switching speed, better color control and higher light intensity are some of the benefits of this technology. In addition to the fact that, they do not require ballasts (increasing savings) because the LEDs allow the producers to place the luminaires very close to the plants by not producing heat (Abidi et al., 2013).

According to Massa et al. (2008); Vänninen et al. (2010), LEDs can provide several benefits to the greenhouse industry, for example, they can reduce the energy consumption up to 70%, and many other benefits.

2.3 The role of different lighting systems in Lettuce growth

Lettuce is used almost throughout the year since there are a number of varieties which are successfully cultivated during different growing seasons (Zdravković et al., 2014). Due to increasing demand, lettuce has become a leading crop cultivated in greenhouses throughout the world and considered to be a model crop because of its rapid growth and sensitivity to diverse range of light qualities (Dougher and Bugbee, 2001). Kader and Rolle, (2004) states the key parameters of quality main lettuce are: based on freshness, overall appearances, color, leaf freshness, nutritional value and size and shape of head. The appearance of biological disorders can be visually observed on the surfaces of leaf (Chutichudet and Chutichudet, 2011).

Dufault et al. (2006) presented in the research that as planting dates developed toward longer days and warmer temperatures, quality and lettuce yield were affected adversely. Bolting requires a definite photoperiod and is different for each plants (Wallace et al., 2012). According to Caldwell (2003), exposure to high radiation and temperature has been demonstrated to enhance the production of phenolic composites in pigmented lettuce and green lettuce (Marin et al., 2015). An adverse impact was confirmed as a result of a reduction of 40 to 50% of the transmission of light (Oh et al., 2011) at the same time a contact to high intensity of light enhanced antioxidant capacity and phenolic accumulation (Zhou et al., 2009; Oh et al., 2009).

According to Dufault et al. (2009), the growth of plants and vegetables in a controlled environment requires nutrients, water, CO_2, temperature and light for optimal development. Several investigations have shown the influence of light, as a factor to control morphogenesis and growth in plants. Light characteristics, such as wavelength, direction, intensity and duration, provide the plants with signals that they monitor through highly sensitive photoreceptors and translate them into cellular signals, which affect the endogenous mechanisms of growth and differentiation control. As a consequence, light modulates a variety of processes in the life of the plant, such as germination, etiolation of the seedling, avoidance of Shade and induction of flowering, characteristics collectively defined as photomorphogenesis.

Generally, fluorescent lamps have been used in growth chambers and greenhouses to promote the development of the plants. However, these light sources contain unnecessary and low quality wavelengths to promote growth. Johkan et al. (2010) also reported greater dry weight of lettuce seedlings cultured under RB LED than Fluorescent.

The use of LED technology has emerged as an attractive option for the growth of plants in a controlled environment. According to several researchers, Lian et al. (2002); Nhut et al. (2003); Lee et al. (2007) Combined RB LED lights were proven to be an effective lighting source for producing many plant species, including lettuce, in controlled environments.

In the wild, seeds germinate in the dark when being buried in the ground, reason why the seedlings quickly develop hypocotyls that lengthen without opening the cotyledons above the surface. Upon reaching the light, the elongation of the hypocotyl is inhibited and the cotyledons begin to expand and the development of the photosynthetic apparatus begins. These developmental changes are collectively called de-ethiolation. The general rule is that, light causes the developing seedling to cease rapid elongation and adopt a strategy of vegetative aerial growth appropriate for the light environment (Wang and Folta, 2013). Far Red and Red light diminish the elongation of the hypocotyl by acting mainly through the phytochromes phyB and phyA respectively (Parks et al., 2001). Blue light strongly inhibits stem elongation under high illumination rates (Folta and Spalding, 2001; Ahmad et al., 2002). This effect is mainly mediated by cryptochromesb cry and is maintained while blue light is present (Wang and Folta, 2013).

In the experiment the growth of the seedlings was evaluated with the variable medium length of the hypocotyl (LMH), where it was clear to observe that the treatments with green light (12 hours) and red light (12 hours) achieved the greatest increases with 39% and 21% compared to the control respectively. The effect of green light is explained by Wang and Folta (2013) where it indicates that this type of light inactivates the action of cryptochromes cry, so that the growth of hypocotyl is maintained. These results with green light are in accordance with the statements made by McCoshum and Kiss (2011) and Johkan et al. (2012), who indicated that, the growth of adult plants and seedlings are improved with the use of green light. On the contrary, all the treatments with blue light of this investigation caused the hypocotyl to grow much less, where the longer the exposure, the lower the growth, which agrees with that described in the previous paragraphs for blue light. Similar results were obtained by Shoji et al. (2010) and Kobayashi et al. (2013), as the increase in blue light decreased the hypocotyl length in lettuce seedlings. Regarding green light, recent research considers the use of it to improve growth in combination with other wavelengths (Kim et al., 2004b; Massa et al., 2008), as happened in this investigation. The use of intense green light is biostimulator of seeds in presowing, because they found a considerable increase of biomass in plants (Sommer and Franke, 2006; Dechaine et al., 2009; Goggin and Steadman, 2012). Bewley and Black (1994) and Daud et al. (2013) reported that Red light may initiate seed germination and root development and seed germination (Bewley and Black, 2012; Chen et al., 2013).

2.4 Shading effect

Shade netting is used as a major agriculture technique and has been practiced for ornamentals, vegetables and fruit trees (Shahak et al., 2004a; Shahak et al., 2004b; Ilić et al., 2017a). The light through the holes in the Shade cloth will be same quality as the normal light (Jaimez and Rada, 2006; Appling, 2012).

There are many beneficial effects in using the Shade nets (Wallace et al., 2012). Moreover, lower intensities of light enhance the elongation of stem, blade area of leaf and area index of leaf. Generally, texture of leaf and shape of head were among the things that were improved expressively by the color Shade nets and developed from the acceptability of consumer's perspective (Ilić et al., 2017b).

Higher yield and quality of lettuce has been achieved with the selection of correct cultivar (Maboko and Du Plooy, 2008) and correct technique (Ilić et al., 2017a) like Shade growing (Bergquist, 2006). The quality of lettuce under different Shade-nets (Zdravković et al., 2014) and spring production (Mladenovic et al., 2013) were reported previously.

The Shade effects on lettuce growth and quality with production in commercial scale have been reported earlier (Zhao and Carey, 2009; Jenni et al., 2013; Ntsoane et al., 2016; Ilić et al., 2017a; Ilić et al., 2017b).

2.5 Vertical hydroponics

Vertical hydroponics have been proposed as an engineering solution to increase productivity per unit area of land by extending crop production into the vertical dimension (Despommier, 2011). Vertical hydroponics is a method for plant culture that using the height of a greenhouse in addition to the ground space and this can increase the number of plants and thus enhance yield. Other benefits of vertical culture include more economic use of water and nutrition, easy harvesting and a reduction in labor costs. The two chief merits of the hydroponics are, first, much higher crop yields, and second, the fact that hydroponics can be used in places where ordinary agriculture or gar dening is impossible. There is also a considerable reduction in growing area; weeds are practically non-existent, while automatic operation results in less labor, cost, and maintenance (DeMitchell & Tarzian, 2011).

On the other hand, according to (Poorter et al., 2012), light intensity in growth chambers is known to decrease as distance from the light source increases. As spacing between vertical columns influenced crop productivity in vertical farming system glasshouse trials (Liu et al., 2004). from a commercial point of view, if lettuce was grown to be sold as individual heads, then the nonuniform productivity of the vertical farming system would be a potential weakness of the vertical farming system over the horizontal farming system (Touliatos et al., 2016).

2.6 Leaf area index

Leaf area index (LAI), defined as half the total green leaf area per unit ground surface area (Chen and Black, 1992; Weiss et al., 2004; Ryu et al., 2012). LAI is an important parameter for photosynthesis models (Chen et al., 1999; Silva et al., 2012; Savoy and Mackay, 2015). It will be varying based on the plants and light effects (Liu et al., 2015). LAI can be obtained by both direct and indirect methods (Breda et al., 2003).

Chapter 3: Materials and Methods

3.1 Experimental site

The experiments were conducted in the Greenhouse of Al Foah, College of Food and Agriculture United Arab Emirates University. It lies in the co-ordinate latitude and longitude of 24.2191 °N and 55.7146 °E.

3.2 Experimental set-up and growth conditions

On 14-01-2018, in the agricultural greenhouse and in 26.5 °C, seeds of lettuce *(Lactuca sativa crispa. "Lollo bionda")* shown in moisturized Rockwool cubes (2.0 cm × 2.0 cm × 2.0 cm), placed in plastic containers and sprayed with water every two days. They were also covered with white gauze to protect them from insects.

Figure 3: Grown seedlings in Rockwool cubes before transplanted to Rockwool slabs

As shown in Fig. 3, after 39 days, 240 seedlings were selected in good health, and transplanted each 4 seedlings in a Rockwool slabs (100 cm × 20 cm × 2.5 cm), where the distance between each two seedlings was 16 cm, connected to the hydroponics system, as shown in Fig. 4.

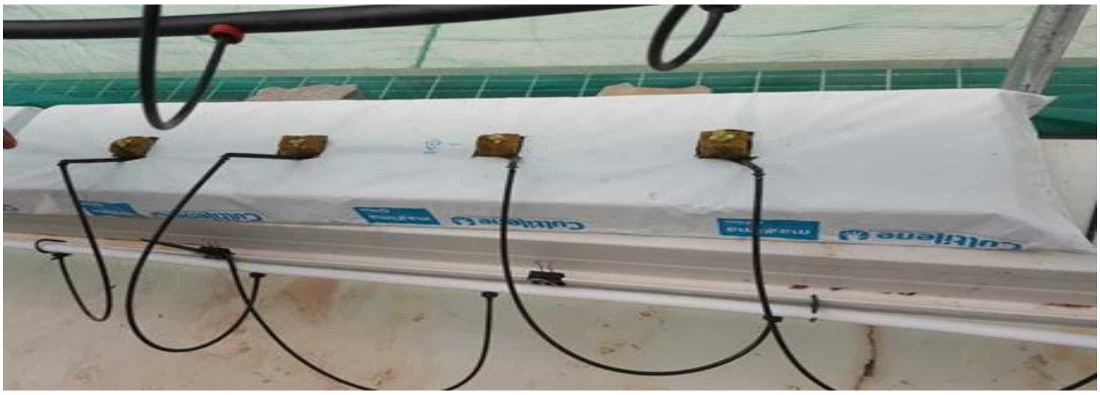


Figure 4: Seedlings in Rockwool slab connected to the hydroponics system

The hydroponic system was included of four tanks. The first tank contained fresh water and three other tanks that contained various chemicals and fertilizers necessary for lettuce growth.

A “closed” hydroponic system was used which allows water and nutrient reuse. Where the water is pumped through a pump which is also attached at single point to the three tanks. The minerals are mixed in water which is then passed on to the growing area. The water passes through the plants and is absorbed. Any extra water is then pumped out. The irrigation water then passes through a special water filter which results in refining of the irrigation water which is ready to be used again. In order to maintain an enough supply of nutrients to the lettuce plant, a frequent testing of the nutrient solution composition is made.

Electrical conductivity (EC) and pH was adjusted to 1.2 m S/cm and 5.5 respectively. The chemicals used in this study are analytical grade and procured from Sigma-Aldrich, USA. The details of the composition of nutrients are given below in Table 2.

Table 2: Nutrient composition for hydroponic culture of *(Lactuca sativa crispa “Lollo bionda”)*

	Elements	**Salts**	**Nutrient Concentration (mM)**
Macro	N	NH_4NO_3	0.2
	K, N	KNO_3	5.0
	Mg, S	$MgSO_4$	2.0
	P,K	KH_2PO_4	0.1
	Si	Na_2SiO_3	0.0
Micro			(µM)
	B	H_3BO_3	12.5
	Mn	$MnCl_2$	2.0
	Zn	$ZnSO_4$	3.0
	Cu	$CuSO_4$	0.5
	Mo	Na_2MoO_3	0.1
	Ni	$NiSO_4$	0.0
	Cl	KCl	0.0

3.3 System layout

The seedlings were planted in 4 rows; each row (8 m × 50 cm × 28 cm) comprising of 3 levels, the distance between each level and other was 50 cm and between each row and other was 80 cm. Each level accommodated 5 Rockwool slabs, each Rockwool slab included 4 seedlings replicates (4 plants per replicate, 5 replicates per treatment). Thus, in total (240) seedlings were planted. It must be noted that the hydroponic system was already in place at the greenhouse, prior to the plantation. The water was given to the plants four times, at an interval of six hours. The duration of watering the plants was ten minutes each time.

Plants were exposed to light radiation using three photo treatments with different radiation methods described below and harvested in 80 days after transplanting.

The first row (control), in which 3 levels were exposed to the natural light which from the polycarbonate cover of the greenhouse. While the other three rows have the upper levels exposed to natural light, the middle levels covered from all sides with the Shade net (60%), and the low levels closed tightly sealed from all sides with horticulture reflection sheet, as shown in Fig. 5.

Figure 5: Four rows and three levels in each row, all connected to the hydroponic system

3.4 Light quality treatments

Illumination treatments were performed using natural light, Shade (60%), and three-color LED panels (RGB). The LED light was a strip extending along the third level (8 meters) and a width of 1 cm. The three-color LED panels provide red, blue and green. The distance between LED panels and plant canopy was 40 cm. Also, the photoperiod at the lower levels exposed to LED were set to 12/12. Irradiation intensity, temperature and relative humidity were measured three times a week for each level at 8 am, 12 pm and 4 pm.

3.5 Studies of growth parameters

Four plants randomly taken from each treatment were regarded as a repetition for biometric and biochemical measurements. Among which, plant height/width, number of leaves were measured once every 7 days while other indices were measured at harvest (80 days). The fresh weight (FW), leaf area as well as the contents of total chlorophyll, chlorophyll a, chlorophyll b, carotenoid, were all determined using fresh lettuce samples. The dry weight (DW) was determined using the oven-dried lettuce samples (70 °C for 3 d).

3.6 Determination of chlorophyll and carotenoid

Concentrations of the chlorophyll and carotenoid were determined using the following equations (Lichtenthaler and Wellburn, 1983):

Chl a (mg/g) = (12.7 × OD663 − 2.59 × OD645) V/W

Chl b (mg/g) = (22.9 × OD645 − 4.67 × OD663) V/W

Total Chl (mg/g) = (20.2 × (OD645) + 8.02(OD663)) × Chl.a − 104 × Chl.b) V/W

Car (mg/g) = ((OD440 − 3.27 × Chl.a – 104 × Chl.b) / 229) V/W

Where;

OD: optical density at certain wave length (645 nm, 663 nm or 440 nm)

V is the total volume of acetone extract (50 mL) and W is the fresh weight (500 g) of the sample.

3.7 Measuring equipment's used in the experiment

1 - Spectral radiation measurement

The light quality measurement was performed using spectrometer (model MK350N PREMIUM). Placed it horizontal to the light source, twice a day, 8 am and 2 pm, to measure the emissions of wavelengths of each treatment and control levels.

2 - Photosynthetically active radiation

Using a Photosynthetically Active Radiation (PAR) sensor (Model: LI-1500 Light Sensor Logger). Every 24 hours the PAR sensor was shifting from one level to the other in hydroponic set up.

3 - Light intensity measurements

LUX (Lumen/m^2) measurement: using DIGI- SENSE Light Meter (Model 20250-00), used three times a day, at 8 am, 12 am and 4 pm, placed it horizontal to the light source for each level of treatment and control three levels.

4 - Temperature and relative humidity measurement

Used DIGI- SENSE Thermohygrometer (Model 20250-11), to measure the temperature, and relative humidity, was used 3 times a day, at 8 am, 12 am and 4 pm, placed it horizontal in each level of treatment and control levels through the period of experiment.

5 - Leaf area measurement

The LA (cm^2) of lettuce plant was measured by AREA METER (Model CI-202) at harvest.

3.8 Statistical analysis

The results were presented as mean values and standard error. Data were tested using SPSS (version 16.0, SPSS Inc.). Statistical analysis of the results was based on Analysis of Variance ANOVA for Randomized Complete Block Design RCBD for treatments data and Completely Randomized Design CRD for Control Data with subsampling. Where Row considered as Blocks. Means for significant effects were compared using t-test at $p<0.05$.

Chapter 4: Results

The lettuce namely (*Lactuca sativa "Lollo bionda"*). Was grown using different light systems. Different parameters of the growth of lettuce like fresh weight, dry weight, leaf area, plant length, plant width, leaves number, different pigment values like total Chlorophyll, Chlorophyll a, Chlorophyll b, Carotene, and different micro climatic parameters like light Intensity, temperature, and relative humidity were recorded and the results are discussed in this chapter.

Light quality was also measured and used for comparison, that included PAR and light spectrum parameters.

4.1. Plant morphology

As shown in Fig. 6, in the end of the experiment, plants under natural light looked large and vigorous while those with 60% Shade and (RGB) LED treatments looked small and weak, lettuce under natural light had the most compact morphology with dark green leaves while plants with other treatments were detected sparse and fragile.

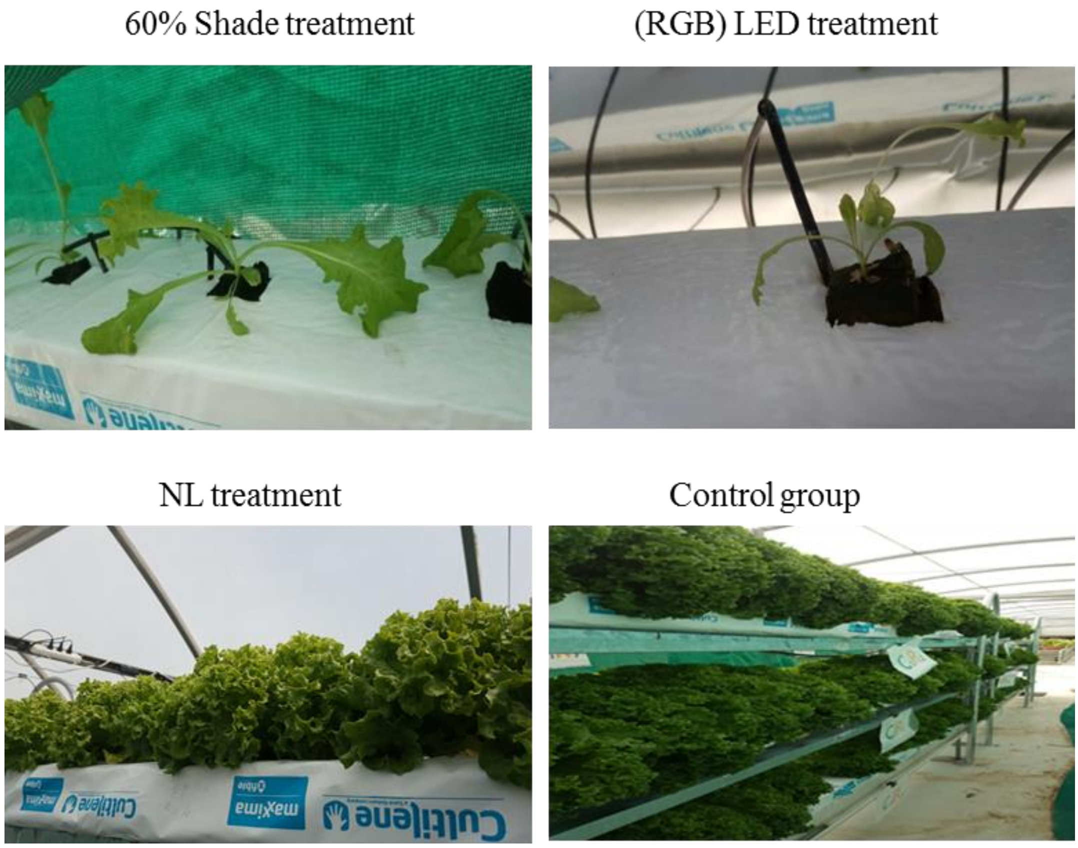


Figure 6: Lettuce under natural light, 60% Shade, (RGB) LED treatments and control group

4.2 Growth parameters

The length, width, and number of leaves of lettuce were measured through six weeks of the experiment, at the latest day of each week. According to ANOVA results, there is a significant difference among the parameters of lettuce under different light set up.

As shown in Fig. 7, the average growth rate of plant height, plant width, number of leaves during the whole culture period was respectively 0.31 cm, 0.36 cm and 0.30 number of leaves per day with natural light treatment, the width and number of leaves were the highest among all the three treatments, followed by 60% Shade, while no significant difference between length of lettuce in NL and 60% Shade treatments.

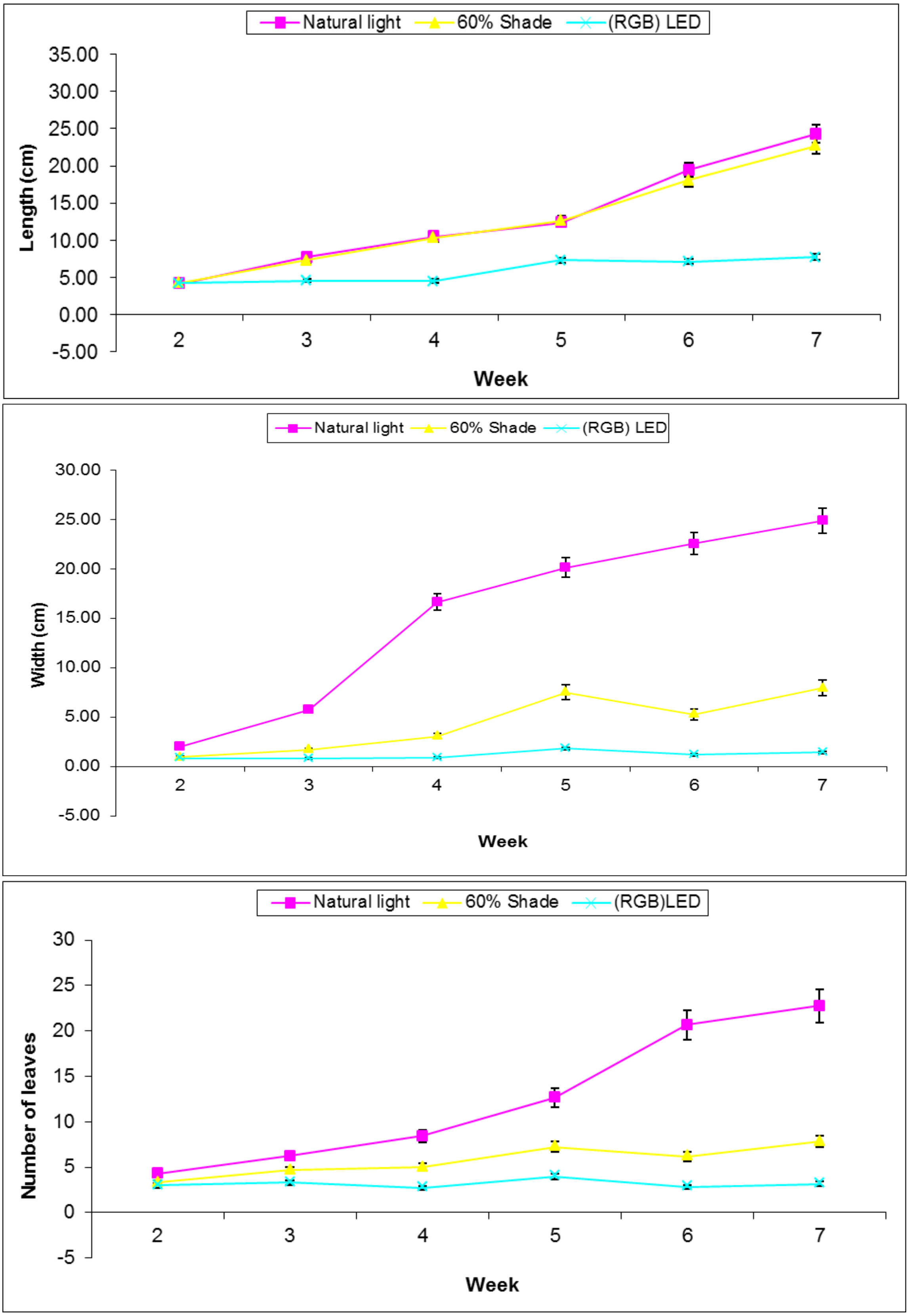


Figure 7: Plant length, plant width, number of leaves growths of lettuce cultivated under natural light, 60% Shade and (RGB) LED

Table 3 displays the growth parameters of lettuce at the latest week (7th) of the experiment. Compared with 60% Shade and (RGB) LED, the length of lettuce under NL, 60% Shade, (RGB) LED treatments was increased respectively by 44.3%, 41.5% and 14.1%, while the width of lettuce was increased respectively by 72.7%, 23.1% and 4.1%, and the number of leaves was increased respectively by 67.4%, 23.2% and 9.4%.

Table 3: Plant height, plant width, number of leaves growths of lettuce cultivated under different light treatments of natural light, 60% Shade, (RGB) LED. The alternating irradiation provided by LED is 12 h a day

Variable	**Length (cm)**	**Width (cm)**	**Leaves number**
Treatment *p*-value	0.0004	<0.0001	<0.0001
Natural light	24.29 ± 0.87^{a}	24.88 ± 0.78^{a}	22.75 ± 0.76^{a}
Shade	22.75 ± 2.43^{a}	7.92 ± 2.04^{b}	7.83 ± 0.81^{b}
LED	7.75 ± 2.48^{b}	1.42 ± 0.45^{c}	3.17 ± 0.98^{c}

a,b,c means with different letters are significantly different at $p<0.05$

As for the control, which was composed of three levels above each other and all exposed to natural light, the growth parameters were approximately equal, as shown in both the Fig. 8 and Table 4.

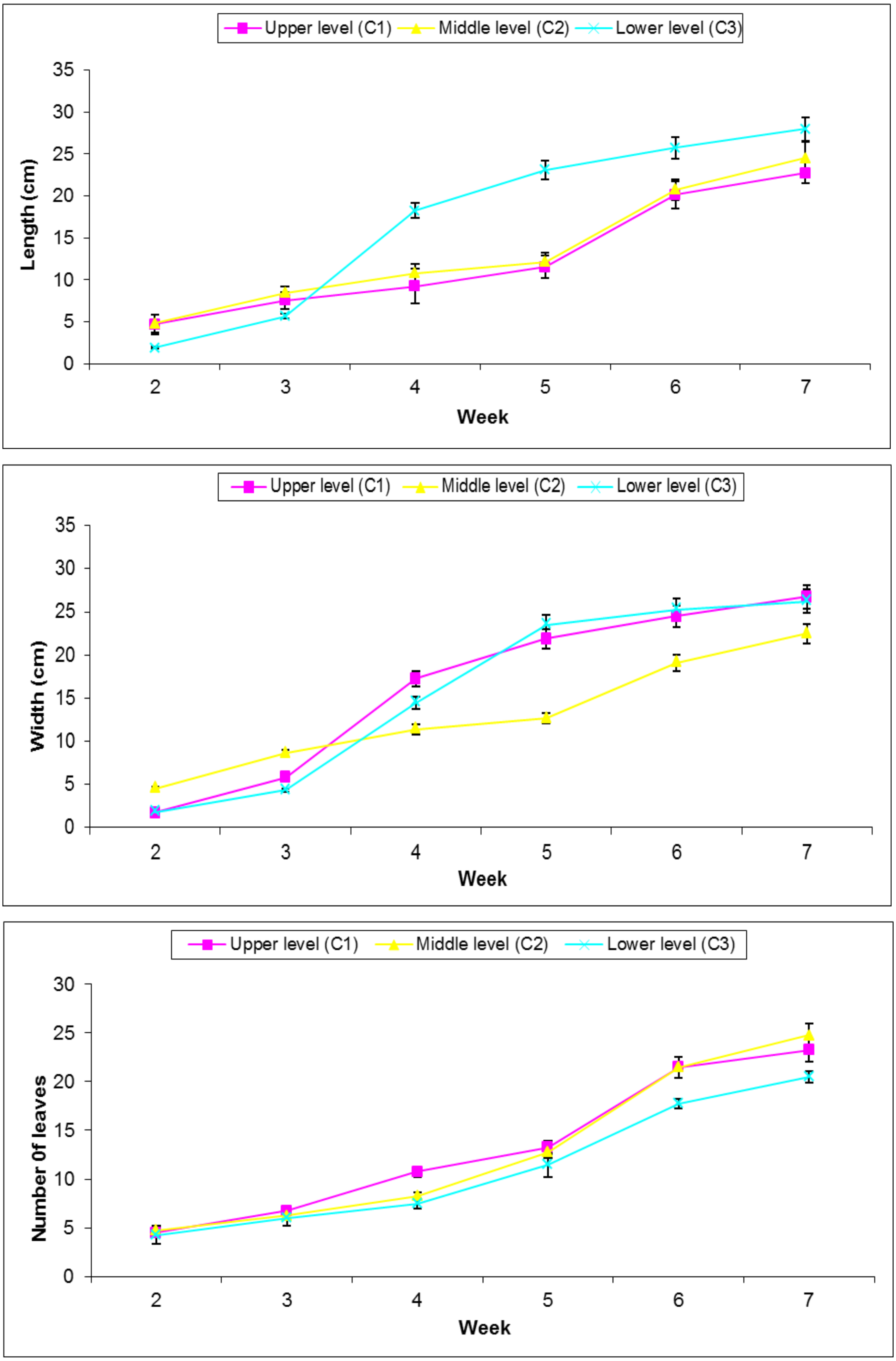


Figure 8: Plant height, plant width, number of leaves growths of lettuce cultured under natural light in levels of control

Table 4: Influence of natural light of three levels of control on plant height, plant width, and leaves number of lettuces at latest week of experiment

Variable	Length (cm)	Width (cm)	Leaves number
Level *p*-value	NS	NS	NS
Upper level (C1)	22.75±1.26	26.75±1.71	23.25±2.63
Middle level (C2)	24.50±1.91	28.00±1.83	24.75±2.99
Lower level (C3)	22.50±1.29	26.25±2.50	20.50±0.58

NS Not significant at $p<0.05$

The other plant growth parameters of lettuce reported at harvest, represented in the leaf area, fresh weight and dry weight are given in the Table 5 and Fig. 9, 10. The results showed that the leaf area, fresh weight and dry weight of the biomass under NL treatment were significantly high i.e. 147.91±10.65 cm^2, 542.52±30.48 g, 27.39±1.78 g. The lettuce grown under (RGB) LED showed the lowest in terms of leaf area, biomass in fresh weight, dry weight (3.94±1.66 cm^2, 0.89±0.42 g, not detectable).

Table 5: Leaf area (cm^2), fresh weight (g), and dry weight (g) of lettuce under NL, 60% Shade and (RGB) LED treatment at harvest

Variable	Leaf area (cm^2)	Fresh weight (g)	Dry weight (g)
Treatment *p*-value	0.0039	0.0001	0.0001
Natural light	147.91±10.65^a	542.52±30.48^a	27.39±1.78^a
Shade	57.87±15.74^b	13.00±2.19^b	0.35±0.07^b
LED	3.94±1.66^c	0.89±0.42^b	Not detectable

a,b,c means with different letters are significantly different at $p<0.05$

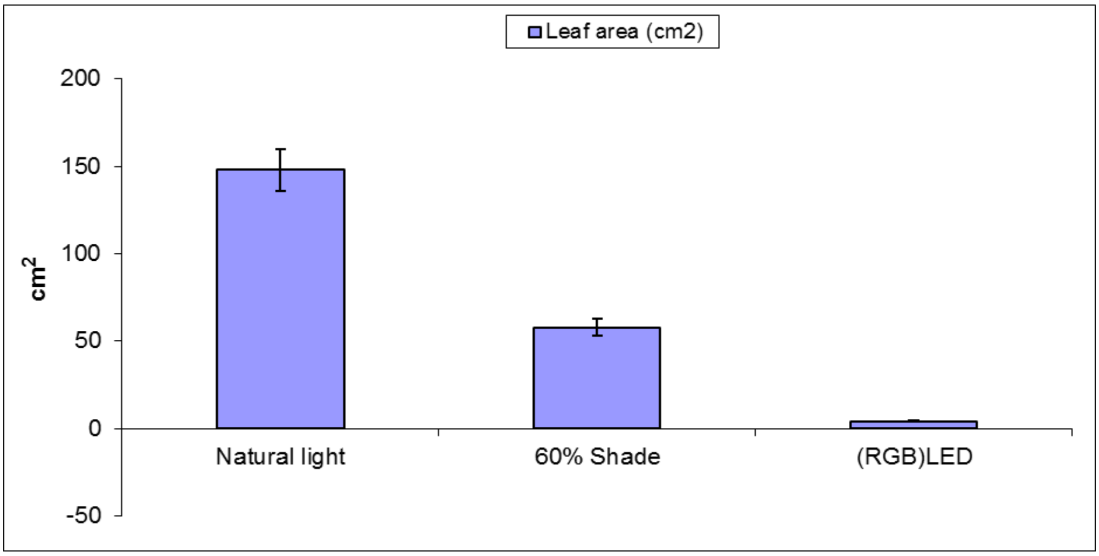


Figure 9: Leaf area (cm²) of lettuce under NL, 60% Shade and (RGB) LED treatment at harvest

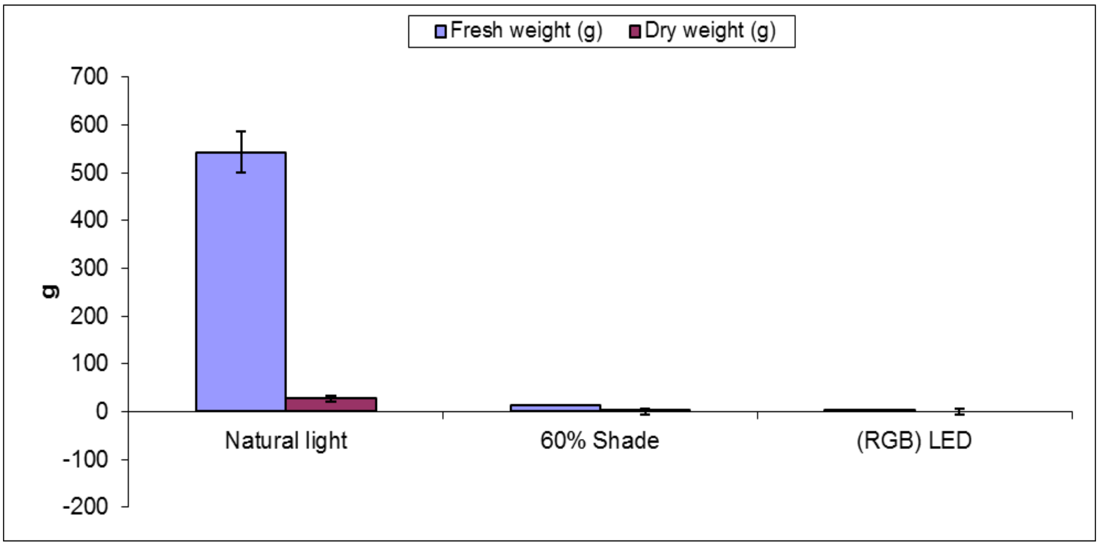


Figure 10: Fresh weight (g) and dry weight (g) of lettuce under NL, 60% Shade and (RGB) LED treatment at harvest

The lettuce planted in control row where three levels are exposed to natural light with the highest biomass, (FW, DW) in the upper level (616.33±78.07g, 32.74±4.56g) then follow it middle level i.e. (366.78±41.04g, 15.22±3.21g). While the least biomass in the lower level (237.90±47.16g, 9.45±1.33g). However, the leaf area in the mid-level was the highest value, follow upper then lower level, as shown in Table 6 and Fig. 11, 12.

Table 6: Leaf area (cm^2), fresh weight (g), and dry weight (g) of lettuce planted in control levels under natural light at harvest

Variable	Leaf area (cm^2)	Fresh weight (g)	Dry weight (g)
Level *p*-value	<0.0001	<0.0001	<0.0001
Upper level (C1)	167.62±52.90	616.33±78.07[a]	32.74±4.56[a]
Middle level (C2)	207.91±68.24	366.78±41.04[b]	15.22±3.21[b]
Lower level (C3)	99.34±41.54	237.90±47.16[c]	9.45±1.33[c]

NS Not significant at $p<0.05$. a,b,c means with different letters are significantly different at $p<0.05$

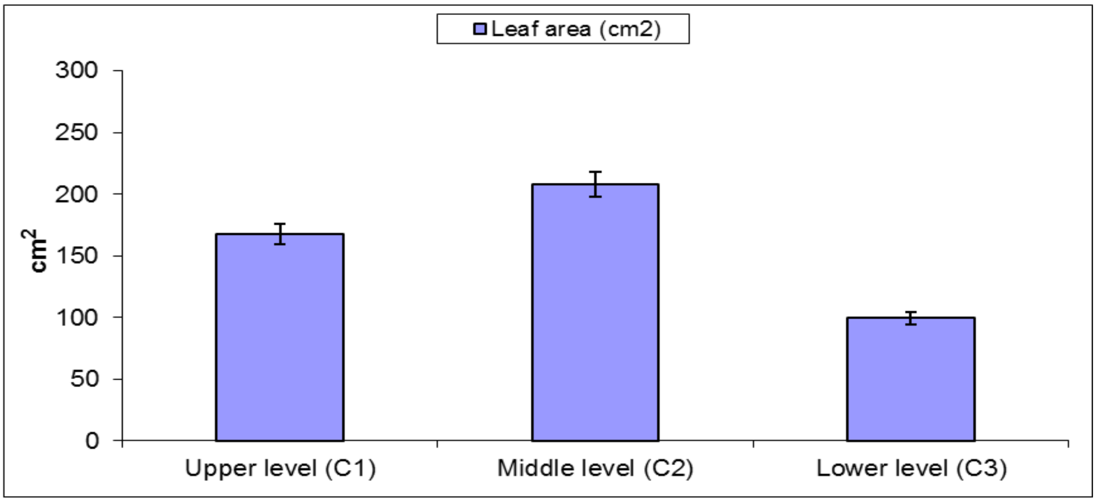


Figure 11: Leaf area (cm^2) of lettuce planted in control group under natural light at harvest

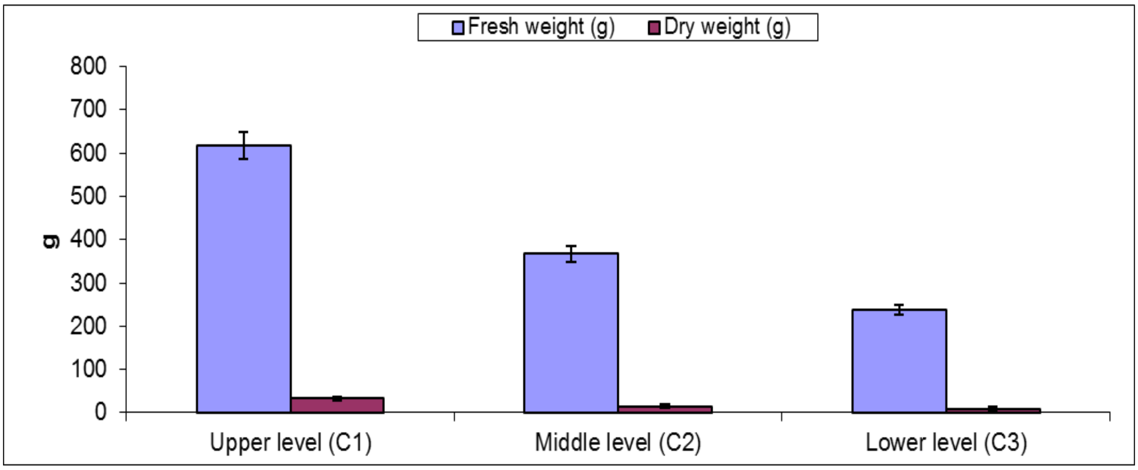


Figure 12: Fresh weight (g) and dry weight (g) of lettuce planted in control group under natural light at harvest

4.3 Chlorophyll and carotenoid contents

Fig. 13 indicates the chlorophyll and carotenoid contents of lettuce plants cultured with different lighting modes. The content of Chl a was approximately more than three times as much as that of Chl b irrespective of the various light treatments except (RGB) LED. Compared with 60% Shade, the content of chlorophyll a, chlorophyll b, total chlorophyll and carotenoid under NL were significantly increased by (1.14±0.15, 0.91±0.11, 0.24±0.04 and 0.50±0.06 mg/g) respectively. No values were detected under (RGB) LED light for the pigment contents mentioned above, as shown in Table 7.

Table 7: Chlorophyll and carotenoid contents of plants grown under different light treatments of NL, 60% Shade and (RGB) LED treatments at harvest

Variable	**Total Chlorophyll (mg/g)**	**Chlorophyll A (mg/g)**	**Chlorophyll B (mg/g)**	**carotenoid mg/g**
Treatment *p*-value	0.003	0.0031	0.0026	0.001
Natural light	1.14 ± 0.15^{a}	0.91 ± 0.11^{a}	0.24 ± 0.04^{a}	0.50 ± 0.06^{a}
Shade	0.46 ± 0.23^{b}	0.36 ± 0.18^{b}	0.10 ± 0.05^{b}	0.20 ± 0.10^{b}
LED	Not detectable	Not detectable	Not detectable	Not detectable

a, b means with different letters are significantly different at $p<0.05$

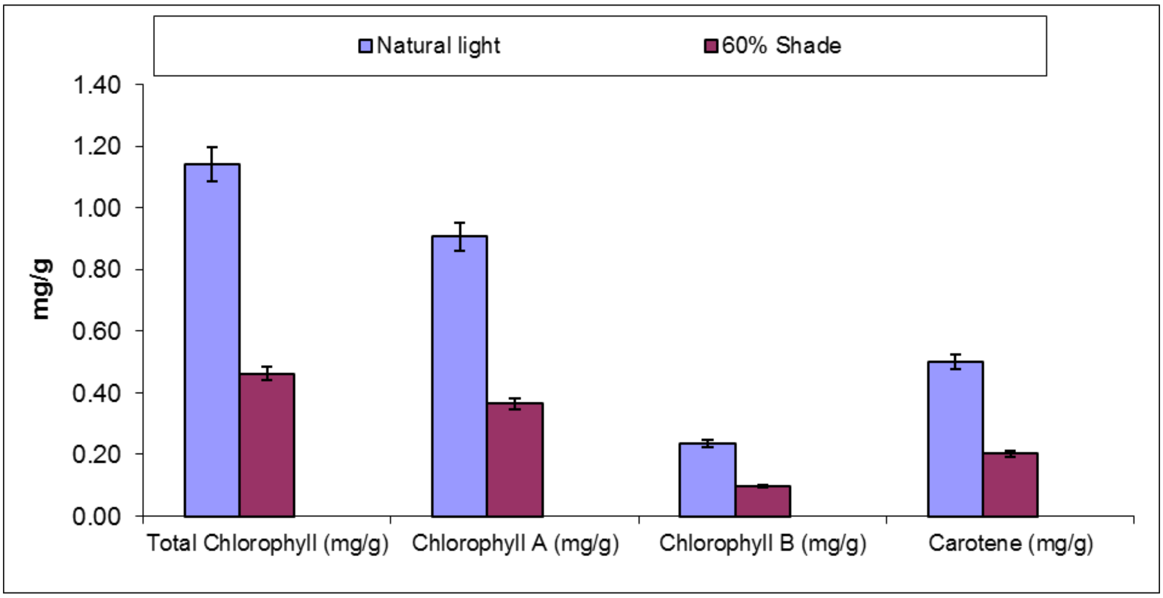


Figure 13: Chlorophyll and carotenoid contents of plants grown under different light treatments of NL, 60% Shade treatments at harvest

For the three levels of control, the content order of chlorophyll and carotenoid pigments was no significant difference as in the Table 8 and Fig. 14.

Table 8: Chlorophyll and carotenoid contents of control plants grown under NL at harvest

Variable	**Total Chlorophyll (mg/g)**	**Chlorophyll A (mg/g)**	**Chlorophyll B (mg/g)**	**Carotene mg/g**
Level *p*-value	NS	NS	NS	NS
Upper level (C1)	1.14±0.113	0.90±0.088	0.24±0.030	0.50±0.039
Middle level (C2)	1.16±0.058	0.90±0.053	0.25±0.008	0.50±0.049
Lower level (C3)	1.18±0.117	0.92±0.099	0.26±0.040	0.47±0.013

NS Not significant at $p<0.05$

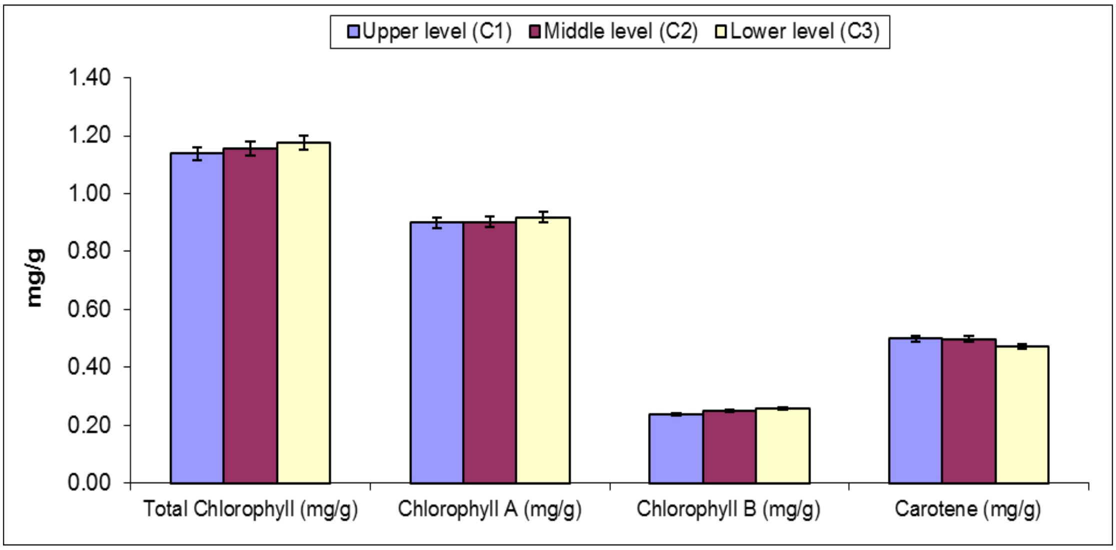


Figure 14: Chlorophyll & carotenoid contents of control group under natural light at harvest

4.4 Light intensity, temperature and relative humidity

The light intensity, temperature and relative Humidity of the treatments were measured three times a day for three days a week through the experiment and displayed in the Table 9.

Table 9: The light intensity, temperature and relative humidity of the NL, 60% Shade and (RGB) LED treatments

Variable	**Light intensity (LUX)**	**Temperature °C**	**Relative Humidity %**
Treatment *p*-value	0.0008	NS	NS
Natural light	77450 ± 31115^{a}	28.71±11.02	53.62±6.50
Shade	6223 ± 4796^{b}	27.22±2.13	53.96±6.34
LED	1420 ± 653^{b}	27.07±1.95	54.44±6.29

NS Not significant at $p<0.05$
a,b means with different letters are significantly different at $p<0.05$

The results showed that, very significant difference could be noticed among the light intensity values measured. The highest light intensity (77450±31115 lux) was noticed in the NL treatment, followed by 60% Shade treatment i.e. (6223±4796 lux), while light intensity of the (RGB) LED treatment recorded the lowest term i.e. (1420±653 lux). While the temperature and relative humidity was almost equal under all treatments as shown also in the Fig. 15.

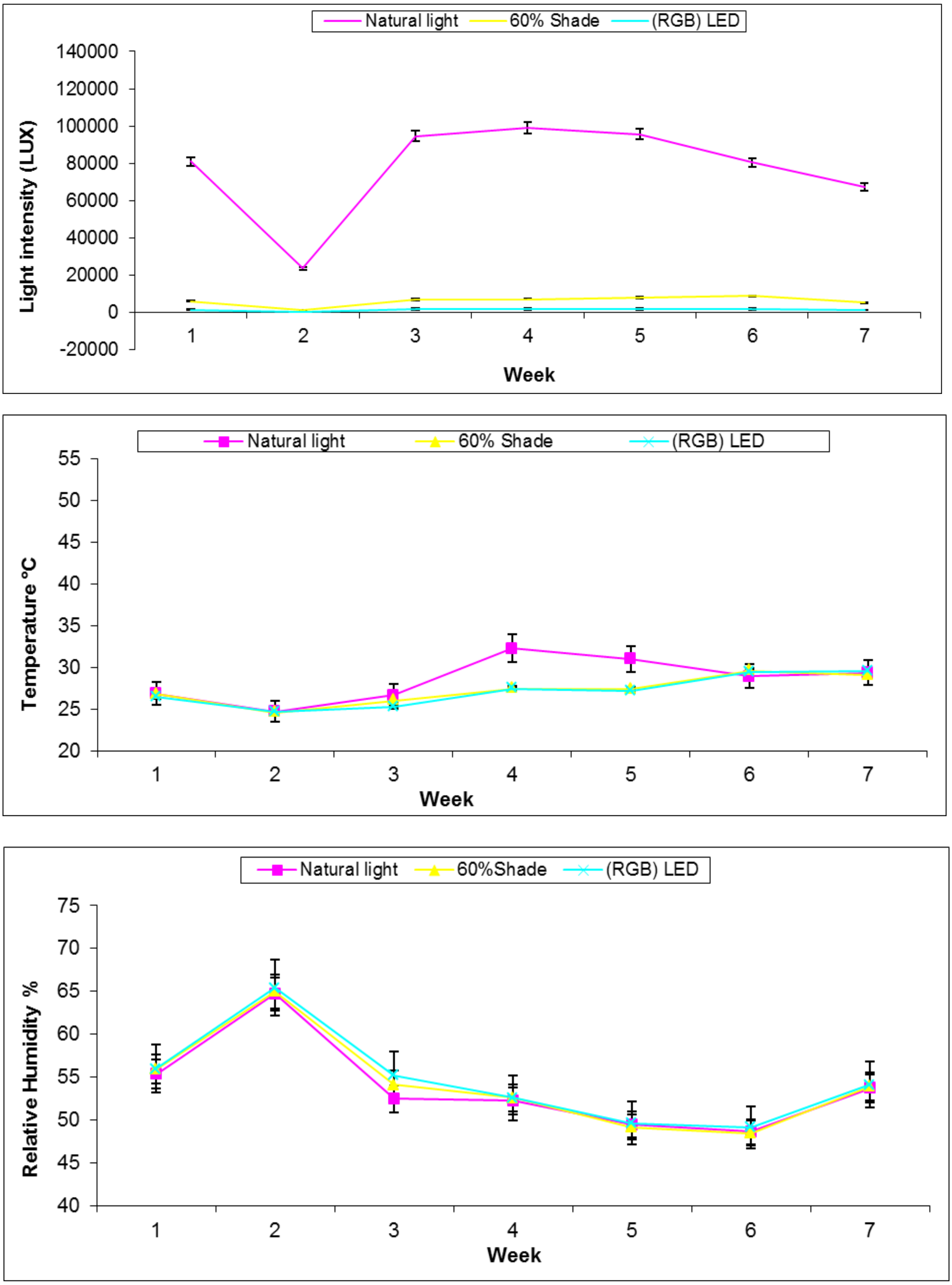


Figure 15: Light intensity, temperature and relative humidity of treatments for seven weeks

As well as control, the difference in intensity of light is clear between the three levels in the Table 10, where the intensity of the light is the highest in the upper level followed by the middle and then the lower level. While the temperature and relative humidity of approximately equal at all levels of control, as shown in Fig.16.

Table 10: Light intensity, temperature and relative humidity of control levels.

Variable	**Light intensity (LUX)**	**Temperature °C**	**Relative Humidity %**
Level *p*-value	0.0052	NS	NS
Upper level (C1)	93306±33467 [a]	28.65±2.22	51.24±6.56
Middle level (C2)	30161±11320 [b]	27.74±2.32	52.44±6.52
Lower level (C3)	18936±7308 [c]	27.67±2.31	53.54±6.34

NS Not significant at $p<0.05$. a,b,c means with different letters are significantly different at $p<0.0$

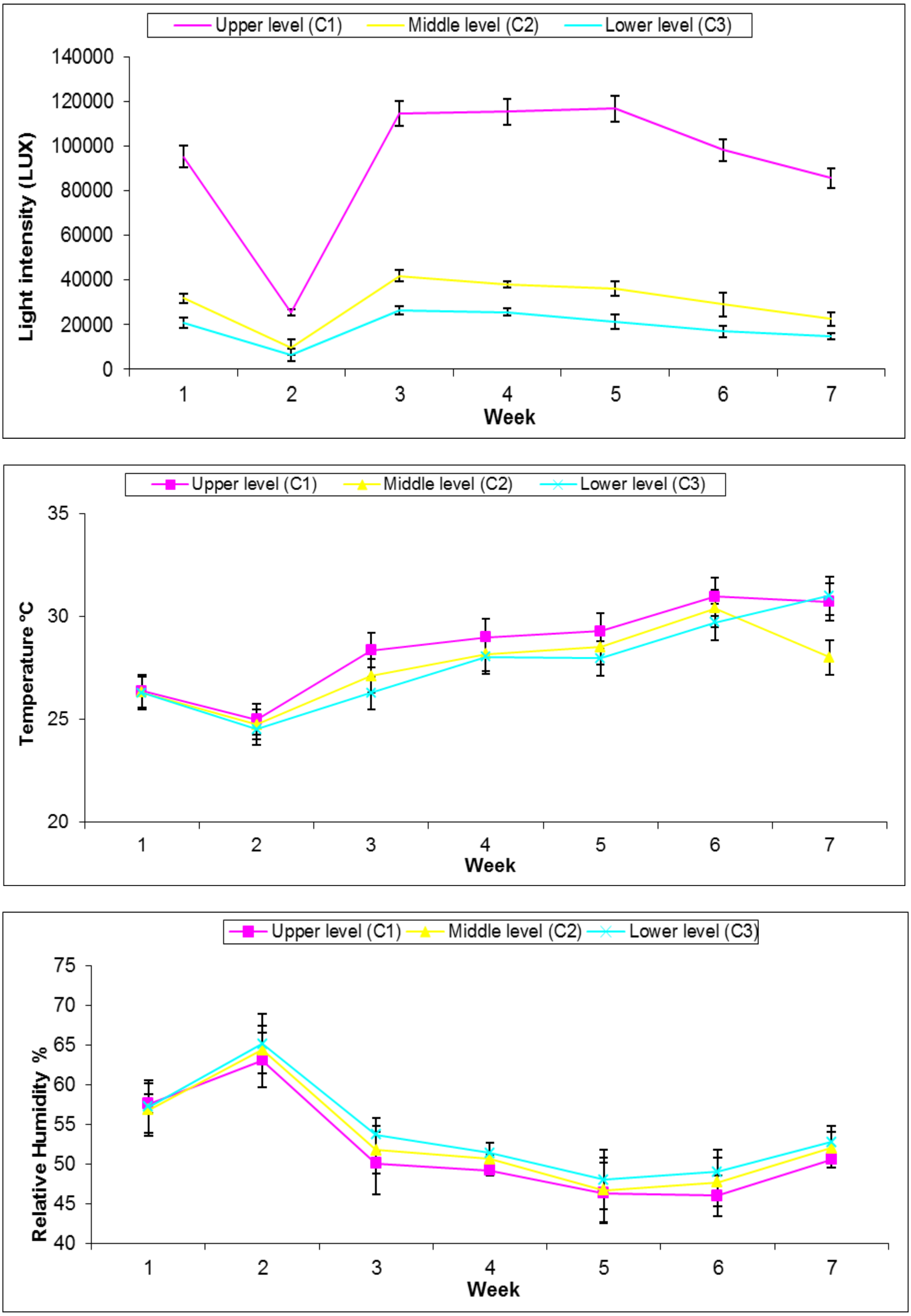


Figure 16: Light intensity, temperature and relative humidity of control levels for 7 weeks

4.5 Spectrometric measurements

Plants were exposed to different light spectra of the treatments (NL), 60% Shade, (RGB) LED, to measure the peak wavelengths of the light sources were determined with a spectrophotometer (model MK350N PREMIUM). The results are given in Table 11. The highest peak wavelength was 747 nm, at NL treatment in the range of infrared. Followed 552 nm, at (RGB) LED treatment, while the lowest peak wavelength was 552 nm at 60% Shade treatment. While the value and PPFD of the wavelengths were highest at the NL, followed 60% Shade and (RGB) LED treatments respectively as shown in Fig. 17. The values of Blue, Green and Red peak wavelengths of NL, 60% Shade and (RGB) LED of treatments are given in Table 12.

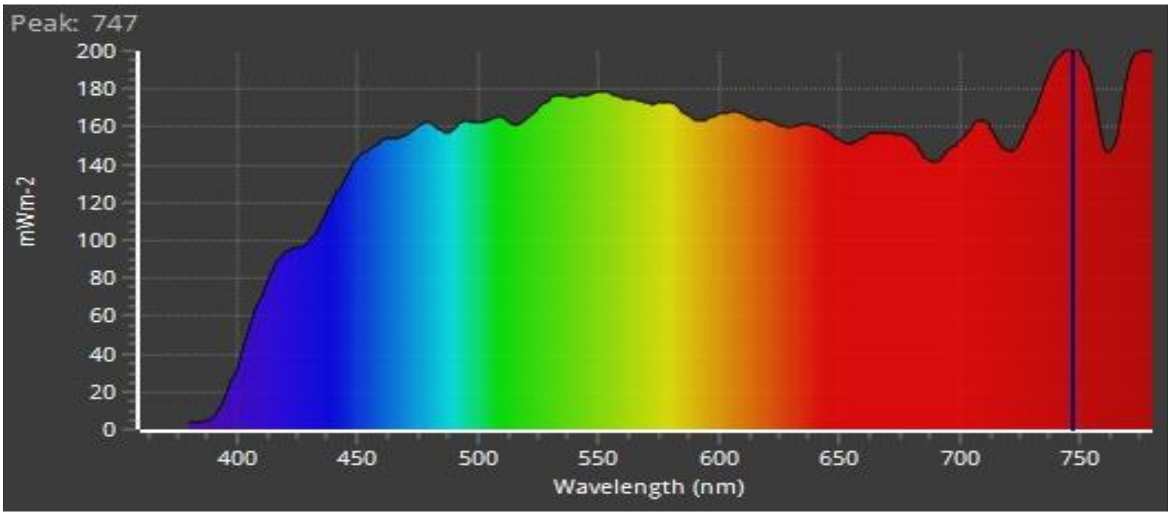
Table 11: Peak wavelength, peak wavelength value and PPFD of treatments

Variable	**peak wavelength (nm)**	**Irradiance (mW/m^2)**	**PPFD (µmol/m^2/s)**
Natural light	747 (Far-red)	201.7	212.3
60% Shade	533 (Green)	24.0	21.24
(RGB) LED	552 (Green)	16.10	18.68

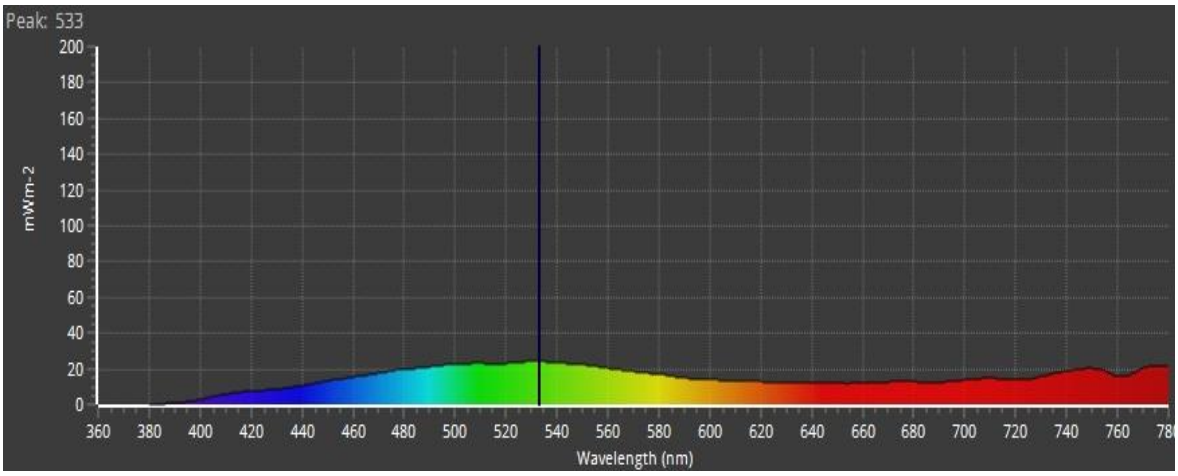
Table 12: Blue, Green and Red peak wavelengths and their values of NL, 60% Shade and (RGB) LED of treatments

Variable	**peak wavelength (nm)**			**Irradiance (mW/m^2)**		
Natural light	B (450)	G (550)	R (640)	B (140.7)	G (180.9)	R (150)
60% Shade	B (440)	G (533)	R (700)	B (10.0)	G (24.0)	R (13.5)
(RGB) LED	B (437)	G (552)	R (640)	B (8.0)	G (16.10)	R (15.0)

Natural light treatment



60% Shade treatment



(RGB) LED treatment

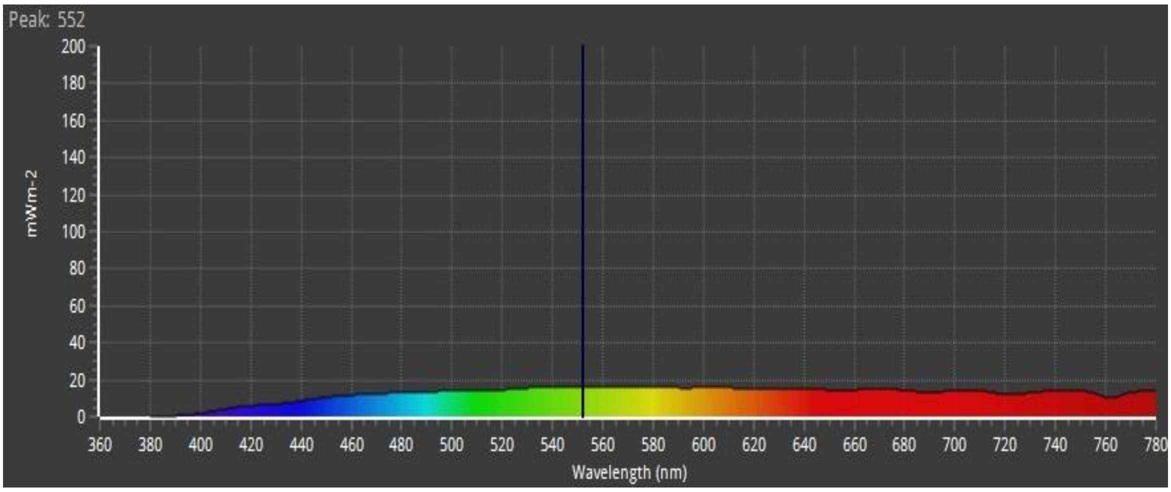


Figure 17: Peak wavelengths of natural light, 60% Shade and (RGB) LED treatments

The spectral distribution of the radiation at natural light, 60% Shade and (RGB) LED treatments with the highest peak wavelength was 747 nm at natural light treatment as shown in Fig. 18.

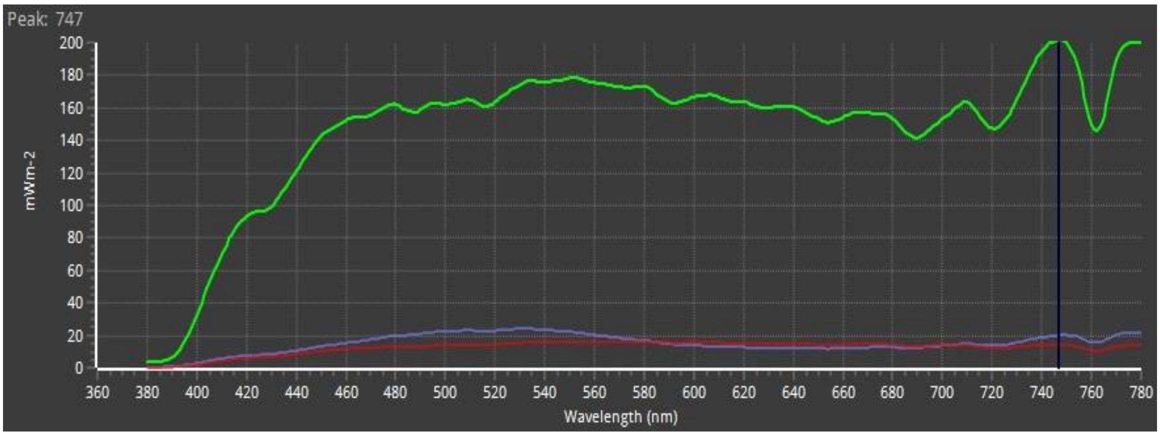


Figure 18: Spectral distribution of the radiation at natural light, 60% Shade and (RGB) LED treatments

Regarding the three levels of control, overall results indicate that, the upper level of control which was the nearest to the source of natural light, found significantly the highest value and PPFD of peak wavelength at 748 nm, followed was middle control at 777 nm, while the lowest value and PPFD of peak wavelength was lower control at 778 nm, Observed that, all peak values of control group in the range of infrared as shown in Table 13 and Fig. 19. The values of Blue, Green and Red peak wavelengths of control levels are given in Table 14.

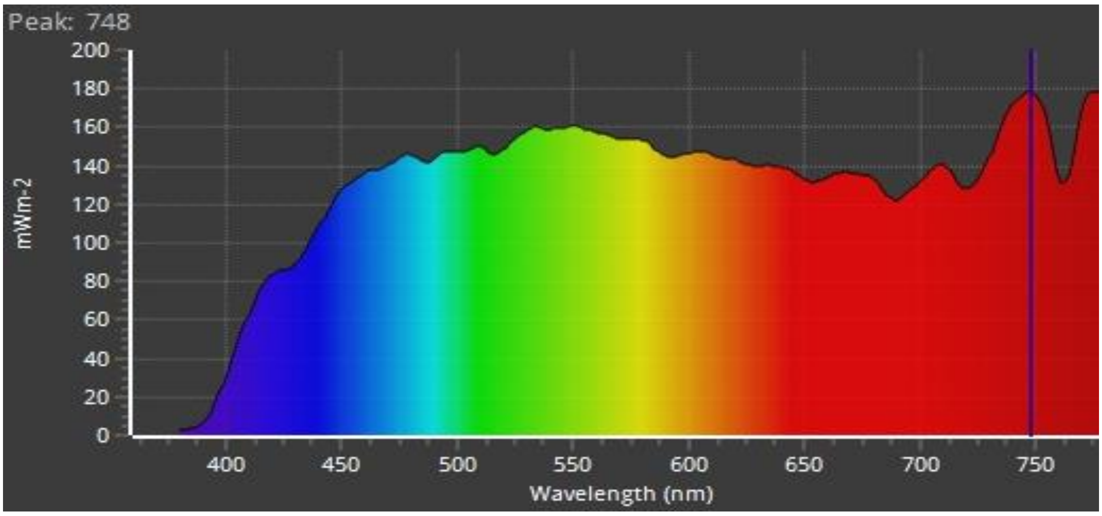
Table 13: Peak wavelength, peak wavelength value and PPFD of control levels

Variable	**peak wavelength (nm)**	**Irradiance (mW/m^2)**	**PPFD ($\mu mol/m^2/s$)**
Control (upper level)	748	187.9	188.3
Control (middle level)	777	108.2	111.3
Control (lower level)	778	71.60	59.20

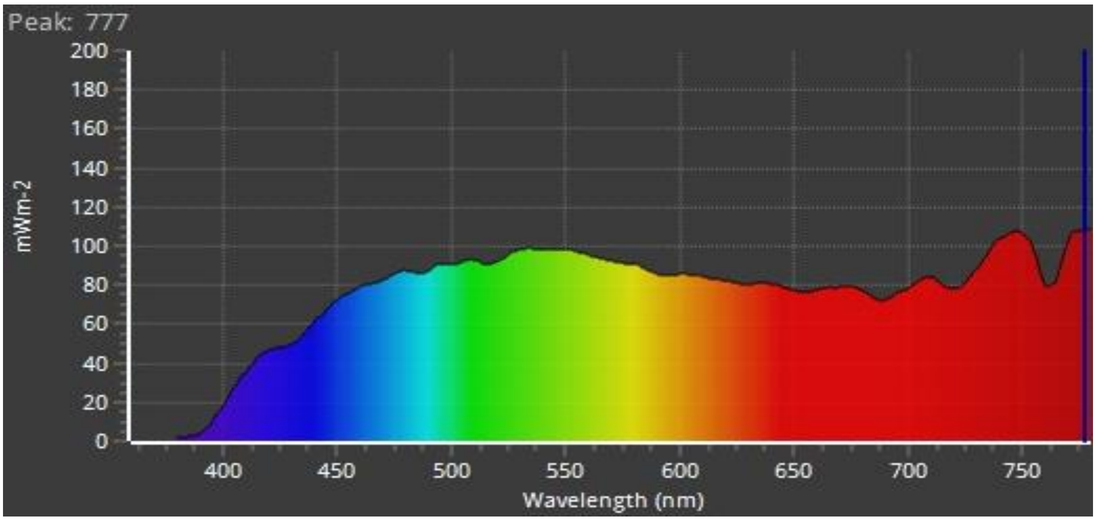
Table 14: Blue, Green and Red peak wavelengths and their values of control group

Variable	**peak wavelength (nm)**			**Irradiance (mW/m^2)**		
Control (upper level)	B (460)	G (550)	R (700)	B (100)	G (160)	R (145)
Control (middle level)	B (460)	G (550)	R (700)	B (75)	G (98)	R (80)
Control (lower level)	B (467)	G (550)	R (700)	B (40)	G (55)	R (45)

Control (upper level)



Control (middle level)



Control (lower level)

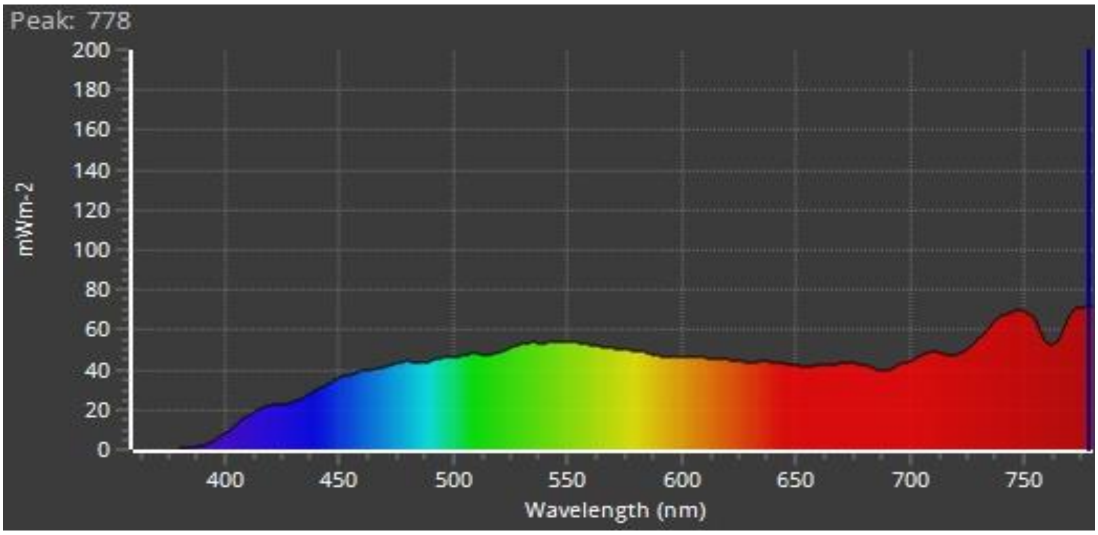


Figure 19: Peak wavelengths of control group

The spectral distribution of the radiation at control group with the highest value of peak wavelength at 748 nm at the upper control, as shown in Fig. 20.

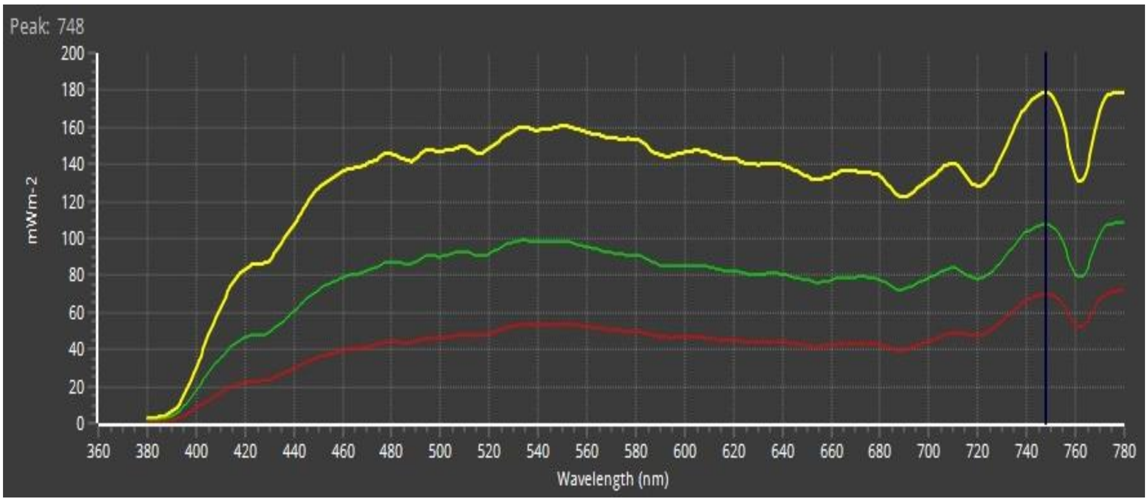


Figure 20: Spectral distribution of the radiation at control group

While when compared with outside of the greenhouse, the value of peak wavelength was (539.0 mW/m^2) and PPFD of peak wavelength was (680.1 µmol/m^2/s) at 581 nm as in Fig. 21.

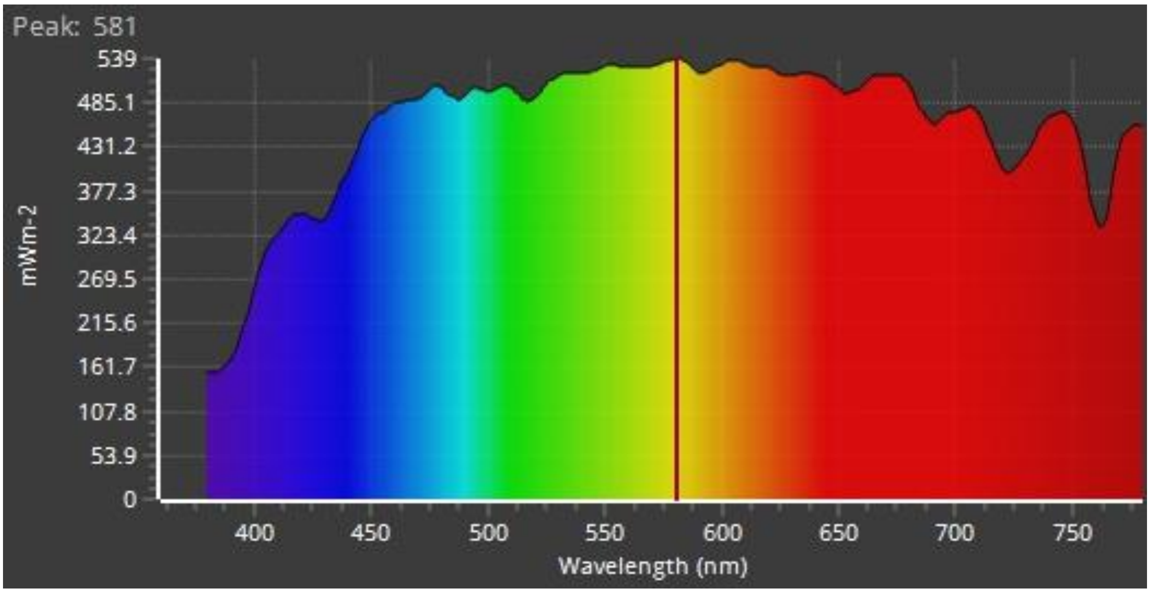


Figure 21: Peak wavelength of outside the greenhouse

4.6 PAR measurement

The PAR was measured 24 hours of each level in hydroponic system. The results for different radiation treatments showed that, the PPFD of NL treatment, which the nearest to the source of natural light was significantly highest i.e. 221.17±201.47 μmol/m^2/s. While 60% Shade treatment was significantly lower i.e. 10.80±7.45 μmol/m^2/s, followed by the (RGB) LED treatment i.e. 5.71±3.40 μmol/m^2/s, as showed in Table 15.

Table 15: PPFD (μmol/m^2/s) and accumulative PPFD (μmol/m^2/day) of NL, 60% Shade and (RGB) LED treatments

Variable	Natural light	60% Shade	(RGB) LED	Treatment P-value
Average PPFD (μmol/m^2/s)	221.17±201.47a	10.80±7.45b	5.71±3.40c	<0.0001
Accumulative PPFD (μmol/m^2/day)	185779.89	9073.07	4822.95	-

a,b,c means with different letters are significantly different at $p<0.05$

On the other hand, the cumulative PAR per day was also measured for treatments, the results were the NL treatment was significantly highest i.e. 185779.89 μmol/m^2/day, followed by the 60% Shade i.e. 9073.07, while the significantly lowest 4822.95 μmol/m^2/day at (RGB) LED treatment, as shown in Table 15 and Fig. 22.

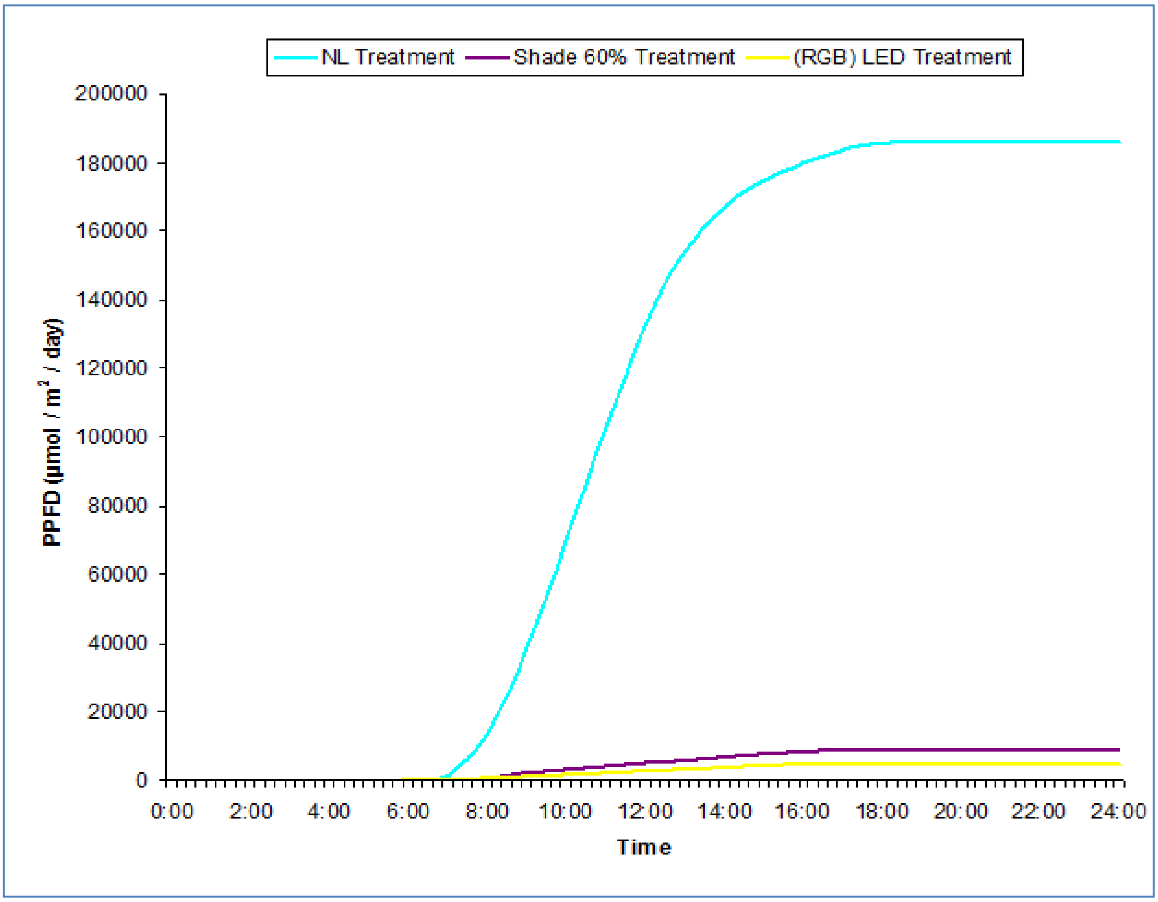


Figure 22: Cumulative PAR (µmol/m^2/day) of NL, 60% Shade and (RGB) LED treatments

Also, the PPFD (µmol/m^2/s) of the PAR was measured 24 hours of each level of control in hydroponic system. The three levels of control exposed to natural light, where the light intensity decreased gradually from top to bottom. Thus, as we expected, the results showed that, the upper level of control was the highest PPFD i.e. 340.56±261.40 µmol/m^2/s, while the lowest PPFD at the lower control, which was the most far from the source of natural light i.e. 74.22±55.29 µmol/m^2/s, as showed in Table 16.

Table 16: PPFD (µmol/m^2/s) and a cumulative PPFD (µmol/m^2/day) of control levels

Variable	Upper level	Middle level	Lower level	Treatment *p*-value
Average PPFD (µmol/m^2/s1)	340.56±261.40a	107.36±77.54b	74.22±55.29c	<0.0001
Accumulative PPFD (µmol/m^2/day)	286072.51	90182.51	62341.07	-

a,b,c means with different letters are significantly different at p<0.05

The cumulative PAR per day was also measured for control group and the result showed the upper level was the highest i.e. 286072.51 µmol/m^2/day, followed by the middle level i.e. 90182.51, while the lower level was 62341.07 µmol/m^2/day, as shown in Table 16 and Fig. 23.

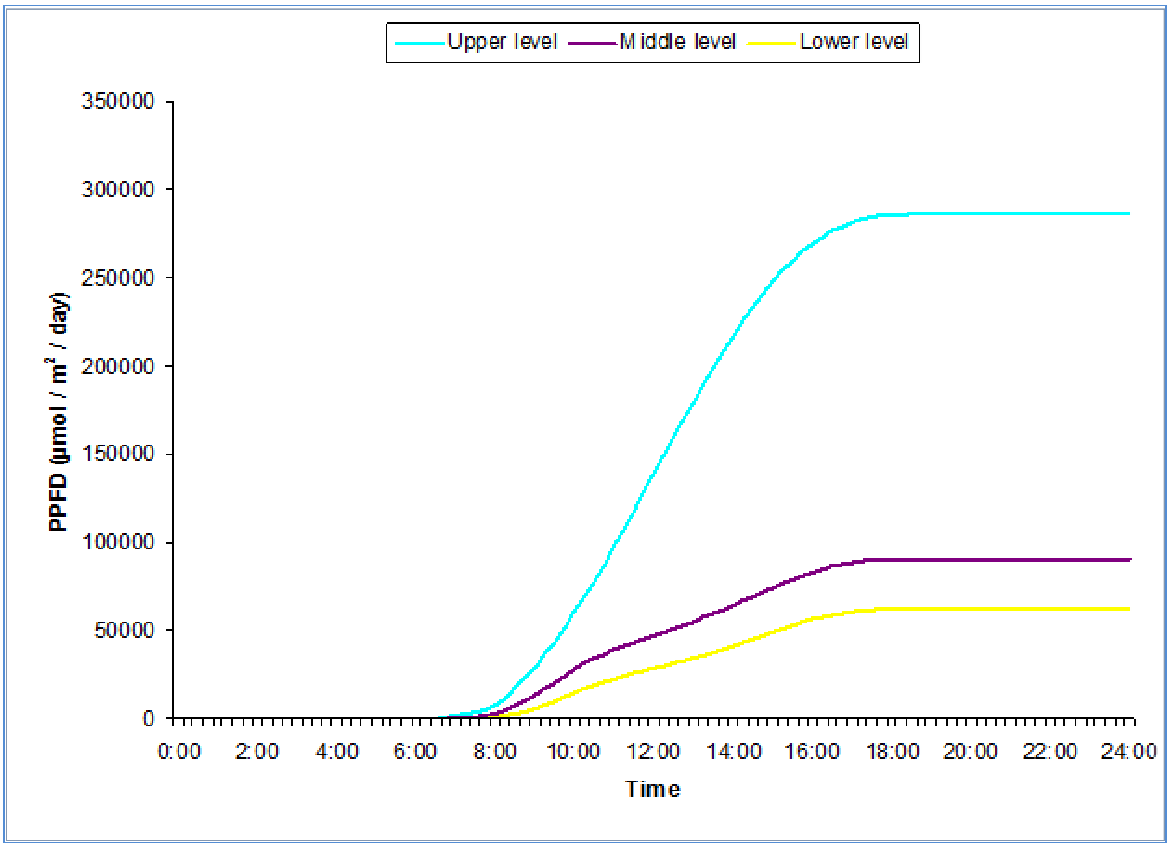


Figure 23: Cumulative PAR (µmol/m^2/day) of control levels

Chapter 5: Discussion

The present study examined the effects of different light systems namely Natural light, Shade 60% and (RGB) LED were compared by growing the yield and quality of lettuce (*Lactuca sativa crispa. "Lollo bionda"*) on vertical hydroponic system, grown under the same climate conditions in the greenhouse. Lettuce *(Lactuca sativa)* is found to be the most cultured vegetable in hydroponic system. This is due to its easy adaptation to this system, which has been showing high productivity in cycle compared with the soil cultivation (Cometti et al., 2013). Also, the use of vegetable such as lettuce should be a standard practice in most greenhouses that contain hydroponics (Dougher and Bugbee, 2001).

The plant length, width and number of leaves were measured once every 7 days, through six weeks of the experiment. At 6^{th} week, in terms of length of lettuce plant under NL and 60% Shade treatments showed only a slight variation i.e. 24.29±0.87 cm, 22.75±2.43 cm respectively, in spite of the significant different value PPFD were i.e. 221.17±201.47, 10.80±7.45 μmol/m^2/s respectively. Jaimez and Rada (2006) stated that the PAR at full insolation (1519 μmol/m^2/s) is lowered to 931 μmol/m^2/s when shaded to 40% PAR, and to below 550 μmol/m^2/s when shaded to 60% PAR. It is interesting to note that, the principal reason for this result may be due to the high light intensity limits the elongation of the plant stem, while low light intensity due to the use of 60% Shade in our experiment enhances the length. For example (Wang and Folta, 2013) indicate that, the high light causes a rapid cessation of elongation in the development of the seedling to adopt a strategy of vegetative aerial growth appropriate for the light environment. Moreover, lower intensities of light enhance the elongation of stem, the highest values were found in the lettuce plants cultivated under red color nets (97 mm), while the control lettuce showed stem length of (60 mm) (Ilić et al. 2017b). Jenni et al. (2013) reported that a shorter stem length indicates higher quality for crisphead lettuce. As for the LED treatment our experiment, three colors (Red, Green, and Blue) of light-emitting diode (LED) lights, with different wavelengths were used to investigate the effect of them on lettuce growth, the distance between LED panels and plant canopy was 40 cm. Also, the photoperiod at the lower three replicates levels exposed to LED were set to (12/12) hour. The use of LEDs in horticultural production with different benefits (Massa et al., 2008; Morrow, 2008). According to several researchers, (Hoenecke et al., 1992; Lian et al., 2002; Nhut et al., 2003; Lee et al., 2007), which has a long wavelength, promoted stem and leaf elongation. Blue light suppresses hypocotyl elongation and induces biomass production, which has a short wavelength, suppressed stem elongation (Kim et al., 2004a; Folta, 2004; Ohasi-Kaneko et al., 2007). In our experiment, the result was the length of the lettuce plant under LED treatment was significantly lower i.e. (7.75±2.48 cm), where the light intensity was the lowest by PPFD (5.71±3.40 μmol/m^2/s). One reason for this result may be was the low of light intensity and the second reason may be that distance between LED panels and plant canopy was 40 cm, which means it was a great distance between seedlings and light source.

As for the plant width and leaves number, were significantly high in plants grown under NL treatment i.e. 24.88±0.78 cm, 22.75±0.76, than 60% Shade treatment i.e. 7.92±2.04 cm, 7.83±0.81 and (RBG) LED treatment i.e. 1.42±0.45 cm, 3.17±0.98. Consequently, the Light intensity decreasing significantly from top to base of vertical levels within the vertical hydroponics in different light systems, led to deterioration of quality the parameters of the yield from top to base.

While the other plant growth parameters of lettuce reported at harvest, represented in the leaf area, fresh weight and dry weight. Many vegetable species present leaf and stem morphological and physiological adaptations in response to Shade. Although plants grown in the Shade to have larger leaf areas, because cells expand more under low light intensities in order to increase photosynthesis. Ilic et al. (2017b) found that all Shade nets significantly increase the leaf area index. The overall results indicate the NL treatment was 147.91±10.65 cm^2 better in terms of leaf area when compared to 60% Shade treatment i.e. 57.87±15.74 cm^2. (Rajapakse and Shahak, 2007) suggest a shading rate of 30% or less, instead of 40%, as a way to limit the impact on vegetable development caused by excessive shading. In our experiment the reason for this result was the shading rate, the use of Shade rate 60% has limited the growth of lettuce and this is clear from the inability of the leaves under the Shade used by the extension to get enough light to complete photosynthesis process. Regarding to (RGB) LED, in many experiments which confirmed that, the plant development and physiology are strongly influenced by Blue, Red and Green industrial light (Li et al., 2010; Hogewoning et al. 2010; Johkan et al., 2012). Red light induces hypocotyl elongation and expansion in leaf area (McNellis and Deng, 1995; Johkan et al., 2010). Also (Kim et al., 2004b) reported that, the higher leaf area under RB light is a good indicator of higher photosynthetic surface area per unit investment in leaf tissue. G light also affects plant morphology and physiology, including leaf growth, stomatal conductance and early stem elongation (Folta, 2004; Kim et al., 2004a; Kim et al., 2004b). However, the result in our experiment was unexpected; the leaf area of the lettuce plant exposed to LED at the lower level of vertical hydroponics was the least value i.e. 3.94±1.66 cm^2. This may be because light intensity of LED treated was significantly lower than 60% Shade and Natural light-treated, which has compromised the photosynthesis.

The result showed that, the fresh weight of the lettuce shoots significantly decreased with (RGB) LED treatment i.e. 0.89±0.42 g. Where NL treatment was the highest i.e. 542.52±30.48 g, probably due to the enlarged leaf area as a result of high PAR value. The larger leaf allowed greater light interception, which may have led to the significant increase in biomass. While 60% Shade treatment was 13.00±2.19 g. These results indicate that NL-treated plants exhibited puffiness, large and vigorous shoot structure, while the shoot structure of Shade and LED-treated plants had a small and weak appearance, but observations of the growth and morphological features indicated that LED treatment was deleterious or adversely affected plant performance. Reductions in the lettuce biomass under Shade and LED treatments suggest that light intensity can alter growth, decrease the mean weight of lettuce.

Yorio et al. (2001) reported that, there was high dry matter weight accumulation in lettuce grown under R LED supplemented with B LED than in lettuce grown under R LED. Red and blue LED irradiation with green light from fluorescent lamps increased the production (Kim et al. 2004b). However, shoot dry weight of leaf lettuce plants under 60% Shade treatment decreased significantly i.e. (0.35±0.07 g) compared with the NL treatment i.e. (27.39±1.78 g).

The overall previous results indicate the unevenness in the treatments was caused by the differences in the light environment and as expected that photosynthesis rate under a certain light quality influences the parameters of lettuce plant. Consequently, it was noticed that the leaves of plants under the natural light conditions had a significantly higher values in all parameters when compared to planting under 60% Shade and (RGB) LED.

On the other hand, where the lettuce plant was cultured in control in three levels of vertical hydroponics and exposed to natural light were no significant. Also, it can be said that the parameters of lettuce in the upper level of control and in the NL treatment seem almost the same, were no significant difference. Whilst, the significant difference exists between the middle and lower levels of control and the 60% Shade, (RGB) LED treatments. Also, a difference exists in parameters of lettuce between the control groups in the three levels. The impact of solar natural radiation on the control levels of all parameters was observed. Light gradients from top to base of vertical systems in strawberry was reported earlier (Ramírez- Gómez et al., 2012). Light intensity is known to decrease with light source increases (Poorter et al., 2012). Our Results showed that, although the natural light intensity decreased significantly from top to base of vertical hydroponics, where in the upper level was PPFD 340.56±261.40 μmol/m^2/s, in the mid-level was PPFD 107.36±77.54 μmol/m^2/s, and in the lower level was PPFD 74.22±55.29 μmol/m^2/s.

However, the parameters which comprise length, width and leaves number, no significant difference in was observed in the three levels, which means that, the quality and intensity of light was sufficient in the three levels of control to satisfy plant needs. Leaf area of the lettuce seedlings was benefited from natural light intensity under the control in the three levels which exposed to natural light with hydroponically where the values of leaf area in the three levels of control were high. Moreover, the results revealed greater leaf area for control plants cultivated in the mid-level i.e. 207.91±68.24 cm^2, compared to plants grown in the upper level which is characterized by high natural light intensity was 167.62±52.90 cm^2, The principal reason for this result may be due to the leaves of lettuce in the middle level, had the ability to expand to catch more light to complete photosynthesis process, therefore led to increase of leaf area. Whereas plants leaves cultivated in the lower level were smaller, where the natural light intensity was the lowest in the control. Also, the result showed that, natural light intensity influenced growth in the control. There was a significant positive relationship between shoot fresh weight, dry weight and PPFD in the vertical hydroponics, indicating that as light intensity in the PAR range increased so did crop productivity.

In the experiment, there was significant difference among the photosynthetic pigments, where the chlorophyll a, b, (a + b), and carotenoid contents higher in the lettuce under the NL treatment than 60% Shade treatments. However, in the studies conducted by Dong et al. (2014) and Manivannan et al. (2015) on *Triticum aestivum* and *R. glutinosa*, respectively, the best effect on chlorophyll synthesis was found for red LED light. Green light can stimulate photosynthesis deep in the canopy providing to carbon gain, especially within shaded canopies (Smith, 1994). While, the results showed the three LED colors inhibited the chlorophyll and carotenoid synthesis in lettuce plantlets, where the photosynthetic pigments not detectable under (RGB) LED treatment. Definitely, the applied light level in LED treated had reached a certain minimal light intensity, which is not enough for activity of photosynthetic pigment.

On the other side, the Chl a, Chl b, Chl (a + b), and Car contents in the leaves of three control levels did not statistically differ among them, where all have high values and approximately similar the pigment values of lettuce leaves under NL treatment. Observe that, the top level of the control received similar PPFD to all the three replicates of NL treatments. However, within the vertical three levels of control, as distance from the light source increased, there was a significant drop in PPFD values within the vertical hydroponics. This refers to the main role of natural light intensity quantity and quality which was availability in the NL treatment and control levels.

The results showed that the temperature and relative humidity at all levels of treatments and control group were approximately similar through 7 weeks, where were in the mean 27.22±2.13 °C, 53.62±6.50%. Beside temperature, lettuce production also depends on light properties (Dufault et al., 2009), light quality and light intensity (Ilić and Fallik, 2017). while the intensity of the light was significantly different in term of 77450±31115 lux at NL treatment to 6223±4796, 1420±653 lux respectively at 60% Shade and (RGB) LED treatments.

As for the control group, the light intensity was significantly reduced from the upper level which was closest to the solar natural light source, to the lower level, i.e. from 93306±33467, to 18936±7308 lux. Although the light intensity of the control group was significantly decreased, the parameters and pigments values were high, as in the NL treatment which exposed also to solar natural light. This means that, the light intensity was suitable for the lettuce growth in the control group and NL treatment. Our results confirm emphasize that, for the same temperature, and relative humidity, the impact of light intensity enhanced lettuce growth. This fact is important when selecting the cultivation vertical hydroponics system in greenhouses.

In the experiment, to measure the spectral distribution of the radiation, spectrometer (model MK350N PREMIUM) was used. The result showed, the 400–700 nm of wavelengths were available in all levels of the experiment with variable intensity. The most important part of the light spectrum is 400–700 nm which is known as photosynthetically active radiation (PAR). Although the blue, green and red wavelengths were in the range of spectral distribution of the radiation in NL, 60% Shade and (RGB) LED treatments, however, the difference in the intensity spectra radiation of wavelengths was the main reason of the difference in the growth and development of lettuce seedlings under each treatment. In the experiment, the value of peak wavelength irradiance (201.7 mW/m^2) and PPFD (212.3 $\mu mol/m^2/s$) at (747 nm) NL treatment which exposed to solar natural light, where the highest values of parameters and pigments. While (533 nm) at 60% Shade treatment the peak wavelength irradiance value (24.0 mW/m^2) and PPFD (21.24 $\mu mol/m^2/s$). The peak emissions of the B (454 nm) and R (660 nm) LEDs closely coincide with the absorption peaks of chlorophylls a and b, and the reported wavelengths are at their respective maximum photosynthetic efficiency (McCree, 1972). In this study, (552) at (RGB) LED treatment the peak wavelength irradiance value (16.10 mW/m^2) and PPFD (18.68 $\mu mol/m^2/s$) which produced the significantly lowest yield of lettuce.

On the other hand, the three levels of control which exposed to solar natural light and had the values of yield quality parameters and pigments high. The results showed that, the intensity of spectra radiation decreased from upper to lower level, where the irradiance and PPFD decreased from 236.4 mW/m^2, 141.1 $\mu mol/m^2/s$ to 71.60 mW/m^2, 59.20 $\mu mol/m^2/s$. This explained that, the greater the distance from light source, the less intensity of the spectra radiation.

Spectral light intensity affects photosynthesis (Singh et al., 2015). Wu et al. (2007) studied the effect of variable light intensities on the quality of broccoli shoots and they suggested that transition from high (350 $\mu mol/m^2/s$) to low (41 $\mu mol/m^2/s$) light intensities may increase carotenoids, glucosinolates, macro and micronutrients contents. In the experiment the impact of PAR on the different treatments was investigated. The expected result was found, significant differences were observed for the values of parameters and pigments. The NL treatment was highest in parameters and pigments values of lettuce subjected to the highest PAR dose (221.17±201.47 μmol/m^2/s) when compared to the lower PAR dose (10.80±7.45 μmol/m^2/s) 60% Shade, and lowest PAR dose (5.71±3.40 μmol/m^2/s) (RGB) LED. The principle reasons were the lettuce seedlings exposed to natural light at the upper level had taken a sufficient dose of PAR, led to a high-value lettuce yield of parameters and pigments. Light intensity affects the quality not only of leafy but also fruit vegetables. While 60% shading rate in the middle level appeared high, where insufficient PAR dose reached to the lettuce seedlings, resulting in poor production of lettuce, where the values of growth parameters were low. Kläring and Krumbein (2013) indicated that reducing light intensity decreased growth and yield of tomato plants, as well as β-carotene. Although the blue, green, and red wavelengths were available in LED plates, the significant lowest of parameters and pigments values of lettuce seedling recorded under (RGB) LED treatment, which the lowest PAR dose recorded compared with the other treatments. Perhaps the reason was the number of panels was insufficient, which in the experiment used a single panel with 1 cm width, while the width of each Rock wool slab, which includes 4 lettuce seedlings was 20 cm. The second reason was the distance between the LED panel and the lettuce seedlings was high (40 cm).

Knowing that, the top level of the control received similar PPFD to all the three replicates NL treatments. However, within the vertical three levels of control, as distance from the light source increased, there was a significant drop in PPFD values within the vertical hydroponics, where decreased the PAR dose from the upper level (340.56±261.40 μmol/m^2/s) to the lower level (74.22±55.29 μmol/m^2/s), while the results showed approximality similar in high values of parameters and pigments in three levels of control. This means that, the PAR dose emitted from natural light was sufficient even at the lower level of control to obtain high-quality yield of lettuce similar to upper level.

Our results clearly demonstrate that, control group compared to treatments, PPFD from 74.22±55.29 μmol/m^2/s to 340.56±261.40 μmol/m^2/s, the parameters and pigments values of lettuce plants were better. Meanwhile, the yield of lettuce was higher. More important, in our research, we found that there was no substantial gain from a PPFD above 74.22±55.29 μmol/m^2/s at lower level of control.

Chapter 6: Conclusion

The final goal of our project is to determine the best light system optimized for vegetable production in vertical hydroponics. In the present study, we investigated the effective light with sufficient intensity for growing healthier lettuce plants more rapidly. Based on this study, it appears that the Natural light treatment resulted in many positive effects on growth, development, nutrition and appearance of lettuce plants.

In fact, results in our study showed that optimized indices of lettuce such as higher yield or higher pigments value could be generated by solar natural irradiation without use one panel of (RGB) LED or 60% Shade treatments.

The lettuce cultivation using the vertical hydroponic system can produce in greenhouse through winter season which low temperature and solar natural radiation is available in UAE. This research is being conducted with the purpose to provide an effective alternative method of lettuce production. This system can provide a breakthrough for agriculture in the UAE, once the method of lettuce production in multi-tier hydroponic system is standardized.

Conclusions and recommendations

1. Lettuce performed better under natural light than the 60% Shade and (RGB) LED, while it was not different in the three vertical levels of control.

2. There was no significant difference between NL treatment and the upper level of control group which all exposed to solar natural light.

3. Natural light is still the best source of radiation in terms of light quality and intensity, and it is available without charge.

4. The low PPFD in the 60% Shade (21.24 $\mu mol/m^2/s$) and LED (18.68 $\mu mol/m^2/s$)

treatments, induced lower health parameters for lettuce plant, indicating that low PPFD at these values were not suitable for lettuce growth.

5- There was no substantial gain from a PPFD above (74.22±55.29 μmol/m^2/s) at lower level of control group.

6. The addition of LED light panels and decrease the Shade percentage may will lead to further increased plant growth.

7. Vertical Hydroponics system should be evaluated according to its water and energy use efficiency.

References

Abidi F, T. Girault, O. Douillet, G. Guillemain, G. Sintes, M. Laffaire, N. Leduc 2013. Blue light effects on rose photosynthesis and photomorphogenesis. Plant Biol., 15 (1) , pp. 67-74.

Ahmad M. 2002. Action spectrum for cryptochrome-dependent hypocotyl growth inhibition in Arabidopsis. Plant Physiol., 129, pp. 774-785.

Alados I, I. Foyo-Moreno, L. Alados-Arboledas, 1996. Photosynthetically active radiation: measurement and modeling. Agricultural and Forest Meteorology, 78, pp. 121-131.

Allende A, B. Martínez, V. Selma, M.I. Gil, J.E. Suárez, A. Rodríguez 2007. Growth and bacteriocin production by lactic acid bacteria in vegetable broth and their effectiveness at reducing Listeria monocytogenes in vitro and in fresh-cut lettuce. Food Microbiology, 24 (7–8), pp. 759-766.

Anderson T.S., M.R. Martini, D. Villiers, and M.B. Timmons, 2017. Growth and tissue elemental composition response of Butterhead lettuce (Lactuca sativa, cv. Flandria) to hydroponic conditions at different pH and alkalinity. *Horticulturae*, *3*, p.41.

Appling S.M. 2012. Colored Shade Cloth Affects the Growth of Basil, Cilantro, and Parsley. M.S.c. Thesis. Polytechnic Institute and State University, Blacksburg, Virginia.

Baroli I, G. Price, M. Badger, S. Caemmerer 2008. The contribution of photosynthesis to the red light response of stomatal conductance. Plant Physiol, 146, pp. 737-747.

Bergquist S. 2006. Bioactive Compounds in Baby Spinach (Spinacia Oleracea L.). Effects of Pre − and Postharvest Factors. Doctoral Dissertation. Swedish University of Agricultural Sciences, Alnarp, Sweden.

Berkovich Yu.A, I.O.Konovalova , S.O.Smolyanina , A.N.Erokhin , O.V.Avercheva , E.M.Bassarskaya, G.V.Kochetova, T.V.Zhigalova, O.S.Yakovleva , I.G.Tarakanov 2017. LED crop illumination inside space greenhouses. Reviews in Human Space Exploration 6, Pages 11-24.

Bewley J. D. and M. Black 1994. Seeds: Physiology of Development and Germination. (2nd ed.), Plenum Press, New York, USA.

Breda N.J., 2003. Ground-based measurements of leaf area index: a review of methods, instruments and current controversies. J. Exp. Bot., 54 (392), pp. 2403-2417.

Brown C.S, A.C. Schuerger, J.C. Sager 1995. Growth and photomorphogenesis of pepper plants under red light-emitting diodes with supplemental blue or far-red lighting. J. Am. Soc. Hortic. Sci., 120, pp. 808-813.

Caldwell C.R., 2003. Alkylperoxyl radical scavenging activity of red leaf lettuce (Lactuca sativa L.) phenolics. J. Agric. Food Chem., 51, pp. 4589-4595.

Carvalho R.F, M. Takaki, R.A. Azevedo 2011. Plant pigments: the many faces of light perception. Acta Physiol. Plant., 33 (2), pp. 241-248.

Chen J.M. and T.A. Black 1992. Defining leaf area index for non-flat leaves Plant Cell Environ., 15, pp. 421-429.

Chen J.M., J. Liu, J. Cihlar, M. Goulden 1999. Daily canopy photosynthesis model through temporal and spatial scaling for remote sensing applications. Ecol. Model., 124, pp. 99-119.

Chen H., M. Cao, J.M. Baskin, C.C. Baskin 2013. Temperature regulates positively photoblastic seed germination in four Ficus (Moraceae) tree species from contrasting habitats in a seasonal tropical rainforest. Am. J. Bot., 100, pp. 1683-1687.

Chen X.L, Q.C. Yang, W.P. Song, L.C. Wang, W.Z. Guo, X.Z. Xue 2017. Growth and nutritional properties of lettuce affected by different alternating intervals of red and blue LED irradiation. Scientia Horticulturae. 15(223), pp.44-52.

Choi H.G, B.Y. Moon, N.J. Kang, 2015. Effects of LED light on the production of strawberry during cultivation in a plastic greenhouse and in a growth chamber Sci. Hort., 189, pp. 22-31.

Choosria P, S. Janjaia, M..Nunezb, S. Buntounga, D. Charuchittipan, 2017. Mapping diffuse photosynthetically active radiation from satellite data in Thailand. Advances in Space Research. Volume 60, Issue 11, PP, 2345-2354.

Chung J.P, C.Y. Huang, T.E. Dai 2010. Spectral effects on embryogenesis and plantlet growth of Oncidium ‘Gower Ramsey’. Sci. Hortic., 124 , pp. 511-516.

Chutichudet B and P. Chutichudet 2011. Shading application on controlling the activity of polyphenol oxidase and leaf browning of ‘Grand Rapids’ lettuce. Inter. J. Agr Res., 6, pp. 400-409.

Cometti N.N, D. M. Bremenkamp, K. Galon, L. R. Hell, M. F. Zanotelli 2013. Cooling and concentration of nutrient solution in hydroponic lettuce crop. Horticultura Brasileira, 31, pp. 287-292.

Daud N., A. Faizal, D. Geelen 2013. Adventitious rooting of Jatropha curcas L. is stimulated by phloroglucinol and by red LED lightIn Vitro Cell. Dev. Biol. – Plant, 49, pp. 183-190.

Dechaine J. M., G. Gardnerand C. WeinIg. 2009. Phytochromes differentially regulate seed germination responses to light quality and temperature cues during seed maturation. Plant, Cell & Environment 32, pp. 1297 – 1309.

DeMitchell M. and M.Tarzian, 2011. Vertical Hydroponics System. U.S. Patent Application No 12/871,060.

Deram P., M. Lefsrud, V. Orsat 2014. Supplemental lighting orientation and red-to-blue ratio of light-emitting diodes for greenhouse tomato production. Hortscience, 49, pp. 448-452.

Despommier, D. 2011. The vertical farm: controlled environment agriculture carried out in tall buildings would create greater food safety and security for large urban populations. J. Für Verbraucherschutz Leb. 6, pp. 233–236.

Dey P.M and J.B. Harborne, 1997. Plant Biochemistry. Academic Press, New York. pp. 49–51.

Dong C, Y. Fu, G. Liu, H. Liu 2014. Growth photosynthetic characteristics, antioxidant capacity and biomass yield and quality of wheat (Triticum aestivum L.) exposed to LED light sources with different spectra combinations. J. Agron. Crop Sci., 200, pp. 219-230.

Dougher T.A and B. Bugbee 2001. Differences in the response of wheat, soybean and lettuce to reduced blue radiation Photochem. Photobiol., 73, pp. 199-207.

Drozdova I. S, V.V. Bondar, N.G. Bukhov, A.A. Kotov, L.M. Kotova, S.N. Maevskaya, A.T. Mokronosov 2001. Effects of light spectral quality on morphogenesis and source–sink relations in radish plant. Russ. J. Plant Physiol., 48, pp. 415-420.

Dufault R.J , B. Ward, R.L. Hassell 2006. Planting date and romaine lettuce cultivar affect quality and productivity. HortScience, 41, pp. 640-645.

Dufault R.J , B. Ward, R.L. Hassell 2009. Dynamic relationships between field temperatures and romaine lettuce yield and head quality. Sci. Hortic., 120, pp. 452-459.

Escobedo J.F, E.N. Gomes, A.P. Oliveira, J. Soares, 2009. Modeling hourly and daily fraction of UV, PAR and NIR to global solar radiation under various sky conditions at Botucatu, Brazil. Applied Energy, 86, pp. 299-309.

Folta K.M and E.P. Spalding 2001. Opposing roles of phytochrome A and phytochrome B in early cryptochrome-mediated growth inhibition. Plant J., 28, pp. 333-340.

Folta K.M. 2004. Green light stimulates early stem elongation: antagonizing light-mediated growth inhibition. Plant Physiol, 135, pp. 1407-1416.

Fu W, P. Li, Y. Wu 2012. Effects of different light intensities on chlorophyll fluorescence characteristics and yield in lettuce. Sci. Hortic., 135, pp. 45-51.

Goggin D. E. and K. J. Steadman 2012. Blue and green are frequentlyseen: Responses of seeds to short-and mid-wavelength light. SeedScience Research 22, pp.27 – 35.

Giliberto L, G. Perrotta, P. Pallara, J.L. Weller, P.D. Fraser, P.M. Bramley 2005. Manipulation of the blue light photoreceptor cryptochrome 2 in tomato affects vegetative development, flowering time, and fruit antioxidant content Plant Physiol., 137, pp. 199-208.

Gruda N 2005. Impact of environmental factors on product quality of greenhouse vegetables for fresh consumption. Crit Rev Plant Sci, 24, pp. 227-247.

Hahn E.J, T. Kozai, K.Y. Paek 2000. Blue and red light-emitting diodes with or without sucrose and ventilation affect in vitro growth of Rehmannia glutinosa plantlets. J. Plant Biol., 43 , pp. 247-250.

Hårdh J. E 1966. Trials with carbon dioxide, light and growth substances on forest tree plants. Helsinki : Suomen Metsätieteellinen Seura.

Hoenecke M, R.J. Bula, T.W. Tibbitts 1992. Importance of 'blue' photon levels for lettuce seedings grown under red light-emitting diodes. J. HortScience., 27, pp. 427-430.

Hogewoning S.W, G. Trouwborst, H. Maljaars, H. Poorter, W. van Ieperen, J. Harbinson 2010. Blue light dose-responses of leaf photosynthesis, morphology, and chemical composition of Cucumis sativus grown under different combinations of red and blue light J. Exp. Bot., 61, pp. 3107-3117.

Ilić S.Z, L. Milenković, L. Šunić, E. Fallik, 2017a. Effect of shading by colour nets on plant development, yield and fruit quality of sweet pepper grown under plastic tunnels and open field. Zemdirbyste-Agric., 104, pp. 53-62.

Ilic S.Z., L. Milenkovic, A. Dimitrijevic, L. Stanojevic, D. Cvetkovic, Ž. Kevrešan, E. Fallik, J. Mastilovic, 2017b. Light modification by colour nets improve quality of lettuce from summer production. Sci. Hortic., 226, pp. 389-397.

Ilić Z.S and E. Fallik 2017. Light quality manipulation improves vegetable quality at harvest and postharvest: a review. Environ. Exp. Bot., 139, pp. 79-90.

Jacovides C.P, F.S. Tymvios, G. Papaioannou, D.N. Asimakopoulos, C.M. Theofilou, 2004. Ratio of PAR to broadband solar radiation measured in Cyprus. Agricultural and Forest Meteorology, 121, pp. 135-140.

Jaimez R. and F. Rada, 2006. Flowering and fruit production dynamics of sweet pepper (Capsicum chinense Jacq) under differents shade conditions in humid tropical region. J. Sustain. Agric., 27, pp. 97-108.

Jenni S, M.J. Truco, R.W. Michelmore, 2013. Quantitative trait loci associated with tipburn, heat stress-induced physiological disorders, and maturity traits in crisphead lettuce. Theor. Appl. Genet., 126, pp. 3065-3079.

Johkan M , K. Shoji, F. Goto, S.N. Hashida, T. Yoshihara 2010. Blue light-emitting diode light irradiation of seedlings improves seedling quality and growth after transplanting in red leaf lettuce. HortScience, 45, pp. 1809-1814.

Johkan M, K. Shoji, F. Goto, S. Hahida, T. Yoshihara 2012. Effect of green light wavelength and intensity on photomorphogenesis and photosynthesis in Lactuca sativa Environ. Exp. Bot., 75, pp. 128-133.

Kader A.A and R.S. Rolle 2004. The Role of Post-harvest Management in Assuring the Quality and Safety of Horticultural Produce. Food and Agriculture Organization of the United Nations, Rome, pp. 1-52.

Kim S.J, E.J. Hahn, J.W. Heo, K.Y. Paek 2004a. Effects of LEDs on net photosynthetic rate, growth and leaf stomata of chrysanthemum plantlets in vitro Sci. Hortic., 101, pp. 143-151.

Kim H.H, G.D. Goins, R.M. Wheeler, J.C. Sager 2004b. Green-light supplementation for enhanced lettuce growth under red- and blue-light-emitting diodes. HortSci, 39, pp. 1617-1622.

Kläring H.P and A. Krumbein 2013. The effect of constraining the intensity of solar radiation on the photosynthesis, growth, yield and product quality of tomato. J. Agron. Crop Sci., 199, pp. 351-359.

Kobayashi M, S. Akutsu, D. Fujinuma, H. Furukawa, H. Komatsu, Y. Hotota, Y. Kato, Y. Kuroiwa, T. Watanabe, M. Ohnishi-Kameyama, H. Ono, S. Ohkubo, H. Miyashita 2013. Physicochemical properties of chlorophylls in oxygenic photosynthesis — succession of co-factors from anoxygenic to oxygenic photosynthesis. Z. Dubinsky (Ed.), Photosynthesis, InTech, pp. 47-90.

Kozai T, G. Niu, M. Takagaki 2016. Plant factory. an indoor vertical farming system for efficient quality food production. Academic Press, Elsevier Inc.

Lazcano C, J. Arnold, A. Tato, J.G. Zaller, J. Domínguez 2009. Compost and vermicompost as nursery pot components: effects on tomato plant growth and morphology. Span. J. Agric. Res., 7 , pp. 944-951.

Lee S.H, R.K. Tewari, E.J. Hahn, K.Y. Pack 2007. Photon flux and light quality induce changes in growth, stomatal development, photosynthesis and transpiration of Withania somnifera (L.) Dunal. Plantlets. Plant Cell Tissue Organ Cult., 90, pp. 141-151.

Lefsrud M.G, D.A. Kopsell, C.E. Sams 2008. Irradiance from distinct wavelength light-emitting diodes affect secondary metabolites in kale. HortScience, 43, pp. 2243-2244.

Li H.M, Z.G. Xu, C.M. Tang 2010. Effect of light emitting diodes on growth and morphogenesis of upland cotton (Gossypium hirsutum L.) plantlets in vitro. Plant Cell Tissue Organ Cult. 103, pp. 155-163.

Li H., C. Tang, Z. Xu 2013. The effects of different light qualities on rapeseed (Brassica napus L.) plantlet growth and morphogenesis in vitro Sci. Hortic., 150, pp. 117-124.

Li Q. and C. Kubota 2009. Effects of supplemental light quality on growth and phytochemicals of baby leaf lettuce Environ. Exp. Bot., 67, pp. 59-64.

Lian M. L, H.N. Murhy, K.Y. Pack 2002. Effects of light emitting diodes (LEDs) on the in vitro induction and growth of bulblets of Lilium oriental hybrid ‘Pesaro’. Sci. Hortic., 94, pp. 365-370.

Lichtenthaler H.K, A.R. Wellburn 1983. Determinations of total carotenoids and chlorophylls a and b of leaf extracts in different solvents. Biochem. Soc. Trans., 603, pp. 591-592.

Lillo C. and K.J Appenroth 2001. Light regulation of nitrate reductase in higher plants: which photoreceptors are involved? Plant Biol., 3, pp. 455-465.

Liu W. 2012. Light environmental management for artificial protected horticulture. Agrotechnology, 1, p. 101.

Liu Z., J.M. Chen, G. Jin, Y. Qi 2015. Estimating seasonal variations of leaf area index using litterfall collection and optical methods in four mixed evergreen-deciduous forests. Agric. Forest Meteorol., 209–210, pp. 36-48.

Liu, W., D. K. Chen, and Z. X. Liu. 2004. High efficiency column culture system in China. Acta Hortic. 691:495–500.

Maboko M.M, C.P. Du Plooy, 2008. Evaluation of crisphead lettuce cultivars (Lactuca sativa L.) for winter production in a soilless production system. Afr. J. Plant Sci., 2, pp. 113-117.

Manivannan A, P. Soundararajan, N. Halimah, C.H. Ko, B.R. Jeong 2015. Blue LED light enhances growth, phytochemical contents, and antioxidant enzyme activities of Rehmannia glutinosa cultured in vitro. Hortic. Environ. Biotechnol. 56, pp. 105-113.

Marin A, F. Ferreres, G. Barbera, M. Gil 2015. Weather variability influences color and phenolic content of pigmented baby leaf lettuces throughout the season. J. Agric. Food Chem., 63, pp. 1673-1681.

Massa G. D, H.H. Kim, R.M. Wheeler, C.A. Mitchell 2008. Plant productivity in response to LED lighting HortScience, 43, pp. 1951-1956.

McCoshum S and J. Z. Kiss 2011.Green light affects blue-light-based phototropism inHypocotyls of Arabidopsis thaliana. The Journal of the Torrey Botanical Society 138(4), PP- 409-417.

McCree K.J 1972. The action spectrum, absorptance and quantum yield of photosynthesis in crop plants. Agric. Meteorol., 9, pp. 90-98.

McNellis T.W and X.W. Deng 1995. Light control of seedling morphogenetic pattern. Plant Cell, 7, pp. 1749-1761.

Mladenovic J, G. Acamovic-Djokovic, R. Pavlovic, J. Zdravkovic, P. Maskovic, M. Zdravkovic, 2013. Antioxidant and antimicrobial activities of lettuce. IV International Symposium ‘Agrosym 2013’ Jahorina Book Procced. pp. 619–624.

Morrow R.C. 2008. LED lighting in horticulture. HortSci, 43, pp. 1947-1950.

Murchie E. H, M. Pinto, P. Horton, 2008. Agriculture and the new challenges for photosynthesis research.Tansley review., 181, PP 532–552.

Nanya K, Y. Ishigami, S. Hikosaka, E. Goto 2012. Effects of blue and red light on stem elongation and flowering of tomato seedlings. Acta Hortic., 956, pp. 261-266,

Nhut D.T, T. Takamura, H. Watanabe, K. Okamoto, M. Tanaka 2003. Responses of strawberry plantlets cultured in vitro under superbright red and blue light-emitting diodes (LEDs) Plant Cell Tissue Organ Cult., 73 (1), pp. 43-52.

Ntsoane L.M, P. Soundy, J. Jifon, D. Sivakumar, 2016. Variety-specific responses of lettuce grown under the different-coloured shade nets on phytochemical quality after postharvest storage. J. Hortic. Sci. Biotechnol., 91, pp. 520-528.

Ohashi-Kaneko K, R. Matsuda, E. Goto, K. Fujiwara, K. Kurata 2006. Growth of rice plants under red light with or without supplemental blue light. Soil Sci. Plant Nutr., 52, pp. 444-452.

Ohashi-Kaneko K, M. Takase, N. Kon, K. Fujiwara, K. Kurata 2007. Effect of light quality on growth and vegetable quality in leaf lettuce: spinach and komatsuna. Environ. Control Biol., 45, pp. 189-198.

Oh M.M , E.E. Carey, C.B. Rajashekar 2011. Antioxidant phytochemicals in lettuce grown in high tunnels and open field. Hort. Environ. Biotech., 52, pp. 133-139.

Oh M.M , E.C. Edward, C.B. Rajashekar 2009. Environmental stresses induce health promoting phytochemicals in lettuce. Plant physiol. Biochem, 47, pp. 578-583.

Okamoto K, T. Yanagi, S. Takita, M. Tananka, T. Higuchi, Y. Ushida, H. Watamabe 1996. Development of plant growth apparatus using blue and red as artificial light source. Acta Hortic., 440, pp. 111-116.

Park E.K, G.C. Lee 2001. Astaxanthin production by Haematococcuspluvialisunder various light intensity and wavelength. J Microbiol Biotech, 11, pp. 1024-1030.

Pinho L.X, J. Azevedo, V.M. Vasconcelos, V.J.P. Vilar, R.A.R. Boaventura 2012. Decomposition of Microcystis aeruginosa and microcystin-LR by TiO2 oxidation using artificial UV light or natural sunlight. J. Adv. Oxidation Technol., 15, pp. 98-106.

Poorter, H., F. Fiorani, M. Stitt, U. Schurr, A. Finck, Y. Gibon, et al. 2012. The art of growing plants for experimental purposes: a practical guide for the plant biologist. Funct. Plant Biol. 39, pp. 821–838.

Qi L.D, S.Q. Liu, L. Xu, 2007. Effects of light qualities on accumulation of oxalate: tannin and nitrate in spinach Trans. Chin. Soc. Agric. Eng., 4, pp. 201-205.

Rajapakse N. M and Y. Shahak 2007. Light quality manipulation by horticulture industry. G. Whitelam, K. Halliday (Eds.), Light and Plant Development, 30, pp. 290-312.

Ramírez-Gómez, H., M. Sandoval-Villa, A. Carrillo-Salazar, and A. Muratalla-Lúa. 2012. Comparison of hydroponic systems in the strawberry production. Acta Hortic. 947, pp.165–172.

Ryu Y., J. Verfaillie, C. Macfarlane, H. Kobayashi, O. Sonnentag, R. Vargas, S. Ma, D.D. 2012. BaldocchiContinuous observation of tree leaf area index at ecosystem scale using upward-pointing digital cameras. Remote Sens. Environ., 126, pp. 116-125.

Savoy P. and D.S. Mackay 2015. Modeling the seasonal dynamics of leaf area index based on environmental constraints to canopy development. Agric. For. Meteorol., 200, pp. 46-56.

Shahak Y, E.E. Gussakovsky, E. Gal, R. Ganelevin, 2004b. ColorNets: crop protection and light-quality manipulation in one technology. Acta Hortic., 659 (2004), pp. 143-151.

Shahak Y, E.E. Gussakovsky, Y. Cohen, S. Lurie, R. Stern, S. Kfir, A. Naor, I. Atzmon, I. Doron, Y. Greenblat-Avron, 2004a. ColorNets: a new approach for light manipulation in fruit trees. Acta Hortic., 636 (2004), pp. 609-616.

Shoji K, E. Goto, S. Hashida, F. Goto, T. Yoshihara, 2010. Effect of red light and blue light on the anthocyanin accumulation and expression of anthocyanin biosynthesis genes in red-leaf lettuce. Journal of Science and High Technology in Agriculture., 22, pp.107-113.

Silva B., K. Roos, I. Voss, N. König, R. Rollenbeck, R. Scheibe, E. Beck, J. Bendix 2012. Simulating canopy photosynthesis for two competing species of an anthropogenic grassla community in the Andes of southern Ecuador. Ecol. Model., 239, pp. 14-26.

Singh D., C. Basu, M. Meinhardt-Wollweber, and B. Roth, 2015. LEDs for energy efficient greenhouse lighting. *Renewable and Sustainable Energy Reviews*, *49*, pp.139-147.

Smith H., 1994. Sensing the light environment: the functions of the phytochrome family. Photomorphogenesis in Plants, Springer, Netherlands, pp. 377-416.

Sommer A. P and R. P Franke 2006. Plants grow better when seeds see green. Naturwissenschaften, 93, pp. 334-337.

Sun J.D., J.N. Nishio, T.C. Vogelmann 1998. Green light drives CO2 fixation deep within leaves. Plant Cell Physiol., 39, pp. 1020-1026.

Swatz T.E., S.B. Corchnoy, J.M. Christie, J.W. Lewis, I. Szundi, W.R. Brigs, et al. 2001. The photocycle of flavin-binding domain of the blue light photoreceptor phototropin. Journal of Biological Chemistry, 276, pp. 3693-36500.

Theiler L. H, L. Crespel, J. Gourrierec, P. Morel, S. Sakr, N. Leduc, 2016. Light signaling and plant responses to blue and UV radiations—Perspectives for applications in horticulture. Environmental and Experimental Botany. Volume 121, PP 22-38.

Touliatos D., C. Ian, D & M McAinsh 2016.Vertical farming increases lettuce yield per unit area compared to conventional horizontal hydroponics. Food and Energy Security; 5 (3): pp.184–191.

Vänninen I., D.M. Pinto, A.I. Nissinen, N.S. Johansen, L. Shipp 2010. In the light of new greenhouse technologies: plant-mediates effects of artificial lighting on arthropods and tritrophic interactions. Ann Appl Biol, 157, pp. 393-414.

Wallace R.W, A.L. Wszelaki, C.A. Miles, J.S. Cowan, J. Martin, J. Roozen, D.A. Inglis 2012. Lettuce yield and quality when grown in high tunnel and open-field production systems under three diverse climates. HortTechnology, 22, pp. 659-668.

Wang Y.H. and K.M. Folta 2013. Contributions of green light to plant growth and development. Am. J. Bot., 100, pp. 70-78.

Weiss M., F. Baret, G. Smith, I. Jonckheere, P. Coppin 2004. Review of methods for in situ leaf area index (LAI) determination: Part II Estimation of LAI errors and sampling. Agric. For. Meteorol., 121, pp. 37-53.

Wu M.C, C.Y. Hou, C.M. Jiang, Y.T. Wang, C.Y. Wang, H.H. Chen, H.M. Chang 2007. A novel approach of LED light radiation improves the antioxidant activity of pea seedlings. Food Chem., 101, pp. 1753-1758.

Xu, Y., Y. Chang, G. Chen, H. Lin 2016. The research on LED supplementary lighting system for plants. Optik-International Journal for Light and Electron Optics, 127(18), pp.7193-7201.

Yorio N.C, G.D. Goins, H.R. Kagie 2001. Improving spinach, radish, and lettuce growth under red light-emitting diodes (LEDs) with blue light supplementation. HortScience, 36, pp. 380-383.

Zdravković J, G. Aćamović-Djoković, J. Mladenović, R. Pavlović, M. Zdravković, 2014. Antioxidant capacity and contents of phenols, ascorbic acid, β-carotene and lycopene in lettuce. Hem. Indus., 68, pp. 193-198.

Zhao X, E.E. Carey 2009. Summer production of lettuce, and microclimate in high tunnel and open field plots in Kansas. HortTechnology, 19, pp. 113-119.

Zhou Y.H , Y.Y. Zhang, X. Zhao, H.J. Yu, H.K. Shi, J.Q. Yu 2009. Impact of light vari-ation on development of photoprotection, antioxidants, and nutritional value in Lactuca sativa L. J. Agric. Food Chem., 57, pp. 5494-5500.