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Effects of LED light quality and mixing ratio on the morphology, physiology and phytochemical content of green and red pakchoi in hydroponic indoor vertical farming

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LIST OF ABBREVIATIONS

B- Blue light

DAS- Days after sowing

FR- Far-red

G- Green light

LED- Light Emitting Diode

PAR- Photosynthetically active radiation

PPF- Photosynthetic Photon Flux

PPFD- Photosynthetic Photon Flux Density

R- Red light

VCE- Vertical Farming in Controlled-environment

Y- Yellow

W- White light

ABSTRACT

The global population is expected to reach 10 billion by 2050, with more than 50% of the world population live in cities. Growing urban population necessitates high-quality food as well as food security, resulting in increasing pricing for fresh produce. Hydroponic indoor vertical farming with artificial lighting is one of the latest method for producing high-quality food crops efficiently, particularly in urban settings. LED light is the ideal artificial light choice for vertical farming since it is efficient, long-lasting, and emits less heat. LED light emits a particular wavelength that may influence plant growth and development. Furthermore, the use of LED wavelengths on various crops has shown excellent results in terms of plant quality, production, and nutrition. Understanding the effects of different light wavelengths on the plant development and accumulation of essential nutrients such as antioxidants is crucial for achieving ideal light conditions for the production of high-quality vegetables in hydroponic indoor vertical farming. The purpose of this study is to examine the influence of various LED wavelengths on green and red pakchoi in the hydroponic vertical farm by measuring morphological and physiological responses as well as secondary metabolite accumulation. The research was carried out at the LED Light Research Lab MARDI, Serdang, which is a walk-in growing chamber with controlled environmental conditions. Green and red pakchoi seedlings were exposed to six distinct wavelengths for 40 days as prescribed by the treatment with photoperiod 12-h day/12-h night. The LED light arrays were; White light (W) as a control (the proportions of R, B and G wavelengths were 48%, 17% and 35%), monochromatic red light (100R) (the proportions of R and B wavelengths were 100% and 0%), combination red and blue light (82R12B) (the proportions of R and B wavelengths were 82% and 12%), combination red and blue light (50R50B) (the proportions of R and B wavelengths were 50% and 50%), monochromatic blue light (100B) (the proportions of R and B wavelengths were 0% and 100%), and the combination red, blue and green light (R69B24G7) (the proportions of R, B and G wavelengths were 69%, 24% and 7%). The findings reveal that 82R18B and 69R24B7G are the best light spectrums for green and red pakchoi in terms of morphology, growth, and phytochemical accumulation. The G wavelength is beneficial to enhance the plants' nutritional quality such as vitamin c, vitamin a and phenolic content. Incorporating a small proportion of G wavelength into growth light sources might improve the indoor vertical farming

environment without lowering yield, quality, or phytochemical content of green and red pakchoi. G wavelengths were discovered to be equally as crucial for plants as R and B wavelengths. These findings are expected to be a reference and basis for the application of led light formulation in the production of vegetables in plant factories or any controlled-environment planting system with LED light. However, further research is required to understand the best G proportions to include on R and B wavelengths, as well as to assess other variety of potential vegetables that that may be grown in hydroponic indoor vertical farming with LED lights.

CHAPTER ONE

INTRODUCTION

1.1 General background

By year 2050, the global population is predicted to reach around 10 billion people, with an estimated 70% of the world's population living in urban regions (UN, 2019). Global population growth and urban migration have increased demand for a more equitable social economy in terms of health, employment, housing, and transportation. The expansion in global population, particularly in metropolitan areas, has resulted in an increase in demand for high-quality fresh food (Despommier, 2013; Kozai, 2013). On the other hand, climate change consequences such as changed rain patterns, increased frequency of droughts and floods, and altered pest and disease infection patterns have had a direct influence on global food supply. These threats are already jeopardising world food production, and today we have posed to the risks by the Covid-19 pandemic. Adaptation towards the environmental and population challenges may be addressed through sustainable agriculture and controlled environment farming, with vertical farming being one of the approaches that can be expected to give a long-term solution for the food security.

Food security involving different factors such as food availability (supply), food accessibility (affordability and utilisation (food safety and quality). Urban agriculture has a significant contribution to nutrition and food security in developing countries. The constant migration of people from rural to urban areas will lead to the increase of the importance of urban agriculture in the future (Orsini et al., 2013). By implementing urban farming in the cities may improve all the factors and a greater scale of food security can be achieved. Even though in order to achieve the global food security, attention has to be focused on both urban and conventional agriculture; the urban food production on a large scale could absorb some of the burden in producing fresh produce from the conventional agriculture (Specht et al., 2014). Which by implementing the urban farming it can helps to balance the food availability and distribution between urban and rural areas. Whereas it can increase the accessibility of fresh and affordable food for urban consumer without having a long carbon food

prints. Cuba is the best example of self-sustained city in term of urban agriculture. Cuba started to plant in urban areas after the split down of Soviet Union, whereas they lost the major trade partner. Urban agriculture was found as the solution for self-sufficiency and food security in Cuba. The capital of Cuba, Havana experienced annual average growth of 38% in the urban agriculture industry from 1997 to 2003 and today about 35 000 ha of urban and peri-urban areas in Havana are utilised for food production. This scenario makes Cuba as the leading country in urban agriculture in the world (Hamilton et al., 2014).

However, one of the major challenges in urban food production is the land availability and accessibility. The effects of climate change and rapid urbanization has also impacted the food production sector. One of the main contributors to climate change is agriculture. 20 t0 30 per cent of global greenhouse gas emissions are thought to be caused by food production (Kulak et al., 2013). The advanced solution to address these issues are through the application of vertical farming. Vertical farming is one of the urban farming option with advance technology approach which involving growing crops in controlled environments. Vertical farming usually referred to as a system of crop production which maximizes the uses of land by having vertical planting system whereby plants, animals, fungi and other life forms are cultivated for food, fuel and fibre (Kalantari et al., 2017). The goal to implement vertical farming as one of high technology urban farming method is to provide quality and nutritional source of food for the urban dwellers in sustainable way. The amount of food produced as well as its quality is very important towards the urban society (Despommier, 2013).

Therefore, it can be seen that some countries especially developed countries have taken the initiative to develop the cultivation of vertical farming. Experts from various fields have joined together to develop a vertical farming system. Vertical farming has incorporates multiple disciplines such as engineering and natural science to apply in both society and environment (Mendez and Perez, 2014). At present, vertical farming cultivation is largely implement in cities such as Japan, China, Holland, Canada, Italy, USA, Singapore, UAE and United Kingdom (Sivamani et al., 2014). However, the actual adoption of vertical farming around the world is still limited to selected countries, especially the developed countries. Mostly the start-up for infrastructure if vertical farms are subsidized by the government (Pinstrup-Andersen,

2018). As an example, Japan is one of the leading countries in cultivation using vertical farming system, which they being called the system as plant factory (Kozai, 2013). Plant factory in Japan focus largely on lettuce production compared to other crops, with the estimation of production around 13.8% in 2013 and the amount is rising (Ogura, 2013). While the numbers of plant factories in Japan was 35 in 2009 (Kozai, 2013) and increased to more than 150 in the year of 2017 (Hayashi, 2017).

The Malaysian government has prioritised vertical farming as the most recent technology for effectively producing agro-crops. This cultivation system is a sunrise technology in Malaysia that has a high potential as a problem solver in vegetable production in the local market. The advanced controlled-environment system can solve the land-scarcity, labour-intensive, pest & disease, and unpredictable weather issues. It is expected that the Malaysian population will increase to 41.2 million by 2040; thus an effective and sustainable vegetable production technology as vertical farming is needed to reduce the country's dependence on imports and to ensure national food security. In recent years, Malaysia has received higher variability in rainfall, abnormally heavy floods, increased period of extreme rainfall and wind events and increased occurrence of thunderstorms. While, waters' mean sea levels have risen at an average rate of 3.67 ± 0.15 mm / year, higher than the expected global sea-level increase of 1.7 – 3.1 mm / year (Kuok Ho, 2018). For example, in 2015, an unprecedented flood event had once hit the northeast of Peninsular Malaysia. The agricultural sector was estimated to loss RM299 million as a result of damage to agricultural produce, infrastructure and assets (The Star, 2015). The consequences of the climate crisis, if not well handled, would not only jeopardize Malaysia’s food security, but also the livelihoods of agriculture-dependent people, making disparities worse.

Unprecedented crises, such as political and health crises, also have a part in defining the present degree of food security, not just in Malaysia, but globally. Recently, the Covid-19 pandemic outbreaks directly impact the livelihood of the world's population. In Malaysia, the food production sector is no exception, the movement’s control order (MCO) implemented affected food supply chain and distribution that connects farm production to the final consumers. According to Malaysian Vegetables Farmers Association, there are about 6000 farmers that are working on 30, 000 ha of

land and producing about 960, 000 tonnes of vegetables per year. However, during the MCO implemented by the government due to Covid-19 outbreak the supply of the vegetables reduced almost 30%. This is because of the farmers unable to distribute the fresh produce to various markets local and internationally and this constitutes losses about 790 metric tonnes per day. The average price for 1kg of vegetables is RM1.20, therefore 790 metric tonnes would translate to RM 948, 000 losses in a day.

On the other hand, concerns about the food supply chain disruption has led some countries to stop exporting staple foods to avoid domestic shortages. As example, Vietnam has reduced the rice exports by 40% in April and May 2020 compared to the same period in 2019 (Abdullah et al., 2020) As can be seen in the crisis, each country is more concerned with producing food resources for its own country than to be exported. Furthermore, the panic purchases of has been significantly subsided, where most residents, especially in big cities, have made emergency purchases when the government has announced a lock-down. This scenario is happening in almost every country in the world. Supply chain issues for the fresh produce become the key problem, which sparked the concern about how self-sufficient is in food production to endure future emergencies and possible trade disruptions. This situation creates social instability as well as rising food cost prices due to the high demand. Health crises like Covid-19 have been found to have further increased the risk of world food security. Every country needs to be prepared to meet the population's food demand at an unexpected time as it is now without having to rely on imports from foreign countries.

Addressing the daunting problems of food security compounded by the climate crisis and the pandemic Covid-19, conventional methods of farming will not be able to keep up. Referred to National Farmers' Organisation (NAFAS) board of directors member; Datuk Nazilah Abd Latif the MCO that has been implemented in Malaysia had made major impact on Malaysian fresh produce supply and it is important to give a priority on the importance of sufficient food supply (Kanyakumari, 2020). This current situation can be an opportune to Malaysia to shift towards a more sustainable agriculture such as urban farming with the application of high technology and innovation such as vertical farming. The best example can be looked from the Netherland, whereas the country utilising agriculture technology to achieve national

commitment to produce ‘twice amount of food by using half of the resources’. Which lead the country to become the second-largest food exporter in the world with only 0.4% of the United States’ land size (Kate, 2019).

Vertical farming can be implement conveniently by integrating with ready infrastructure such as empty building or warehouse, which much more efficient than planting in empty area or public gardens (Kalantari et al., 2020). The better access towards the fresh produce by the application of vertical farming has made this system much better than conventional farming. It is estimated that one square block of vertical farming with 30 floors, can produce 2000 calories a day for every person. Which can be translate it can cater the needs of 10 000 people in the city (Despommier, 2009). The implementation of vertical farming holds a solution to address the fresh food production in the cities by enabling more food production with less usage of resources. Nevertheless, urban agriculture not only prevent food production from being influenced by pollution or weather extremes due to climate change, but it also has potential to mitigate climate change as these systems work energy efficiently and therefore have less carbon emissions (Specht et al., 2014). Therefore, it could only have a greater impact on the mitigation of climate change if the systems were adopted on a larger scale. Even though, is not very likely in the coming decades due to high costs and policy restraints. It can be conclude that urban agriculture in general can mitigate climate change in terms of carbon emissions caused by food miles, storage, cooling, and packaging (Specht et al., 2014).

Vertical farming is the method of growing crops in vertically stacked layers. It often incorporates with hydroponic system and controlled-environment agriculture (CEA). The artificial control of temperature, light, humidity, and gases makes indoor plants’ production possible. Vertical farming is comparable to greenhouses in many aspects, where metal reflectors and artificial lighting supplement natural sunshine. The primary goal of vertical farming is maximizing crops output in a limited space (Despommier, 2011; Birkby, 2016). The other goal of this method is also to lower the threat of pests and diseases, while also increasing efficiency, sustainability, and productivity. The source of light that nourishes the plants in an indoor farm is controlled for maximum efficiency. LED lights are the most often used lighting instruments in indoor farming, allowing for more control over the growth environment.

Lighting is one of the crucial components in vertical farm in controlled-environment (Jiang et al., 2018). Lack of access to natural daylight in the indoor condition leads to the need for supplementary lighting. Artificial lighting has been shown to increase photosynthesis and promote plant growth by providing low, moderate-intensity light levels (Canham, 1954; Pinho et al., 2012; Weir, 1975). Conventionally, lights for horticultural applications were high-intensity discharge lamps such as high-pressure sodium (HPS), metal-halide (MH), and mercury (HPMV). Even though these sources induce an increase of daily photosynthetic flux levels, the conventional lamps' disadvantages are high-energy costs, heat generation and suboptimal spectrum for photosynthesis (Bantis et al., 2016; Jiang et al., 2018). Light emitting diode (LED) is a type of semiconductor diode that allows the control of spectral composition and light intensity to be matched with the plant photoreceptors to promote better growth and influence plant morphology and physiological processes (Yeh and Chung, 2009). The first LED application in controlled-environment agriculture was in the mid-1980s, when the primary source of light irradiation using LEDs were designed for plant growth chambers in the space shuttles and stations (Yeh and Chung, 2009; Naznin et al., 2016). The potential use of LED has nowadays linked with controlled-environment agriculture, such as growth chambers, greenhouses, and the latest addition is in the vertical farming system. LEDs are increasingly being installed in newly built vertical farms. (Mickens et al., 2019).

LED light is gaining popularity in facilitating plant physiology and photobiological research for almost 20 years (Bantis et al., 2018). LED have been used to confirm the role and importance of light quality and its ability to strategically manipulate plant growth and development (Kendric, 2013; Naznin et al., 2016). The LED lighting testing on various plants species such as vegetables, herbs as well as ornamental plants has shown promising results in terms of plant quality, maximal productivity and optimal nutritional quality, although varying among the different species (Singh et al., 2015; Bantis et al., 2016). Recognizing the effects of light on plants are closely related to the plant species and environmental variables. Aside from that, light spectral and light ratio have a significant impact on plant development. However, previous studies have focused on the main spectra wavelengths needed by plants, namely red (R) and blue (B) wavelengths, while the green (G) wavelength is less explored as it is considered less efficient absorbed by plants. Therefore, in this research aims to evaluate and

identify the effect of R, B and G light spectra ratio on green and red pakchoi vegetables.

1.2 Research problems

The urbanisation of the world has been accompanied by a change in eating patterns, which has had a considerable impact on the food system. Demand for food and agricultural goods has resulted in an increase in the cost of fresh produce. Due to a dysfunctional supply chain, insufficient production, and price instability, fresh vegetables have been priced out of reach for millions of urban families or are only accessible on an inconsistent basis at a high cost (Pinstrup-Andersen, 2018). Consumers in cities depend almost solely on food purchases, which translates directly into decreased purchasing power and higher rates of food insecurity, jeopardising both quantity and quality (FAO, 2017a). A paradigm change in food production is necessary, since the rising urban population will need around 70% more food than it does presently by 2050 (FAO, 2009).

Looking into Malaysia context, in terms of food self-sufficiency, Malaysia ranks 41st out of 133 nations for Self-Sufficiency Level (SSL) (The Economist Intelligence Unit, 2017). Even though the Self-Sufficiency Level (SSL) seems to be promising, Malaysia continues to struggle to reach a minimum level of food security for several basic fresh produce, such as vegetables (46.3%) (The Office of Chief Statistician Malaysia, 2017). Malaysia's over-reliance on particular agricultural producing regions has impacted its food security. The conventional agricultural practices will not be able to keep up with the overwhelming difficulties of food security in urban areas exacerbated by the climatic change, and recently in dealing with the pandemic Covid-19. The conventional agriculture practice is where agriculture is carried out commonly in agricultural area located far from the city due to the constraints of agricultural areas in urban areas. This makes the food supply chain long and easily disrupted due to the above factors. It is high time for the agricultural industry to undergo changes toward more sustainable agriculture through urban farming. This is not to say that the conventional agriculture is irrelevant; rather, urban farming may assist expand agricultural resources that were previously covered only by conventional agriculture.

The groundbreaking agricultural technology and developments such as hydroponics and vertical farming are becoming more essential. These technologies are such sustainable methods of food production that could improve livelihood and redefining the future agricultural industry in the global and in Malaysia. Hydroponic vertical farm in controlled-environment is one of the new planting systems for urban food production. This planting system is geared at the development of high-density plant production on a small scale in a controlled environment (Kozai, 2013). Hydroponic vertical farm in controlled-environment is one of the most effective and sustainable agriculture approach for urban food security, besides it significantly reduces the required agricultural space and resources such as water, fertilisers, and pesticides (Pinstrup-Andersen, 2018).

Indoor vertical farming is one of the urban farming approach, which is relatively a new technology in Malaysia compared to developed countries such as USA, Europe, Japan and Korea. In the Eleventh Malaysia Plan, 2016-2020, the Government vision is to guarantee the national food security as well as reducing environmental risks and ecological destruction in order to improve the quality of life and well-being of the Malaysians (EPU, 2015). In the National Agro-Food Policy (NAP), the Malaysian government has identified the vertical farming as a new technology that can be applied in the country's agricultural industry in order to reduce dependency on imported food sources (MOA, 2020). Investment in food and agriculture is also required to achieve sustainable food security and eliminate poverty, while at same time addressing climate issues, conserving natural resources and facilitating the transition to sustainable production systems.

Apart from ensuring the country's food security, vertical farm technology is crucial to ensure that Malaysians have easy access to affordable nutritional food. On the other hand, could introduce the sustainable agricultural technology to farmers especially in urban areas. This can also provide opportunities for those who want to venture into urban agriculture. There are several approaches of vertical farming, some are installed outside and use full sunlight, some are placed in a greenhouse and the more advance option is using the controlled environment. Hydroponic vertical farm in controlled environment is one of the most advance method of vertical planting and lighting become a critical component (Jiang et al., 2018). Lack of natural light in the

interior environment necessitates the use of supplemental lighting. By supplying low, moderate-intensity light levels, artificial lighting has been found to be beneficial at increasing photosynthesis and fostering plant development (Pinho et al.,2012).

LED lighting for plant growth is a relatively recent use in the agricultural and horticulture industries. Previously, high-intensity discharge lamps such as high-pressure sodium (HPS), metal-halide (MH), and mercury were used for horticultural purposes (HPMV). LEDs are a form of semiconductor diode that enable the spectrum content and intensity of light to be tailored to the photoreceptors of plants, hence promoting growth and influencing plant morphology and physiological processes (Yeh and Chung, 2009). Due to advancements in technology and specific requirements on plant, research on the technology and applications in vertical farming in controlled environments is required, particularly in the area of LED lighting.

LED lighting application on various vegetables has shown good result in terms of maximal productivity and optimal nutritional quality. Although red (R) and blue (B) wavelengths has received a lot of attention, the influence of green (G) wavelength has yet to be investigated in order to establish the possibility for high yield and quality of vegetable production in the controlled environment vertical farm. Additionally, it is demonstrated that vegetables' reactions to light quality are species-specific, and data on physiological responses to a broad range of light quality ratios are few. There are many studies focused on the effects of R and B wavelengths on plant growth and response. However, studies on G wavelength have received relatively less attention than R and B wavelengths. Due to the belief that R and B wavelength are more effective than G wavelength in terms of plant utilisation (Singh et al., 2015). Nevertheless, in more recent research have begun to evaluate the effects of G wavelength on plants and the relevance of G wavelength for photosynthesis has been more established (Terashima et al., 2009). Extensive research regarding plants interaction on the changing ratio of R, B and effect of supplementation of G is still required. Therefore, in this study the focus is to understand the green and red pakchoi reaction on the morphology, physiology and accumulation of secondary metabolites under exposure of different ratio of R, B and G wavelengths treatments.

1.3 Plants selected in this study

The Brassicaceae family is highly important economically, with approximately 340 genera and 3700 species (Pedras, 2010). According to a World Vegetables Survey, the most widely eaten vegetables were vegetable crops with leaves or young leafy shoots which are 53 percent of the total survey. While in Guangxi Province China, one of the largest vegetable production areas in the world, the most planted vegetables type are Chinese cabbage and pak-choy–type vegetables which come from Brassicaceae family consist of 19.1% from the total plantation. Those findings show that Brassicaceae family are abundance in local markets, low cost, and preferred by the consumer, which lead to among the most common vegetables consumed around the world (Hounsome et al., 2009; Lee et al., 2011).

Besides of being widely consumed in human diet, Brassicacea family also highly valuable in the nutritional point of view. These species possess a very rich of vitamins, minerals and dietary fibers, as well as a high variety of phytochemicals (Pereira et al., 2011; Hassini et al., 2017). Moreover, phytochemicals such as ascorbic acid and phenolic compounds have high antioxidant activity, which may have an impact on the potential use of the beneficial effects of brassica vegetables as an antioxidant functional food (Vale et al., 2014).

In this study, two brassica cultivars green and red pakchoi (*Brassica rapa chineensis)* was selected as research crops. These cultivars were chosen because of Brassica *rapa chineensis* is widely cultivated and consumed in the Malaysia and other South East Asia countries such as Philippines, Indonesia and Thailand (Welbaum, 2015). In Malaysia, pakchoi is the second most consumed vegetable after round cabbage, with a rate of 4.4kgs/year per capita consumption (Department of Statistics Malaysia, 2021b). Furthermore, these cultivars are widely grown by farmers is because of its short crop duration (harvesting time at 40–45 days after sowing) (Yusuk et al., 2018). The use of crops that are widely consumed by the population and are commonly grown by farmers appears to be very practical; the findings obtained will significantly contribute to the growth of the country's urban agricultural industry in particular, and the global in general. Apart from that, based on previous studies, it was found that pakchoi has a positive response in term of growth and secondary

metabolites accumulation towards the light treatment given (Son and Oh, 2013; Zheng et al., 2018). Therefore, the studies conducted on these selected cultivars are expected to contribute to the expansion of previous findings.

1.4 Research aims and objectives

This study aims to determine the effect of different wavelengths of LED lighting composition ratio (Blue, Red, Green) by evaluating the physiological responses, morphological changes and phytochemical accumulation on leafy vegetables, green and red pakchoi specifically. The results obtained from this study are expected to provide baseline information toward formulating artificial light wavelength combinations for vertical farming productions, especially in Malaysia.

The specific objectives of the study are;

1. To evaluate the morphological and physiological responses of green and red pakchoi under red, blue and green wavelengths
2. To investigate the effect of red, blue, and green wavelengths towards phytochemical accumulation on green and red pakchoi.
3. To determine the optimal wavelength combination for green and red pakchoi production in indoor vertical farming.

1.5 Research significance

This research will provide a theoretical basis for the development of optimal light composition for high yield and improved quality of nutritional values of plants growth in indoor vertical farm specifically for green and red pakchoi vegetables. Through this research, will get a better understanding of the response and requirements of LED lighting in Malaysian setups with Malaysian crop cultivars, which will contribute significantly to the growth and innovation of vertical farming in Malaysia. Moreover, the analysis that is presented in this study will convey valuable information for future research that will explore the various artificial light (especially LED light) requirement on plants which is the essential element in the vertical farming system in controlled-environment.

1.6 Research limitation

While this study successfully executed, there were some limitations. The first issue was that the available vertical farm racks were limited. There were only three vertical farm racks available, each with three layers of planting slots. The experiments need to be done by stages to ensure that all treatments and cycles are implemented. Another limitation was time constraint due to the Movement's Control Order (MCO) on effect of the Covid-19 implemented during the experiments and data collection process. There were times when the experiments were interrupted and had to be stopped. This includes no access to the laboratory during MCO. Research work can only be restarted after the MCO is relaxed.

1.7 Structural outline of the thesis

This thesis is divided into 6 chapters as follows;

Chapter One, Introduction; the context of the study has been introduced. The research objectives and questions have been identified, and the limitations of the study have also been discussed.

Chapter Two, Literature Review; reviews the existing literature to understand the context and scenario of vertical farming as a whole. This chapter also includes the importance and function of LED lighting and its application in photobiology to meet the needs of plants.

Chapter Three, Materials and Methods; explains the study methodology and approach, beginning with plant and site preparation and progressing through laboratory environment control, data collection, and data analysis.

Chapter Four, Results; presents the research results from the first, second and overall planting cycles of this study. The findings will be presented by division; morphology, physiology and phytochemical.

Chapter Five, Discussion; discusses the findings from the study conducted. Discussions are also will be made on a division basis; morphology, physiology and phytochemical.

Chapter Six, Conclusion; summarises the overall findings of the study and describe the achievements of the study based on the objectives of the study that have been determined.

CHAPTER TWO

LITERATURE REVIEW

Chapter overview

This chapter addresses and investigates global food security concerns, as well as the necessity of confronting several current and future difficulties to provide enough food for the population. Agriculture is the most critical industry when it comes to ensuring food security. Technology and innovation in agriculture, such as vertical farming in a controlled environment (VCE), should be examined in greater detail, particularly with regard to critical components such as lighting. The light source used in the VCE system, the LED light quality can be manipulated to improve the quality of growth as well as the nutrient content of the plant. Therefore, in this study green and red pakchoi (*Brassica rapa chineensis)* were selected to identify the effect of LED light quality on their growth.

2.1 Population Increment and Urbanisation: Implication towards food security

The world population is projected to reach 8.5 billion in 2030, to increase further to 9.7 billion in 2050 and 11.2 billion by 2100 (United Nation, 2019) (Figure 1). Nearly 90% of this population increase will occur in developing countries (UN, 2013) and Asia remains as the most populous continent. The United Nations projects that by the end of the century, more than 8 out of every 10 people in the world will live in Asia or Africa (United Nation, 2019).

The increase in the world's population will bring new opportunities and challenges. An increase in food and energy demand, is expected to increase. Every population in the world has daily needs and this increase requires adequate food resources. This is in line with the situation reported by FAO, more than half of those suffering from extreme food insecurity lived in Asia, while approximately 40% lived in Africa. The remaining 10% was divided among the Americas, Europe, and Oceania (FAO, 2020a).

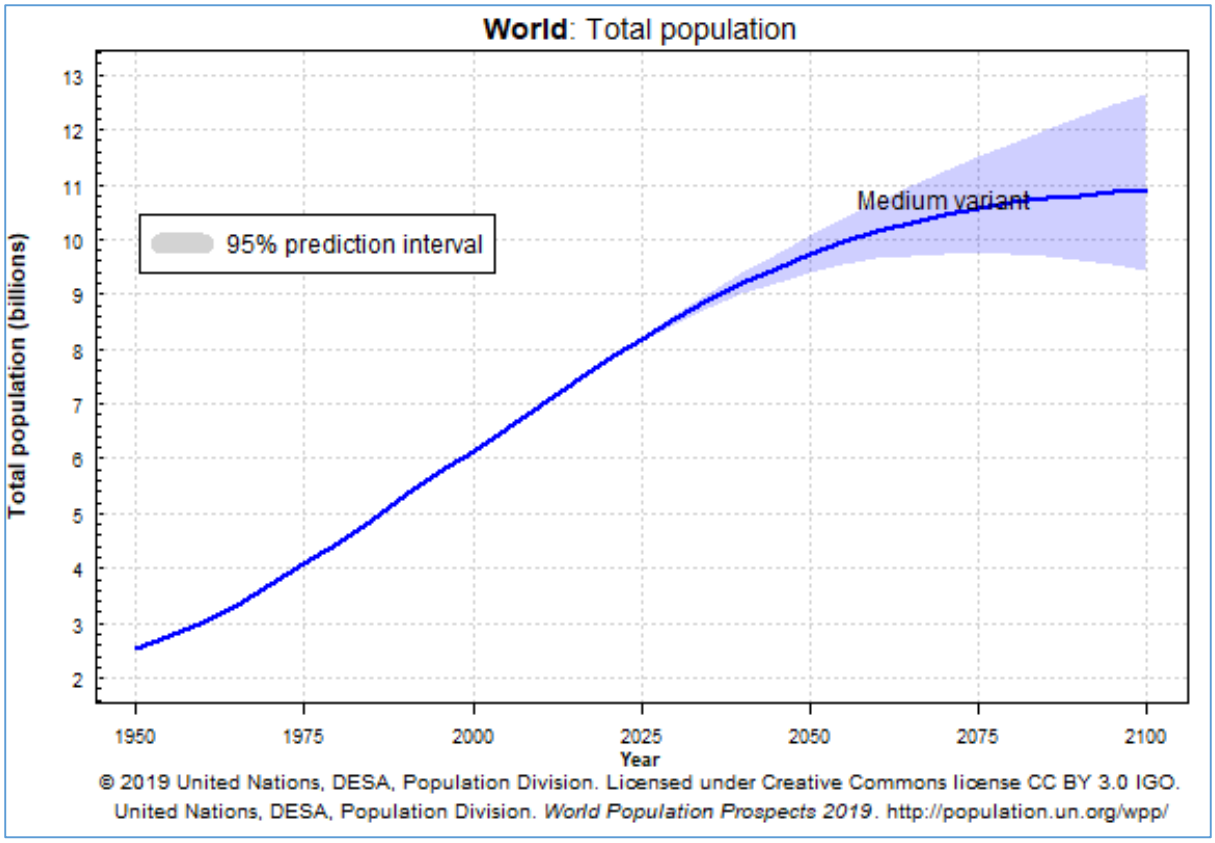


Figure 1 UN 2019 world population (solid blue line), with 95% prediction interval (light shaded area) and (b) UN 2019 populations projection by continent.

The urban population of the world has grown almost six-fold since 1950, from 751 million to 4.2 billion in 2018. (United Nation, 2018). Urbanization will continue at an accelerated pace, and about 70% percent of the world's population will be in urban areas by 2050 (United Nation, 2014). The United Nations cited two main reasons for urbanisation; the rise in the general population that is unevenly distributed by region, and an upward trend in people migrating to cities. The world's urban population has surpassed the portion of people in rural areas in 2009 and the rural population is projected to stabilize and gradually decrease over the next few decades, while urban growth will continue to shoot up to six billion people and beyond (Figure 2) (United Nation, 2018).

This unprecedented growth of urbanisation is one of the major factors influencing the socio-economic environment, including in the prospects for food and nutrition security. Urban areas are expected to absorb virtually all the future growth of the world's population. Rapid urban growth presents an important opportunity, but it also poses challenges to the implementation of an ambitious urban development

agenda to provide cities and human settlements inclusive, safe, resilient and sustainable future (United Nation, 2019). As rapid urbanisation continues to shape the global economy, finding ways to provide the right infrastructure and services in cities will be a key challenge for communities and organizations around the world.

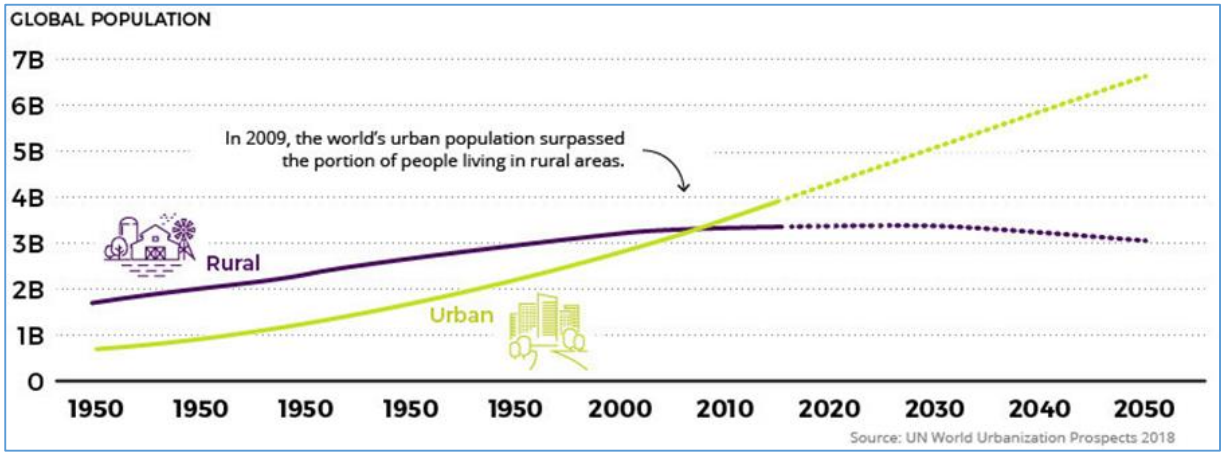


Figure 2 Global population in rural and urban areas between 1950 to 2050 (United Nation 2018)

The urbanisation process goes together closely with food insecurity. As cities expand, it creates demand for fresh food to ensure a healthy urban population. By 2030, the world is projected to have 43 megacities with more than 10 million inhabitants, most of them in developing regions (United Nation, 2018). According to the United Nations World Food Programme, nearly 1 billion people worldwide are undernourished, and the number keeps rising to 11% of the world's population (FAO, 2017a). Hunger and undernourished are widespread problems that affect millions of people around the world today, particularly in developing countries. Even though in recent years' undernourishment has a steady decreased progress by 17 percent from 1992, there is still significant room for improvement (FAO, 2009).

The fact from United Nation the world food production is actually enough food to feed everyone. Unfortunately, 821 million of world's population or one in nine still go to bed on an empty stomach each night. Even more, one of three is suffer from some form of malnutrition (United Nation, 2019). The vast majority of hungry people live in developing regions, where the prevalence of undernourishment is estimated at 14.3% (FAO, 2017a). Based on these facts, urbanisation greatly affects the rate of food adequacy for the population. This can be seen clearly where the hunger and

malnutrition rate of the population of the developing region is the highest in line with the urbanisation rate of the region. The consequences of the problem are not only cause suffering and poor health, it also will negatively impact other areas of development such as social, education and employment.

Refers to the current scenario, agriculture plays a very important in ensuring that sufficient food resources for the world's population are not only easily available but also affordable for all walks of life. Conventional agriculture is unlikely to meet the needs of the world's population. Transformation in agricultural methods is very necessary to ensure the social problems can be avoided.

2.2 Climate Change and World Pandemic Crisis Threatened Food Security

Climate change and intensified competition for natural resources would lead to resource depletion and scarcity. This has a detrimental effect on livelihoods and food security. Climate change has an effect on food supply and crop yields. According to the FAO, climate change is a significant ‘hunger-risk multiplier,' limiting access to food. As estimated by 2050, as a result of climate change, an additional 120 million people will be at risk of malnutrition (FAO, 2016).

Climate change and natural and human-induced disasters that lead to damage and losses to production; degradation of land, forest, water and other natural resources (FAO, 2017b). This situation effect on the agricultural production system and ecosystems. Agriculture is not only prone to climate change but also the main contributor to global greenhouse gas emissions. It is assumed around 20-30% are from food production activities (Kulak et al., 2013). As the pressure on scares land and water resources increases, the agriculture food sector must find solution of reducing environmental impact towards food production while ensuring the welfare of current and future generations.

Agricultural production is increasingly threatened by environmental issues such as insufficient available land and also risks and uncertainties from biotic and abiotic stresses, such as pest attacks, water shortages and floods (Kozai et al., 2016). Climate change leads to unusual weather add to these uncertainties. The global

projections show that approaching 2040 agricultural land can only be increased by another 2% (FAO, 2012). On the other hand, water resources are also in scarce condition (Gleick, 1993). Due to limited natural resources, 90% of the growth in global crop production is expected from higher yields and increased cropping intensity, with remaining 10% from the expansion of productive land (FAO, 2009).

The environmental impact includes greenhouse gas emissions, water usage, food loss and waste, soil health, ecosystem services and biodiversity. Intensive production and longer food supply chains may have associated with greenhouse gas emissions from the production inputs such as fertiliser, machinery, pesticides and transport. This continues with the activities beyond the farm gate which includes transportation, processing and retailing (FAO, 2017b). The level of overall emissions from food production process is determined not only by transport but also by production, processing, storage and distribution (Kneafsey et al., 2013). This scenario clearly shows that longer value chains may have a larger environmental footprint.

In the year of 2000, the mega-cities took just around 2% of the Earth's surface but encountered around 60% of human water use and almost 80% of human produce carbon emission (UNDP, 2008). This shows that besides the growing human population, the concentration in social agglomerates has also increased. The common practice in fresh food production often has to travel a long distance to reach the consumers, besides the fresh produce losing the quality and nutrition along the way, it also required energy cost for transportation and storage as well as, more packaging and preservatives require to prolonged storage life. These common practices lead to more production of carbon emission and waste that will affect the environment. Such issues may have avoided or reduced by applying the latest and more sustainable agricultural technologies in urban areas.

Today, food and agriculture are receiving more attention than before due to the threat of pandemic COVID-19. Due to COVID-19, an unprecedented health, economic and social crisis is threatening lives and livelihoods, making the achievement of zero hunger even more challenging. United Nation reported that in 2019, nearly 690 million people went hungry, an increase of 10 million from 2018, and an increase of nearly 60 million in five years. Costs and affordability issues often prevent billions from eating

healthfully or nutritiously. The report estimates that the COVID-19 pandemic could push an additional 132 million people into chronic hunger by the end of 2020 (United Nation, 2020).

The World Bank estimates that the economic effect of the pandemic will drive approximately 100 million people into extreme poverty (FAO, 2020b). In both developed and developing countries, raising unemployment rates, income losses, and rising food prices are jeopardising food access and will have long-term consequences for food security. The agricultural production sector was also severely affected by COVID-19 pandemic, where the productivity and incomes of the producers are systematically lower than before on average (United Nation, 2020). The serious concern that the producers will not be able to plant this year, or will plant insufficiently due to affected by the pandemic. This pandemic issue to exacerbate existing problems such as natural disasters, climate change and pests and diseases that are already straining the agricultural systems and contributing to global food insecurity.

Addressing the daunting problems of food security compounded by the climate crisis and in particular, in coping with the pandemic, conventional methods of farming will not be able to keep up. All countries ought to take urgent measures to mitigate the longer-term impacts on food systems and food security. According to FAO recommendation to mitigate the risks of the pandemic on food security; it is critical to protect the most vulnerable, maintain global food supply chains, mitigate pandemic effects through the food system, protect and even increase food production to the maximum extent possible, and, looking beyond the pandemic, rebuild stronger, more robust food systems. Which is one of the approach is through food systems transformation (FAO, 2020b).

While the world is looking forward to improve the post-COVID-19 economy, investment in sustainable agricultural technologies and infrastructure should be a priority. It is high time that much-needed for the agricultural industry to reforms towards more sustainable agriculture. Multidisciplinary research and development (R&D) and multi-party collaborations are needed. This is where revolutionary agriculture technologies and innovations such as hydroponics and vertical farming are becoming the most important components. These technologies are such sustainable ways of

growing food are changing our lives for the better and are reshaping the future agriculture industry.

2.3 Worldwide Vegetable Industry Scenario

In many parts of the world, vegetables have been in use for healthy and nutritious living for decades. These days due to increased consumer awareness of natural and organic foods, vegetables are becoming increasingly popular among the general public. They play a vital role in a daily healthy diet. Vegetables make up a significant component of the diet in order to fulfil human daily nutrient requirements. Vegetables are a rich source of nutrients, high in dietary fiber, low in lipids, and rich in vitamins (C, A, B1, B6, B9, E) and minerals. They also carry plenty of phytochemicals such as β-carotene flavonoids.(Craig, 1999; Randhawa et al., 2015).

Vegetables have been recognised for their nutritional value, and the benefits of vegetable-rich diets are to ensure sufficient intake of the majority of micronutrients, dietary fibers and phytochemicals that promote health. According to statistics from the Food and Agriculture Organization (FAO), the production of vegetables in the world in 2019 was more than 300 million tonnes (Figure 3). Figure 4 shown the Asia region produced 86.2 % of the world's vegetables (276 million tonnes) on 72.8% of the world's vegetable production area (18 million ha). China has always been a large contributor to world vegetable production and currently produces over 50% of the world's vegetables (FAOSTAT, 2021).

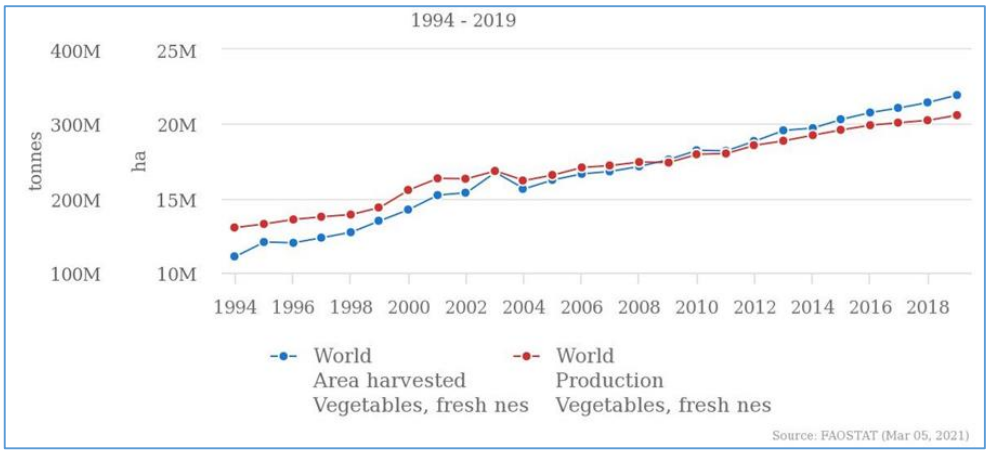


Figure 3 Vegetables production in the world

However, due to a lack of production data, it is difficult to estimate global vegetable consumption and value in the diet. Even in areas where crop reporting services are a vital part of the agricultural infrastructure, data on only a small percentage of the vegetable crops grown is available (Silva and Ryder, 2011). Vegetable intake and caloric contribution vary greatly depending on geographic area, ethnicity, local traditions, and cuisine. China the world's largest producer of vegetables, average vegetables intake per capita intake in China is also the highest in the world. According to FAO, in 2017 China consume vegetables 1000 grams per day for every person. This is almost 4 time higher that the National and World Health Organization (WHO) recommendations range between 200-250g per day (FAO, 2020a). Other southern Asian countries that grow and consume a lot of vegetables include Bangladesh, Cambodia, North and South Vietnam, Laos, and the Philippines (Silva and Ryder, 2011).

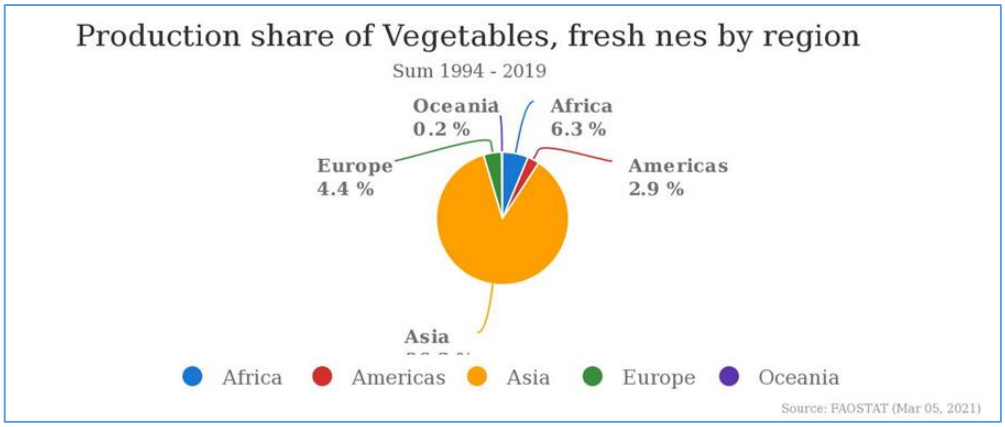


Figure 4 Vegetables production by region

Rapid growth in mean income during the 1990s enabled people in developed countries to buy a broader range of relatively expensive vegetable commodities, such as off-season produce, relatively new or renewed vegetables, and organic produce. Higher consumer incomes in developing countries have also increased demand for other attributes, such as better quality vegetables and more variety on the regular menu. In developed countries, consumption and domestic vegetable markets are also expanding due to an emerging educated middle class with rising incomes (Silva and Ryder, 2011). China, India, and Indonesia, three of the world's most populous countries, have significant emerging middle classes, which influence demand for high-value vegetables. (Senauer et al., 2003). The need for year-round availability and

increased diversity and understanding of health have also been important reasons for increased vegetable consumption in developed countries. For example, in the United States, fresh produce accounted for roughly 25% of the overall increase in vegetable consumption between 1977 and 1999 (Regmi and Gehlhar, 2001).

The consumers' awareness and concern about the farm residues in vegetables is rising. Residues not only have a negative impact on the health of farmers and consumers, as well as contaminating the environment. Additionally, pesticide residues can limit trade opportunities. This is due to some countries have strict regulation on farm residues content (Silva and Ryder, 2011). In order to ensure that these impacts are handled adequately, it is important that policy makers are able to measure the risk and level of pesticide contamination. This will also help to improve the application of current environmental policy tools and help to define the alternative solution to reduce the usage of pesticides. One of the best alternative is the use of latest technology and innovation in in vegetable farming which can help reduce the use of pesticides and insecticides. The burden over synthetic chemicals can be reduced by encouraging the agriculture industry to apply the controlled environment vertical farming. This planting method can produce fresh produce that are better in quality, safer to eat and can reduce the cost of using chemicals.

2.4 Vegetables Industry in Malaysia

Malaysia is located in Southeast Asia lying close to the Equatorial line, Latitude 1° and 7° North and Longitudes 100° and 119°. Malaysia has ecological conditions with an average uniform temperature 27-32°c and received fairly evenly distributed rainfall all year round. The humidity is high within 80-85%. In Malaysia, agriculture divided by two groups; plantation and food production. Plantation crop mainly palm oil has dominated the agricultural industry in Malaysia and provides much of foreign exchange with the value of RM 70 billion in a year. There are five million hectares of land in Malaysia being cultivated for palm oil, while only one million hectares for food crop (Abdul Shukor Juraimi, 2018).

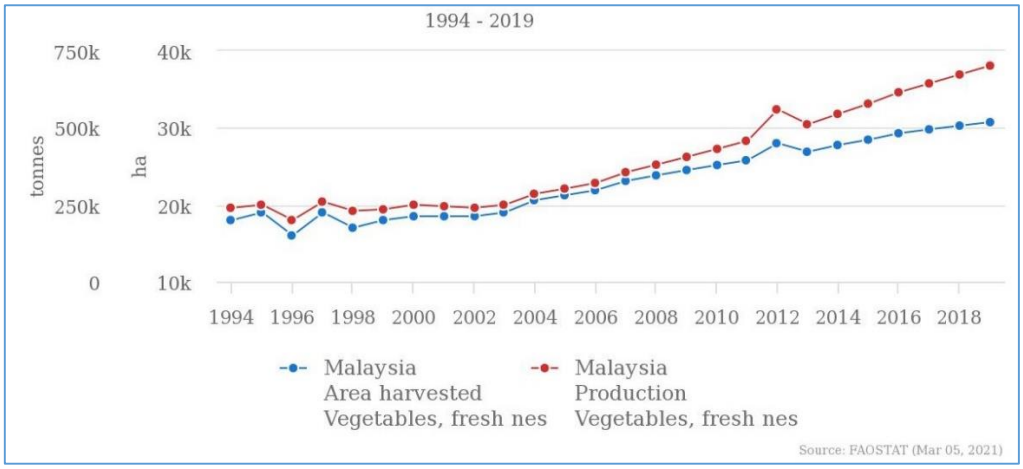


Figure 5 Vegetables production in Malaysia

Vegetables is one of the significant group of food crops that provides essential sources of nutrients in daily diet of Malaysians (Tee, 1979). In Malaysia, vegetables are commonly consumed fresh. There are wide range of temperate and tropical vegetables cultivated in Malaysia. Besides that, there are many native and wild plants that being consumed as vegetables or salad. Generally, the vegetables industry in Malaysia is consider as a small industry. It is carried out by the small-holder farmers with average size of farm between one to 1.5 hectares. (Halim and Dardak, 2017). In 2019, vegetables are cultivated in approximately 30 000 hectares or only 0.58% of the total agricultural land in Malaysia (FAOSTAT, 2021). The land area for vegetables plantation seems to be static since 2015 due to conversion of land usage to other industries such as housing estate and manufacturing, especially in urban areas (PEMANDU, 2016). According to statistics from the Food and Agriculture Organization of the United Nations (FAO), in 2019 the production of vegetables in Malaysia was more than 700 000 tonnes; more than 70% increment since 1994 production (Figure 5).

Malaysia is the net importer for vegetables and this industry is contributing to the 8.2% of national Gross Domestic Product (GDP) in 2017 (DOS Malaysia, 2018). According to the statistical data from FAMA in 2014, the country imported about 2.2 million metric tons or RM 5.5 billion of vegetables. This figure is being almost three times higher compare to country's exports of vegetables which is 620 000 metric tonnes or RM 1.6 billion. Malaysia's per capita consumption (PCC) for vegetables 58.5 per cent in 2014, 1.2 per cent higher from 2013. The PCC for vegetables recorded a

steady increase of about one per cent each year between 2009 and 2014 (FAMA & DOS Malaysia, 2014). Generally, urbanization makes the population consume more vegetables in their diet (Halim and Dardak, 2017). The consumers are aware and concern about the importance of health care and the greater buying power also contributes to the change in food habit and choice of foods (Halim and Dardak, 2017).

According to FAMA, the biggest factors that brought Malaysia to import vegetables are land scarcity, the high cost of labour & materials (e.g. pesticides & fertilizers) and the taxation. These factors minimized the production of local vegetables which is already high even at the production level and when it reaches the wholesale or retail markets, the price increased by several folds. The end price of the local produced vegetables is not competitive compared to the imports, especially from China and India.

2.5 Urbanisation and Vegetables Production Issues in Malaysia

Malaysia confronts a land-use conflict between urbanisation and agricultural production (Gumma et al., 2017). It is one of the most developed countries in South East Asia, with a population of 32,700,000 people in 2021, covering Peninsular and East Malaysia (Sarawak and Sabah). Malaysia yearly population growth rate is 1.0 percent (Department of Statistics Malaysia, 2021a). Malaysia's economy has shown diversity since independence, with agriculture and natural resources were the primary pillars of the economy, before transitioning to an industry-based economy. In the early 1970s, 1980s, and 1990s, Malaysia accelerated the industrialization of its economy (Yaakob et al., 2010). This rise has produced enormous work opportunities in metropolitan areas, resulting in a constant flood of rural migrants that sparked the urbanisation. As a result, smaller towns developed into cities, and cities developed into megacities, as seen by the Klang Valley, Johor Bahru, and Georgetown. As of 2020, urban regions accounted for 75% of Malaysia's population (Department of Statistics Malaysia, 2022; Yaakob et al., 2010)

Rapid expansion and economic booms in the early 1980s and 1990s resulted in unregulated development in Malaysia. To meet the needs of the urban population, land that was formerly set aside for tin mine, agriculture, rubber plantations, and palm

oil plantations has been transformed to housing estates and commercial development (Abdullah et al., 2009). Living in a city has a number of issues, one of which is ensuring long-term food security (FAO, 2017). Maintaining food security in Malaysia in the face of increasing urbanisation becomes a challenging issue. The basic requirements of urban dwellers, especially source of food, became pressing concern that needed to be addressed for sustainable food security. As urbanisation accelerates, the dependence and sustainability on food sources shifts away from localised food supply systems and toward a more globalised supply chain. This indicates that, rather of involving several separate suppliers, a centralised supply chain has taken control. This lead to a lengthier supply chain before reaching the end consumers, which reduces the freshness of food and increases the costs (Jennings et al., 2015).

Malaysia ranks 41st out of 133 countries in terms of food self-sufficiency (The Economist Intelligence Unit, 2017). The Self-Sufficiency Level (SSL) seems to be encouraging, notwithstanding the persistent trade deficit in food imports. However, the country still struggles to meet a minimal level of food security for some basic goods such as vegetables (48.3 percent) (The Office of Chief Statistician Malaysia, 2017). Malaysia's over-reliance on certain areas for food production has harmed its food security. For instance, the Cameron Highlands continue to be the nation's salad bowl, providing over 20% of domestic vegetables (Yusoff, 2015). Apart from this location, Malaysia cultivates a variety of food crops, although on a limited scale. As metropolitan regions expanded, aggravated by rural population movement, the supply of food often associated with rural communities became disturbed. The workforce required to grow and harvest food-based agricultural goods has migrated elsewhere in search of a higher standard of life, clearly to the detriment of this industry. Cameron Highlands, for example, employed almost 13,000 immigrants to meet the demand for agricultural produce (Fernando and Tasnim, 2018).

Agriculture has been put back into the national development agenda from the last 10 years through The National Agro-Food Policy 2011-2020 (NAP 1.0) and a continuation of this is The National Agro-Food Policy 2021-2030 (NAP 2.0). This comeback may be attributed to the government's recognition of the issue of food security and resilience in the shifting population structure (MOA, 2020). The Minister of Ministry of Agriculture and Food Industry (MAFI), Datuk Seri Dr. Ronald Kiandee

explained The National Agro-Food Policy 2.0 (NAP 2.0); In the 12th Malaysia Plan, the target outlined that MAFI has identified several directions that will be focusing on agriculture, rice production, ruminant and fisheries. MAFI's main agenda is transformation and modernisation of the agriculture industry, raising the SSL levels as well as increasing the industry revenue.

The ministry is also targeting 70% SSL for local vegetable production (MAFI, 2021). The National Agro-Food Policy 2.0 (NAP 2.0) is the guiding principle for Malaysia to stay competitive in the agriculture and agri-based industry while providing food security at affordable price for the populace, despite their burgeoning socio-economic status. Begin with NAP 1.0 until the NAP 2.0, government has introduced several strategies to promote vegetables industry with following initiatives; open new cultivation area and increase productivity, enhance post-harvest facilities and marketing logistics and strengthening organic vegetables market.(MOA, 2020; MAFI, 2021).

Referring to open new cultivation area and increase productivity strategy, government has planned to expand the vegetables cultivation area from 39, 300 hectares in 2010 to 45, 700 hectares in 2020 (MOA, 2020). The vegetables production will be enhanced through application of new technologies such as vertical farming and fertigation. The National Agro-Food Policy 2.0 (NAP 2.0) for the period 2021 to 2030, the government has targeted strategies to manage food demand and supply by accelerating the process of modernizing the Agro-food industry by the application of latest technology. The use of technology, direct infiltration into the supply chain, and re-engineering poverty via agriculture were among the measures used to revitalise the agricultural sectors (Sen, 2007).

Hydroponic vertical farm in controlled-environment is one the latest technology to produce agro-crops efficiently that has been focused by the government. This cultivation system is a sunrise technology in Malaysia that have a high potential as a problem solver in vegetables production in local market. The advanced controlled-environment system can solve the land-scarcity, labour intensive, pest & disease and unpredictable weather issues. It is expected that the Malaysian population will increase to 41.2 million by 2040, thus an effective and sustainable vegetables

production technology as hydroponic vertical farm in controlled-environment is needed to reduce the country's dependency on imports and to ensure national food security.

2.6 Vertical Farming in Controlled Environment Definition

According to Toyoki Kozai, vertical farming in controlled environment or in Japan more common to be referred as plant factory with artificial lighting; is a plant production facility with a thermally insulated and nearly airtight ware-house like structure with multiple culture shelves with electric lamps on each layer that are vertically stacked (Kozai, 2013). Vertical Farming in Controlled Environment is a growing system designed to ensure that food crops are produced in a weather-and climate-proof manner. This planting approach uses hydroponics, aeroponics, and aquaponics, all of which use a form of nutrient liquid distribution with minimal soil, to grow crops indoors in stacked, or standing, layers. The aim of this planting method of maximising crop production in limited space, vertical farming in controlled environment uses enclosed growing practises, regulating the environment's temperature, lighting, gases, and humidity.

In areas where arable land is inaccessible or scarce, such as urban areas where people want to bring food production closer to home, vertical farming in controlled environment has become an appealing alternative to conventional farming. Rather than growing crops on a single level, such as in the field or in a greenhouse, vertical farming in controlled environment grows crops in vertically stacked layers that can be built into high-rise buildings, shipping containers, or repurposed industrial space.

2.7 Hydroponic Vertical Farming in Controlled Environment

The urban population in the future demands the highest quality food and food security. The trend of the demand from the past two decades shows an increase of consumption of quality horticultural products, and the society has a very strong interest in fresh products of high nutrition and functional quality (FAO, 2017b). However, the global population is expanding faster than production. It is a must to find an effective solution to produce a high-quality source of food without compromising the sustainable environment (FAO, 2009).

Controlled-environment agriculture has become the main subject that highlighted in the principles as of the food system optimisation worldwide due to upcoming population and climate changes scenarios (FAO, 2016). Urban agriculture, plant factories and vertical hydroponic farming have become the new perspectives for robust food production systems for urban areas. These systems focusing on the development of local high-density plant production in a controlled environment (Seginer and Ioslovich, 1999; Kozai, 2013). Vertical hydroponic farming is one of the best options for food security in urban areas. Which is, that it decreases the necessary agricultural area and resources such as water, fertilizers and pesticides drastically.

Vertical hydroponic farming in controlled-environment or also known as plant factory is referred to a multi-story plant production facility with a thermally insulated and highly controlled environmental condition (Kozai, 2013; Graamans et al., 2017). The vertical farming term is commonly used in Western countries, while the term plant factory is much more associated with Japan and other Asian countries (Kozai et al., 2016), Vertical hydroponic farming in controlled environment facilitates viable agricultural production inside buildings in the urban areas. The vertical hydroponic farming system is the multiple layers planting shelves with artificial light on every layer and completes with necessary equipment such as air conditioners, air-circulation fans, CO_2 and nutrient solutions supply device (Figure 6).

Figure 6 Vertical farming rack with controlling system

Hydroponic system seems to be the best technique for planting in controlled environment, it has been significantly implement worldwide (Hickman, 2011). Various crops have been successfully grown hydroponically; such as *Brassica rapa chineensis* (pakchoi) (Figure 7), *Cucumis sativus* (cucumber), *Lactuca sativa* (lettuce), *Capsicum annuum* (pepper) and *Solanum lycopersicum* (tomato). vertical hydroponic farming in controlled environment is particularly using nutrient solutions in place of soil. The nutrient solutions is usually circulated throughout the system and recycled or alternatively the reservoirs are periodically emptied and refilled (Gentry, 2019). This allows plants to be grown on several levels by stack, thereby it can highly increase the volume that can be grown on a specific area.

This system can be applied in any crop production facilities whether in large or small scales. Which this makes the farm can be closer to population centers and offer many improvements to resource usage, growth efficiency and accessibility towards fresh products (Westphal, 2003). Vertical hydroponic farming can produce an almost consistent production level throughout the year (Graamans et al., 2017). Previous study on lettuce production in hydroponic farming demonstrated that hydroponic farming reduced water usage by 13 times compare to conventional farming. While for the yield production was 11 times greater than conventional farming (Barbosa et al., 2015).

Figure 7 Brassica rapa chineensis (pakchoi) grown in hydroponic vertical farming system

Vertical hydroponic farming is a form of urban agriculture that facilitate sustainable agriculture and the mass production of vegetables and herbs products

inside buildings. The advantages of this approach are increasing the efficiency of land use by growing in vertically planting shelves stacks. Moreover, it can increase in crop yields by using optimized production methods, such as light exposure variations, or the supply of CO_2. Because of the vertical hydroponic farming is indoors production, the crops protected from weather-related problems as well as pest and disease. A vertical farm can minimise the water requirements up to 95% through water recycling (Banerjee and Adenaeuer, 2014; Pinstrup-Andersen, 2018). A vertical hydroponic farming technology is believed to solve problems of cultivation land limitation and enable crops to grow all year round.

2.8 Conventional Farming Vs Vertical Farming in Controlled Environment

Vertical farming in controlled environment (VCE) is an indoor, advanced and intensive form of hydroponic production system where are the growing environment is optimally controlled. VCE is a form of closed plant production system (CPPS), in which all inputs to the VCE are fixed by plants with minimal pollution to the environment. VCE are not a substitute for conventional open-field farming or greenhouses. However, it is opportunities for new markets and business. It provides opportunities for existing players in the field of agriculture to expand their business as well as open option for new crowd to participate in urban agriculture sector. Conventional open-field farming grows plants in the open field, this makes the production yield and quality are subject to weather conditions. As a result, a steady and secure supply of fresh produce is in jeopardy. While the conventional greenhouse production is not energy efficient due to the planting environment cannot be regulated. The intensity of solar light and the direction of lighting are uncontrollable. Solar light intensity has a significant impact on the temperature and relative humidity within a greenhouse, making it difficult to optimise the environment. Furthermore, excessive agrochemicals are frequently used in greenhouse and open-field production, which is less or almost none in VCE and fossil fuels are required for greenhouse heating and cooling as well as transporting produce from the production site to consumers.

2.9 Advantages of Vertical Farming

Year-round crop production for human and livestock consumption, consistent quality, and predictable yield are a few of the obvious advantages of vertical farming. If carefully designed and managed, VCE could provide multiple environmental advantages include (Kozai, 2013);

- The infrastructure can be built anywhere even in the existing building as they do not require solar light or soil.
- The production can be all year round because it is not affected by the outside climate and soil fertility have little impact on the growing ecosystem.
- Efficient resources consumption. It needs less fertiliser to be applied to plants, reducing water consumption by up to 95 percent, and eliminating the need for chemical pesticides by weather-proofing. Thus, can be less pollutants to outside environment.
- VCE technology enables shorter growth cycles and faster harvests, allowing for more food to be grown each year in a much smaller area than a conventional farm. A high-yielding farm produces over 100 times more food per square yard than a conventional farm.
- Fresh produce quality such as the size of the plants and the level of phytonutrients can be tailored and enhanced through the manipulation of the growing environment especially the light quality.
- Can reduce energy consumption, carbon foot print and fresh produce waste if the location of the VCE is located in urban areas. In urban area settings VCE may apply a farm-to-table order-based system, which can drastically reduce the fresh produce waste, packaging, storage which lead to save the energy and fuel consumption.

2.10 Challenge of Vertical Farming

Government administrations and policy makers for most countries still think the VCE approach currently not a feasible option for feeding the world's the population because the infrastructure and the planting systems too costly compare crops grown in conventional systems and this scenario is expected to continue for several more

years. Apart from that, there are several other challenges to applying the VCE method in the existing agricultural industry;

- VCE approaches require a large amount of capital to develop because it requires the installation of high -tech as well as the latest equipment to ensure
- the desired controlled environment achieved. The start-up cost of VCE infrastructure is a significant impediment to their widespread adoption.
- The application of LED light in VCE have made more practical, but it is still considering as energy intensive. In the controlled environment conditions, the
- plants cultivation has to rely entirely on artificial light sources, which has to be used continuously making the vast amounts of electricity consumption.
- VCE growing conditions require plants to adapt with the controlled environment. To suits the condition, new crop genetics would need to be developed specifically for vertical farm production.
- Limited selection of plant types can be grown in the VCE compared to the conventional farms, the plants restricted to mainly leafy and fruity vegetables.

2.11 Light sources and lighting systems for VCE

In the controlled-environment agriculture, lighting is one of the important components (Jiang et al., 2018). Lack of access to natural daylight in the indoor condition leads to the need for supplementary lighting. Artificial lighting has shown to be effective in increase photosynthesis and promoting plant growth by providing low, moderate-intensity light levels (Canham, 1954; Weir, 1975; Pinho et al., 2012). Conventionally, lights for horticultural applications were high-intensity discharge lamps such as high-pressure sodium (HPS), metal-halide (MH) and mercury (HPMV). Even though these sources induce an increase of daily photosynthetic flux level, the disadvantages of the conventional lamps are high-energy costs, heat generation and suboptimal spectrum for photosynthesis (Bantis, et al., 2016; Jiang et al., 2018).

2.11.1 Type of light source

High intensity discharge (HID) lamps are known as conventional horticultural grow light source, this type of light source is widely used in the agricultural industry before the use of LED lighting. HID lamps create light by creating an electrical arc between

tungsten electrodes housed within a transparent fused quartz or fused alumina arc tube. This tube is partially filled with gas and partially filled with metal salts. The gas assists in the initial strike of the arc. The metal salts are heated and evaporated to create light until the arc is initiated, creating a plasma (Tian, 2017). There are few type of HID lamps, High-pressure sodium (HPS) and Metal halide (MH) are the common type being used in agricultural industry;

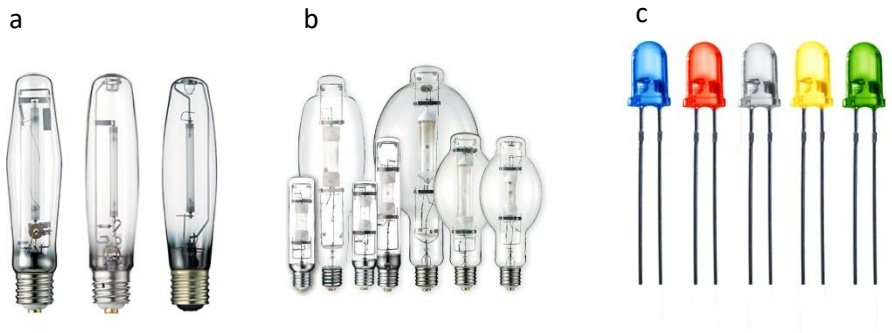


Figure 8 Artificial light sources a) High pressure sodium b) Metal halide c) LED

2.11.2 High-pressure sodium (HPS) lamp

The high-pressure sodium (HPS) lamp (Figure 8a) is a high-lumen output, high-efficiency high-intensity discharge (HID) light. Internal pressure is high in "high" pressure sodium vapour lamps, as the name suggests. The arc tube is constructed of aluminium oxide, and the sodium metal is combined with other elements like mercury to give it a white to light blue glow, which helps to counteract the yellow glow. Sodium, xenon, and mercury are utilised in the arc tube. A high-voltage pulse from the ballast starts an arc in the lamp's xenon gas. The mercury is then heated in the same way that MH lamps do. At temperatures over 240°C, sodium is the last substance to vaporise. A sodium lamp with a greater arc tube pressure could have a higher efficiency. It is widely used in plant cultivation, airports, industrial and mining facilities, parks, roads, squares, and street interchanges. A narrow arc tube is supported by a frame in HPS lights.

2.11.3 Metal-halide (MH) lamp

A metal halide (MH) lamp (Figure 8b) is a type of high-intensity discharge (HID) light source. It is widely used because of its strong colour rendering index and efficiency. While mercury vapour is used to provide the bright light, the lamp also contains additional halide salts (fluorine (F), chlorine (Cl), bromine (Br), iodine (I), and

astatine (At)) to enhance the colour. A halogen is a monovalent element capable of forming negative ions quickly. A halide is a chemical compound formed by the combination of a halogen with an electropositive element. Argon gas creates a low-temperature arc, allowing current to flow from the beginning electrode to the main electrode. The first arc is faint, and it has the potential to convert mercury to vapour. Thus, the more gas molecules ionise, the more current flows through the arc. When the arc reaches the other main electrode, the current via the beginning electrode will cease to flow. While this is occurring, the halides evaporate and dissociate. Before causing harm to the silica or electrodes, the metal atoms drift away from the arc and recombine with the halogen. Finally, the bulb is completely warmed up and emits its characteristic white light. Streets and squares, stadiums, industrial buildings, exposition halls, shopping malls, ports, and railway stations are the most common applications.

2.11.4 LED light source

LED is an abbreviation for light emitting diode (Figure 8c). A diode is an electrical device or component that consists of two electrodes (an anode and a cathode) through which electricity flows - usually in only one direction (in through the anode and out through the cathode) (Figure 9). Diodes are usually made of semi-conductive materials such as silicon or selenium; solid state substances that conduct electricity under some conditions but not others (e.g. at certain voltages, current levels, or light intensities). The system emits visible light as current flows through the semiconductor material. It is the polar opposite of a photovoltaic cell (a device that converts visible light into electrical current).

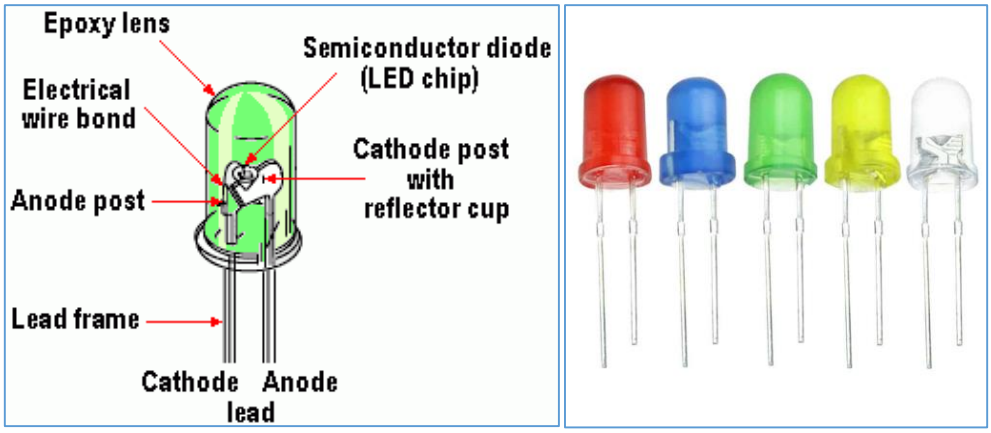


Figure 9 LED bulb

LEDs were first used in practical applications in electronic circuit boards. Since then, the uses have increasingly extended to include traffic lights, illuminated signs, and, more recently, indoor and outdoor lighting. Modern LED lamps, including fluorescent lights, are an excellent for gymnasiums, factories, schools, and commercial buildings. LED make good light source for large public areas such as roads and parking lots which have the broad variety needed for effective and efficient lighting.

LED lights application for cultivation are relatively new in agricultural and horticultural industry. LED is a type of semiconductor diode which allows the control of spectral composition and light intensity to be matched with the plant photoreceptors in order to promote better growth and to influence plant morphology and physiological processes (Yeh and Chung, 2009). The first LED application in controlled-environment agriculture was in the mid-1980s, when primary source of light irradiation using LEDs were designed for plant growth chambers in the space shuttles and stations (Yeh and Chung 2009; Naznin et al., 2016b). The potential use of LED has nowadays linked with controlled-environment agriculture, such as growth chambers, greenhouses, and the latest addition is in the vertical farming system (Figure 10). LEDs are increasingly being installed in newly built vertical farms. (Mickens et al., 2019).

Figure 10 LED light in vertical farming system

Previous years, the research on LEDs has produced technologies that make LED modules more energetically efficient and versatile as lighting systems (Cocetta et al., 2017). Compared to the conventional light source, LED provides a high potentiality to its longer life span and smaller weight and volume (Bantis et al., 2018). LED have the flexibility of spectral configuration. The spectral intensity can be

customized to suits the different stages of plant growth.(Rabara et al., 2017).In addition, LED can be configured to emit high luminous fluxes with the low radiant heat output and maintain their light output efficacy for years (Singh et al., 2015). The low radiant heat output produced by the LEDs make it suitable to be placed close to the canopy without increasing the plant temperature or risk of causing burn.(Tennessen et al., 1994; Michael, 2008)

LED is gaining popularity in facilitating plant physiology and photobiological research for almost 20 years (Bantis et al., 2018). LED have been used to confirm the role and importance of light quality and the spectral quality has the ability to strategically manipulate plant growth and development (Kendric, 2013; Naznin et al., 2016). The LED lighting testing on various plants species such as vegetables, herbs as well as ornamental plants has shown promising results in terms of plant quality, maximal productivity and optimal nutritional quality, although varying among the different species. (Singh et al., 2015; Bantis et al., 2016). This can be a good sign for a wider acceptance of LED technology in controlled-environment agriculture in the future.

2.12 Advantages of LED light

- In comparison to other lighting technologies LEDs have long lifespan. New LEDs can last 50,000 to 100,000 hours or more. The fluorescent bulb lifetime ranges, by comparison, is 10-25% as long at best (roughly 10,000 hours).
- Compared to other commercially available lighting technologies, LEDs are energy-efficient because they produce infrared light in a manner distinct from conventional lights, and use very little energy (this in contrast to traditional lights) (over 180 degrees versus 360 degrees which means there are far fewer losses from the need to redirect or reflect light).
- LEDs are extremely energy efficient relative to every other commercially available lighting technology. There are several reasons for this to include the fact they waste very little energy in the form of infrared radiation (much different than most conventional lights to include fluorescent lights), and they emit light directionally (over 180 degrees versus 360 degrees which means there are far fewer losses from the need to redirect or reflect light).

- LEDs can be designed to generate the entire spectrum of visible light colors without having to use the traditional color filters required by traditional lighting solutions.
- Very high light quality
- Very low maintenance costs and hassle

2.13 Disadvantages of LED Light

LED lights, in particular, are relatively costly. The initial costs of an LED lighting project are normally higher than those of other alternatives. This is by far the most serious disadvantage that must be considered.

2.14 Comparison between LED and HID light source

The following Table 1 is a comparison between the use of LED and HID light source;

Table 1 Comparison between the use of LED and HID light.

Characteristics	LED	HID
Colour range	Color range for LEDs range from 2200K to 6000K (from "hot" yellow to light or "cold" blue).	Well-known for their warm yellow glow (CCT values around 2200K). The spectrum is in the narrow range and limited.
Cycling (Turning On/Off)	LEDs are suitable for turning on and off on purpose because it can almost shift instantly with no warm up or cool down period.	HID light must be ignited before they can run at steady state, there is a brief pause when it can turns on.
Dimming	LEDs are very easy to dim, with choices ranging from 100 percent to 0.5 percent of the light output. Dimming LEDs is accomplished by lowering the forward current or changing the pulse length.	HID lights may be dimmed manually using various electric or magnetic ballasts, but this alters the voltage input to the light and, as a result, change the light characteristics.
Directionality	LEDs have a 180-degree light output. This is the prominent advantage because light is usually desired over a specific area.	HID lights emit light omnidirectional, which means they emit light in 360 degrees.
Efficiency	LEDs are very efficient relative to every lighting type on the market.	HID lights almost efficient as LEDs (values range between 50 and 160

	Typical source efficiency ranges 37 and 120 lumens/watt.	
Heat Emissions	LEDs produce very little heat to it is atmosphere.	HID emitted heat which is absorbed by the ballast or lost to the atmosphere.
Lifespan	LEDs last longer than any other commercial light source. Although life spans vary, average values range from 25,000 to 200,000 hours or more.	HID lights also have a long lifetime although not as good as LED. An HID bulb has a typical lifetime of about 24,000 hours.
Upfront Costs	LED lighting has a high initial cost but a low lifetime cost.	HID lights are inexpensive to buy and maintain.
Warm-Up Time	LEDs need almost no warm-up time. They hit their full brightness almost instantly.	Warm-up times for low and high pressure sodium lights differ depending on the light. The LPS or HPS lamp will take up to 10 minutes to reach its usual operating temperature.

2.15 Light environment for plant growth

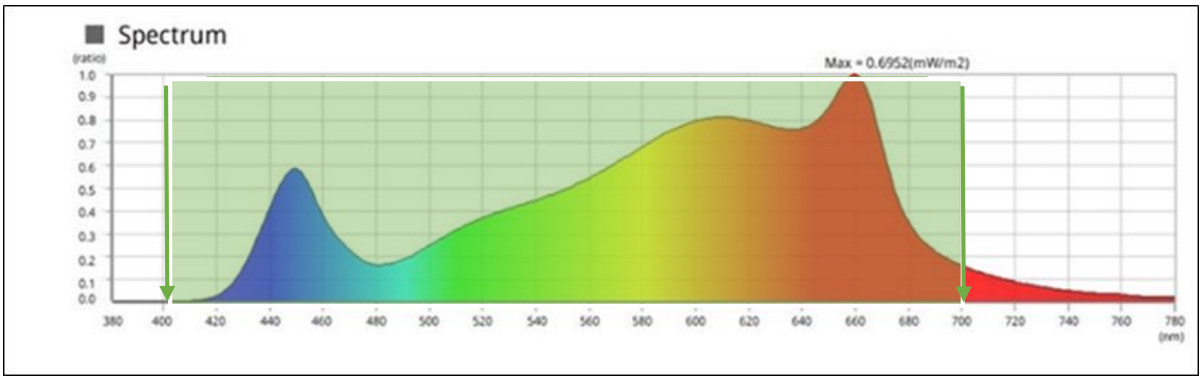


Figure 11 The Photosynthesis Active Radiation (PAR) range from 400nm to 700nm

Light is an important factor among several environmental conditions influences critical developmental and phytochemicals (e.g., growth, yield and quality) in plants (Schuerger et al., 1997). There are three parameters that have variety of influence on plant performance; light quality, light intensity and light duration (photoperiod) (Nishio, 2000). The wavelength spectrum of sunlight is from 290 to 3000 (nm), but plants only utilize radiation energy from 380 to 730nm. Photosynthesis active radiation (PAR) is classified as wavelengths ranging from 400 to 700 nm (Bae, 2001).

2.15.1 Light quality

Light quality is referring to spectral distribution of the radiation. It is part of the electromagnetic spectrum made from the mixture of wavelengths of several colours including violet, indigo, blue, green yellow-orange and red. Light spectral distribution affects the plant shape, development and flowering (photomorphogenesis) (Singh et al., 2015). However the morphological response of plants towards light quality are mainly species and cultivar specific, while the photosynthetic response of the plants are generally similar (McCree, 1971). The plant's photosynthetic activity of light is wavelength dependent. Photosynthetically active radiation (PAR) is commonly characterised as light having a wavelength of 400–700 nm (Figure 11). Light with a wavelength less than 400 nm or more than 700 nm regarded irrelevant for photosynthesis due to its poor quantum yield of CO^2 assimilation when used as a single waveband (McCree, 1971). Plants capture photosynthetically active radiation for photosynthesis using main pigment which is chlorophyll (chlorophyll a & chlorophyll b). These two kinds of chlorophyll complement each other in absorbing wavelength, which they mostly absorb red light (R) and blue light (B), but weakly absorb green light (G) (Nishio, 2000). There are other photosynthetic pigments known as antenna pigments such as; carotenoids (B-carotene), zeaxanthin, lycopene, lutein etc. Most of the photosynthetic plants have wide variety of those pigments which make them able to absorb energy from a wide range of wavelengths (Hernández and Kubota, 2016).

The length of the waves determines the energy and colour of the light. The higher-energy end of the light spectrum contains the shorter wavelengths in the purple and blue range (400nm), while the rest of the spectral colour decreases in the energy to the lowest-energy at the red light (700nm). The photosynthetically active radiation (PAR) spectrum consists of several ranges (Singh et al., 2015).

400-520 nm: Consist of violet, blue and green spectrum. Peak absorption by the chlorophyll. Have a strong influence on vegetative development and photosynthesis process.

520-610 nm: Consist of green, yellow and orange spectrum. Less absorb by the plants and has low influence towards plants' vegetative development and photosynthesis process.

610-720 nm: Consist of red bands and the major amount of absorption happens in this range. Have a very strong influence on vegetative development, photosynthesis, photomorphogenesis and budding.

Regarding to McCree (1971) the light in the red range (600–700 nm) gave plants the greatest quantum yield of CO^2 uptake. While the green light (500–600 nm) has a somewhat greater quantum yield than blue light (400–500 nm) (Figure 11). Green light's poor absorbance contributes to its low quantum yield of CO^2 assimilation. Green leaves absorb the highest in the blue range of the visible spectrum, followed by red range. In contrast, green leaves absorb the least amount of green light, which reflects their green colour. (McCree, 1971; Zhen et al., 2019). However, the misconception that red and blue light are more effectively utilised by plants than green light persists (Singh et al., 2015). This often referred to McCree's action spectrum or chlorophyll pigments poor absorption of green light. Whereas, McCree addressed the constraints of his action spectrum in his research; the quantum yield was determined at low photosynthetic photon flux density (PPFD), utilised narrow waveband light and stated on an incident light basis (McCree, 1971). These restrictions usually overlooked.

The red and blue light are absorbed primarily by the top few cell layers of leaves, but green light may reach deeper into leaf tissues. Thus, it is capable of excitating photosystems in deeper cell layers (Nishio, 2000). Under green light, leaf photosynthesis may benefit from more equal light dispersion across the leaf. Photon absorption by chloroplasts at the adaxial surface may result in heat dissipation of surplus excitation energy, while chloroplasts deeper inside the leaf get minimal excitation energy (Sun et al., 1998). As a result, blue and red photons may be employed inefficiently and are more likely to be dissipated as heat than green photons. In more recent research, the relevance of green light for photosynthesis has been thoroughly established (Terashima et al., 2009; Hogewoning et al., 2012).

2.15.2 Light intensity

Light intensity or light quantity is one of the major factor that affects photosynthesis process, plant development and nutritional values (Hartmann et al.,

1981; Mickens et al., 2019). Light intensity is the illuminance which is refer to brightness of light in the form of radiant energy and it is measured in in lux and micromole (µmol). Photosynthetic Photon Flux (PPF) is a measurement the total amount of PAR produced by lighting system per second. It is measured as µmol/s. PPF represents the measurement of the photons in the range of PAR, which is in the wavelength of light between 400 to 700 nm.

However, light fixtures may be varying in dispersal pattern, some fixtures have focused dispersal and may have wider dispersal. The fixture output and the dispersal known as Photosynthetic Photon Flux Density (PPFD). PPFD describes light intensity delivered to a surface and measured as µmol·m-2·s-1. Plants grown under low PPFD usually have characteristics similar to shaded plants, and previous studies has shown by increasing the PPFD can promote the net photosynthetic rate and induce the carbohydrate accumulation (Mickens et al., 2019). Most of research using LED have used light levels less than 200 µmol·m-2·s-1 (Snowden, 2015).

2.15.3 Photoperiod

Photoperiod is the capacity of plants to adapt their activity to the length of day or night, or more accurately, the ratio of light to darkness in a 24-hour period. (Hernández and Kubota, 2014). Photoperiod usually coordinates plant interaction like as growth, development, dormancy and photomorphogenesis. All of which have a direct effect on survivability and reproductive success (Singh et al., 2015; Bradshaw and Holzapfel, 2017).

Daily Light Integral (DLI) is a standard measurement for measuring the quantity of light plants recieve. It represents the total of all significant light intensities during the previous 24 hours. In general, the more photons plants receive (greater DLI), the better they grow and generate higher yield. However, each species has an ideal light intensity below which light absorption and photosynthesis are less effective. As a result, for optimum vegetative development, lower light intensity over a longer photoperiod are typically preferable. For example, the recommended photoperiod for tomato is 14 to 18 hours and 22 hours for sweet pepper. (Demers and Gosselin, 2002; Paucek et al., 2020).

Light is detected by plants through photoreceptors, which mediate the vast variety of developmental responses to light quality and intensity. Phytochromes and cryptochromes are two categories of photoreceptors implicated in photoperiod. Plants synchronize their physiological decisions with the correct time of the year to maximize growth and to produce offspring (Casal et al., 2004). Thus, sensing of and responding to the photoperiod are important plant functions to adapt to their environment. The terms photoperiod divided plants into the photoperiodic groupings. Short-day plants (SDP) are plants that flowering is accelerated by days that are less than a "critical" daylength. In plants known as long-day plants (LDP), flowering is expedited when the duration of the daily light cycle surpasses a critical daylength. Day-neutral plants (DNP) are those that flower simultaneously regardless of the photoperiodic circumstances (Thomas, 2003).

Plants with long and short days are often sensitive to the light quality (spectral composition). Short-day plants are sensitive to FR and a low R to FR ratio can stimulate flowering. Some of the long-day plants also respond to increased amounts of FR light in a growth spectrum. While FR light may not stimulate bud set directly, it does improve efficiency of light interception or incoming sunlight. To attain the optimum effects, a FR-enriched spectrum during the seedling and early plant stages can be used (Park and Runkle, 2017). In certain species, a lack of FR in the growth spectrum might suppress floral initiation or development (Runkle and Heins, 2001). Photoperiod manipulation by the use of blackouts or supplementary lighting to promote or enhance growth, flowering and secondary metabolites has been used for a wide range of ornamental species. Previous research on lettuce, shown that by extending photoperiod led to increment of fresh weight and soluble sugars and organic acids (Singh et al., 2015; Mickens et al., 2019).

2.16 The response of plants towards light

Plants use light in a variety of complex ways that go well beyond their capacity to photosynthesize low-molecular-weight sugars using only carbon dioxide, light, and water. Photomorphogenesis is the process through which plants grow and develop in response to light. It enables plants to make better use of light and space. The capacity to utilise light to measure time is known as photoperiodism. Plants can identify the time

of day and year by sensing and using different wavelengths of sunlight. Phototropism is a directed reaction that allows plants to grow in the direction of or away from light.

Plants capture photosynthetically active radiation for photosynthesis using the main pigment which is chlorophyll (chlorophyll a & chlorophyll b). These two kinds of chlorophyll complement each other in absorbing wavelength, which they mostly absorb red light (RL) and blue light (BL), but weakly absorb green light (GL) (Nishio, 2000). In the other hand, the plants respond to light as the environmental signal through the use of a distinct group of light-sensitive proteins known as photoreceptors (Figure 12). Photopigments, which are made up of a protein component linked to a non-protein, light-absorbing pigment termed the chromophore, are found in photoreceptors. Photoreceptors come in a variety of shapes and sizes, with various amino acid sequences and chromophore kinds. Plant photoreceptors detect light and trigger a variety of physiological reactions.

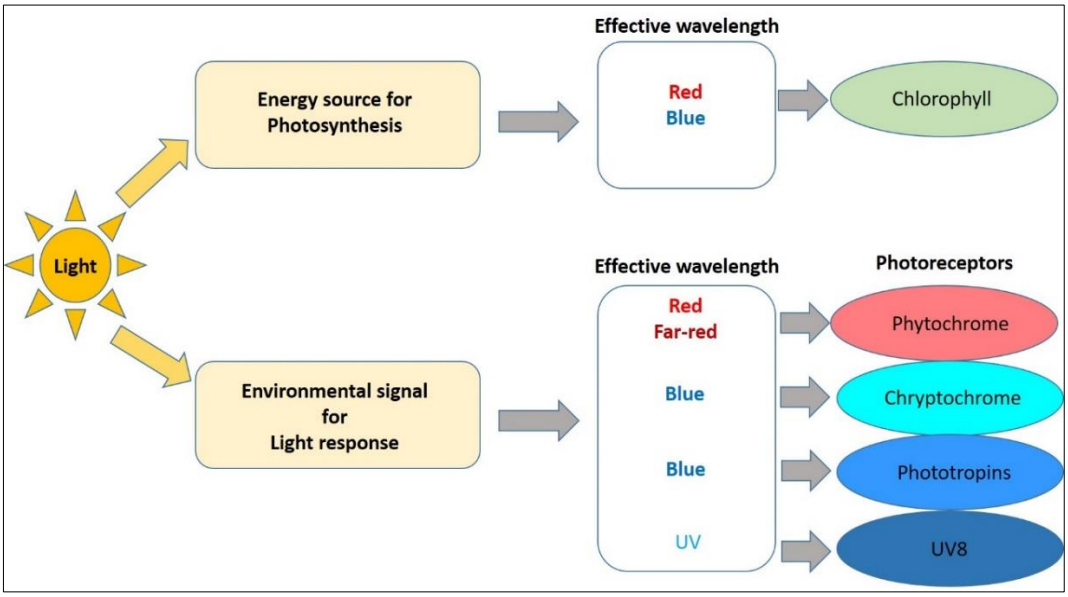


Figure 12 Plants response towards light and the utilization of the absorbed light.

2.17 Photoreceptors protein in plants

Plants mostly absorb wavelengths between 400nm and 700nm to carry photosynthesis process. These wavelengths are called the photosynthetically active radiation (PAR) spectrum. There are four main photoreceptors in plants; chryptochrome, phytochrome, phototropin and UVR8 (Figure 13). These receptors

absorb photons not only in PAR different wavelengths of light, ranging from ultraviolet B (280-315 nanometres) to far-red, have the greatest effect on these kinds (700-750 nanometres). The absorption of light by the chromophore causes structural changes in the photoreceptor, which leads to a sequence of signal transduction processes and changes; such as the biosynthesis of secondary metabolites.

2.17.1 Cryptochromes

Cryptochromes are photosensory receptors that regulate plant growth and development in response to light. The absorption of the protein cryptochrome peaks between 340 and 520 nm (Figure 13) in the UV-A and blue light domains (Schopfer, 2010). Two absorption maxima exist because to cry's non-covalent attachment to one of two potential chromophores. The first maximum occurs at 375 nm and is caused by the chromophore 5,10-methenyltetrahydrofolic acid (MTHF), while the second occurs at 450 nm and is caused by the chromophore flavin in the form of flavin adenine dinucleotide (FAD)]. When exposed to blue light, chrptochrome undergoes a semi-reduction with absorption in the green and yellow domains. The cryptochrome is then deactivated when exposed to green or yellow light. Green light has been shown to be capable of reversing the effects of blue light, such as anthocyanin accumulation, inhibition of extension growth, and stimulation of stomata opening. Cryptochrome is responsible for controlling activities related to the circadian clock, such as seedling development, guard cell opening, photoperiodic flowering regulation, or de-etiolation, as well as morphologic features such as plant or root growth, fruit size, or stem elongation (greening after period of darkness) (Parks et al., 2001) In addition, cryptochrome has high-fluence-rate responses, a separation with other blue light receptors may also be created by altering the light intensity. Besides that, previous research shown that cryptochrome regulates anthocyanin accumulation (Folta and Carvalho, 2015).

2.17.2 Phytochrome

Phytochromes are the primary photoreceptors in plants, detecting red/far-red light and transmitting it to downstream components that govern the gene expression network responsible for photomorphogenic growth. Light is absorbed mostly in the red/far-red area, approximately 665 nm (Pr) and 730 nm (Pfr), but also in the blue/near-UV range (Figure 13). Phytochromes detect and transduce light information,

such as light intensity and duration, to help plants develop nearly every stage of the plant life cycle, from germination through blooming and senescence (Tripathi et al., 2019). The most well-known phytochromes are phyA and phyB, although their stability and functioning inside the cell differ. Pr is produced in the dark for both kinds and is reversible to Pfr when illuminated (Thoma et al., 2020). When light activates phytochrome, activities in the cytoplasm and nucleus begin. Many of these are associated with changes in hormone levels, such as gibberellins and auxins (growth hormones in plants), ethylene, jasmonates (growth and photosynthesis hormones in plants), and abscisic acid (ABA) (plant hormone concerning development, control of organ size, stomatal closure).

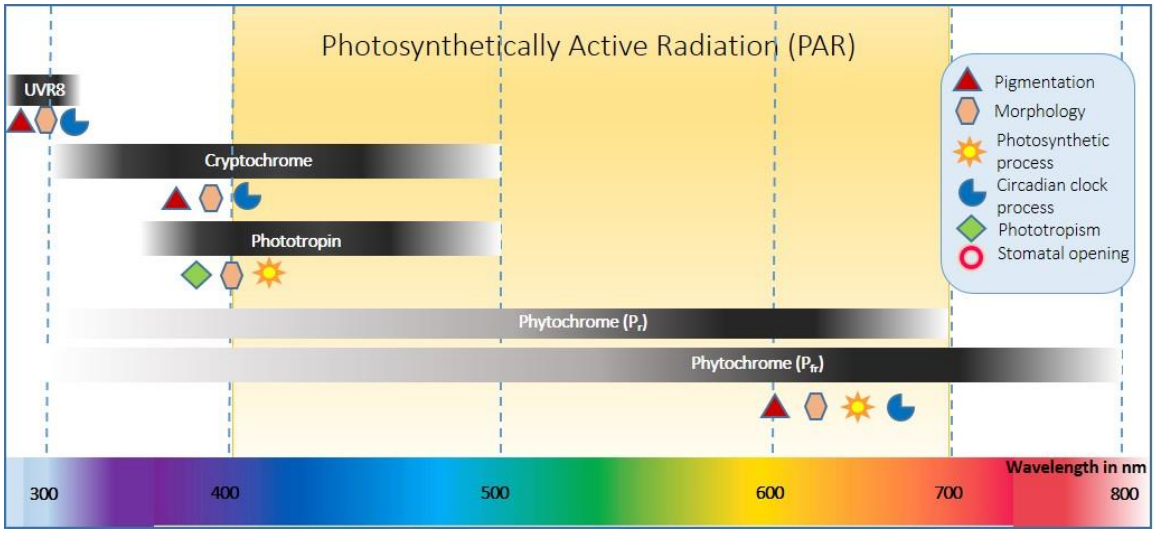


Figure 13 Absorption bands of photoreceptors in plants and their affected quantities, data obtained from Folta and Carvalho (2015). In order to address secondary metabolites in plants, a wider wavelength range (not only PAR) was presented.

2.17.3 Phototropin

Phototropin is a protein that absorbs light between 340 and 520 nm (Figure 13). Phototropins (phot1 and phot2) are blue light receptors that regulate phototropism, chloroplast mobility, leaf expansion, and stomatal opening. Under low light intensity (leaf expansion/position), phot1 active, whereas under higher light intensities, phot2 is triggered and acts redundantly with phot1 (Takemiya et al., 2005). Phototropin is involved in phototropism and the optimization of plant growth and development in order to maximise photosynthesis. Phototropin inhibits leaf curling (which is encouraged by phyB), resulting in flatter leaves and therefore more light absorption

(Folta and Carvalho, 2015). Additionally, phototropin is involved in the regulation of stomatal opening and therefore transpiration (Thoma et al., 2020).

2.17.4 UV8

UV-B radiation (Ultraviolet-B radiation) is a natural component of sunlight that has important biological consequences. UV-B photoreceptor UVR8, which is connected to a particular molecular signalling pathway and leads to UV-B adaptation, is used by plants to sense UV-B (Tilbrook et al., 2013). The protein UVR8 has the highest absorption in the UV region of 280 to 350 nm (Figure 13) (Thoma et al., 2020). Plants contain damage-repair systems and UV-absorbing pigments because UV-radiation, particularly at short wavelengths, may damage DNA or proteins by generating reactive oxygen species (ROS). UVR8 causes the accumulation of these protective pigments by triggering gene expressions (e.g. anthocyanins). UVR8 also has an effect on plant architecture, causing plants to become more compact in terms of stem elongation and leaf expansion. Without photosynthetic light (400–700 nm), UVR8 allows producers to regulate development (Cope and Bugbee, 2013).

2.18 Utilization of light quality by plants

Previous research have proved the success of plant growth under LED illumination, especially under red LEDs (R) and blue LEDs (B) (Bula et al., 1991; Tripathy and Brown, 1995; Yanagi and Okamoto, 1997). Different spectral combinations and quality has shown significant effect on plants physiology and morphology (Barreiro et al., 1992; Sims and Pearcy, 1992). Plants adapts to the light illumination to maximize light interception and growth (Hogewoning et al., 2012). This includes modification of stem and petiole length, leaf thickness, cell size, arrangement and function and number in leaves and stem tissues.(Tracy et al., 2004; Wang et al., 2011)

2.18.1 Effect of Red Light (RL) (610-720 nm)

R wavelength is crucial for the development of the photosynthetic apparatus and photosynthesis (Senger, 1982; Akoyunoglou and Anni, 1984). R wavelength generally induces plant growth by increasing fresh and dry weight, plant height and leaf area (Johkan et al., 2010; Wook Heo et al., 2012). Previous research has shown

that, biomass yield of lettuce increased when the wavelength of R increased from 660 to 690 nm (Goins et al., 2001). Application of far-red light (FR) (730 nm) addition to R (640 nm) on red leaf lettuce *(Lactua sativa)* caused the increment of total biomass and leaf length, while the anthocyanin and antioxidant content was suppressed (Stutte et al., 2009). The application of R (640 nm) as a sole source of light towards red leaf cabbage *(Brasica olearacea)* have resulted increase in anthocyanin contents (Mizuno et al., 2011).

Observation on lettuce crops, supplementing R light to cool white fluorescence lamp boosted chlorophyll content. While, the observation on red leaf lettuce cultivated with R supplemented with fluorescence light had decreased anthocyanin content and antioxidant capacity. In contrast, when R supplemented with B light had the exact opposite effect (Stutte et al., 2009). The monochromatic R light reduced fresh and dry mass production in cucumber when compared to different RB and RGB combinations (Hernández and Kubota, 2016). Non-headed Chinese cabbage was monitored under the monochromatic and dichromatic LED lights. The monochromatic R light, in particular, enhanced plant height but had a detrimental influence on chlorophyll and carotenoid concentrations (Fan et al., 2013).

It was also reported, in tomato, the monochromatic R light enhanced fructose and glucose concentrations, while combination RB (3R1B) increased total carbohydrate, starch, and sucrose accumulation, as well as sucrose synthase activity. Additionally, both R and RB boosted plant height and stem diameter (Li et al., 2017). In a study comparing artichoke cultivation under greenhouse conditions versus monochromatic LEDs in a growth chamber, it was discovered that R LED increased shoot dry weight and height compared to natural light, despite the fact that natural light had three times the total PPFD of R LED (Rabara et al., 2017).

Most of the previous studies have documented the advantages of RB light combinations over those given monochromatically. Mustard, beet, and parsley microgreens cultivated under FR + R supplemented with varied B light dosages increased carotenoids, chlorophylls (a and b), and tocopherol under 16%, 25%, and 33% B light (Samuolienė et al., 2017). RB lights increased the photosynthetic rate of chrysanthemum plantlets when compared to monochromatic B or R light, whereas the

R and FR combination increased stem length when compared to the B and FR combination (Kim et al., 2004). Kim et al also reported that B light increased the number of stomata but reduced their size, while the B and R combination lowered the number of stomata but increased their size. B supplemented with R light increased plant biomass, decreased upward or downward leaf curling, and increased soluble protein, chlorophyll, and carotenoid concentrations in nine tomato genotypes. When B and R lights combined, it has beneficial impacts on the development, physiological, and nutritional properties of a variety of horticultural species (Bantis et al., 2016).

2.18.2 Effect of Blue Light (BL) (400-500 nm)

B wavelength is also important for the synthesis of chlorophyll, choloroplast development, stomatal opening and photomorphogenesis rather than having direct on biomass accumulation (Akoyunoglou and Anni, 1984; Johkan et al., 2010; Senger 1982; Wang et al., 2009). Several experiments have shown the positive effect of B in combination with R. Mature plants had bigger leaves and higher fresh weight when the seedling grown under mixed R and B wavelengths compared to monochromatic R (Johkan et al., 2012). Besides that, it has been found that fresh weight, chlorophyll fluorescence, net photosynthesis rate, electron transport rate and phytochemical accumulation are remarkably lower in plants grown under monochromatic R compared to supplement with B (Mickens et al., 2019). B (440 nm & 476 nm) combined with RL have resulted higher chlorophyll ration in Chinese cabbage (Mizuno et al., 2011; Li et al., 2012). Besides that, previous studies have proved that green vegetables that being supplemented with BL shown increased nutritional value and enhanced in antioxidant contents which are carotenoid, vitamin C, anthocyanin and polyphenol. (Johkan et al., 2012; Lefsrud et al., 2008; Li et al., 2012; Stutte et al., 2009).

Supplementing B light increased anthocyanin concentration and fresh mass production but decreased stem length. Furthermore, it was discovered that increasing the amount of B light in different RB combinations increased leaf mass per area, chlorophyll content per leaf area, leaf net photosynthetic rate, and stomatal conductance while decreasing plant height, hypocotyl and epicotyl length, leaf area, fresh and dry mass (Hernández and Kubota, 2016). It was also recorded that B and RB lights increased soluble protein, chlorophyll, and carotenoids concentrations but

reduced plant height. (Fan et al., 2013). Snowden has discovered decreased dry mass, leaf area index (LAI), stem and petiole length in tomato, cucumber, pepper, and radish grown in the absence of B light. Additionally, he also observed that cucumber, pepper, radish, and lettuce had increased net assimilation. While tomato, cucumber, pepper, and radish had increased chlorophyll production (Snowden, 2015).

2.18.3 Effect of Green Light (GL) (500-600 nm)

G wavelength also contributes to the plant growth and development. The G wavelengths are slightly less efficient than R and B, but it still useful for photosynthesis (Johkan et al., 2012; Hernández and Kubota, 2016).G alone is not sufficient to support the plant growth because it is least absorbed by the plants. When GL being used with the combination of R, B and FR it has been proved that G has contributed towards physiological effect (Singh et al., 2015b). GL at a high PPF (300mmol) has shown a positive impact on the growth of lettuce (Johkan et al., 2012). While the supplementation of G in R and B illumination had enhanced the growth of lettuce (Kim et al., 2004). G have deeper transmission through leaf tissue and canopies, and due to this factor G can be more efficient that R and B in certain conditions (Vogelmann and Martin, 1993; Terashima et al., 2009). G can be used to control plant height and plant shape in some species, but it has a minimal effect on flowering and fresh or dry mass (Cope and Bugbee, 2013). Snowden et al. (2016) discovered that G light had a beneficial effect on the leaf area index (LAI) of cucumber, tomato stem length, radish petiole length, and pepper specific leaf area at 500 $\mu molm^2s^1$. G light, on the other hand, decreased the chlorophyll content of cucumber.

2.19 Effects of light quality for secondary metabolites

Over the last two decades, there has been an increase in demand for high-quality horticultural products, driven by society's increasing interest in fresh foods with high nutritional and functional value (Bisbis et al., 2018). Vegetable bioactive compounds, also known as phytochemicals, can help to regulate human metabolism and well-being (Ferrari and Torres, 2003). One of the most significant factors affecting phytochemical concentrations in plants is light (Lefsrud et al., 2008). Light intensity is well understood to have a beneficial impact on phytochemical accumulation, but the

effects of light quality are more nuanced and often recorded with mixed results (Vergeer, 1995; Keller, 1998). (Li and Kubota, 2009) .

The use of supplementary light (UV-A, blue, green, red and far-red and white LED) of varying quality resulted in substantial variations in the phytochemical (anthocyanins, carotenoids, chlorophylls and flavonoids) content of lettuce leaves. Hence, supplementary light may be a good way to control phytochemical content in plants (Li and Kubota, 2009; Lin et al., 2013). There was a significant enhanced on plants quality and increased of phenolic compounds and pigments of green and red lettuce under exposure of prolonged period of blue light (Ouzounis et al., 2015; Taulavuori et al., 2018; Urrestarazu et al., 2016). The red: blue spectral ratio may also influence the quality of leafy and fruit vegetables, with a ratio of 0.7 being beneficial for the phenolic and flavonoids content, antioxidant activity, and nitrate of basil and strawberry (Piovene et al., 2015).

Furthermore, Rouphael et al. (2018) have suggested that light modulation in the greenhouse setting may be used to enhance the quality of leafy vegetables, primarily by lowering nitrate levels and increasing ascorbic acid, folate, polyphenol, and chlorophyll content. In addition, the supplementary of green and blue spectral may improve antioxidant components such as vitamin C, phenolic compounds, and tocopherols in red, green, and romaine lettuce. (Bliznikas et al., 2012).

It is also reported that UV-A induced anthocyanin accumulation in grape and lettuce, while blue light increased anthocyanin levels in tomato, carotenoids in coffee, and acid ascorbic in lettuce but not spinach. Red light, on the other hand, appears to be the most successful in cranberry fruit anthocyanin development. In many species, either lower red/far-red ratio or a higher red/far-red ratio has been shown to reduce anthocyanin concentration. These findings indicate that the effects of light quality are more nuanced, and that mixed results are frequently recorded (Li and Kubota, 2009).

Several reports in various research have shown the plant response to light quality. Table 2 contains a summary of previous research on different leafy vegetables on the effect of specific LEDs wavelength on the plants' morphology, physiology and secondary metabolites.

Table 2: Effect of LEDs wavelength on morphology, physiology and secondary metabolites of leafy vegetable

Plant	Spectrum	Effect on plant physiology	Reference
Brassica juncea (Indian mustard)	RL (660 & 635 nm) + BL (460 nm)	RL 660 + BL 460 delay in flowering compared to RL 635 + BL 460	(Tarakanov *et al.*, 2012)
Brassica olearaceae (Cabbage)	RL (660 nm)	Anthocyanin content increased	(Piccaglia, Marotti and Baldoni, 2002)
Lactuca sativa cv. Red Cross (Baby leaf lettuce)	RL (658 nm)	Phenolic content increased. Increased chlorophyll	(Li and Kubota, 2009)
	FRL (734nm)	Increased fresh and dry weight, stem length, leaf area. Reduced anthocyanin, carotenoids, chlorophyll content. concentration. Increased anthocyanin concentration	
	BL		
Brassica olearacea L. cv. Wintebor (Kale)	RL (640 nm)	Chlorophyll a & b accumulation increased	(Lefsrud, Kopsell and Sams, 2008)
Lactuca sativa (Lettuce)	RL (638 nm)	Nitrate content reduced	(Li and Kubota, 2009)
Lactuca sativa L. (Green baby leaf lettuce)	RL (638 nm) + HPS lamp	Phenolics, tocopherols, sugars and antioxidant content increased. Vitamin C decreased.	(Li and Kubota, 2009)
Lactuca sativa L (Red, green & light green lettuce)	RL (638 nm) + HPS lamp	Nitrate concentration in light green lettuce increased, in green & red lettuce decreased.	(Samuolienė, Brazaitytė and Urbonavičiūtė, 2010)
Lactuca sativa L (Green leaf 'Lolo Bionda' & red leaf	RL (638 nm) + HPS lamp	Phenolic and α–tocopherol content increased	(Bliznikas.Z. et al. 2012)

'Lola Rosa' lettuce)			
Lactuca sativa L (Red leaf lettuce)	RL (640 nm) + FR (730 nm)	Total biomass increased. Anthocyanin and antioxidant content increased.	(Stutte, Edney and Skerritt, 2009)
Lactuca sativa L (Red leaf lettuce)	RL (640 nm) + BL (440 nm)	Total leaf area, anthocyanin and antioxidant content increased.	(Stutte, Edney and Skerritt, 2009)
Lactuca sativa L. (Red cross baby leaf lettuce)	BL (476 nm)	Anthocyanin and carotenoids increased.	(Lin *et al.*, 2013b)
Lactuca sativa L. cv Banchu red fire (Red leaf lettuce)	GL (510, 520 & 530 nm)	Enhanced growth	(Johkan *et al.*, 2012)
Lactuca sativa L (Frill ice lettuce)	2 RL (600-700 nm) : 2 BL (400-499 nm) & 1 RL (600-700 nm) : 2 BL (400-499 nm)	Fresh weight increased under 2 RL: 2 BL compared to 1 RL:2 BL	(Yan *et al.*, 2019)
Lactuca sativa L (Red leaf lettuce) & *Lactuca sativa* L (Green leaf lettuce)	RL (655) + BL (456 nm)	Chlorophyll content, phenolic, flavonoid and antioxidant capacity higher in RL (655) + BL (456 nm) compared to 0 BL.	(Son and Oh, 2013).
Brassica rapa var. *chineensis*	RL (660 nm) + BL (460 nm)	Leaf area, biomass yield and anthocyanin content increase	(Mickens *et al.*, 2019)

Rubi F (Red pak choi)			
Spinacia oleracea (Spinach)	RL (638 nm) + HPS lamp	Vitamin C increased	(Bliznikas. Z. et al. 2012)

2.20 Health promoting components in vegetables

Vegetables are high in micronutrients (vitamins and minerals), fiber, and a diverse array of phytochemicals, all of which support human health whether individually or in combination. Many biologically explanations for the potential beneficial fact that phytochemicals function as antioxidants, anticarcinogens, and immunomodulators (Yahia et al.,2018). Some phytochemicals contained in vegetables are powerful antioxidants that can reduce the risk of chronic disease by preventing free radical damage, altering the metabolic activation and detoxification of carcinogens, or even influencing processes that modify the direction of tumour cells (Southon, 2000).

Vegetables contain thousands of phytochemicals from various classes, including fibres, pigments (chlorophylls, carotenoids, and betalains), phenolic compounds, and micronutrients (vitamins and minerals) (Elhadi, 2019) ;

2.20.1 Dietary fiber

Dietary fiber is the edible component of plants that is made up of polysaccharides, oligosaccharides, lignin, and other plant substances that are resistant to human small intestinal enzyme activity. The health benefits linked to the dietary fiber is it can stimulate intestinal motility, weight and volume of the bolus and the intestinal transit time. Dietary fibre consumption for adults is recommended to be between 20 and 35 grams per day.

2.20.2 Vitamins and minerals

Vitamins are organic molecules micronutrients that are needed in trace amounts for human metabolism and development. Humans are unable to synthesize these molecules in sufficient quantities and must obtain them through diet, especially vegetables and fruits. In the other hand, minerals are important micronutrients in the

human diet because they are required for many biological activities and normal cellular functions. Manganese (Mn), copper (Cu), iron (Fe), zinc (Zn), sodium (Na), sulphur (S), and selenium are all found in vegetables and fruits (Se).

2.20.3 Carotenoids

Carotenoids are a class of fat-soluble molecules that give certain fruits and vegetables their yellow, orange, and red hues, including apricots, tomatoes, peppers, and carrots. Plant pigments are also essential in the photosynthesis process. Carotenoids have received a lot of attention because of their antitumor effects, which include antioxidant, antiproliferative, and immune function modulation.

2.20.4 Phenolic compounds

Phenolic compounds form the largest class of phytochemicals present in plants. Phosphoric acids, flavonoids (flavonols, flavones, flavanols, flavanones, and anthocyanins), stilbenes, and lignans are among them. Anthocyanins is one of the most abundant flavonoids in plants and can be found in red-purplish or red to blue-colored fruits, leaves, flowers, roots, and grains. Anthocyanins have antioxidative and antimicrobial properties, as well as the ability to enhance visual and neurological health and defend against a variety of non-communicable diseases.

CHAPTER 3

MATERIALS AND METHODS

3.1 Experimental Site

The study was conducted in LED Light Research Laboratory at Horticulture Research Centre in Malaysian Agriculture Research and Development Institute (MARDI), Persiaran MARDI-UPM, Serdang, Selangor, Malaysia (2°59'14.2"N, 101°42'19.2"E). The laboratory is specially designed for the study of crops in controlled-environment. The laboratory measures 6 meters' x 6 meters and the facilities available in this laboratory are, multilayers hydroponic vertical farm system, air- conditioner and air-humidifier.

Figure 14 The set-up of the multilayers hydroponic vertical farm system in the LED Light Research Laboratory, Horticulture Research Centre MARDI

3.2 Experimental Materials

Two types of pakchoi cultivars was used in this study; green pakchoi (*Brassica rapa chineensis*: Figure 14. Code: 7, Green World Genetics Inc., Malaysia*)* and red pakchoi (*Brassica rapa chineensis*: Figure 15. Code: 217, Green World Genetics Inc., Malaysia). Planting is done in urethane foam cubes and 4 units of multilayers hydroponic vertical farm system was utilised. A total of 36 units of LED light tubes were used, which were according to the spectral ratio based on the pre-determined light

treatments. There were 3 LED light tubes used for each layer of the multilayers hydroponic vertical farm system, every layer designated to one light treatment.

Figure 15 The seeds used in the experiments. a) Green pak choi b) Red pak choi

3.3 Treatments and Experimental Design

Treatment consisted the combination of pakchoi cultivars (red and green) and the LED light treatments (100R, 82R12B, 50R50B, 100B, 69R24B7G, W) making 12 treatment combinations. The experimental design is completely randomised design (CRD) and destructive sampling methods have been applied. A total of 7 replicate plants for each treatment combinations were randomly selected on every harvest; at 20, 30 and 40 days after sowing (DAS). The experiments were conducted in two planting cycles per cultivar.

The light source used in this experiment were LED lights consisted of white, blue, red and green LEDs (Impressive Edge Inc, Malaysia). The experimental conditions were set up with six different LED light combinations. The LED arrays were; White light (W) as a control (the proportions of R, B and G wavelengths were 48%, 17% and 35%), monochromatic red light (100R) (the proportions of R and B wavelengths were 100% and 0%), combination red and blue light (82R12B) (the proportions of R and B wavelengths were 82% and 12%), combination red and blue light (50R50B) (the proportions of R and B wavelengths were 50% and 50%), monochromatic blue light (100B) (the proportions of R and B wavelengths were 0% and 100%), and the combination red, blue and green light (R69B24G7) (the proportions of R, B and G wavelengths were 69%, 24% and 7%).

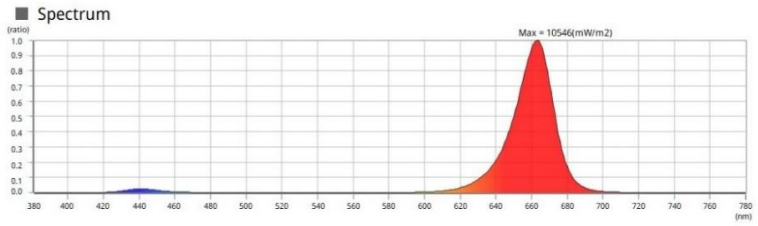
Table 3: Summary of spectral data for each light treatment were recorded and averages at five locations at the 15 cm underneath the light source.

Measurement	Treatments (LED combinations)					
	1	2	3	4	5	6
Photon Flux	100R	82R12B	50R50B	100B	69R24B7G	W
Spectral Composition						
Average PPFD (400-700nm)	209.78	205.94	207.52	205.38	200.91	206.12
Blue (400-500nm)	0.94(0%)	37.07(18%)	101.62(50%)	205.03(100%)	48.22 (24%)	52.40 (17%)
Green (500-600nm)	0.56 (0%)	2.00(0%)	0.15(0%)	0.91(0%)	14.06 (7%)	72.14 (35%)
Red (600-700nm)	208.28 (100%)	166.87(82%)	105.75(50%)	0.35(0%)	138.63 (69%)	98.94 (48%)

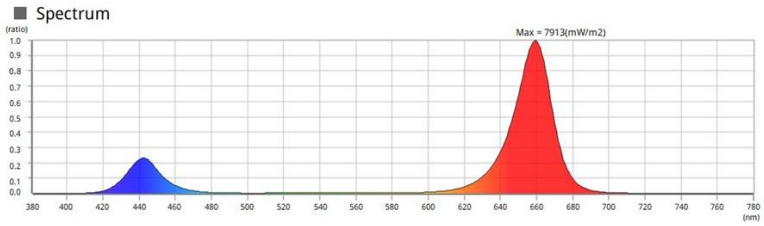
W=White Light (full spectrum); R=Red light; B=Blue light; G=Green light, PPFD=photosynthetic photon flux density

All treatments were maintained at the similar photosynthetic photon flux density (PPFD) range level 200-210. The photoperiod was 12-h from 0600 to 1800 HR for 40 days for each study. Table 3 summarises the output of each treatment in terms of total photosynthetic photon flux density (PPFD) and spectral composition. Figure 16 shows the spectral distribution scans of all treatments taken with a spectrometer LED treatment at 15 cm underneath the light source at five spots in the plant-growth area (Figure 18 (B). LI-180; LI-COR Biosciences, Lincoln, USA).

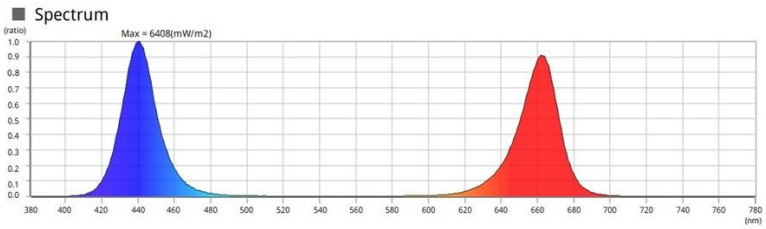
100R



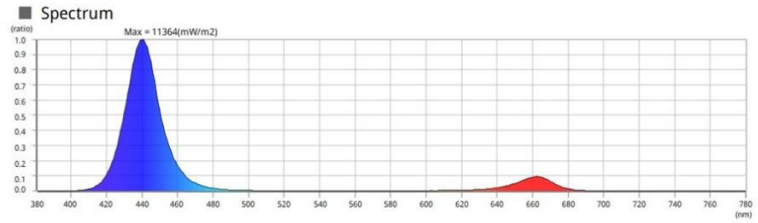
82R12B



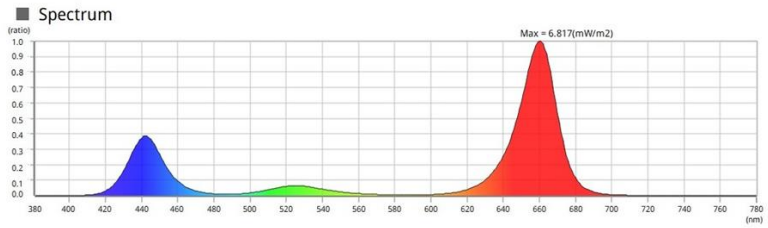
50R50B



100B



69R24B7G



W

Figure 16: Spectral distribution of LED treatments. B represents the blue PF, R the red PF and W the W PF for each treatment. Spectra were recorded and averages at five locations at the 15 cm underneath the light source.

3.4 Experimental Procedure

3.4.1 Nursery Management

Green pakchoi (*Brassica rapa chineensis*: Figure 14 (a). Code: 7, Green World Genetics Inc., Malaysia*)* and red pakchoi (*Brassica rapa chineensis*: Figure 14 (b). Code: 217, Green World Genetics Inc., Malaysia) were sown in wet urethane foam which containing 117 cells (cell size: 2 cm L x 2 cm W x 2 cm H, two seeds per cell) (Wellgrow Seed Trading, Malaysia). Every cell is sown with 2 seeds and the urethane foam cube cells contained with the seeds were then filled into hydroponic pots before transplanted to vertical multilayers hydroponic system (Figure 17). The seeds were exposed under the light treatments that has been determined to germinate.

The germination process took about 7 days. On the seventh day and when 2 leaves have grown then the thinning process is done. Only one seedling is left to be grown for the experiment. Which a total of 30 seedling plants per treatment were grown under six different light treatments for 40 days in the LED light laboratory. The

irrigation was given using water circulation method and the pump was turned on for 24 hours/ day. There was no fertilizer application during the germination period and until the 14th day after sowing. Each cultivar is grown on a separate hydroponic vertical farming rack, which means the cultivation is not mixed between the two cultivars.

3.4.2 Vertical Hydroponic Farming System Management

Four units of multilayers hydroponic vertical farm system (width 590mm x length 119mm x height 180mm) constructed with culture trays on every layer were used (Figure 17). There were 3 layers and every layer contains 3 culture trays (wide 90mm x length 1150mm x height 55mm). Every culture tray had 10 planting holes (distance between holes 82 mm). The distance between the light and the culture bed on every layer is 240mm.

Figure 17: Vertical multilayers hydroponic system in the LED light research lab

At the 15th day after sowing, the plants were sub-irrigated with nutrient solution containing 150 ml nutrient solution per 30 L water. Nutrient set A: Ca, NO_3, NH_4, Fe & K, nutrient set B: H_2PO_4, SO_4, K, Mg, B, Cu & Mo. The concentration of the nutrient solution was maintained at 7.0 to 7.3 ph. The EC was maintained at 1.0 on the first 10 days, and then increased to 1.5 and 2.0 on 15 days and 20 days, respectively. The solution temperature was 23-24°C. The pH and EC meters were used to monitor the solution (Figure 18 (A). EXPERTPH & EXPERTCTS, Thermo Scentific, Inc., MS, USA). The nutrient solution supplies using pump for 24 hours/ day throughout the experiments.

Environmental conditions in the LED light lab were controlled to maintain the temperature, CO_2 and relative humidity (RH). The air-conditioner and air-humidifier is turned-on for 24 hours/ day until the experiment completed. The temperature setting for the air-conditioner was at 20°C. The ambience temperature of was at 21.6 to 23.4 °C, CO_2 at 475 to 497 ppm and relative humidity (RH) at 70 to 78%. Temp/RH/CO_2 Meters was used to monitor the ambience temperature, CO_2 and relative humidity of the lab (Figure 18 (C), 3445, Spectrum Technologies, Inc., IL, USA).

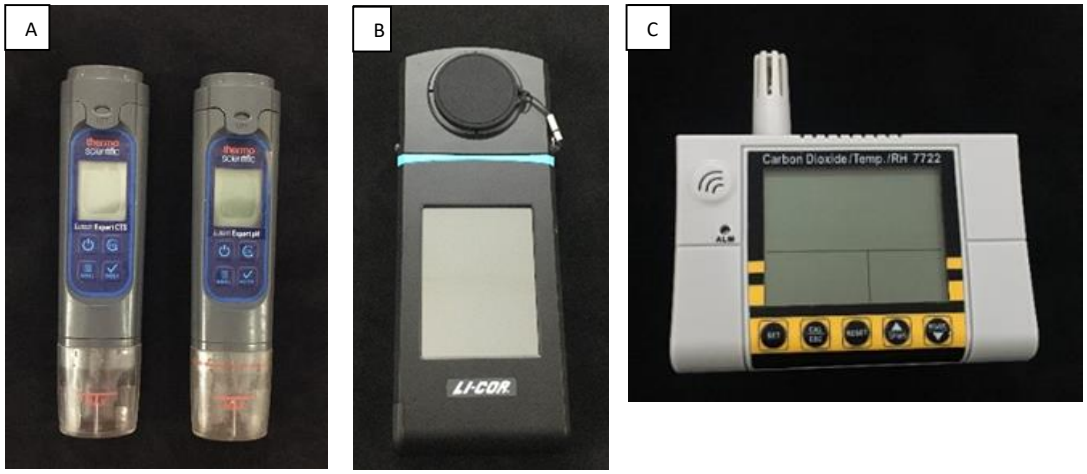


Figure 18: A) pH and EC meter, B) Spectrometer, C) Temp/RH/CO2 Meters

3.5 Data Collection

3.5.1 Determination of growth and physiological characteristics

Growth characteristics included plant height, plant width, total leaf area, fresh yield, dry yield, specific leaf area (SLA) and root morphology. While the physiological characteristics are; photosynthetic capacity, chlorophyll content and chlorophyll fluorescence.

3.5.1.1 Plant height

Plant height was determined by measuring the vertical distance from the base of the stem to the end of the longest leaf on each plant with a ruler. The measurements were performed periodically at 20, 30 and 40 DAS. On each data retrieval session, 7 randomly selected plants replicates were taken for readings. The readings were obtained in metric units, centimetre (cm).

3.5.1.2 Plant width

Plant width were obtained by measuring the horizontal distance between two longest leaves using a ruler. The measurements were taken at 20, 30, and 40 DAS. Readings were acquired from 7 randomly selected plant replicated during each data retrieval session. The measurements were taken in metric units, centimetre (cm).

3.5.1.3 Total leaf area

Total leaf areas were measured using a leaf area meter (Figure 19 (B) 14.LI-3100; LI-COR Biosciences, Lincoln, USA). The measurements were taken at 20, 30, and 40 days after sowing (DAS) and the destructive method was use of measuring leaf area. The samples of 7 replicate plants were taken, which every leaves of each replicate is removed from the stalk of the pakchoi. Each leaf was scanned using the leaf area meter. The readings are taken in metric units, square centimetre (cm^2).

3.5.1.4 Fresh yield

The fresh yields of the leaves and roots were taken at 20, 30, and 40 days after sowing (DAS) and the destructive method was use. The measurements were taking from 7 randomly selected plant replicates during each data retrieval session. The vegetative part (leaves) and the root part were separated, then weighed according to the vegetative (leaves) and root parts. The fresh yield weight of leaves and roots from each harvest were obtained using a scale (ME 3002; Mettler Toledo, Ohio, USA). The readings are taken in metric units, gram (g).

3.5.1.5 Dry yield

Dry yields of leaves and roots were collected at 20, 30, and 40 days after sowing (DAS), using the destructive method. During each data harvest session, measurements were taken from 7 randomly selected plant replicates. The vegetative (leaves) and root portions were separated, then the leaves and roots were dried in a drying oven (Figure 19 (A). UN 30; Memmert, Schwabach, Germany) for 72 hours at 70 c. The dry yield weight of leaves and roots after drying were measured using a scale (ME 3002; Mettler Toledo, Ohio, USA). The measurements were taken in metric units, gram (g).

3.5.1.6 Specific leaf area (SLA)

Specific leaf area (SLA) defined as the ratio of total leaf area to total leaf dry weight, was used as an indicator of leaf thickness (Reich et al.,1992). The readings were recorded in metric units, square centimetre/ gram (cm^2/g). The specific leaf area (SLA) was calculated according the formula below;

$$Specific\ Leaf\ Area = total\ leaf\ area/\ leaf\ dry\ weight$$

3.5.1.7 Leaf area index (LAI)

Leaf area index (LAI) is defined as the total of one sided leaf area leaf area per unit land area (Fang and Liang, 2008). This growth index provides the information of the rate of leaf area determines the rate of increase in the photosynthetic capacity in plants. The readings were recorded in unitless index. The LAI was calculated according the formula below;

$$Leaf\ area\ index = LA/\ A$$

LA = The total one sided leaf area of a crop sample covering a land area of A
A = The land area covered by the crop sample

3.5.1.8 Absolute Growth Rate (AGR)

AGR is the increment in total dry weight per unit time (Hunt, 1990). This growth index is used specifically to quantify growth of single plant (e.g.: in pot experiments) where the components of a crop spread over a given land area is absent. The readings were recorded in g d-1 or g week-1. The AGR was calculated according the formula below;

$$Absolute\ growth\ index = (W2 - W1)/\ (t2 - t1)$$

W1 = The total dry weight per plant at times t1
W2 = The total dry weight per plant at times t2

3.5.1.9 Relative Growth Rate (RGR)

RGR is the increment of total dry weight per unit time per unit existing total dry weight (Hunt, 1990). It expresses growth in terms of a rate of increase in size per unit of size. This allows more equitable comparisons than an absolute growth rate. The readings were recorded in g g-1 d-1, mg g-1 d-1 or g g-1 week-1. The RGR was calculated according the formula below;

$$Relative\ growth\ index = (W2 - W1)/\ (t2 - t1)\ \ X\ \ 1/W$$

W = The mean total dry weight during the period (t2 - t1)
W1 = The total dry weight per plant at times t1
W2 = The total dry weight per plant at times t2

3.5.1.10 Nett Assimilation Rate (NAR)

NAR is the increment of total dry weight per unit time per unit leaf area. It defines the efficiency of biomass production specifically in terms of the amount of photosynthetic tissue (Konings, 1989). It enables comparisons of the efficiency of production between plants of different sizes. The readings were recorded in g g-1 d-1, mg g-1 d-1 or g g-1 week-1. The NAR was calculated according the formula below;

$$Net\ assimilation\ rate = (W2 - W1)/\ (t2 - t1)\ \ X\ \ 1/LA$$

LA = The total one sided leaf area of a crop sample covering a land area of A
W1 = The total dry weight per plant at times t1
W2 = The total dry weight per plant at times t2

3.5.1.11 Photosynthetic capacity

A portable gas exchange analyser (Figure 19 (C), CIRAS-3; PP Systems International, Amesbury, MA) was used to measure the photosynthetic capacity of green and red pakchoi leaves non-destructively at 30 days after sowing (DAS), including the photosynthesis rate (Pn), the transpiration rate (E) and stomatal conductance (Gs). A PLC3 leaf cuvette (PP Systems International, Amesbury, MA) with LED unit (white light) was used and PPFD, relative air humidity and CO_2 concentration inside the leaf chamber were kept constant at mmol, 50% and 390mmol.

The measurements were taken from 7 randomly selected plant replicates. The third leaves from the top were used for measuring gas exchange rate, on both green and red pakchoi plants. Measurement were taken when Pn reached a steady rate.

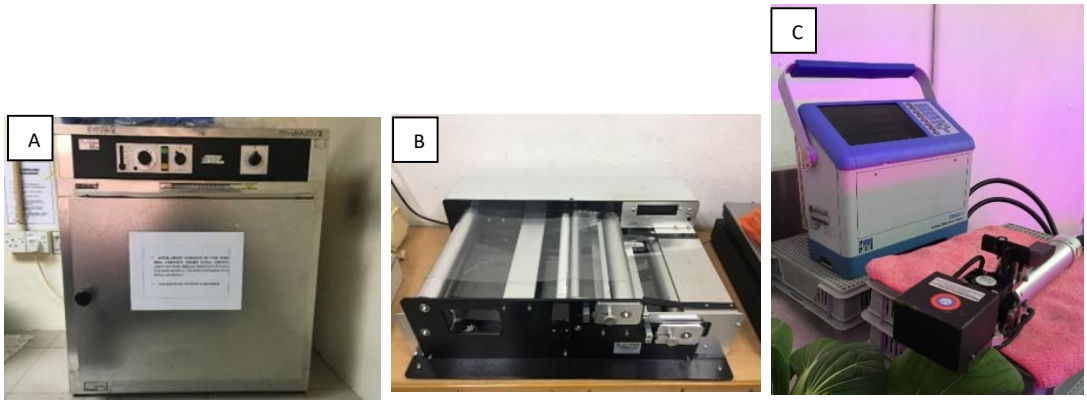


Figure 19: A) Drying oven, B) Leaf area meter C) Portable gas exchange analyser

3.5.1.12 Chlorophyll content

The measurement of chlorophyll content was non-destructive taken at 20, 30, and 40 days after sowing (DAS). A portable chlorophyll meter (Figure 20 (A). SPAD-502DL; Konika Minolta Sensing, Osaka, Japan) was used to measure relative chlorophyll content in dimensionless SPAD units. In every data collection session, measurements were taken from 7 randomly selected plant replicates. Measurements were recorded from three different leaves per plant and the average of those three measurements were recorded for data analysis.

3.5.1.13 Chlorophyll fluorescence (Fv/Fm)

Chlorophyll fluorescence measurement (maximum variable fluorescence (Fv)/maximum fluorescence (Fm) is a way to gain information on the state of photosystem II (PSII). The measurement explains the effect of stresses on the photosynthetic process in the leaves. Decreases of this index are indicative of the reduction of photosystem II (PSII) efficiency (Guidi et al., 2019). This index measurement is useful to understand the fundamental mechanism of photosynthesis due to plant's responses towards environmental change, genetic variation and ecological diversity (Murchie and Lawson, 2013).

The measurement of chlorophyll fluorescence (Fv/Fm) were recorded at 20, 30, and 40 days after sowing (DAS). The data collection was non-destructively using a fluorometer and the Qy (Qy=Fv/Fm) parameter was selected from the option (Figure

20 (B). FP 100-MAX; Photon Systems Instruments, Czech Republic). During each data collection session, readings were taken from 7 randomly selected plant replicates. The measurements were performed on 20 min dark-adapted (wrapped with solid paper) fully expended leaf, one leaf on each plant. Qy (Qy=Fv/Fm) were obtained by induced a saturating light of ~3000 µmol m−2 s−1.

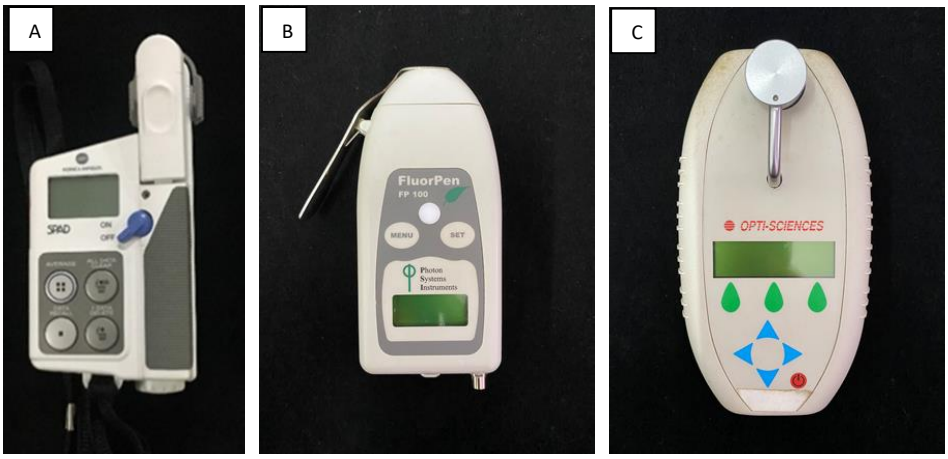


Figure 20: A) Portable chlorophyll meter, B) Flourometer, C) Anthocyanin meter

3.5.1.14 Root morphology

The WinRhizo system consist of image acquisition scanner and root image analysis software run by a computer (Figure 21. WinRhizo; Regent. Inc., Canada). was used to analyse root morphological features; average root diameter, total root length, area, volume and number of tips. The root analysis was obtained during harvests at 30 DAS. During the collection session, readings were taken from 7 randomly selected plant replicates. The parameters that have been recorded are; total root length, total surface area of roots, root volume, and number of tips. The plant sample roots were gently separated from the urethane foam cube and after completely removed the urethane foam cube debris then continue with imaging the roots.

3.5.2 Phytochemical measurement

3.5.2.1 Anthocyanin index

Anthocyanin levels were estimated non-destructively from leaves directly exposed to the light, using an anthocyanin content meter (Figure 20 (C). ACM-200 plus; Opti-Sciences. Inc., USA). The anthocyanin content meter measures the optical

absorbency from two different wavebands (530 and 931 nm), calculate for the chlorophyll content and leaf thickness. The measurement was obtained during harvests at 20, 30 and 40 DAS. During the collection session, readings were taken from 7 randomly selected plant replicates. The sensor compartment was clamped onto the leaf tissue of three different leaves per plant and the average of those three measurement was recorded.

Figure 21: Root scanner

3.5.2.2 Protein

A dried sample of leaves from the harvest of 30 DAS was used. Protein content was determined by using the Kjeldahl method according to method 981.10 of the AOAC International (AOAC, 1995). Approximately 1g of dry leaves were hydrolyzed in a heat block at 420 ^{o}C for 2 hours with 15mL concentrated sulphuric acid (H_2SO_4) containing two copper catalyst tablets. After cooling, the hydrolysates were added to H_2O for neutralisation and titration. To estimate the total protein content, the quantity of total nitrogen in the raw materials was multiplied by both the conventional conversion factor of 6.25 and species-specific conversion factors.

3.5.2.3 Carbohydrate

A dried sample of leaves from the harvest of 30 DAS was used. The method from Pomeranz in Food Analysis Theory and Practice, 2nd Edition (Yeshahaju and Clifton, 1994) was used in determination of carbohydrate. 1g of dried leaves was placed in a 25ml bottle, followed by the addition of 10ml of distilled water and vigorous shaking, followed by the addition of 15cm^3 of 52% perchloric acid. This was constantly agitated for 30 minutes and then filtered through filter paper. In a test tube, 1ml of the filtrate was combined with 4cm^3 of Anthrone reagent and the absorbance of the combination

was determined using a spectrophotometer set to 620nm. The total soluble carbohydrate content was then determined using the glucose standard curve.

3.5.2.4 Crude fibre

The AOAC 992.16 (AOAC, 1995) method was used to measure the total crude fiber. A dried sample of leaves from the 30 DAS harvest was utilised. 1g of dry leaves sample were treated with two amylases, a heat stables a-amylase and an amyloglucosidase to remove starch, and a protease to solubilize protein. The residue was recovered by filtration of the 80% ethanol insoluble precipitate, dried, weighed and the weight corrected forash and crude protein content.

3.5.2.5 Total phenolic content

Total phenolics content was determined using the modified Folin-Ciocalteu reagent method (Waterhouse, 2003). A dried sample of leaves from the 30 DAS harvest was utilised. A 125 ɱl aliquot of a dilution of the extract was added to the test tube and combined with 0.5 ml of Folin–Ciocalteus reagent. The tubes were vortexed for 15 s and then allowed to stand for 6 min at 20°C. About 1.25ml of 7% sodium carbonate solution was then added to the test tubes, and the mixture was diluted to 3ml with distilled, de-ionized water. Colour developed for 90 min, and absorbance was measured at 760 nm using the spectrophotometer. The result will be expressed as milligrams of gallic acid equivalent per gram of fresh weight of leaves.

3.5.2.6 Carotenoid content

The concentration of total carotenoids content is measured using spectrophotometric assay. The leaf sample was obtained during harvests at 30 DAS. The leaf sample is grinded with 5 ml of 80% acetone in a mortar and pestle. The resulting mixture is transferred into centrifuge tubes and 80% acetone is added to obtain a final volume of 10 ml. The mixture is centrifuged at 6000 rpm for 10 minutes. Decant supernatant into another centrifuge tube and further dilute with 80% acetone to make a final volume of 10 ml. The absorbance at 470 nm is measured using a spectrophotometer (Spectrophotometer Libra S12; Biochrom, UK) with 80% acetone as blank. Concentration of pigments in ml/g of tissue are calculated using the following equations (Lichtenthaler, 1987).

Total carotenoid concentration (Cc) = (1000A470 - 1.82Ca – 85.02Cb)/198

Where A470 is the absorbance at 470 nm.

3.5.2.7 Vitamin C

Vitamin C was determined by using the procedure AOAC Method 967.2110 (AOAC, 1995). A dried sample of leaves from the 30 DAS harvest was utilised. 10g of dry leaf sample was accurately weighed and crushed with a mortar and pestle, along with 20ml of metaphosphoric acid acetic acid. The extract was prepared up to 100ml using the metaphosphoric-acetic acid combination after the mixture was crushed and filtered through muslin. 5ml of the metaphosphoric acid-acetic acid solution and 2ml of the sample extract were pipetted into three 50 ml Erlenmeyer flasks. Separately, the samples were titrated with the indophenol dye solution. Titrate this solution with the dye solution to a pink colour. The amount of dye used in the titration was calculated and utilised in the vitamin C content calculation. Titrations involve quantitative addition of one reagent into another to determine the concentration of one of the reagents. The detection of the equivalence point, the point at which chemically equivalent amounts of the reactants have been mixed.

3.6 Data Analysis

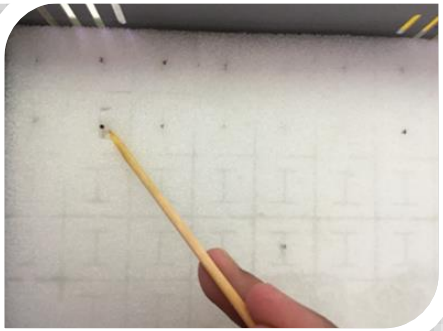
Statistical analysis was performed using the SPSS 23.0 (IBM, Inc., Chicago, IL, USA). All data were analysed for using an analysis of variance (ANOVA) procedure for completely randomised design (CRD) followed by Turkey's test for mean separation at the $P<0.05$ for the main effects (6 LEDs and 2 cultivars). The interaction between the variables were examined using Duncan test for mean separation at $P<0.05$ (6 treatments 2 cultivars=12 combinations). A correlation analysis was also performed to study relation between the variables. Data was tested for normality of residuals and homogeneity of variance prior to carrying out ANOVA.

The step by step method of crop preparation and planting in multilayers hydroponic vertical farm system in controlled-environment has been summarized in the Figure 22.

1. Green & red pakchoi seeds was prepared for sowing

2. Urethane foam soaked in water

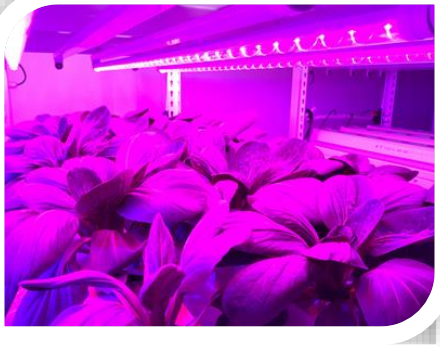
3. The seeds sown in the wet urethane foam



4. The urethane foam separated into single cubes. The urethane foam cubes filled into the hydroponic pots

Method of planting green and red pakchoi from seeds in the hydroponic vertical farm

5. The pots transferred to the vertical hydroponic rack according to the light treatments.



6. The cultivation period was at 20, 30 & 40 days after sowing.

Figure 22 Step by step planting method for green and red pakchoi in hydroponic vertical farm in controlled environment

CHAPTER 4

RESULTS

Chapter Overview

This chapter is divided into three parts according to the plant morphology, plant physiology and phytochemical accumulation. The experimental studies on green and red pakchoi cultivars were conducted twice, and hence the results displayed correspond to the first crop cycle, the second crop cycle, and finally the combined first and second crop cycles. This is to facilitate in the presenting of data and comprehension. On the other hand, the root morphology and phytochemical analysis results only displayed in the combined cycles due the samples in both cycles was merged.

4.1 Visual observation

4.1.1 Visual observation on the green pakchoi

Figure 23 showed an overhead view of one example replicate of green pakchoi for all the LED light treatments at 30 DAS. The plants were arranged based on treatments; begins with treatment White (control), 100R, 100B, 50R50B, 82R18B and 69R24G7R. Visually, it was observed the plants grown under W had the smallest plant size compared to other treatments. Plant exposed to the treatment 82R18B seem to have the most vigorous and large plant size compared to other treatments. While, plants exposed under 100R seems to have longer leaves petiole which is opposite look observed in plant under 100B treatment seems have shorter leaves petiole and looked more compact. From the visual observation, it is difficult to distinguish differences in the plant size between treatments 50R50B and 69R24B7G. According to the visual observation, monochromatic blue light (100B) decreased the leaf area while monochromatic red light (100R) elongates the leaves petiole, compared to the multi-wavelength W (control), 50R50B, 82R18B and 69R24G7R which much more proportionate in the size.

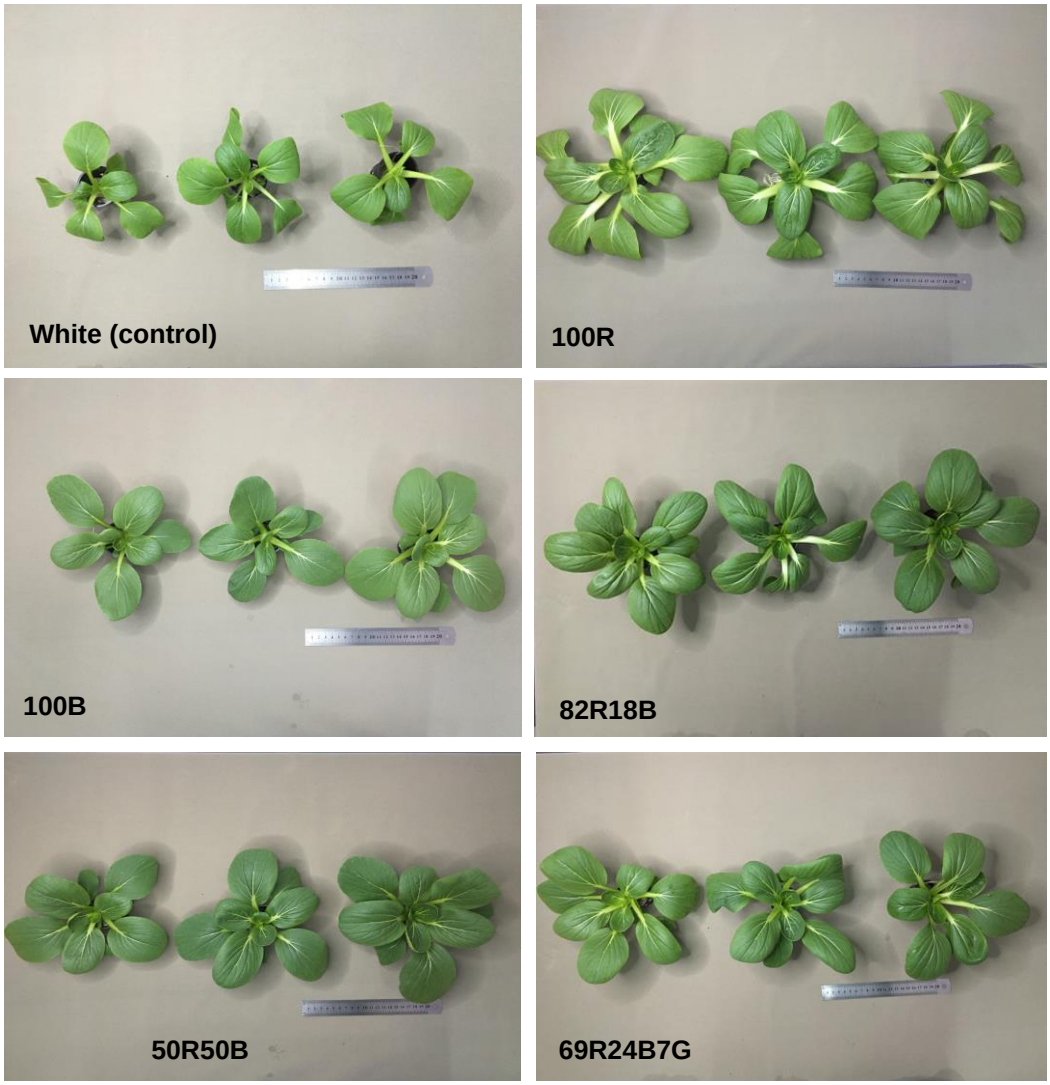


Figure 23 Morphology of green pakchoi all light treatments at 30 days after sowing (DAS). Treatment from left; W, 100R, 100B, 50R50B, 82R18B and 69R24G7R. Light treatment abbreviations as in Table 3.

4.1.2 Visual observation on the red pakchoi

Figure 24 showed an overhead view of one example replicate of red pakchoi for all light treatments at 30 DAS. The plants were arranged based on treatments; begins with W (control), 100R, 100B, 82R18B, 50R50B and 69R24G7R. It was observed that the plant exposed under the control treatment (W) have the smallest plant size among other treatments. In comparison to other treatments, plants subjected to the treatment 82R18B appear to be the most vigorous and bigger in size. Plants exposed to 100R appear to have longer leaves petioles, whilst plants exposed to 100B appear to have shorter leaves petioles and appear to be more compact. It is difficult to tell the difference in plant size between treatments 50R50B and 69R24B7G based on visual inspection. In comparison to the multi-wavelength treatments W (control), 50R50B,

82R18B, and 69R24G7R, which the plants were considerably more proportionate in size, monochromatic blue light (100B) plants size more compacted while monochromatic red light (100R) the plant size elongated.

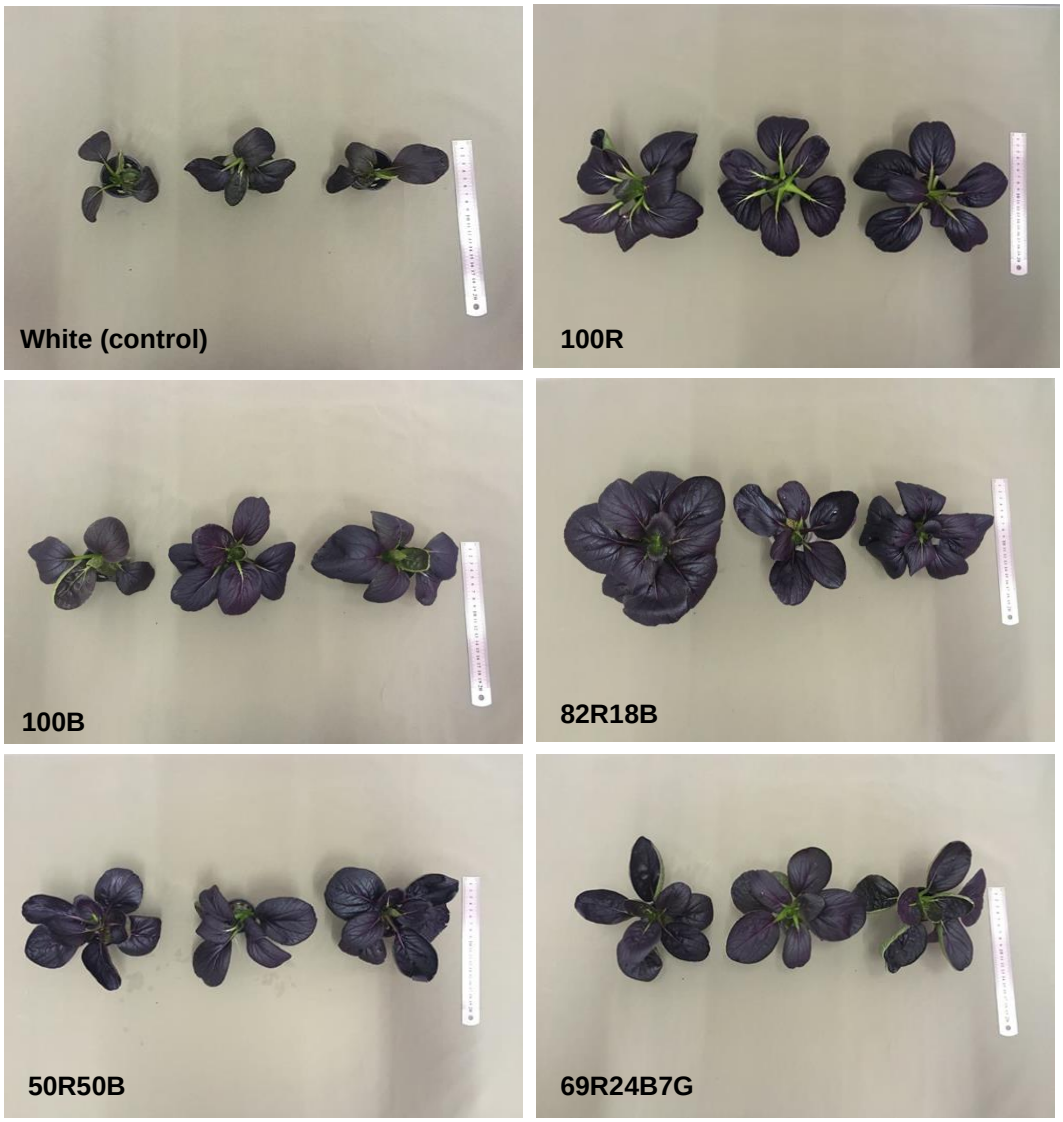


Figure 24 Morphology of red pakchoi under all light treatments at 30 days after sowing (DAS). Treatment from left; W, 100R, 100B, 50R50B, 82R18B and 69R24G7R. Light treatment abbreviations as in Table 3.

4.2 Plant Height

Main effects of LED lights, cultivars and their interaction on the plant height at 20, 30 and 40 DAS in Trial 1 and 2 are presented in Table 4. While the main effects of LED lights, cultivars and their interaction on the plant height at 20, 30 and 40 DAS in Trial 1 and 2 combined are presented in Table 5.

Table 4 Plant height of green and red pakchoi plants at 20, 30 and 40DAS (Days after sowing) grown under different LED-light quality treatments in Trial 1 and 2.

Treatment	Plant Height (cm)					
	Trial 1			Trial 2		
	20 DAS	30DAS	40DAS	20 DAS	30DAS	40DAS
Cultivar (C)						
Green Pakchoi	8.53 [a]	15.76 [a]	19.70 [a]	7.62 [a]	15.28 [a]	19.51 [a]
Red Pakchoi	6.42 [b]	10.42 [b]	14.26 [b]	6.67 [b]	8.18 [b]	15.19 [b]
SEM	0.19	0.20	0.41	0.20	0.27	0.29
P value	0.000	0.000	0.000	0.000	0.000	0.000
LED-Lights mixture (L)						
White	6.92 [bc]	10.91 [d]	14.67 [c]	4.02 [c]	7.86 [d]	12.72 [c]
100R	9.25 [a]	16.31 [a]	19.44 [a]	11.26 [a]	15.24 [a]	20.11 [a]
100B	5.70 [c]	11.73 [cd]	15.81 [bc]	6.31 [b]	10.26 [c]	16.96 [b]
50R50B	6.50 [c]	13.44 [b]	17.59 [ab]	7.26 [b]	12.04 [bc]	18.24 [ab]
82R18B	8.44 [a]	13.50 [b]	17.22 [abc]	7.49 [b]	13.18 [b]	18.56 [ab]
69R24B7G	8.00 [ab]	12.64 [bc]	17.17 [abc]	6.56 [b]	11.80 [bc]	17.49 [b]
SEM	0.32	0.35	0.70	0.34	0.47	0.5
P value	0.000	0.000	0.000	0.000	0.000	0.000
Interaction P values						
C x L	0.000	0.000	0.260	0.010	0.000	0.000

Means in a column followed by same letters are not significantly different using Tukeys at 5% level.

Table 5 Plant height of green and red pakchoi plants at 20, 30 and 40DAS (Days after sowing) grown under different LED-light quality treatments in Trial 1 and 2 combined.

Treatment	Plant Height (cm)		
	Trial 1 & 2 combined		
	20 DAS	30 DAS	40 DAS
Cultivar (C)			
Green Pakchoi	8.08 [a]	15.52 [a]	19.60 [a]
Red Pakchoi	6.55 [b]	9.30 [b]	14.72 [b]
SEM	0.17	0.20	0.26
P value	0.000	0.000	0.000
LED-Lights mixture (L)			
White	5.47 [d]	9.38 [d]	13.70 [c]
100R	10.25 [a]	15.78 [a]	19.77 [a]
100B	6.01 [cd]	10.99 [c]	16.38 [b]
50R50B	6.89 [bc]	12.74 [b]	17.91 [b]
82R18B	7.96 [b]	13.34 [b]	17.89 [b]
69R24B7G	7.28 [b]	12.22 [bc]	17.33 [b]
SEM	0.29	0.35	0.44
P value	0.000	0.000	0.000
Interaction P values			
C x L	0.004	0.001	0.009

Means in a column followed by same letters are not significantly different using Tukeys at 5% level.

Cultivar

Trial one

Cultivar had significant (P<0.05) effect on the plant height at all sampling stages (20, 30 and 40 DAS) (Table 4). Green pakchoi recorded significantly higher plant height than red at 20 DAS (8.53 cm for green and 6.42 cm for red pakchoi), 30 DAS (15.76 for green and 10.42 cm for red pakchoi) and 40 DAS (19.70 cm for green and 14.26 cm for red pakchoi). This increase in height in green pakchoi compared to the red pakchoi was 32.9% at 20 DAS, 51.2% at 30 DAS and 38.1% at 40 DAS.

Trial two

The similar growth trend found in Trial 2. At all sample stages (20, 30, and 40 DAS), cultivar had a significant (P<0.05) influence on plant height (Table 4). Green pakchoi recorded significantly higher plant height than red at 20 (7.62 cm for green and 6.67 cm for red pakchoi), 30 (15.28 for green and 8.18 cm for red pakchoi) and 40 DAS (19.51 cm for green and 15.19 cm for red pakchoi). Green pakchoi grew 14.2% taller than red pakchoi at 20 DAS, 86.8% taller at 30 DAS, and 28.4% taller at 40 DAS.

Trial one and two combined

While for the combination of both trials result, the cultivar showed a significant (P<0.05) influence on plant height at all sample stages (20, 30, and 40 DAS) (Table 5). Green pakchoi had substantially higher plant height than red pakchoi at 20 (8.08 cm for green and 6.55 cm for red pakchoi), 30 (15.52 cm for green and 9.30 cm for red pakchoi), and 40 DAS, respectively (19.60 cm for green and 14.72 cm for red pakchoi). The increase in height in green pakchoi compared to the red pakchoi was 23.4% at 20 DAS, 66.9% at 30 DAS and 33.2% at 40 DAS.

LED-Lights

Trial One

Plant height at 20, 30 and 40 DAS were significantly (P<0.05) influenced by LED lights (Table 4). At all sampling dates, monochromatic 100R (9.25, 16.31 and 19.44 cm at 20. 30 and 40 DAS respectively) obtained significantly (P<0.05) higher plant height compared other LED-light treatments. At all sampling dates, treatment 82R18B was the second highest but was similar to (P>0.05) 69R24B7G and 50R50B. The monochromatic 100B obtained the lowest height (5.7 cm) on 20DAS, while the

treatment W (control) recorded the lowest height (10.91 cm and 14.67 cm) on 30 and 40 DAS compared to other LED-light treatments.

The highest measurement on each sampling date compared to white light (control); 100R was 33.7% higher at 20 DAS, 49.5% at 30DAS and 32.5% higher at 40 DAS.

Trial Two

LED-lights had a significant ($P<0.05$) effect on plant height at 20, 30, and 40 DAS (Table 4). Monochromatic 100R (11.26, 15.24, and 20.11 cm at 20, 30, and 40 DAS, respectively) produced the largest plants at all sample dates. At 20 and 30 DAS, the plant height was significantly ($P<0.05$) greater than with other LED-light treatments. On 40 DAS, monochromatic 100R was the same towards 82R18B and 50R50B ($P>0.05$). In comparison to the other LED-light treatments, white light (control) recorded the lowest height.

The highest measurement on each sampling date compared to white light (control); 100R was 180.1% higher at 20 DAS, 93.9% at 30DAS and 58.1% higher at 40 DAS.

Trial one and two combined

LED lights had a significant ($P<0.05$) impact on plant height at 20, 30, and 40 DAS (Table 5). Monochromatic 100R (10.25, 15.78, and 19.77 cm at 20, 30, and 40 DAS, respectively) achieved significantly (P0.05) greater plant height than other LED-light treatments at all sample dates. Treatment 82R18B was the second highest at all sample dates, although it was similar to ($P>0.05$) 69R24B7G and 50R50B. When compared to other LED-light treatments, white light (control) recorded the lowest height.

The highest measurement on each sampling date compared to white light (control); 100R was 87% higher at 20 DAS, 68% at 30DAS and 44% higher at 40 DAS.

Cultivar x LED-Lights Interaction

Trial one and two combined

The plant height of green and red pakchoi was significantly (P<0.05) affected with LED-light treatments at all sampling dates (Table 5). At 20 DAS sampling date (Table 6), response to LED was higher (P<0.05) in green pakchoi than red pakchoi under all LED-light treatments. Highest plant height was recorded on green pakchoi with 100R LED light treatment. The lowest plant height was indicated on red pakchoi with white light treatment (control). At 30 DAS (Table 6), green pakchoi were significantly (P<0.05) taller than red pakchoi with all the LED-light treatments. Tallest plants were recorded in green pakchoi with 100R light, while the smallest plant was the red pak choi plants exposed under white light treatment (control). Similarly, at 40 DAS (Table 6), green pakchoi were significantly (P<0.05) taller than red pakchoi with all the LED-light treatments. Highest plants were recorded in green pakchoi with the treatment monochromatic 100R light, while the shortest plant was the red pakchoi plants exposed under white light treatment (control).

Table 6 The interaction of plant height at 20 and 30 DAS of green pakchoi and red pakchoi towards LED-light treatments at Trial 1 and 2 combined.

Cultivar x LED-light	Plant height (cm)					
	20 DAS		30 DAS		40 DAS	
	Red pakchoi	Green pakchoi	Red pakchoi	Green pakchoi	Red pakchoi	Green pakchoi
White (control)	4.48 ^{f}	6.46 ^{de}	6.90 ^{g}	11.86 ^{d}	12.34 ^{e}	15.06 ^{cd}
100R	8.71 ^{b}	11.79 ^{a}	11.36 ^{de}	20.20 ^{a}	15.99 ^{c}	23.56 ^{a}
100B	5.90 ^{e}	6.13 ^{de}	7.73 ^{g}	14.26 ^{c}	14.00 ^{de}	18.76 ^{b}
50R50B	6.68 ^{de}	7.10 ^{de}	10.26 ^{ef}	15.21 ^{bc}	15.82 ^{cd}	20.00 ^{b}
82R18B	7.29 ^{cd}	8.64 ^{b}	10.26 ^{ef}	16.42 ^{b}	15.45 ^{cd}	20.34 ^{b}
69R24B7G	6.22 ^{de}	8.64 ^{bc}	9.29 ^{f}	15.15 ^{bc}	14.76 ^{cd}	19.90 ^{b}
SEM	0.41		0.49		0.63	
P value	0.00		0.00		0.01	

For each duration (DAS), means with different letters across rows and columns are significantly different at P<0.05 by Duncan multiple comparisons test. Light treatment abbreviations as in Table 3.

4.3 Plant diameter

Main effects of LED lights, cultivars and their interaction on the plant diameter at 20, 30 and 40 DAS in Trial 1 and 2 are presented in Table 7. While the main effects of LED lights, cultivars and their interaction on the plant diameter at 20, 30 and 40 DAS in Trial 1 and 2 combined are presented in Table 8.

Table 7 Plant diameter of green and red pakchoi plants at 20, 30 and 40DAS (Days after sowing) grown under different LED-light quality treatments in Trial 1 and 2.

Treatment	Plant Diameter (cm)					
	Trial 1			Trial 2		
	20 DAS	30 DAS	40 DAS	20 DAS	30 DAS	40 DAS
Cultivar (C)						
Green Pakchoi	11.03 [a]	24.27 [a]	35.99 [a]	11.76 [a]	28.25 [a]	36.55 [a]
Red Pakchoi	8.50 [b]	16.18 [b]	21.66 [b]	8.61 [b]	16.00 [b]	27.00 [b]
SEM	0.23	0.34	0.39	0.30	0.56	0.51
P value	0.000	0.000	0.000	0.000	0.000	0.000
LED-Lights mixture (L)						
White	7.61 [d]	15.31 [d]	24.14 [c]	6.51 [c]	16.93 [b]	25.38 [c]
100R	12.25 [a]	26.88 [a]	34.73 [a]	16.52 [a]	25.79 [a]	36.23 [a]
100B	8.22 [cb]	18.4 [c]	25.58 [c]	9.03 [b]	16.48 [b]	26.81 [c]
50R50B	9.43 [bc]	21.51 [b]	26.59 [c]	10.36 [b]	20.04 [b]	30.94 [b]
82R18B	10.95 [ab]	20.12 [bc]	31.78 [b]	10.07 [b]	28.21 [a]	36.75 [a]
69R24B7G	10.13 [b]	19.12 [bc]	30.15 [b]	8.63 [bc]	25.30 [a]	34.56 [ab]
SEM	0.40	0.59	0.67	0.52	0.97	0.88
P value	0.000	0.000	0.000	0.000	0.000	0.000
Interaction P values						
C x L	0.000	0.000	0.000	0.000	0.000	0.000

Means in a column followed by same letters are not significantly different using Tukeys at 5% level.

Table 8 Plant diameter of green and red pakchoi plants at 20, 30 and 40DAS (Days after sowing) grown under different LED-light quality treatments in Trial 1 and 2 combined.

Treatment	Plant Diameter (cm)		
	20 DAS	30 DAS	40 DAS
Cultivar (C)			
Green Pakchoi	11.40 [a]	26.26 [a]	36.27 [a]
Red Pakchoi	8.55 [b]	16.09 [b]	24.34 [b]
SEM	0.22	0.43	0.42
P value	0.000	0.000	0.000
LED-Lights mixture (L)			
White	7.06 [d]	16.12 [d]	24.76 [d]
100R	14.39 [a]	26.33 [a]	35.48 [a]
100B	8.63 [c]	17.44 [d]	26.19 [bc]
50R50B	9.89 [bc]	20.78 [c]	28.76 [c]
82R18B	10.51 [b]	24.17 [ab]	34.26 [ab]
69R24B7G	9.38 [bc]	20.21 [bc]	32.36 [b]
SEM	0.38	0.74	0.72

P value	0.000	0.000	0.000
Interaction P values			
C x L	0.000	0.00	0.002

Means in a column followed by the same letters are not significantly different using Tukeys at 5% level.

Cultivar

Trial one

At all sampling stages (20, 30, and 40 DAS), the cultivar showed a significant ($P<0.05$) effect on plant diameter (Table 7). Green pakchoi had considerably larger plant diameters than red pakchoi at 20 (11.03 cm for green and 8.50 cm for red pakchoi), 30 (24.27 cm for green and 16.18 cm for red pakchoi), and 40 DAS, respectively (35.99 cm for green and 21.66 cm for red pakchoi). This increase in diameter in green pakchoi compared to the red was 29.8% at 20 DAS, 50% at 30 DAS and 66.2% at 40 DAS.

Trial two

Cultivar had significant ($P<0.05$) effect on the plant diameter at all sampling stages (20, 30 and 40 DAS) (Table 7). Green pakchoi recorded significantly higher plant diameter than red at 20 (11.76 cm for green and 8.61 cm for red pakchoi), 30 (28.25 for green and 16.00 cm for red pakchoi) and 40 DAS (36.55 cm for green and 27.00 cm for red pakchoi). This increase in diameter in green pakchoi compared to the red pakchoi was 36.6% at 20 DAS, 76.6% at 30 DAS and 35.4% at 40 DAS.

Trial one and two combined

At all sample stages (20, 30 and 40 DAS), the cultivar had a significant ($P<0.05$) influence on the plant diameter (Table 8). Green pakchoi had significantly larger plant diameter than red pakchoi at 20 DAS (11.40 cm for green and 8.55 cm for red pakchoi), 30 DAS (26.26 cm for green and 16.09 cm for red pakchoi), and 40 DAS (36.27 cm for green and 24.34 cm for red pakchoi). The increase in diameter in green pakchoi compared to the red pakchoi was 33.3% at 20 DAS, 63.2% at 30 DAS and 49% at 40 DAS.

The results for cultivars in Trials 1 and 2, as well as the combination of Trials 1 and 2, indicated that the results were consistent, the green pakchoi had a larger plant diameter than the red pakchoi.

LED-Lights

Trial one

Plant diameter at 20, 30 and 40 DAS were significantly (P<0.05) influenced by LED lights (Table 7). At all sampling dates, monochromatic 100R (12.25 cm, 26.88 cm and 34.73 cm at 20. 30 and 40 DAS respectively) obtained significantly (P<0.05) higher plant height compared other LED-light treatments. Besides that, at all sampling dates, treatment 82R18B was the second highest but was similar to (P>0.05) 69R24B7G and 50R50B. White light (control) recorded the significantly (P<0.05) lowest diameter compared to other LED-light treatments at 20 and 30 DAS.

The highest measurement on each sampling date compared to white light (control); 100R was 61% higher at 20 DAS, 75.6% at 30DAS and 43.9% higher at 40 DAS.

Trial two

LED-light treatments had a significant (P<0.05) effect on plant diameter at 20, 30, and 40 DAS (Table 7). At 20 DAS sampling date, monochromatic 100R (16.52 cm) obtained significantly (P<0.05) higher plant diameter among other LED-light treatments. At 30 and 40 DAS sampling dates, 82R18B had the highest plant diameter but was no significant (P>0.05) towards 100R and 69R24B7G.White light (control) recorded the lowest height compared to other LED lights.

The highest measurement on each sampling date compared to white light (control); 100R was 153.8% higher at 20 DAS. While 82R18B was 66.6% higher at 30DAS and 44.8% higher at 40 DAS.

Trial one and two combined

Plant diameter at 20. 30 and 40 DAS were significantly (P<0.05) affected by LED lights (Table 8). At all sampling dates, monochromatic 100R (14.39, 26.33 and 35.48 cm at 20, 30 and 40 DAS respectively) obtained higher plant diameter compared other LED-light treatments. However, it was significantly (P<0.05) different only at 20 DAS, while at 30 and 40 DAS there were no significant (P>0.05) towards treatment 82R18B (20.21 cm and 32.36 at 30 and 40 DAS respectively). At all sampling dates, treatment 82R18B was the second highest but was similar to (P>0.05) 69R24B7G and

50R50B. White light (control) recorded the lowest height compared to other LED-light treatments.

The highest measurement on each sampling date compared to white light (control); 100R was 103.8% higher at 20 DAS, 63.3% at 30DAS and 43.3% higher at 40 DAS.

The results for plant diameter in Trials 1 and 2, as well as the combination of Trials 1 and 2, indicated that the results were almost similar. The LED-light treatment monochromatic 100R produced a greater plant diameter in Trial 1. While in the Trial 2, the monochromatic 100R and 82R18B both produced the largest diameter throughout the sampling stages. While in the combined results showed the monochromatic 100R produced the largest diameter compared to other LED-light treatments.

Cultivar x LED-Lights Interaction

Trial one and two combined

The plant diameter of green and red pakchoi was significantly ($P<0.05$) affected with LED-light treatments at all sampling dates (Table 8). At 20 DAS sampling date (Figure 25), response to LED-light treatment was higher ($P<0.05$) in green pakchoi than red pakchoi for all LED-light treatments. The highest plant diameter was recorded on green pakchoi under the treatment monochromatic 100R. The lowest plant diameter was found on red pakchoi under the treatment white light (control). At 30DAS (Figure 26), green pakchoi were significantly ($P<0.05$) wider than red pakchoi with all the LED-light treatments. Widest plants were recorded in green pakchoi with the treatment monochromatic 100R and the lowest diameter measurement was obtained on red pakchoi exposed to white light (control) treatment. Similarly, at 40 DAS (Figure 27), green pakchoi significantly ($P<0.05$) larger plant diameter than red pakchoi under all LED-light treatments. When compared to all LED-light treatments, the green pakchoi with monochromatic 100R remains the broadest plant, while the red pakchoi with white light (control) remains the smallest plant diameter.

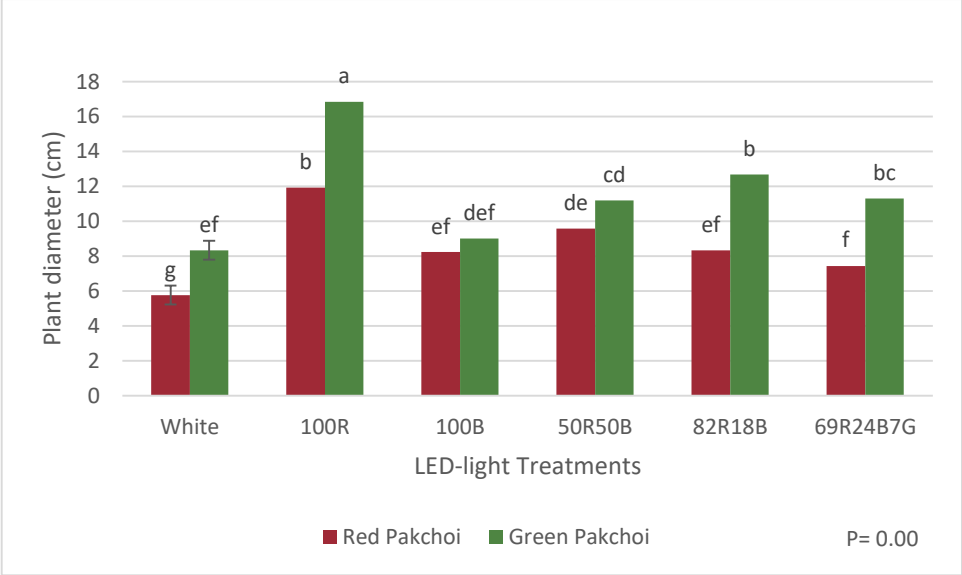


Figure 25 The interaction of plant diameter at 20 DAS of green pakchoi and red pakchoi towards LED-light treatments. Means with different letters are significantly different at P= 0.05 by Duncan multiple comparisons test. Light treatment abbreviations as in Table 3.

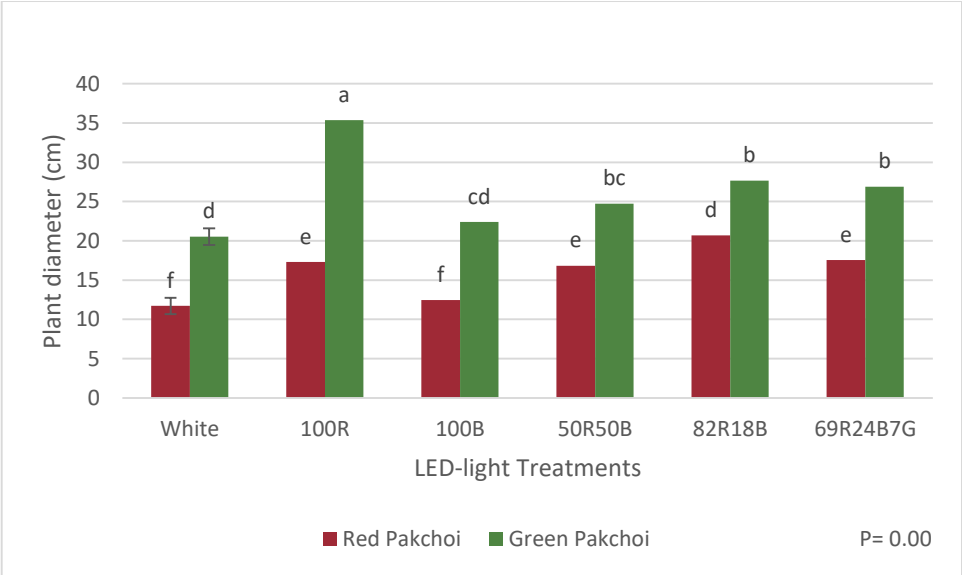


Figure 26 The interaction of plant diameter at 30 DAS of green pakchoi and red pakchoi towards LED-light treatments. Means with different letters are significantly different at P= 0.05 by Duncan multiple comparisons test. Light treatment abbreviations as in Table 3.

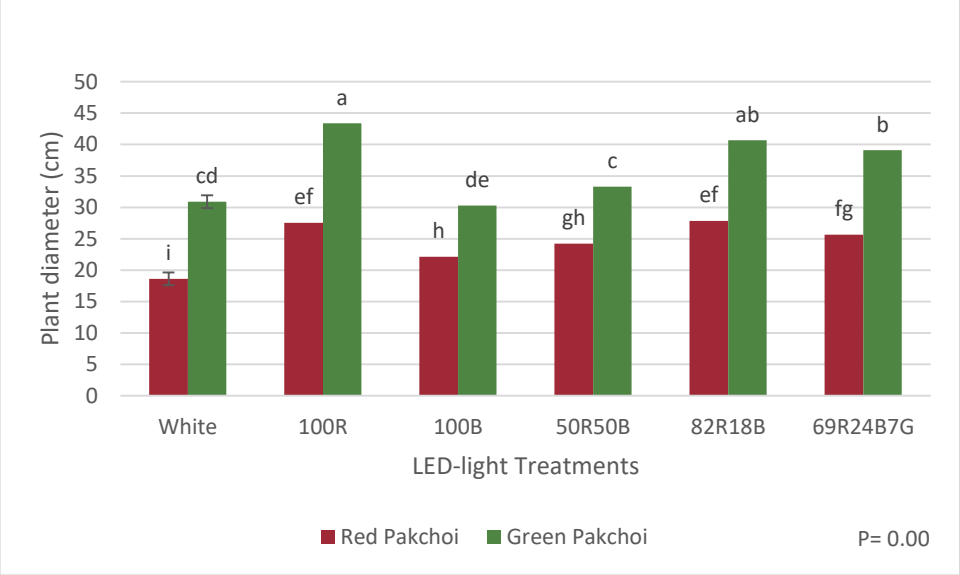


Figure 27 The interaction of plant diameter at 40 DAS of green pakchoi and red pakchoi towards LED-light treatments. Means with different letters are significantly different at P= 0.05 by Duncan multiple comparisons test. Light treatment abbreviations as in Table 3.

4.4 Leaf Number

Main effects of LED lights, cultivars and their interaction on the leaf numbers at 20, 30 and 40 DAS in Trial 1 and 2 are presented in Table 9. While the main effects of LED lights, cultivars and their interaction on the leaf numbers at 20, 30 and 40 DAS in Trial 1 and 2 combined are presented in Table 10.

Table 9 Leaf numbers of green and red pakchoi plants at 20, 30 and 40 DAS (Days after sowing) grown under different LED-light quality treatments in Trial 1 and Trial 2.

Treatment	Leaf Number					
	Trial 1			Trial 2		
	20 DAS	30 DAS	40 DAS	20 DAS	30 DAS	40 DAS
Cultivar (C)						
Green Pakchoi	7.38 a	12.36 a	22.02 a	7.83 a	11.93 a	19.12 a
Red Pakchoi	5.60 b	7.55 b	8.74 b	6.10 b	7.24 b	11.50 b
SEM	0.10	0.21	0.31	0.13	0.18	0.29
P value	0.000	0.000	0.000	0.000	0.000	0.000
LED-Lights mixture (L)						
White	5.71 c	8.57 c	12.43 c	5.79 c	7.00 d	12.86 c
100R	6.50 b	10.57 ab	15.14 b	8.00 a	10.57 ab	16 ab
100B	6.43 bc	9.57 bc	15.36 b	7.00 b	10.14 abc	14.36 bc
50R50B	7.36 a	11.43 a	15.36 b	7.93 a	11.07 a	13.93 bc
82R18B	6.50 b	9.57 bc	17.79 a	6.79 b	9.5 bc	17 a
69R24B7G	6.30 bc	10.00 abc	16.21 ab	6.29 bc	9.21 c	17.71 a
SEM	0.18	0.36	0.53	0.22	0.31	0.5
P value	0.000	0.000	0.000	0.000	0.000	0.000
Interaction P values						
C x L	0.120	0.010	0.000	0.120	0.000	0.000

Means with the same letters across column are not significantly different using Tukeys at 5% level.

Table 10 Leaf number of green and red pakchoi plants at 20, 30 and 40DAS (Days after sowing) grown under different LED-light quality treatments in Trial 1 and Trial 2 combined.

Treatment	Leaf Numbers		
	20 DAS	30 DAS	40 DAS
Cultivar (C)			
Green Pakchoi	7.61 [a]	12.14 [a]	20.57 [a]
Red Pakchoi	5.85 [b]	7.39 [b]	10.12 [b]
SEM	0.09	0.19	0.27
P value	0.000	0.000	0.000
LED-Lights mixture (L)			
White	5.75 [d]	7.79 [c]	12.64 [c]
100R	7.25 [ab]	10.57 [ab]	15.57 [ab]
100B	6.71 [bc]	9.86 [b]	14.86 [b]
50R50B	7.64 [a]	11.25 [a]	14.64 [b]
82R18B	6.64 [bc]	9.54 [b]	17.39 [a]
69R24B7G	6.36 [cd]	9.61 [b]	16.96 [a]
SEM	0.16	0.32	0.47
P value	0.000	0.000	0.000
Interaction P values			
C x L	0.355	0.001	0.000

Means with the same letters across column are not significantly different using Tukeys at 5% level.

Cultivar

Trial one

Cultivar had significant (P<0.05) effect on the leaf numbers at all sampling stages (20, 30 and 40 DAS) (Table 9). Green pakchoi recorded significantly higher number of leaves than red at 20 (7.38 for green and 5.6 for red pakchoi), 30 (12.36 for green and 7.55 for red pakchoi) and 40 DAS (22.02 for green and 8.74 for red pakchoi). This increase in leaf numbers in Green pakchoi compared to the red was 31.8% at 20 DAS, 63.7% at 30 DAS and 151.9% at 40 DAS.

Trial two

For the Trail 2, at all sample stages (20, 30, and 40 DAS), cultivar showed a significant (P<0.05) influence on leaf number (Table 9). Green pakchoi had substantially greater leaf counts than red pakchoi at 20 (7.83 for green and 6.10 for red pakchoi), 30 (11.93 for green and 7.24 for red pakchoi), and 40 DAS, respectively (19.12 cm for green and 11.50 cm for red pakchoi). Green pakchoi grew more leaf number than red pakchoi; 28.4% at 20 DAS, 64.8% at 30 DAS, and 66.3% at 40 DAS.

Trial one and two combined

At all three sample stages (20, 30 and 40 DAS), the cultivar had a statistically significant (P<0.05) influence on the number of leaves (Table 10). Green pakchoi recorded significantly higher leaf numbers than red pakchoi at 20 (7.61 for green and 5.85 for red pakchoi), 30 (12.14 for green and 7.39 for red pakchoi) and 40 DAS (20.57 for green and 10.12 for red pakchoi). The increase in leaf numbers in green pakchoi compared to the red pakchoi was 30.1% at 20 DAS, 64.3% at 30 DAS and 103.3% at 40 DAS.

The results for cultivars in Trials 1 and 2, as well as the combination of Trials 1 and 2, indicated that the results on leaf numbers were consistent, green pakchoi produced a greater leaf numbers in both trials and the combined results than the red pakchoi.

LED-Lights

Trial one

The number of leaves at 20. 30 and 40 DAS were significantly (P<0.05) influenced by LED lights (Table 9). At 20 and 30 DAS sampling dates, the treatment 50R50B (7.36 and 11.43 at 20 and 40 DAS respectively) produced significantly (P<0.05) higher leaf numbers compared other LED-light treatments. On the 20 DAS of sampling date, the treatments 82R18B and 100R were the second highest with 6.5 number of leaves. On the 30 DAS of sampling date, the treatment 100R had the second highest leaf numbers but was similar to (P>0.05) 69R24B7G. However, on 40 DAS sampling date 82R18B obtained the highest leaf numbers (17.79) but was similar to (P>0.05) 69R24B7G. White light (control) recorded the lowest leaf numbers compared to other LED lights in every sampling dates.

The highest measurement on each sampling date compared to white light (control); 50R50B was 28.9% higher at 20 DAS and 33.4% at 30DAS. While 82R18B 43.1% higher at 40 DAS.

Trial two

A significant (P<0.05) difference was seen in the number of leaves at 20, 30, and 40 DAS when treated by the LED-light treatments (Table 9). At 20 DAS sampling date, the monochromatic 100R (8.00) produced the highest leaf number but it was

similar (P>0.05) to 50R50B (7.93). At 30 DAS of sampling date, the treatment 50R50B (11.07) obtained the highest number of leaves but no significant (P>0.05) difference with the treatments 100R and 100B (10.57 and 10.14). While at 40 DAS of sampling date, the treatment 69R24B7G (17.71) indicated the highest leaf numbers and no significant (P>0.05) towards 82R18B and 100R (17.00 and 16.00). White light (control) recorded the lowest leaf numbers compared to other LED lights in every sampling dates.

The highest measurement on each sampling date compared to white light (control); 100R was 38.2% higher at 20 DAS, 50R50B was 58.1% higher at 30DAS and 82R18B was 37.7% higher at 40 DAS.

Trial one and two combined

Leaf numbers at 20. 30 and 40 DAS were significantly (P<0.05) influenced by LED lights (Table 10). At 20 and 30 DAS sampling dates, 50R50B (7.64 and 11.25 at 20 and 30 DAS respectively) obtained higher leaf numbers compared other LED-light treatments. However, significantly (P>0.05) no difference towards the treatment 100R (7.25 and 10.57 at 20 and 30 DAS respectively). While at 40 DAS sampling date, 82R18B (17.39) obtained the highest leaf numbers but similar (P>0.05) to 69R24B7G and 100R (16.96 and 15.57). White light (control) recorded the lowest leaf numbers compared to other LED-light treatments.

The highest measurement on each sampling date compared to white light (control); 50R50B was 32.9% higher at 20 DAS and 44.4% at 30DAS and 37.6% higher at 40 DAS.

The results for the influence of LED-light treatments on leaf numbers in Trials 1 and 2, as well as the combination of Trials 1 and 2, the results obtained was almost similar. The LED-light treatment 50R50B and monochromatic 100R seems to produce a greater leaf numbers in both trials and the combined results compared to other LED-light treatments.

Cultivar x LED-Lights Interaction

Trial one and two combined

LED-lights had a significant (P<0.05) effect on the number of leaves of green and red pakchoi at 30 and 40 DAS sampling dates. While at 20 DAS sampling date the number of leaves was not significantly affected by the LED-light treatments (Table 10). At 30DAS (Figure 28), green pakchoi was significantly (P<0.05) indicated higher leaf number than red pakchoi with all the LED-light treatments. The highest leaf numbers were achieved in green pakchoi treated with 50R50B, while the lowest leaf numbers were obtained in red pakchoi treated with white light (control). At 40 DAS (Figure 29), green pakchoi significantly (P<0.05) had the highest leaf numbers compare to red pakchoi under all LED-light treatments. The green pakchoi grown under 69R24B7G had the most leaf numbers. While red pakchoi under the treatment white light (control) had the lowest leaf numbers.

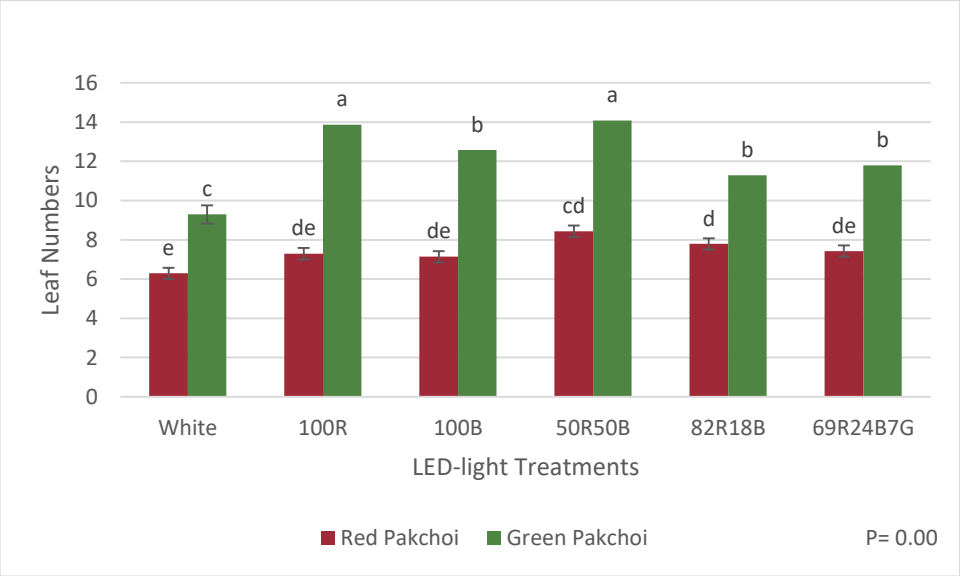


Figure 28 The interaction of leaf number at 30 DAS of green pakchoi and red pakchoi towards LED-light treatments. Means with different letters are significantly different at P= 0.05 by Duncan multiple comparisons test. Light treatment abbreviations as in Table 3.

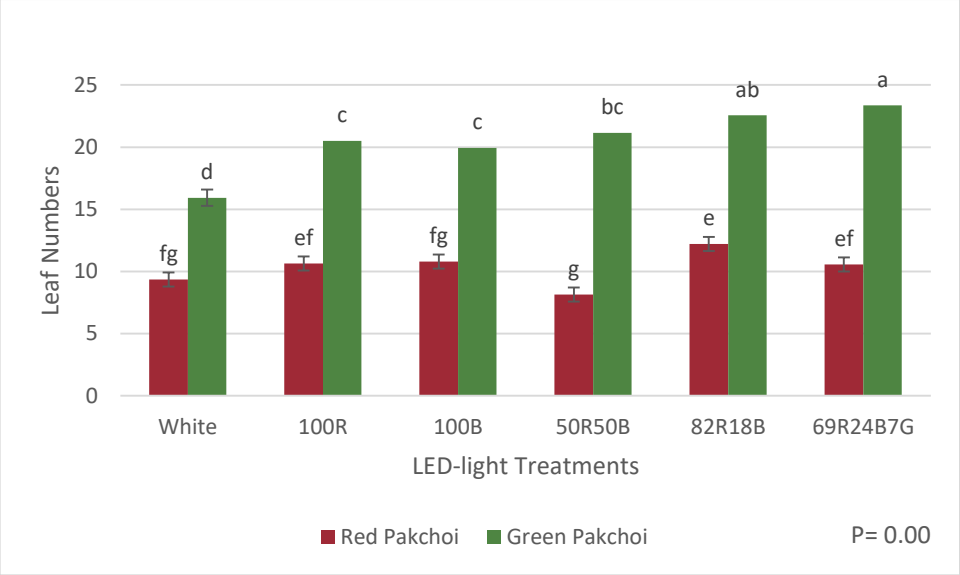


Figure 29 The interaction of leaf number at 40 DAS of green pakchoi and red pakchoi towards LED-light treatments. Means with different letters are significantly different at P= 0.05 by Duncan multiple comparisons test. Light treatment abbreviations as in Table 3.

4.5 Leaf Area

Main effects of LED lights, cultivars and their interaction on the leaf area at 20, 30 and 40 DAS in Trial 1 and 2 are presented in Table 11. While the main effects of LED lights, cultivars and their interaction on the leaf area at 20, 30 and 40 DAS in Trial 1 and 2 combined are presented in Table 12.

Table 11 Leaf area of green and red pakchoi plants at 20, 30 and 40DAS (Days after sowing) grown under different LED-light quality treatments in Trial 1 and Trial 2.

Treatment	Leaf Area (cm2)					
	Trial 1			Trial 2		
	20 DAS	30 DAS	40 DAS	20 DAS	30 DAS	40 DAS
Cultivar (C)						
Green Pakchoi	13.97 b	84.98 a	262.31 a	14.64 a	81.62 a	215.82 a
Red Pakchoi	17.93 a	46.26 b	58.45 b	11.64 b	23.21 b	72.42 b
SEM	0.88	2.87	7.04	0.66	2.38	5.42
P value	0.000	0.000	0.000	0.000	0.000	0.000
LED-Lights mixture (L)						
White	8.20 c	31.7 c	69.21 c	5.79 c	22.32 d	61.60 c
100R	22.19 a	98.53 a	167.74 ab	20.91 a	76.52 a	179.11 a
100B	13.55 bc	50.38 bc	150.50 b	10.43 bc	40.78 c	130.27 b
50R50B	17.98 ab	63.98 b	198.58 ab	15.06 b	57.90 b	163.85 ab
82R18B	18.16 ab	91.14 a	210.52 a	15.04 b	63.64 ab	176.73 a
69R24B7G	15.32 b	57.98 b	165.74 ab	11.60 b	53.31 bc	153.15 ab
SEM	1.52	4.96	12.19	1.14	4.11	9.39
P value	0.000	0.000	0.000	0.000	0.000	0.000
Interaction P values						
C x L	0.090	0.000	0.000	0.000	0.000	0.000

Means with the same letters across column are not significantly different using Tukeys at 5% level.

Table 12 Leaf area of green and red pakchoi plants at 20, 30 and 40DAS (Days after sowing) grown under different LED-light quality treatments in Trial 1 and Trial 2 combined.

Treatment	Leaf Area (cm2)		
	20 DAS	30 DAS	40 DAS
Cultivar (C)			
Green Pakchoi	14.78 [a]	83.30 [a]	239.06 [a]
Red Pakchoi	14.25 [b]	34.73 [b]	65.44 [b]
SEM	0.63	2.11	4.82
P value	0.000	0.000	0.000
LED-Lights mixture (L)			
White	6.99 [d]	27.01 [d]	65.41 [d]
100R	21.55 [a]	87.52 [a]	173.42 [abc]
100B	11.99 [c]	45.58 [c]	140.39 [c]
50R50B	16.52 [b]	60.94 [b]	181.21 [ab]
82R18B	16.6 [b]	77.39 [a]	193.62 [a]
69R24B7G	13.46 [bc]	55.64 [bc]	159.44 [bc]
SEM	1.09	3.66	8.37
P value	0.000	0.000	0.000
Interaction P values			
C x L	0.000	0.000	0.000

Means with the same letters across column are not significantly different using Tukeys at 5% level.

Cultivar

Trial one

Cultivar had significant (P<0.05) effect on the leaf area at all sampling stages (20, 30 and 40 DAS) (Table 11). Red pakchoi recorded significantly bigger leaf area than green at 20 DAS (17.93 cm2 for red and 13.97 cm2 for green pakchoi). While on 30 (84.98 cm2 for green and 46.26 cm2 for red pakchoi) and 40 DAS (262.31 cm2 for green and 58.45 cm2 for red pakchoi), green pakchoi obtained significantly larger leaf area. This increase in leaf area in the red compared to the green pakchoi was 28.3% at 20 DAS. While at 30 DAS and 40 DAS, the increase in leaf area in the green compared to red pakchoi were 79.8% and 348.8%.

Trial two

At all three sample stages (20, 30 and 40 DAS), the cultivar had a statistically significant (P<0.05) influence on the leaf area (Table 11). Green pakchoi recorded significantly higher leaf area than red at 20 (14.64 cm2 for green and 11.64 cm2 for red pakchoi), 30 (81.62 cm2 for green and 23.21 cm2 for red pakchoi) and 40 DAS (215.82 cm2 for green and 72.42 cm2 for red pakchoi). This increase in leaf area in green pakchoi compared to the red pakchoi was 25.8% at 20 DAS, 251.7% at 30 DAS and 198% at 40 DAS.

Trial one and two combined

Cultivar significantly (P<0.05) effected the leaf area at all sampling stages (20, 30 and 40 DAS) (Table 12). Green pakchoi recorded significantly higher leaf area than red at 20 (14.78 cm2 for green and 14.25 cm2 for red pakchoi), 30 (83.30 cm2 for green and 34.73 cm2 for red pakchoi) and 40 DAS (239.06 cm2 for green and 65.44 cm2 for red pakchoi). This increase of leaf area in green pakchoi compared to the red pakchoi was 3.7% at 20 DAS, 139.9% at 30 DAS and 265.3% at 40 DAS.

The results regarding the influence of cultivars on leaf area in Trials 1 and 2, as well as the combination of Trials 1 and 2, were fairly similar. During the first trial, the red pakchoi had the largest leaf area only at 20 DAS. Whereas, the green pakchoi produced greater leaf area than the red pakchoi at all other sampling stages and trials.

LED-Lights

Trial one

Leaf area at 20. 30 and 40 DAS were significantly (P<0.05) influenced by LED lights (Table 11). At 20 and 30 DAS sampling dates, monochromatic 100R (22.19 cm2 and 98.53 cm2 at 20 and 30 DAS respectively) obtained the largest leaf area compared other LED-light treatments. However, it was similar to (P>0.05) 82R18B and 50R50B at 20 DAS and similar to (P>0.05) 82R18B at 30 DAS. While at 40 DAS, 82R18B produced the biggest leaf area (210.52 cm2) compared other LED-light treatments. However, it was no significant (P>0.05) towards 100R and 69R24B7G. White light (control) recorded the smallest leaf area compared to other LED lights in every sampling dates.

The highest measurement on each sampling date compared to white light (control); 100R was 170.6% higher at 20 DAS and 210.8% at 30DAS. While 82R18B 204.2% higher at 40 DAS.

Trial two

LED-lights had a significant (P<0.05) effect on leaf area at 20, 30, and 40 DAS (Table 11). At all sampling dates, monochromatic 100R (20.91, 76.52 and 179.11 cm at 20. 30 and 40 DAS respectively) obtained the highest leaf area among other LED-light treatment. However, only at 20 DAS sampling date was significantly (P<0.05)

higher leaf area compared other LED-light treatments. At 30 DAS sampling date, 100R was similar (P>0.05) to the treatment 82R18B (63.64). While at 40 DAS, 100R was similar (P>0.05) to the treatment 50R50B, 82R18B and 69R24B7G (163.85 cm2, 153.15 cm2 and 153.15 cm2, 50R50B, 82R18B and 69R24B7G respectively). White light (control) recorded the lowest height compared to other LED-light treatments.

The highest measurement on each sampling date compared to white light (control); 100R was 261.1% higher at 20 DAS, 242.8% higher at 30DAS and 190.8% higher at 40 DAS.

Trial one and two combined

The leaf area at 20, 30, and 40 DAS significantly (P<0.05) affected by LED lighting (Table 12). At 20 and 30 DAS sampling dates, monochromatic 100R (21.55 cm2 and 87.52 cm2 at 20 and 30 DAS respectively) obtained higher plant height compared other LED-light treatments. However, only at 20 DAS was significantly different (P<0.05), meanwhile at 30 DAS the treatment 100R was similar (P>0.05) to treatment 82R18B (77.39). At 40 DAS, treatment 82R18B was the highest but was similar (P>0.05) to 50R50B and 100R (181.21 and 173.42). White light (control) recorded the lowest leaf area compared to other LED-light treatments.

The highest measurement on each sampling date compared to white light (control); 100R was 208.3% higher at 20 DAS, 224% at 30DAS and 196% higher at 40 DAS.

The results for the LED-light treatments influenced on leaf area in Trials 1 and 2, as well as the combination of Trials 1 and 2, the results obtained was almost similar. The LED-light treatments monochromatic 100R and 82R18B seems to produce a greater leaf area in both trials and the combined results compared to other LED-light treatments.

Cultivar x LED-Lights Interaction

Trial one and two combined

The leaf area of green and red pakchoi was significantly (P<0.05) affected with LED-light treatments at all sampling dates (Table 12). At 20 DAS sampling date (Figure 30), response towards LED-light treatment was mixed between red and green

pakchoi. Leaf area was higher (P<0.05) in green pakchoi than red pakchoi under 82R28B, 69R24B7G and white light (control) LED-light treatments. While leaf area in red pak choi was higher (P<0.05) under the treatments monochromatic 100R and 50R50B. While for the treatment monochromatic 100B, leaf area between red and green pakchoi was similar (P>0.05). The highest leaf area was recorded on red pakchoi under the treatment monochromatic 100R. The lowest leaf area measurement was found on the red pakchoi under the treatment white light (control). During 30 DAS (Figure 31), green pakchoi were significantly (P<0.05) had higher leaf area than red pakchoi with all the LED-light treatments. The highest leaf area was recorded in green pakchoi with the treatment monochromatic 100R and the lowest diameter measurement was obtained on red pakchoi exposed to white light (control) treatment. Similarly, at 40 DAS (Figure 32), green pakchoi were significantly (P<0.05) had higher leaf area than red pakchoi with all the LED-light treatments. The highest leaf area was recorded in green pakchoi with the treatment 50R50B and the lowest diameter measurement was obtained on red pakchoi exposed to white light (control) treatment.

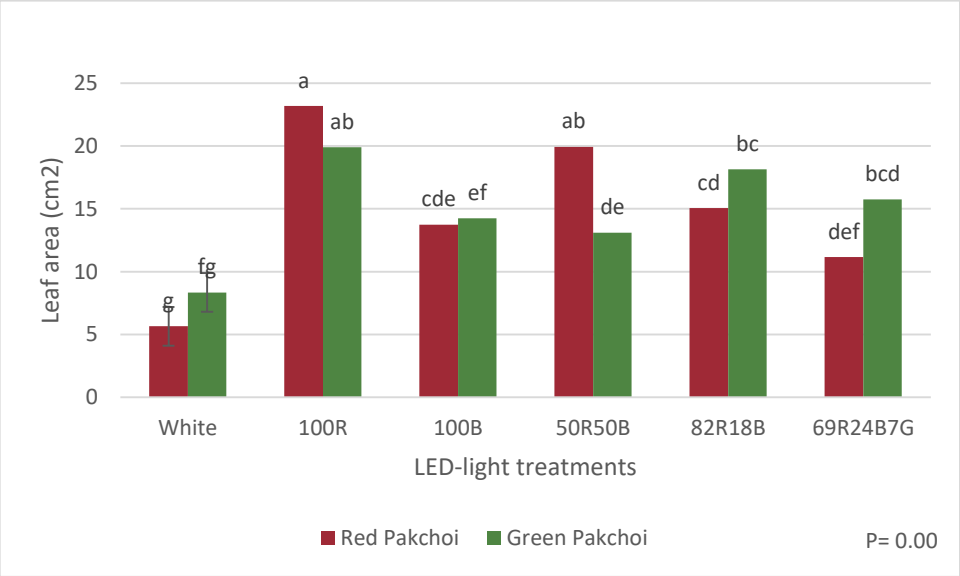


Figure 30 The interaction of leaf area at 20 DAS of green pakchoi and red pakchoi towards LED-light treatments. Means with different letters are significantly different at P= 0.05 by Duncan multiple comparisons test. Light treatment abbreviations as in Table 3.

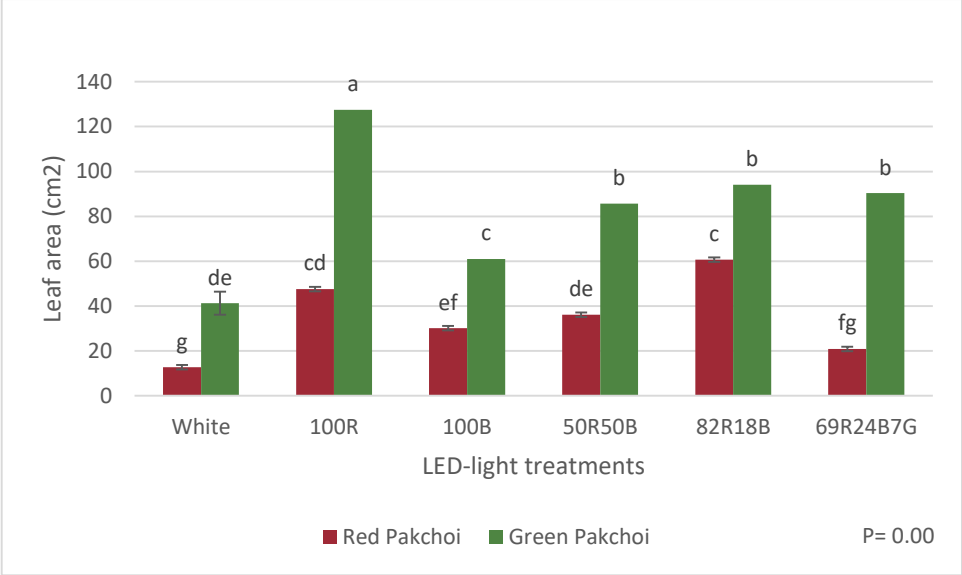


Figure 31 The interaction of leaf area at 30 DAS of green pakchoi and red pakchoi towards LED-light treatments. Means with different letters are significantly different at P= 0.05 by Duncan multiple comparisons test. Light treatment abbreviations as in Table 3.

Figure 32 The interaction of leaf area at 40 DAS of green pakchoi and red pakchoi towards LED-light treatments. Means with different letters are significantly different at P= 0.05 by Tukey's multiple comparisons test. Light treatment abbreviations as in Table 3.

4.6 Specific leaf area (SLA)

Specific leaf area (SLA) defined as the ratio of total leaf area to total leaf dry weight, used as an indicator of leaf thickness (Reich et al 1992). The main effects of LED lights, cultivars and their interaction on the plant specific leaf area (SLA) at 20, 30 and 40 DAS in Trial 1 and 2 are presented in Table 13. While the main effects of LED lights, cultivars and their interaction on the specific leaf area at 20, 30 and 40 DAS in Trial 1 and 2 combined are presented in Table 14.

Table 13 Specific leaf area (SLA) of green and red pakchoi plants at 20, 30 and 40DAS (Days after sowing) grown under different LED-light quality treatments in Trial 1 and Trial 2.

Treatment	Specific Leaf Area (SLA)					
	Trial 1			Trial 2		
	20 DAS	30 DAS	40 DAS	20 DAS	30 DAS	40 DAS
Cultivar (C)						
Green Pakchoi	46.97 ^{b}	69.72 ^{b}	58.02 ^{b}	69.63 ^{b}	53.61 ^{a}	35.17 ^{b}
Red Pakchoi	145.95 ^{a}	136.65 ^{a}	74.99 ^{a}	139.52 ^{a}	33.29 ^{b}	44.32 ^{a}
SEM	23.58	10.68	5.52	10.18	2.64	1.93
P value	0.000	0.000	0.030	0.000	0.000	0.000
LED-Lights mixture (L)						
White	93.24 ^{a}	94.8 ^{abc}	102.61 ^{a}	105.86 ^{a}	50.96 ^{a}	40.05 ^{bc}
100R	108.93 ^{a}	140.35 ^{ab}	41.89 ^{b}	85.02 ^{a}	44.25 ^{ab}	57.80 ^{a}
100B	83.88 ^{a}	159.41 ^{a}	51.85 ^{b}	119 ^{a}	50.45 ^{a}	46.47 ^{ab}
50R50B	142.07 ^{a}	91.36 ^{abc}	53.91 ^{b}	79.16 ^{a}	44.60 ^{ab}	47.04 ^{ab}
82R18B	76.25 ^{a}	72.34 ^{bc}	67.89 ^{ab}	109.6 ^{a}	40.11 ^{ab}	20.16 ^{d}
69R24B7G	74.38 ^{a}	60.85 ^{c}	80.86 ^{ab}	128.8 ^{a}	30.32 ^{b}	26.95 ^{c}
SEM	40.84	18.50	9.56	17.64	4.58	3.35
P value	0.850	0.000	0.000	0.32	0.02	0.000
Interaction P values						
C x L	0.620	0.000	0.010	0.02	0.000	0.05

Means with the same letters across column are not significantly different using Tukeys at 5% level.

Table 14 Specific leaf area (SLA) of green and red pakchoi plants at 20, 30 and 40DAS (Days after sowing) grown under different LED-light quality treatments in Trial 1 and Trial 2 combined.

Treatment	Specific Leaf Area (cm)		
	20 DAS	30DAS	40DAS
Cultivar (C)			
Green Pakchoi	58.3 ^{b}	61.67 ^{b}	46.6 ^{b}
Red Pakchoi	142.73 ^{a}	84.97 ^{b}	59.65 ^{a}
SEM	12.69	7.39	3.72
P value	0.000	0.030	0.010
LED-Lights mixture (L)			
White	99.55 ^{a}	72.88 ^{ab}	71.33 ^{a}
100R	96.97 ^{a}	92.30 ^{ab}	49.85 ^{ab}
100B	101.44 ^{a}	104.93 ^{a}	49.16 ^{ab}
50R50B	110.61 ^{a}	67.98 ^{ab}	50.48 ^{ab}
82R18B	92.92 ^{a}	56.22 ^{ab}	44.02 ^{b}
69R24B7G	101.59 ^{a}	45.58 ^{b}	53.91 ^{ab}
SEM	21.98	12.81	6.44
P value	0.990	0.010	0.060
Interaction P values			
C x L	0.17	0.23	0.080

Means with the same letters across column are not significantly different using Tukeys at 5% level.

Cultivar

Trial one

Cultivar had significant ($P<0.05$) effect on the SLA at all sampling stages (20, 30 and 40 DAS) (Table 13). Red pakchoi recorded significantly higher SLA than green at 20 (145.95 for red and 46.97 for green pakchoi), 30 (136.65 for red and 69.72 for green pakchoi) and 40 DAS (74.99 for red and 58.02 for green pakchoi). This increase

in SLA in red pakchoi compared to the green was 210.7% at 20 DAS, 96% at 30 DAS and 29.2% at 40 DAS.

Trial two

At all sampling stages (20, 30 and 40 DAS), the cultivar had a statistically significant ($P<0.05$) effect on the SLA (Table 13). At 20 and 40 DAS, red pakchoi recorded significantly higher SLA than green, 20 DAS (139.52 for red and 69.63 for green pakchoi) and 40 DAS (44.32 for red and 35.17 for green pakchoi). While at 30 data sampling, green pakchoi recorded significantly higher SLA than red (53.61 for green and 33.29 for red pakchoi). This increase in SLA in red pakchoi compared to the green pakchoi was 100.4% higher at 20 DAS and 26% higher at 40 DAS. While at 30 DAS, the increase of SLA in green pakchoi compared to the red pakchoi was 61.0%.

Trial one and two combined

The cultivar had a statistically significant ($P<0.05$) effect on SLA at all sampling stages (20, 30, and 40 DAS) (Table 14). Red pakchoi recorded significantly higher SLA than red at 20 (142.73 for red and 58.30 for green pakchoi), 30 (84.97 for red and 61.67 for green pakchoi) and 40 DAS (59.65 for red and 46.60 for green pakchoi). This increase in SLA in red pakchoi compared to the green pakchoi was 144.8% at 20 DAS, 37.8% at 30 DAS and 28% at 40 DAS.

The results regarding the influence of cultivars on SLA in Trials 1 and 2, as well as the combination of Trials 1 and 2, were almost consistent. Red pakchoi had the greater SLA compared to green pakchoi all other sampling stages and trials, except at 30 DAS on Trial 2.

LED-Lights

Trial one

SLA at 20 DAS was not significantly ($P>0.05$) influenced by LED lights. On 30 and 40 DAS, the SLA were significantly ($P<0.05$) influenced by LED lights (Table 13). At 30 DAS sampling date, monochromatic 100B (159.41) obtained higher SLA measurement compared other LED-light treatments. However, it was similar ($P>0.05$) with the treatments 100R, White (control) and 50R50B. While on 40 DAS, White

(control) had the highest SLA (102.61) compared to other LED-light treatments, but was similar to (P>0.05) 82R18B and 69R24B7G.

The highest measurement on each sampling date compared to white light (control); 50R50B was 52.4% higher at 20 DAS, monochromatic 100B was 162% higher at 30DAS. While at 40DAS, white (control) indicated the highest measurement.

Trial two

At the 20 DAS sampling date, there was no significant difference (P>0.05) between the LED-light treatments in SLA (Table 13). At 30 DAS sampling date, the White (control) treatment (50.96) indicated the higher SLA measurement compared to other LED-light treatments. However, it was similar (P>0.05) towards other LED-light treatments (50.45, 44.60, 44.25 and 40.11 for 100B, 50R50B, 100R and 82R18B respectively) except 69R24B7G. During 40 DAS sampling date, 100R (57.80) obtained the higher SLA among the LED-light treatment but there was no significant difference (P>0.05) with treatments 50R50B and 100B (47.04 and 46.47). 69R24B7G recorded the lowest SLA at 30 and 40 DAS compared to other LED-light treatments.

The highest measurement on each sampling date compared to white light (control); 62R24B7G was 51.5% higher at 20 DAS and 100R was 44.3% higher at 40 DAS. While at 30 DAS, white light (control) was the highest measurement.

Trial one and two combined

SLA was significantly (P<0.05) influenced by LED-light treatments only at 30 DAS of sampling date. While at 20 and 40 DAS, SLA was not significantly influenced by LED-light treatments (Table 14). 30 DAS sampling date, monochromatic 100B (104.93) obtained the highest SLA compared other LED-light treatments. However, the was no significant difference (P>0.05) towards all treatment (92.30, 72.88, 67.98 and 56.22 for 100R, White, 50R50B and 82R18B respectively) except for 69R24B7G.

The highest measurement on each sampling date compared to white light (control); 50R50B was 11.1% higher at 20 DAS, 100B was 44% higher at 30DAS and 40 DAS white light (control) was the highest measurement.

Cultivar x LED-Lights Interaction

Trial one and two combined

The SLA of green and red pakchoi was not significantly (P>0.05) affected with LED-lights (Table 14) at all sampling dates. There was no significant interaction between the SLA of green and red pak choi with the LED-light treatments.

4.7 Fresh yield

Main effects of LED lights, cultivars and their interaction on the fresh yield at 20, 30 and 40 DAS in Trial 1 and 2 are presented in Table 15. While the main effects of LED lights, cultivars and their interaction on the plant height at 20, 30 and 40 DAS in Trial 1 and 2 combined are presented in Table 16.

Table 15 Fresh yield of green and red pakchoi plants at 20, 30 and 40 DAS (Days after sowing) grown under different LED-light quality treatments in Trial 1 and Trial 2.

Treatment	Fresh Yield (g/plant)					
	Trial 1			Trial 2		
	20 DAS	30 DAS	40 DAS	20 DAS	30 DAS	40 DAS
Cultivar (C)						
Green Pakchoi	4.14 [a]	16.05 [a]	86.21 [a]	4.49 [a]	28.81 [a]	109.98 [a]
Red Pakchoi	2.92 [b]	6.26 [b]	9.16 [b]	1.08 [b]	3.58 [b]	26.76 [b]
SEM	0.26	0.53	1.99	0.14	1.21	2.61
P value	0.000	0.000	0.000	0.000	0.000	0.000
LED-Lights mixture (L)						
White	0.95 [c]	3.53 [e]	14.48 [b]	0.56 [d]	4.4 [b]	25.31 [d]
100R	5.70 [a]	20.5 [a]	50.86 [a]	6.69 [a]	21.27 [a]	48.82 [c]
100B	2.74 [bc]	8.91 [cd]	49.38 [a]	2.01 [c]	7.63 [b]	42.13 [cd]
50R50B	4.57 [ab]	12.46 [bc]	54.88 [a]	3.8 [b]	10.12 [b]	51.85 [c]
82R18B	4.08 [ab]	13.41 [b]	63.05 [a]	2.05 [c]	27.15 [a]	132.61 [a]
69R24B7G	3.13 [b]	14.11 [b]	53.45 [a]	1.6 [c]	26.59 [a]	109.51 [b]
SEM	0.46	0.91	3.44	0.24	2.09	4.53
P value	0.000	0.000	0.000	0.000	0.000	0.000
Interaction P values						
C x L	0.17	0.00	0.00	0.000	0.000	0.000

Means with the same letters across column are not significantly different using Tukeys at 5% level.

Table 16 Fresh yield of green and red pakchoi plants at 20, 30 and 40 DAS (Days after sowing) grown under different LED-light quality treatments Trial 1 and Trial 2 combined.

Treatment	Fresh yield (g/plant)		
	20 DAS	30 DAS	40 DAS
Cultivar (C)			
Green Pakchoi	4.31 [a]	22.43 [a]	98.10 [a]
Red Pakchoi	2.00 [b]	4.92 [b]	17.96 [b]
SEM	0.18	1.03	2.69
P value	0.000	0.000	0.000
LED-Lights mixture (L)			
White	0.76 [d]	3.97 [d]	19.9 [c]
100R	6.19 [a]	20.88 [a]	49.84 [b]
100B	2.38 [c]	8.27 [cd]	45.76 [b]

50R50B	4.19 [b]	11.29 [bc]	53.36 [b]
82R18B	3.06 [bc]	17.28 [ab]	97.83 [a]
69R24B7G	2.36 [c]	20.35 [a]	81.48 [a]
SEM	0.31	1.78	4.66
P value	0.000	0.000	0.000
Interaction P values			
C x L	0.000	0.000	0.000

Means with the same letters across column are not significantly different using Tukeys at 5% level.

Cultivar

Trial one

Cultivar had significant (P<0.05) effect on the fresh yield at all sampling stages (20, 30 and 40 DAS) (Table 15). Green pakchoi recorded significantly higher fresh yield than red at 20 (4.14 g for green and 2.92 g for red pakchoi), 30 (16.05 g for green and 6.26 g for red pakchoi) and 40 DAS (86.21 g for green and 9.16 g for red pakchoi). This increase in fresh yield in green pakchoi compared to the red pakchoi was 41.8% at 20 DAS, 156.4% at 30 DAS and 841.2% at 40 DAS.

Trial two

At all sample stages (20, 30, and 40 DAS), cultivar had a significant (P<0.05) influence on fresh yield (Table 15). Green pakchoi produced substantially more fresh yield than red pakchoi at 20 (4.49 g for green and 1.08 g for red pakchoi), 30 (28.81 g for green and 3.58 g for red pakchoi), and 40 DAS, respectively (109.98 g for green and 26.76 g for red pakchoi). Green pakchoi had a 315.7% increase in fresh yield over red pakchoi at 20 DAS, 704.7% percent increase at 30 DAS, and 311% increase at 40 DAS.

Trial one and two combined

At all three sample stages (20, 30 and 40 DAS), the cultivar had a statistically significant (P<0.05) impact on the fresh yield (Table 16). Green pakchoi recorded significantly higher fresh yield than red at 20 (4.31 g for green and 2.00 g for red pakchoi), 30 (22.43 g for green and 4.92 g for red pakchoi) and 40 DAS (98.10 g for green and 17.96 g for red pakchoi). This increase of fresh yield in green pakchoi compared to the red pakchoi was 115.5% at 20 DAS, 355.9% at 30 DAS and 446.2% at 40 DAS.

LED-Lights

Trial one

Fresh yield at 20, 30 and 40 DAS were significantly ($P<0.05$) influenced by LED lights (Table 15). At 20 DAS sampling date, monochromatic 100R (5.75 g) obtained the highest fresh yield but was similar ($P>0.05$) with treatments 50R50B and 82R18B. At 30 DAS monochromatic 100R (20.50 g) produced the significantly ($P<0.05$) highest fresh yield compared other LED-light treatments. At the 40 DAS sampling date, treatment 82R18B was the highest fresh yield measurement but was similar ($P>0.05$) to the all LED-light treatments except towards white light (control). White light (control) recorded the lowest fresh yield compared to other LED-light treatments.

The highest measurement on each sampling date compared to white light (control); 100R was 500% higher at 20 DAS and 480.7% higher at 30DAS. While 82R18B was 335.4% higher at 40 DAS.

Trial two

LED lighting had a statistically significant ($P<0.05$) effect on fresh yield at 20, 30, and 40 DAS, respectively (Table 15). At 20 DAS sampling date, monochromatic 100R (6.69 g) obtained significantly ($P<0.05$) higher fresh yield compared other LED-light treatments. While treatment 50R50B (3.80 g) was the second highest treatment and significantly different ($P<0.05$) compared to other treatments. At 30 DAS sampling date, monochromatic 100R (21.27 g) indicated the higher fresh yield compared to other LED-light treatments but was similar ($P>0.05$) to the treatments 82R18B and 69R24B7G (27.15 and 26.59). While at 40 DAS of sampling date, 82R18B (132.61 g) was the highest fresh yield measurement and significantly different ($P<0.05$) towards other LED-light treatments. 69R24B7G indicated the second highest measurement and have a significant difference ($P<0.05$) towards other LED-light treatments. White light (control) recorded the lowest height compared to other LED-light treatments.

The highest measurement on each sampling date compared to white light (control); 100R was 1094.6% higher at 20 DAS and 383.4% higher at 30DAS. While 82R18B was 423.9% higher at 40 DAS.

Trial one and two combined.

Fresh yield at 20. 30 and 40 DAS were significantly (P<0.05) influenced by LED lights (Table 16). At 20 DAS sampling date, monochromatic 100R (6.19 g) obtained significantly (P<0.05) higher fresh yield compared other LED-light treatments. The treatment 50R50B (4.19 g) was the second highest but was similar to (P>0.05) 82R18B (3.06 g). At 30 DAS sampling date, the treatment 100R (20.88 g) indicated the highest fresh yield but there was no difference (P>0.005) to 69R24B7G and 82R18B (20.35 g and 17.28 g). While at 40 DAS sampling date, 82R18B (97.83 g) gained the highest fresh yield but it was similar (P>0.05) towards 69R24B7G (81.48 g). White light (control)recorded the lowest fresh yield compared to other LED-light treatments.

The highest measurement on each sampling date compared to white light (control); 100R was 717.5% higher at 20 DAS and was 425.9% higher at 30DAS. While 82R18B was 391.6% higher at 40 DAS.

Cultivar x LED-Lights Interaction

Trial one and two combined

The fresh yield of green and red pakchoi was significantly (P<0.05) affected with LED-light treatments (Table 16) at all sampling dates. During 20 DAS sampling date (Figure 33), response to LED-light treatment was higher (P<0.05) in green pakchoi than red pakchoi in all LED-light treatments except under the treatment white (control). The highest fresh yield was recorded on green pakchoi under the treatment monochromatic 100R. The lowest leaf area measurement was found on the green pakchoi under the treatment white light (control). At 30 DAS (Figure 34), green pakchoi were significantly (P<0.05) had higher fresh yield than red pakchoi with all the LED-light treatments. The highest fresh yield was recorded in green pakchoi with the treatment 69R24B7G and the lowest diameter measurement was obtained on red pakchoi exposed to white light (control) treatment. The almost similar pattern found at 40 DAS (Figure 35), green pakchoi were significantly (P<0.05) had higher fresh yield than red pakchoi with all the LED-light treatments. The highest fresh yield was recorded in green pakchoi with the treatment 82R18B and the lowest diameter measurement was obtained on red pakchoi exposed to white light (control) treatment.

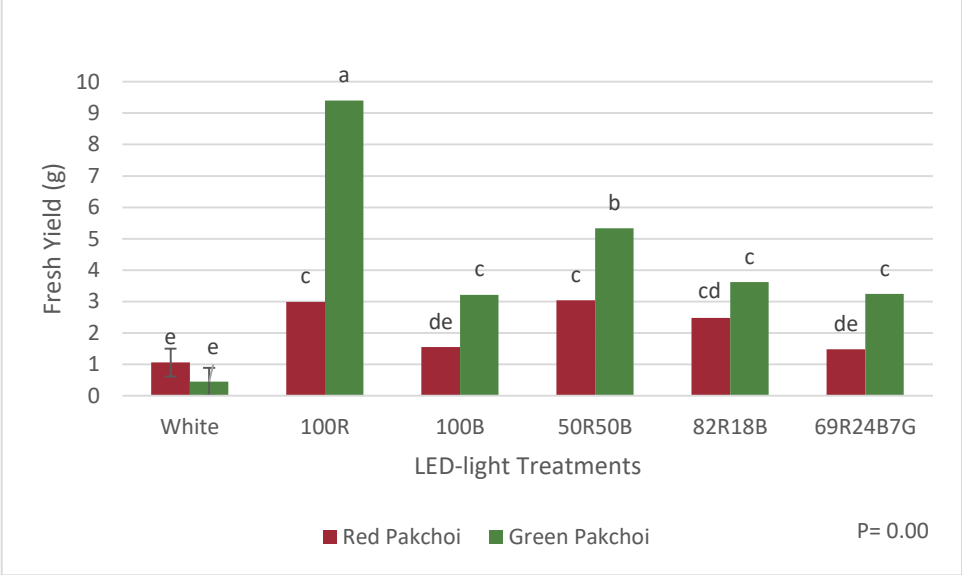


Figure 33 The interaction of fresh yield at 20 DAS of green pakchoi and red pakchoi towards LED-light treatments. Means with different letters are significantly different at P= 0.05 by Duncan multiple comparisons test. Light treatment abbreviations as in Table 3.

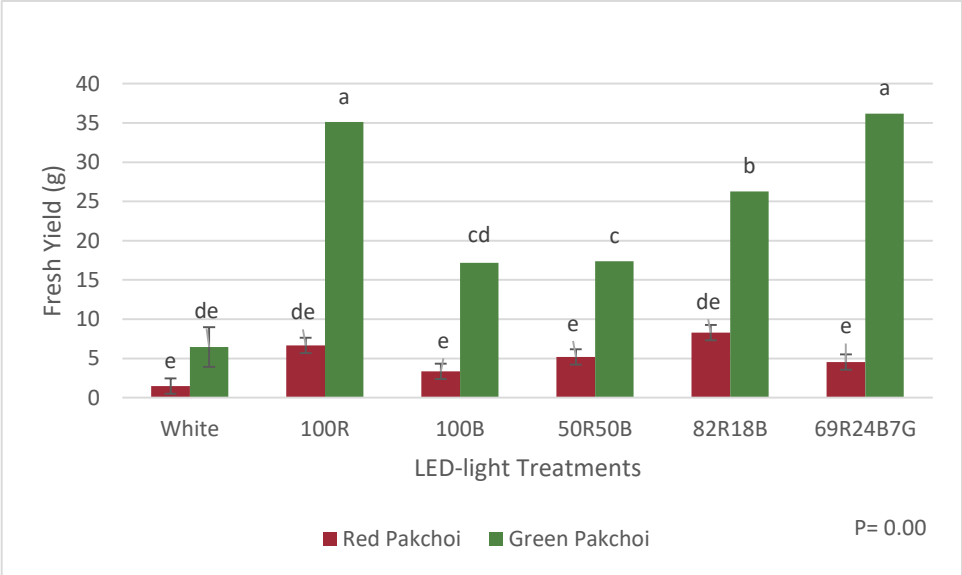


Figure 34 The interaction of fresh yield at 30 DAS of green pakchoi and red pakchoi towards LED-light treatments. Means with different letters are significantly different at P= 0.05 by Duncan multiple comparisons test. Light treatment abbreviations as in Table 3.

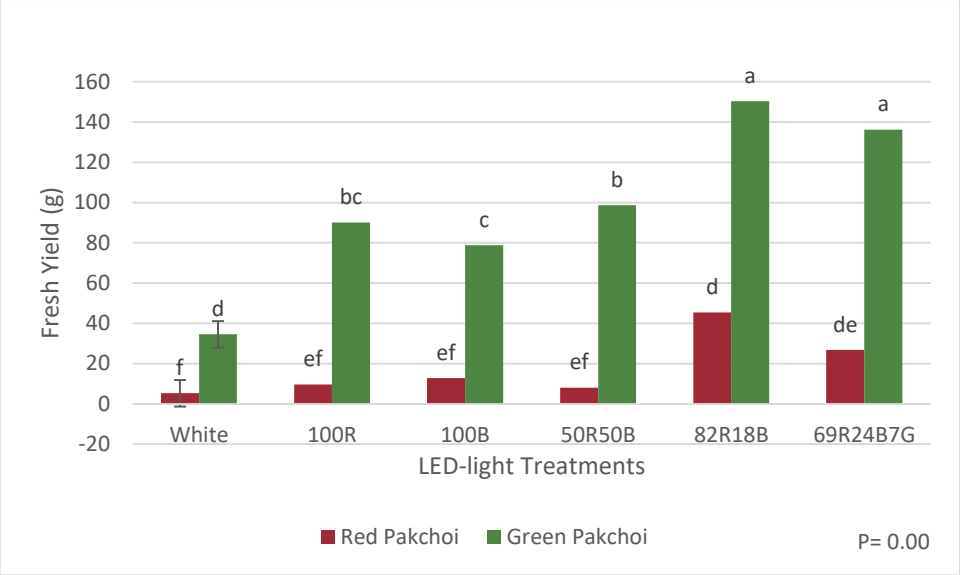


Figure 35 The interaction of fresh yield at 40 DAS of green pakchoi and red pakchoi towards LED-light treatments. Means with different letters are significantly different at P= 0.05 by Duncan multiple comparisons test. Light treatment abbreviations as in Table 3.

4.8 Dry yield

Main effects of LED lights, cultivars and their interaction on the dry yield at 20, 30 and 40 DAS in Trial 1 and 2 are presented in Table 17. While the main effects of LED lights, cultivars and their interaction on the plant height at 20, 30 and 40 DAS in Trial 1 and 2 combined are presented in Table 18.

Table 17 Dry yield of green and red pakchoi plants at 20, 30 and 40DAS (Days after sowing) grown under different LED-light quality treatments in Trial 1 and Trial 2.

Treatment	Dry yield (g/plant)					
	Trial 1			Trial 2		
	20 DAS	30 DAS	40 DAS	20 DAS	30 DAS	40 DAS
Cultivar (C)						
Green Pakchoi	0.35 ^{a}	1.21 ^{a}	4.84 ^{a}	0.28 ^{a}	1.74 ^{a}	7.34 ^{a}
Red Pakchoi	0.28 ^{b}	0.49 ^{b}	1.12 ^{b}	0.1 ^{b}	0.82 ^{b}	2.17 ^{b}
SEM	0.05	0.04	0.11	0.01	0.07	0.30
P value	0.000	0.000	0.000	0.000	0.000	0.000
LED-Lights mixture (L)						
White	0.10 ^{b}	0.26 ^{d}	0.90 ^{c}	0.05 ^{c}	0.39 ^{d}	1.71 ^{b}
100R	0.40 ^{ab}	1.09 ^{ab}	3.57 ^{ab}	0.38 ^{a}	1.59 ^{ab}	3.59 ^{b}
100B	0.22 ^{ab}	0.57 ^{c}	2.91 ^{b}	0.16 ^{b}	0.76 ^{cd}	2.92 ^{b}
50R50B	0.54 ^{a}	0.87 ^{b}	3.49 ^{ab}	0.32 ^{a}	1.26 ^{bc}	3.57 ^{b}
82R18B	0.32 ^{ab}	1.31 ^{a}	3.97 ^{a}	0.15 ^{b}	1.95 ^{a}	9.37 ^{a}
69R24B7G	0.30 ^{ab}	1.01 ^{b}	3.04 ^{b}	0.09 ^{bc}	1.73 ^{ab}	7.61 ^{a}
SEM	0.09	0.06	0.19	0.02	0.12	0.51
P value	0.000	0.000	0.000	0.000	0.000	0.000
Interaction P values						
C x L	0.17	0.00	0.00	0.000	0.000	0.000

Means with the same letters across column are not significantly different using Tukeys at 5% level.

Table 18 Dry yield of green and red pakchoi plants at 20, 30 and 40DAS (Days after sowing) grown under different LED-light quality treatments in Trial 1 and Trial 2 combined.

Treatment	Dry yield (g/ plant)		
	20 DAS	30 DAS	40 DAS
Cultivar (C)			
Green Pakchoi	0.31 [a]	1.48 [a]	6.13 [a]
Red Pakchoi	0.19 [b]	0.66 [b]	1.64 [b]
SEM	0.03	0.05	0.23
P value	0.001	0.000	0.000
LED-Lights mixture (L)			
White	0.08 [c]	0.32 [c]	1.31 [c]
100R	0.39 [ab]	1.34 [ab]	3.58 [b]
100B	0.19 [c]	0.67 [c]	2.92 [bc]
50R50B	0.43 [a]	1.06 [b]	3.53 [b]
82R18B	0.23 [bc]	1.63 [a]	6.67 [a]
69R24B7G	0.19 [c]	1.37 [ab]	5.32 [a]
SEM	0.05	0.09	0.41
P value	0.000	0.000	0.000
Interaction P values			
C x L	0.177	0.000	0.000

Means with the same letters across column are not significantly different using Tukeys at 5% level.

Cultivar

Trial one

Cultivar had significant (P<0.05) effect on the dry yield at all sampling stages (20, 30 and 40 DAS) (Table 17). Green pakchoi recorded significantly higher dry yield than red at 20 (0.35 g for green and 0.28 g for red pakchoi), 30 (1.21 g for green and 0.49 g for red pakchoi) and 40 DAS (4.84 g for green and 1.12 g for red pakchoi). This increase in dry yield in green pakchoi compared to the red pakchoi was 25% at 20 DAS, 146.9% at 30 DAS and 332.1% at 40 DAS.

Trial two

At all three sample stages (20, 30 and 40 DAS), the cultivar had a statistically significant (P<0.05) effect on the dry yield (Table 17). Green pakchoi recorded significantly higher dry yield than red at 20 (0.28 g for green and 0.10 g for red pakchoi), 30 (1.74 g for green and 0.82 g for red pakchoi) and 40 DAS (7.34 g for green and 2.17 cm for red pakchoi). The increase in dry yield in green pakchoi compared to the red pakchoi was 180% at 20 DAS, 112.2% at 30 DAS and 238.2% at 40 DAS.

Trial one and two combined

At all sample stages (20, 30 and 40 DAS), the cultivar had a significant (P<0.05) influence on the dry yield (Table 18). Green pakchoi recorded significantly higher dry yield than red at 20 (0.31 g for green and 0.19 g for red pakchoi), 30 (1.48 g for green and 0.66 g for red pakchoi) and 40 DAS (6.13 g for green and 1.64 g for red pakchoi). This increase in dry yield in green pakchoi compared to the red pakchoi was 63.2% at 20 DAS, 124.2% at 30 DAS and 273.8% at 40 DAS.

LED-Lights

Trial one

Dry yield at 20. 30 and 40 DAS were significantly (P<0.05) influenced by LED lights (Table 17). At 20 DAS sampling date, 50R50B (0.54 g) obtained higher dry yield compared other LED-light treatments but not significantly different (P>0.05) towards other LED-light treatments except towards the white light control (0.10 g). At 30 DAS sampling date, treatment 82R18B (1.31 g) indicated the highest dry yield but was similar (P>0.05) to 100R (1.09 g). While at 40 DAS sampling date, 82R18B (3.97 g) gained the highest dry yield but was no significant difference (P>0.05) to the treatment 100R and 50R50B (3.57 g and 3.59 g, respectively). White light (control) recorded the lowest dry yield compared to other LED-light treatments.

The highest measurement on each sampling date compared to white light (control); 50R50B was 440% higher at 20 DAS. While 82R18B was 403.8% higher at 30 DAS and 341.1% higher at 40 DAS.

Trial two

LED lighting had a significant (P<0.05) effect on dry yield at 20, 30, and 40 DAS (Table 17). At 20 DAS sampling date, monochromatic 100R (0.38 g) indicated the higher dry yield compared other LED-light treatments but was similar (P>0.05) to 50R50B (0.32 g). At 30 DAS sampling date, 82R18B (1.95 g) obtained the higher dry yield compared to other LED-light treatments. However, there was no difference (P>0.05) towards 69R24B7G and 100R (1.73 g and 1.59 g). While at 40 DAS sampling date, 82R18B (9.37 g) was higher compared to other LED-light treatments but was similar (P>0.05) to 69R24B7G (7.61 g). White light (control) recorded the lowest dry yield compared to other LED-light treatments.

The highest measurement on each sampling date compared to white light (control); 100R was 600% higher at 20 DAS. While 82R18B was 400% higher at 30DAS and 448% higher at 40 DAS.

Trial one and two combined

LED lighting had a statistically significant ($P<0.05$) impact on dry yield at 20, 30, and 40 DAS, respectively (Table 18). At 20 DAS sampling date, 50R50B (0.43 g) obtained higher dry yield compared other LED-light treatments but not significantly different ($P>0.05$) towards monochromatic 100R (0.39 g). At 30 DAS sampling date, treatment 82R18B (1.63 g) indicated the highest dry yield but was similar ($P>0.05$) to 69R24G7G and 100R (1.37 g and 1.34 g). While at 40 DAS sampling date, 82R18B (6.67g) gained the highest dry yield but was no significant difference ($P>0.05$) to the treatment 69R24G7G (5.32 g). White light (control) recorded the lowest dry yield compared to other LED-light treatments.

The highest measurement on each sampling date compared to white light (control); 50R50B was 437.5% higher at 20 DAS. While 82R18B was 409.4% higher at 30DAS and 409.2% higher at 40 DAS.

Cultivar x LED-Lights Interaction

Trial one and two combined

Only at 30 and 40 DAS did LED-light treatments have a significant ($P<0.05$) effect on the dry yield of green and red pakchoi. However, at 20 DAS, the dry yield of red and green was not affected ($P>0.05$) with the LED-light treatments (Table 18). At 30 DAS (Figure 36), green pakchoi was significantly ($P<0.05$) had higher dry yield than red pakchoi with all the LED-light treatments. The highest dry yield was recorded in green pakchoi with the treatment 82R18B and the lowest dry yield measurement was obtained on red pakchoi exposed to white light (control) treatment. Similarly, at 40 DAS (Figure 37), green pakchoi was significantly ($P<0.05$) had higher dry yield than red pakchoi with all the LED-light treatments. The highest dry yield was recorded in green pakchoi with the treatment 82R18B and the lowest diameter measurement was obtained on red pakchoi exposed to white light (control) treatment.

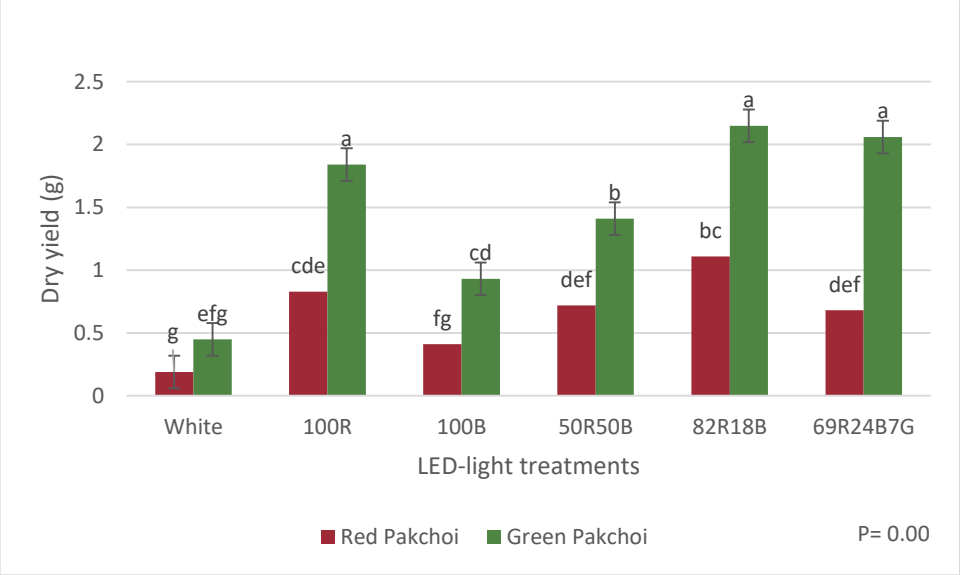


Figure 36 The interaction of dry yield at 30 DAS of green pakchoi and red pakchoi towards LED-light treatments. Markers with different letters are significantly different at P= 0.05 by Duncan multiple comparisons test. Light treatment abbreviations as in Table 3.

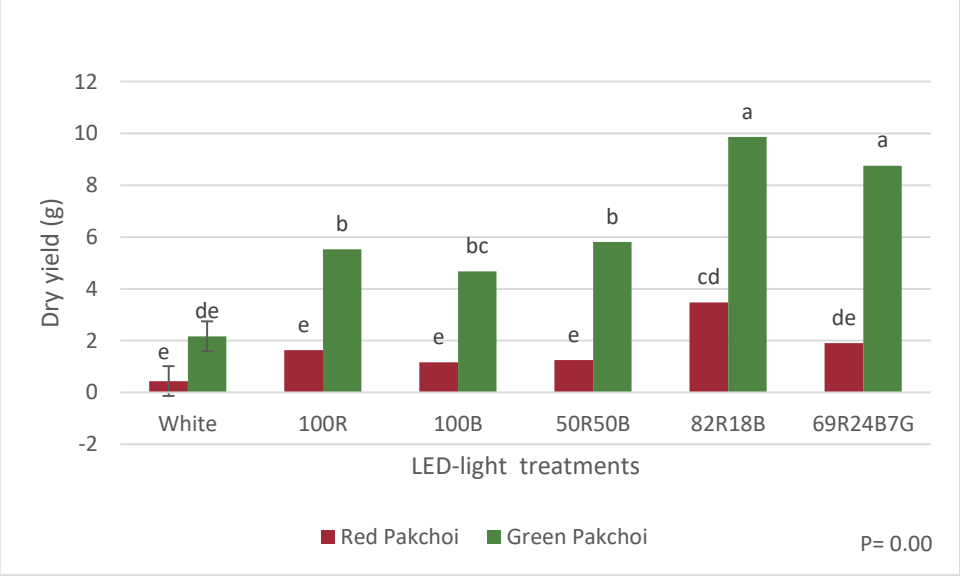


Figure 37 The interaction of dry yield at 40 DAS of green pakchoi and red pakchoi towards LED-light treatments. Means with different letters are significantly different at P= 0.05 by Duncan multiple comparisons test. Light treatment abbreviations as in Table 3.

4.9 Growth indices

Growth indices are used to make specific comparisons between the cultivars and the treatments given. The growth indices that being calculated in this study are; Leaf area index (LAI), Absolute growth rate (AGR), Relative growth rate (RGR) and Leaf area index (LAI).

4.9.1 Leaf area index (LAI)

LAI is the amount of one sided leaf area of a crop per unit land area. This growth index provides the information of the rate of leaf area determines the rate of increase in the photosynthetic capacity in plants. Main effects of cultivars and their interaction on the leaf area index (LAI) at 30 DAS in Trial 1 and 2 combined presented in Table 19. While the main effects of LED lights, and their interaction on the leaf area index (LAI) at 30 DAS in Trial 1 and 2 combined presented in Figure 38-41.

Table 19 Leaf area index (LAI) of green and red pakchoi plants at 30 DAS (Days after sowing) grown under different LED-light quality treatments in Trial 1 and Trial 2 combined.

Treatment	Leaf area index (g)		
	20 DAS	30 DAS	40 DAS
Cultivar (C)			
Green Pakchoi	0.12 [b]	0.12 [b]	0.19 [a]
Red Pakchoi	0.20 [a]	0.14 [a]	0.11 [b]
SEM	0.01	0.01	0.01
P value	0.000	0.000	0.000

Means with the same letters across column are not significantly different using Tukeys at 5% level.

Cultivars

At all sample stages (20, 30 and 40 DAS), the cultivar had a significant (P<0.05) influence on the leaf area index (LAI) (Table 19). Red pakchoi recorded significantly higher leaf area index (LAI) than green at 20 (0.20 for red and 0.12 for green pakchoi) and 30 DAS (0.14 for red and 0.12 for green pakchoi). While at 40 DAS, (0.19 for green and 0.11 for red pakchoi). This increase in leaf area index (LAI) in red pakchoi compared to the green pakchoi at 20 and 30 DAS was 66.7% at 20 DAS, 16.7% at 30 DAS. While the increase in leaf area index (LAI) in green pakchoi compared to the red pakchoi 72.7% at 40 DAS.

LED-lights

LED lighting had a statistically significant (P<0.05) effect on leaf area index (LAI) at 30, and 40 DAS, while not significant (P>0.05) at 20 DAS (Figure 38). At 20 DAS sampling date, 69R24B7G (0.18) obtained higher leaf area index (LAI) compared other LED-light treatments but not significantly different (P>0.05) between the treatments. At 30 DAS sampling date, treatment 100B (0.16) indicated the highest leaf area index (LAI) but was similar (P>0.05) towards other LED-light treatments. While at 40 DAS sampling date, 50R50B (0.19) gained the highest leaf area index (LAI) but

was no significant difference (P>0.05) to the treatment 100B (0.18). White light (control) (0.09) recorded the lowest leaf area index (LAI) compared to other LED-light treatments.

The highest measurement on each sampling date compared to white light (control); 69R24B7G was 28.6% higher at 20 DAS. While 100B was 60% higher at 30 DAS and 50R50B 111.1% higher at 40 DAS.

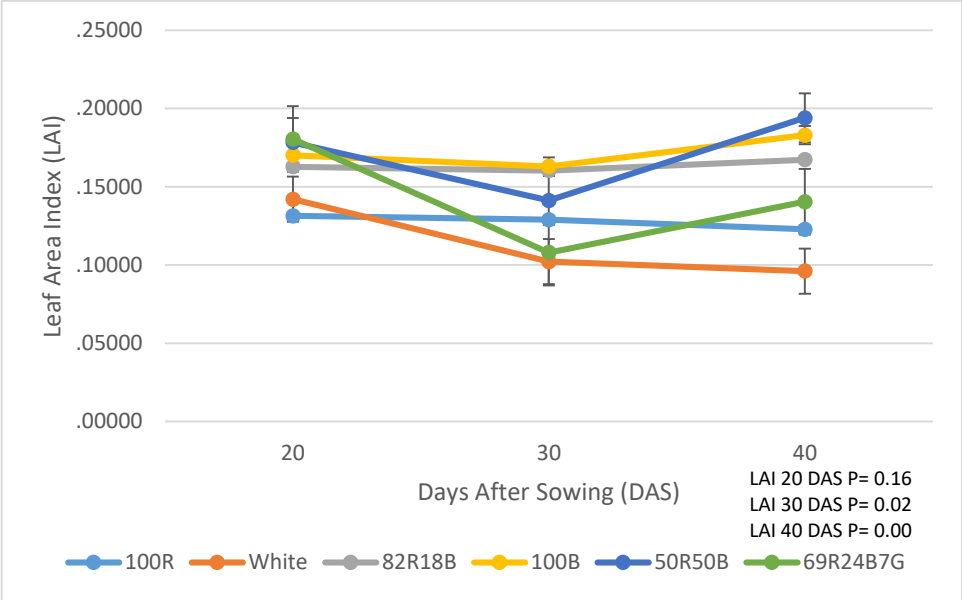


Figure 38 Leaf area index (LAI) of green and red pakchoi plants at 20, 30 and 40 DAS (Days after sowing) grown under different LED-light quality treatments in Trial 1 and Trial 2 combined. Light treatment abbreviations as in Table 3.

Cultivar x LED-Lights Interaction

LED-light treatments have a significant (P<0.05) effect on the leaf area index (LAI) of green and red pakchoi. At 20 DAS (Figure 39), red pakchoi was significantly (P<0.05) had higher LAI than red pakchoi under all the LED-light treatments. The highest LAI was recorded in red pakchoi with the treatment 50R50B and the lowest LAI measurement was obtained on green pakchoi exposed to white light (control) treatment. While at 30 DAS (Figure 40), red pakchoi was significantly (P<0.05) had higher LAI than green pakchoi under all the LED-light treatments. The highest LAI was recorded in red pakchoi with the treatment 100B and the lowest LAI measurement was obtained on red pakchoi exposed to 69R24B7G treatment.

However, at 40 DAS (Figure 41), green pakchoi was significantly (P<0.05) had higher LAI than red pakchoi in almost all the LED-light treatments. The highest LAI was recorded in green pakchoi with the treatment 50R50B and the lowest LAI measurement was obtained on green pakchoi exposed to white light (control) treatment.

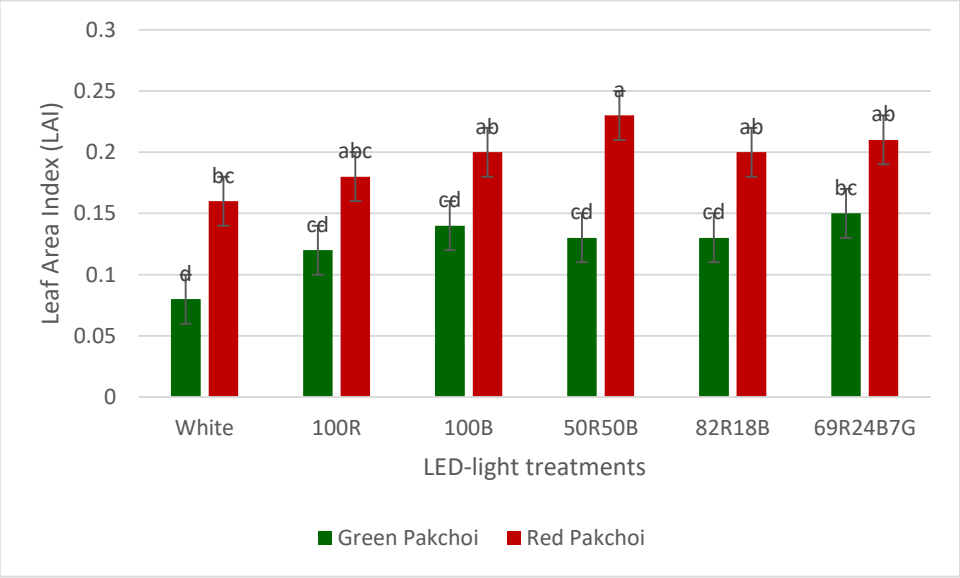


Figure 39 The interaction of leaf area index (LAI) at 20 DAS of green pakchoi and red pakchoi towards LED-light treatments. Means with different letters are significantly different at P= 0.05 by Duncan multiple comparisons test. Light treatment abbreviations as in Table 3.

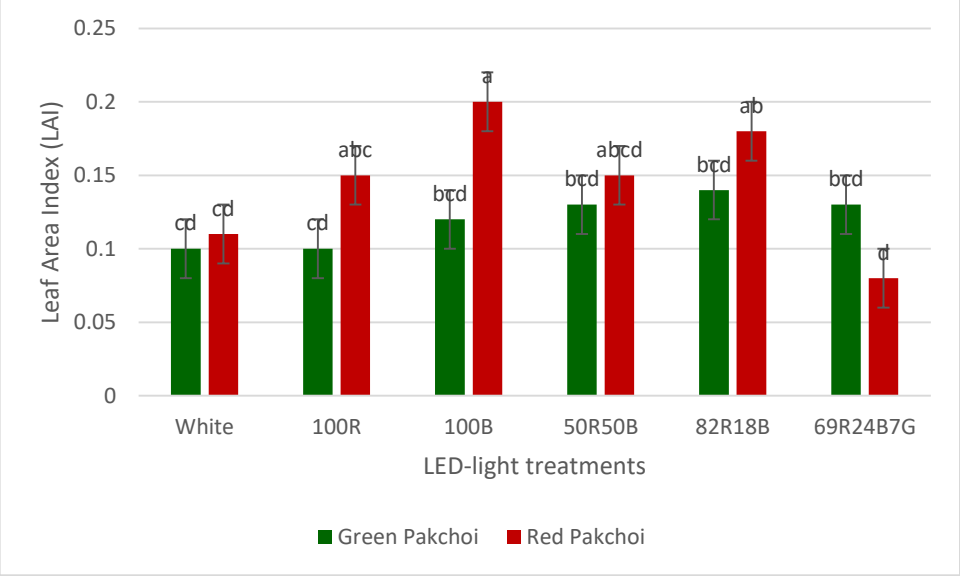


Figure 40 The interaction of leaf area index (LAI) at 30 DAS of green pakchoi and red pakchoi towards LED-light treatments. Means with different letters are significantly different at P= 0.05 by Duncan multiple comparisons test. Light treatment abbreviations as in Table 3.

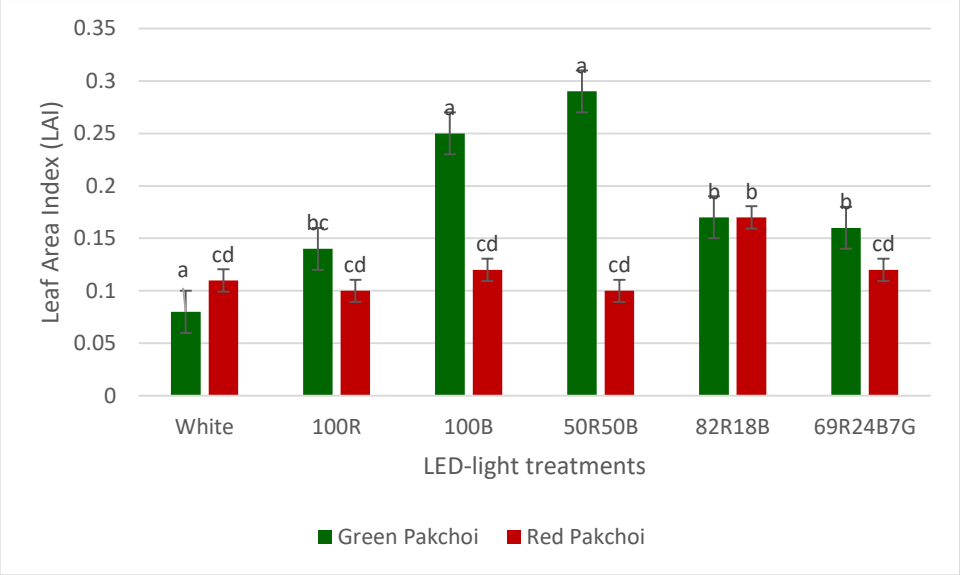


Figure 41 The interaction of leaf area index (LAI) at 40 DAS of green pakchoi and red pakchoi towards LED-light treatments. Means with different letters are significantly different at P= 0.05 by Duncan multiple comparisons test. Light treatment abbreviations as in Table 3.

4.9.2 Absolute Growth Rate (AGR)

AGR is the increment in total dry weight per unit time. Main effects of cultivars and their interaction on the absolute growth rate (AGR) at 30 DAS in Trial 1 and 2 combined presented in Table 20. While the main effects of LED lights, and their interaction on the absolute growth rate (AGR) at 30 DAS in Trial 1 and 2 combined presented in Figure 42-45.

Table 20 Absolute growth rate (AGR) of green and red pakchoi plants at 30 DAS (Days after sowing) grown under different LED-light quality treatments in Trial 1 and Trial 2 combined.

Treatment	Absolute Growth Rate (AGR)		
	20 DAS	30DAS	40 DAS
Cultivar (C)			
Green Pakchoi	0.02 [a]	0.12 [a]	0.47 [a]
Red Pakchoi	0.01 [b]	0.05 [b]	0.11 [b]
SEM	0.00	0.01	0.03
P value	0.000	0.000	0.000

Means with the same letters across column are not significantly different using Tukeys at 5% level.

Cultivars

At all sample stages (20, 30 and 40 DAS), the cultivar had a significant (P<0.05) influence on the dry yield (Table 20). Green pakchoi recorded significantly higher absolute growth rate (AGR) than red at 20 (0.02 for green and 0.01 for red pakchoi), 30 (0.12 for green and 0.05 for red pakchoi) and 40 DAS (0.47 for green and 0.11 for

red pakchoi). This increase in absolute growth rate (AGR) in green pakchoi compared to the red pakchoi was 100% at 20 DAS, 140% at 30 DAS and 327.3% at 40 DAS.

LED-lights

LED lighting had a statistically significant (P<0.05) impact on absolute growth rate (AGR) at 20, 30, and 40 DAS, respectively (Figure 42). At 20 DAS sampling date, 50R50B (0.02) obtained higher absolute growth rate (AGR) compared other LED-light treatments but not significantly different (P>0.05) towards monochromatic 100R (0.02). At 30 DAS sampling date, treatment 82R18B (0.14) indicated the highest absolute growth rate (AGR) but was similar (P>0.05) to 69R24G7G and 100R (0.12 and 0.10). While at 40 DAS sampling date, 82R18B (0.51) gained the highest absolute growth rate (AGR) but was no significant difference (P>0.05) to the treatment 69R24G7G (0.41). White light (control) (0.10) recorded the lowest absolute growth rate (AGR) compared to other LED-light treatments.

The highest measurement on each sampling date compared to white light (control); 50R50B was 400% higher at 20 DAS. While 82R18B was 600% higher at 30 DAS and 69R24B7G 355.6% higher at 40 DAS.

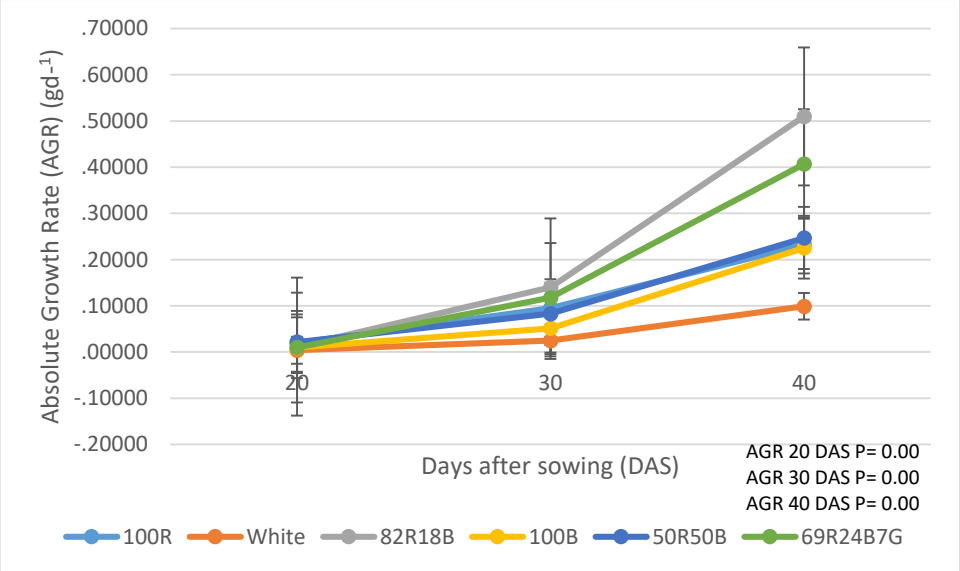


Figure 42 Absolute growth rate (AGR) of green and red pakchoi plants at 20, 30 and 40 DAS (Days after sowing) grown under different LED-light quality treatments in Trial 1 and Trial 2 combined. Light treatment abbreviations as in Table 3.

Cultivar x LED-Lights Interaction

LED-light treatments have a significant (P<0.05) effect on the absolute growth rate (AGR) of green and red pakchoi. At 20 DAS (Figure 43), green pakchoi was significantly (P<0.05) had higher AGR than red pakchoi under all the LED-light treatments. The highest AGR was recorded in green pakchoi exposed with the treatment 100R and the lowest AGR measurement was obtained on red pakchoi exposed to white light (control) treatment. Similarly, at 30 DAS (Figure 44), green pakchoi was significantly (P<0.05) had higher AGR than red pakchoi under all the LED-light treatments. The highest AGR was recorded in green pakchoi with the treatment 82R18B and the lowest AGR measurement was obtained on green pakchoi exposed to white (control) treatment. At 40 DAS (Figure 45), green pakchoi was significantly (P<0.05) had higher AGR than red pakchoi in all the LED-light treatments. The highest AGR was recorded in green pakchoi with the treatment 82R18B and the lowest AGR measurement was obtained on red pakchoi exposed to white light (control) treatment.

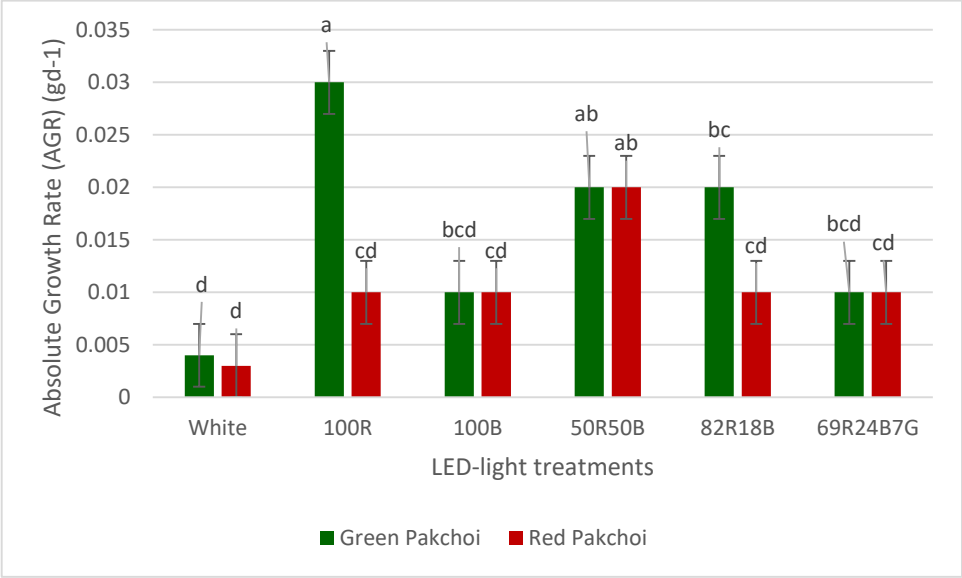


Figure 43 The interaction of absolute growth rate (AGR) at 20 DAS of green pakchoi and red pakchoi towards LED-light treatments. Means with different letters are significantly different at P= 0.05 by Duncan multiple comparisons test. Light treatment abbreviations as in Table 3.

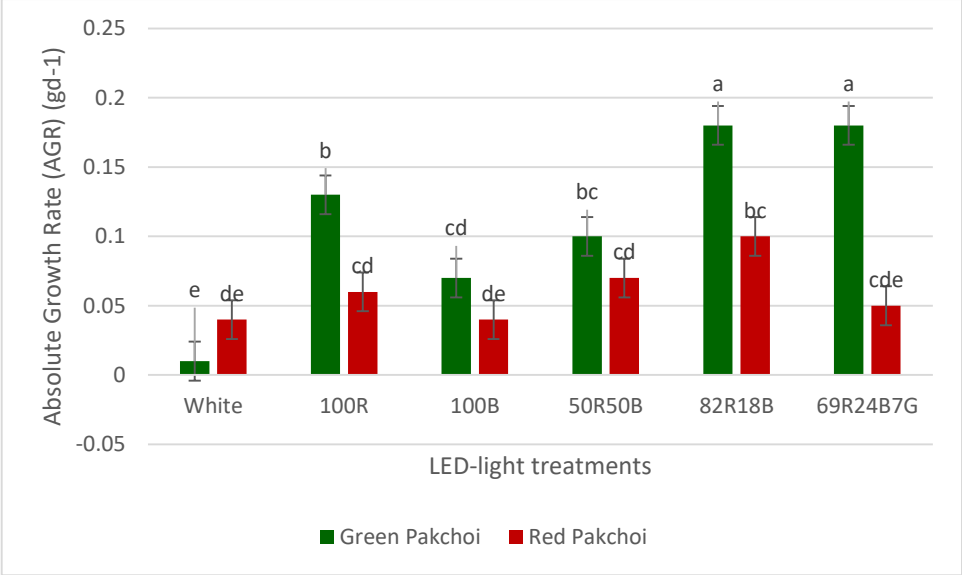


Figure 44 The interaction of absolute growth rate (AGR) at 30 DAS of green pakchoi and red pakchoi towards LED-light treatments. Means with different letters are significantly different at P= 0.05 by Duncan multiple comparisons test. Light treatment abbreviations as in Table 3.

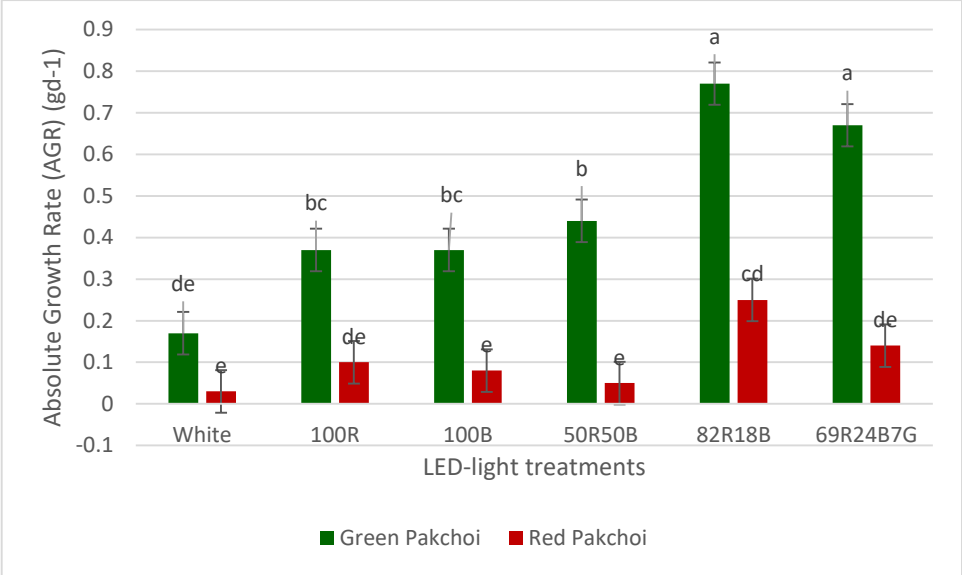


Figure 45 The interaction of absolute growth rate (AGR) at 40 DAS of green pakchoi and red pakchoi towards LED-light treatments. Means with different letters are significantly different at P= 0.05 by Duncan multiple comparisons test. Light treatment abbreviations as in Table 3.

4.9.3 Relative Growth Rate (RGR)

RGR is the increment of total dry weight per unit time per unit existing total dry weight. Main effects of cultivars and their interaction on the relative growth rate (RGR) at 30 DAS in Trial 1 and 2 combined presented in Table 21. While the main effects of LED lights, and their interaction on the relative growth rate (RGR) at 30 DAS in Trial 1 and 2 combined presented in Figure 46 and 47.

Table 21 Relative Growth Rate (AGR) of green and red pakchoi plants at 30 DAS (Days after sowing) grown under different LED-light quality treatments in Trial 1 and Trial 2 combined.

Treatment	Relative Growth Rate (RGR)		
	20 DAS	30 DAS	40 DAS
Cultivar (C)			
Green Pakchoi	0.10 [a]	0.15 [a]	0.39 [a]
Red Pakchoi	0.10 [a]	0.15 [a]	0.29 [a]
SEM	0.00	0.01	0.04
P value	0.1	0.86	0.14

Means with the same letters across column are not significantly different using Tukeys at 5% level.

Cultivars

At all sample stages (20, 30 and 40 DAS), the cultivar was not significant (P>0.05) influence on the relative growth rate (RGR) (Table 21).

LED-lights

LED lighting had a statistically significant (P<0.05) impact on relative growth rate (RGR) only at 30 DAS, respectively (Figure 46). At 30 DAS sampling date, treatment 82R18B (0.17) indicated the highest relative growth rate (RGR) but was similar (P>0.05) to 69R24G7G, 100B and 100R (0.16, 0.16 and 0.13). White light (control) recorded the lowest relative growth rate (RGR) compared to other LED-light treatments.

The highest measurement on each sampling date compared to white light (control); 82R18B was 30.8% higher at 30 DAS and 55.6% higher at 40 DAS.

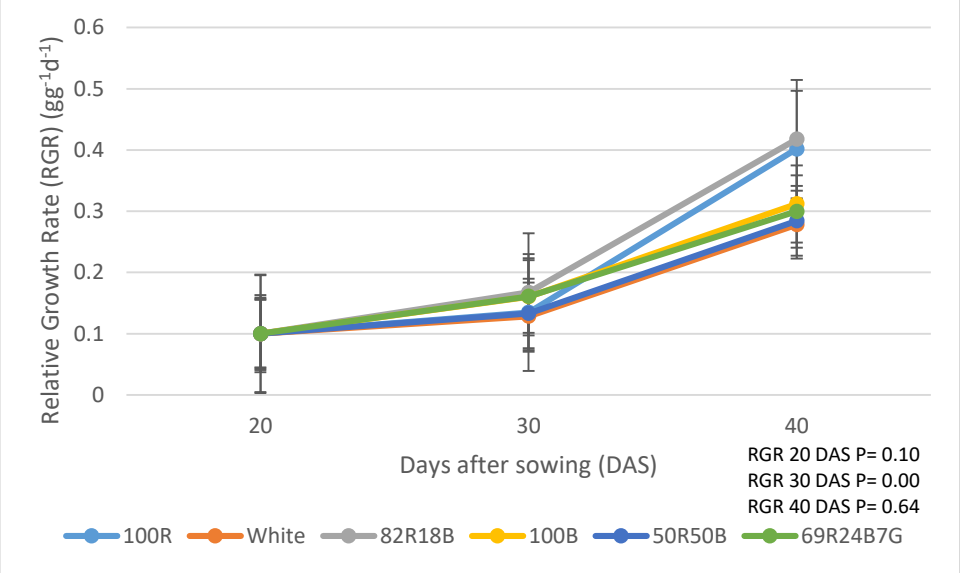


Figure 46 Relative growth rate (RGR) of green and red pakchoi plants at 20, 30 and 40 DAS (Days after sowing) grown under different LED-light quality treatments in Trial 1 and Trial 2 combined. Light treatment abbreviations as in Table 3.

Cultivar x LED-Lights Interaction

Only at 30 DAS LED-light treatments have a significant (P<0.05) effect on the relative growth rate (RGR) of green and red pakchoi. At 30 DAS (Figure 47), green pakchoi was significantly (P<0.05) had higher RGR than red pakchoi with all the LED-light treatments. The highest AGR was recorded in green pakchoi with the treatment 100B and the lowest dry yield measurement was obtained on red pakchoi exposed to white light (control) treatment.

Figure 47 The interaction of relative growth rate (RGR) at 30 DAS of green pakchoi and red pakchoi towards LED-light treatments. Means with different letters are significantly different at P= 0.05 by Duncan multiple comparisons test. Light treatment abbreviations as in Table 3.

4.9.4 Nett Assimilation Rate (NAR)

NAR is the increment of total dry weight per unit time per unit leaf area. It defines the efficiency of biomass production specifically in terms of the amount of photosynthetic tissue. Main effects of cultivars and their interaction on the nett assimilation rate (NAR) at 30 DAS in Trial 1 and 2 combined presented in Table 22. While the main effects of LED lights, and their interaction on the nett assimilation rate (NAR) at 30 DAS in Trial 1 and 2 combined presented in Figure 48-51.

Table 22 Nett Assimilation Rate (NAR) of green and red pakchoi plants at 30 DAS (Days after sowing) grown under different LED-light quality treatments in Trial 1 and Trial 2 combined.

Treatment	Nett Assimilation Rate (AGR)		
	20 DAS	30 DAS	40 DAS
Cultivar (C)			
Green Pakchoi	0.02 [a]	1.30 [a]	0.03 [a]
Red Pakchoi	0.01 [b]	0.03 [b]	0.03 [a]
SEM	0.00	0.06	0.00
P value	0.000	0.000	0.80

Means with the same letters across column are not significantly different using Tukeys at 5% level.

Cultivars

At 20 and 30 sample stages, the cultivar had a significant (P<0.05) influence on the nett assimilation rate (NAR). While at 40 DAS, the was no significant difference (P>0.05) (Table 22). Green pakchoi recorded significantly higher nett assimilation rate (NAR) than red at 20 (0.02 for green and 0.01 for red pakchoi) and 30 DAS (1.30 for green and 0.03 for red pakchoi). This increase in nett assimilation rate (NAR) in green pakchoi compared to the red pakchoi was 100% at 20 DAS and 4233% at 30 DAS.

LED-lights

LED lighting had a statistically significant (P<0.05) impact on nett assimilation rate (NAR) only at 20 and 40 DAS, respectively (Figure 48). At 20 DAS sampling date, 50R50B (0.03) obtained higher nett assimilation rate (NAR) compared other LED-light treatments but not significantly different (P>0.05) towards monochromatic 100R (0.02). While at 40 DAS sampling date, 69R24B7G (0.04) gained the highest nett assimilation rate (NAR) but was no significant difference (P>0.05) to other LED-light treatments except towards white light (control) 69R24G7G (5.32 g). White light (control) recorded the lowest nett assimilation rate (NAR) compared to other LED-light treatments.

The highest measurement on each sampling date compared to white light (control); 50R50B was 200% higher at 20 DAS. While 82R18B was 32.3% higher at 30 DAS and 100% higher at 40 DAS.

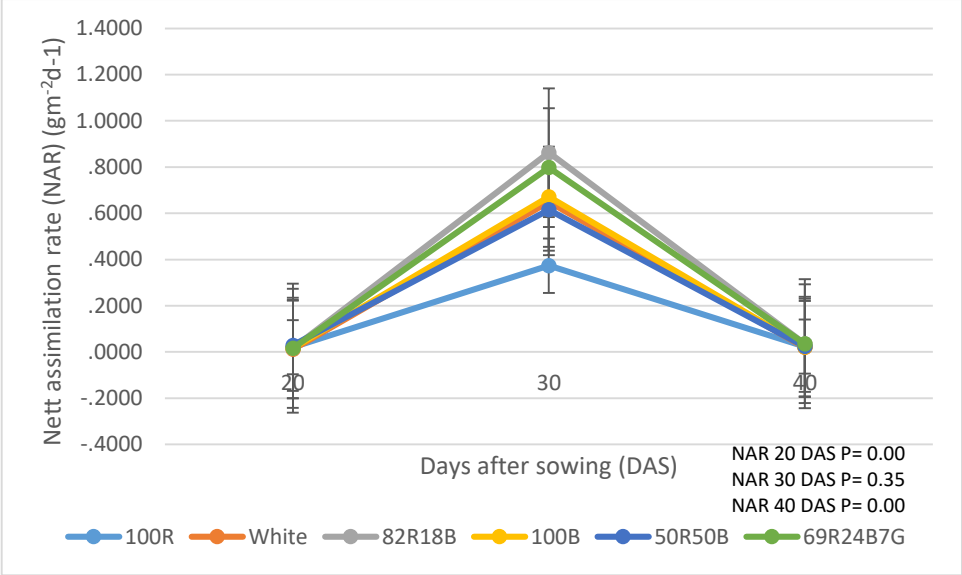


Figure 48 Nett assimilation rate (AGR) of green and red pakchoi plants at 20, 30 and 40 DAS (Days after sowing) grown under different LED-light quality treatments in Trial 1 and Trial 2 combined. Light treatment abbreviations as in Table 3.

Cultivar x LED-Lights Interaction

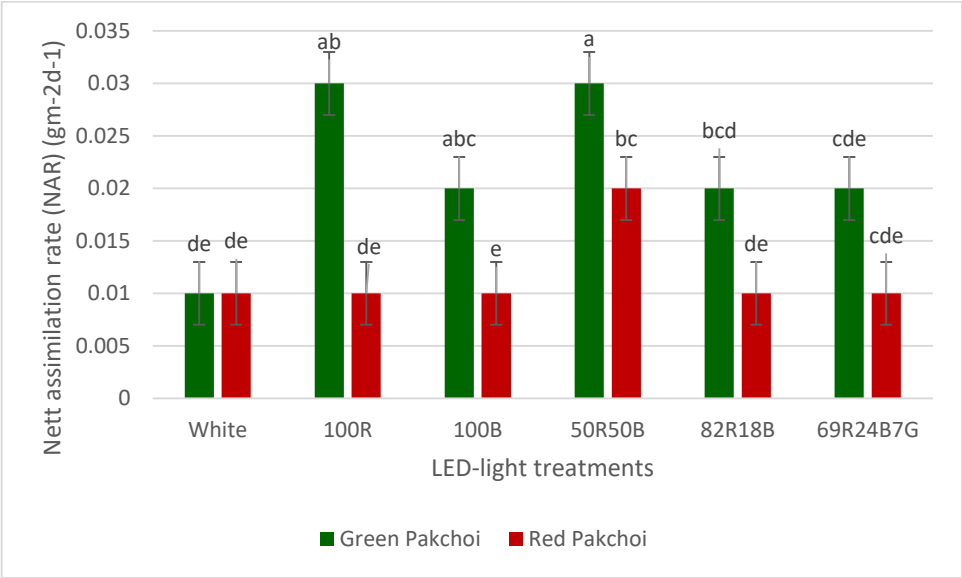


Figure 49 The interaction of nett assimilation rate (NAR) at 20 DAS of green pakchoi and red pakchoi towards LED-light treatments. Means with different letters are significantly different at P= 0.05 by Duncan multiple comparisons test. Light treatment abbreviations as in Table 3.

LED-light treatments have a significant (P<0.05) effect on the nett assimilation rate (NAR) of green and red pakchoi. At 20 DAS (Figure 49), green pakchoi was significantly (P<0.05) had higher NAR than red pakchoi under all the LED-light treatments. The highest NAR was recorded in green pakchoi exposed with the treatment 50R50B and the lowest NAR measurement was obtained on red pakchoi exposed to 100B treatment. At 30 DAS (Figure 50), green pakchoi was significantly

(P<0.05) had higher NAR than red pakchoi under all the LED-light treatments. The highest NAR was recorded in green pakchoi with the treatment 82R18B and the lowest NAR measurement was obtained on red pakchoi exposed to white (control) treatment. At 40 DAS (Figure 51), green pakchoi was significantly (P<0.05) had higher NAR than red pakchoi in almost all the LED-light treatments. The highest NAR was recorded in green pakchoi with the treatment 69R24B7G and the lowest NAR measurement was obtained on red pakchoi exposed to white light (control) treatment.

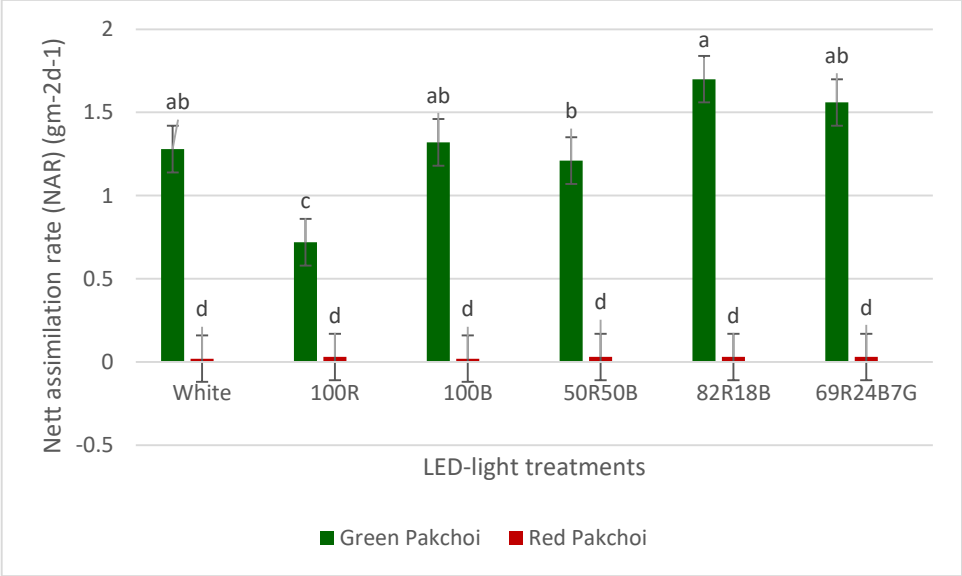


Figure 50 The interaction of nett assimilation rate (NAR) at 30 DAS of green pakchoi and red pakchoi towards LED-light treatments. Means with different letters are significantly different at P= 0.05 by Duncan multiple comparisons test. Light treatment abbreviations as in Table 3.

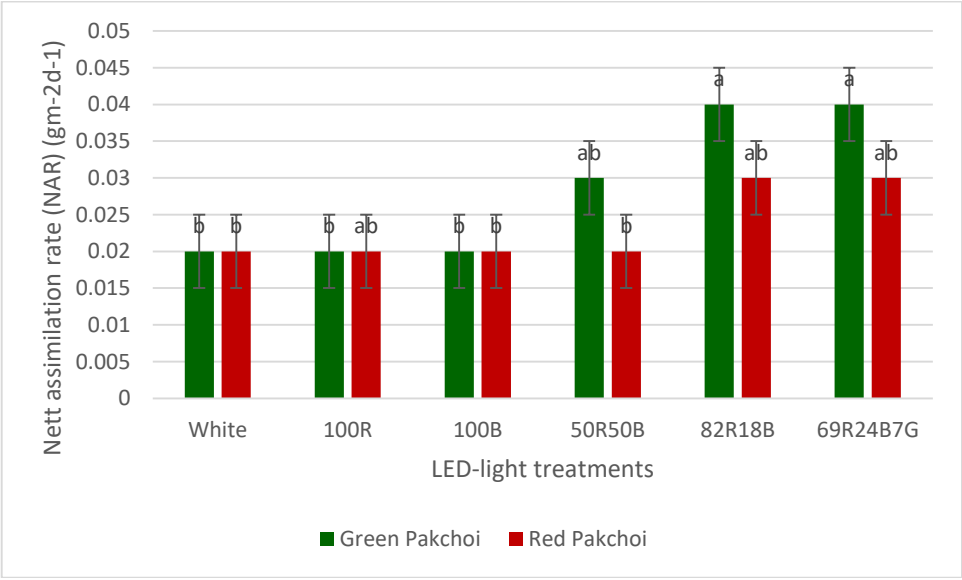


Figure 51 The interaction of nett assimilation rate (NAR) at 40 DAS of green pakchoi and red pakchoi towards LED-light treatments. Means with different letters are significantly different at P= 0.05 by Duncan multiple comparisons test. Light treatment abbreviations as in Table 3.

4.10 Relative chlorophyll content (a+b)

Main effects of LED lights, cultivars and their interaction on the relative chlorophyll content (a+b) at 20, 30 and 40 DAS in Trial 1 and 2 are presented in Table 23. While the main effects of LED lights, cultivars and their interaction on the chlorophyll content (a+b) at 20, 30 and 40 DAS in Trial 1 and 2 combined are presented in Table 24.

Table 23 Relative chlorophyll content of green and red pakchoi plants at 20, 30 and 40DAS (Days after sowing) grown under different LED-light quality treatments in Trial 1 and Trial 2.

Treatment	Relative chlorophyll content (a+b)					
	Trial 1			Trial 2		
	20 DAS	30 DAS	40 DAS	20 DAS	30 DAS	40 DAS
Cultivar (C)						
Green Pakchoi	47.77 a	58.01 a	57.94 a	39.47 a	52.89 a	45.80 a
Red Pakchoi	37.64 b	45.72 b	47.7 b	38.12 a	43.25 b	43.13 b
SEM	0.84	0.75	0.87	0.78	1.01	0.88
P value	0.000	0.000	0.000	0.220	0.000	0.040
LED-Lights mixture (L)						
White	34.71 c	42.61 c	46.7 c	27.94 c	35.51 b	38.83 c
100R	40.66 bc	49.87 b	53.18 ab	43.16 a	50.21 a	49.07 a
100B	41.18 b	52.76 ab	47.24 bc	42.81 ab	49.18 a	40.38 bc
50R50B	43.79 ab	55.46 a	56.96 a	43.12 ab	52.53 a	50.08 a
82R18B	48.04 a	54.57 ab	55.84 a	38.08 ab	52.33 a	46.26 ab
69R24B7G	47.84 a	55.89 a	57.01 a	37.60 b	48.67 a	42.14 bc
SEM	1.45	1.29	1.5	1.33	1.76	1.52
P value	0.000	0.000	0.000	0.000	0.000	0.000
Interaction P values						
C x L	0.940	0.080	0.000	0.000	0.000	0.000

Means with the same letters across column are not significantly different using Tukeys at 5% level.

Table 24 Relative chlorophyll content of green and red pakchoi plants at 20, 30 and 40DAS (Days after sowing) grown under different LED-light quality treatments in Trial 1 and Trial 2 combined.

Treatment	Relative chlorophyll content (a+b)		
	20 DAS	30DAS	40DAS
Cultivar (C)			
Green Pakchoi	43.62 a	55.45 a	51.87 a
Red Pakchoi	37.91 b	44.48 b	45.41 b
SEM	0.72	0.70	0.87
P value	0.000	0.000	0.000
LED-Lights mixture (L)			
White	31.33 b	39.06 b	42.76 c
100R	41.91 a	50.04 a	51.13 a
100B	41.99 a	50.97 a	43.81 bc
50R50B	43.46 a	53.99 a	53.52 a
82R18B	43.24 a	53.45 a	51.05 a
69R24B7G	42.72 a	52.28 a	49.58 ab
SEM	1.24	1.21	1.5
P value	0.000	0.000	0.000
Interaction P values			
C x L	0.203	0.000	0.003

Means with the same letters across column are not significantly different using Tukeys at 5% level.

Cultivar

Trial one

Cultivar had significant (P<0.05) effect on the relative chlorophyll content at all sampling stages (20, 30 and 40 DAS) (Table 23). Green pakchoi recorded significantly higher relative chlorophyll content than red at 20 (47.77 for green and 37.64 for red pakchoi), 30 (58.01 for green and 45.72 for red pakchoi) and 40 DAS (57.94 for green and 47.70 for red pakchoi). This increase in relative chlorophyll content in green pakchoi compared to the red pakchoi was 26.9% at 20 DAS, 26.9% at 30 DAS and 21.5% at 40 DAS.

Trial two

Cultivar had no significant (P>0.05) effect on the relative chlorophyll content at 20 DAS sampling date. While at 30 and 40 DAS sampling stage, there were significant (P<0.05) effect on the relative chlorophyll content (Table 23). Green pakchoi recorded significantly higher relative chlorophyll content than red at 30 (52.89 for green and 43.25 for red pakchoi) and 40 (45.80 for green and 43.13 for green pakchoi). This increase in relative chlorophyll content in green pakchoi compared to the red pakchoi was 3.5% at 20 DAS, 22.3% at 30 DAS and 6.2% at 40 DAS.

Trial one and two combined

At all sample stages (20, 30 and 40 DAS), the cultivar had a significant (P<0.05) influence on the relative chlorophyll content (Table 24). Green pakchoi recorded significantly higher relative chlorophyll content than red at 20 (43.62 for green and 37.91 for red pakchoi), 30 (55.45 for green and 44.48 for red pakchoi) and 40 DAS (51.87 for green and 45.41 for red pakchoi). This increase in relative chlorophyll content in green pakchoi compared to the red was 15.1% at 20 DAS, 24.7% at 30 DAS and 14.2% at 40 DAS.

LED-Lights

Trial one

Relative chlorophyll content was significantly (P<0.05) influenced by LED lights only at 40 DAS sampling date (Table 23). While at 20 and 30 DAS sampling date, the LED-light treatments have no significant (P>0.05) influenced towards the relative chlorophyll content. 82R18B (48.04) obtained the highest relative chlorophyll content

among all the LED-light treatments but was similar (P>0.05) with the treatments 69R24B7G and 50R50B. At 20 and 30 DAS sampling dates, 69R24B7G (55.89 and 57.01 at 30 and 40 DAS respectively) accumulated the highest relative chlorophyll content among all the LED-light treatments was similar (P>0.05) with the treatments 69R24B7G and 50R50B. White light (control) recorded the lowest height compared to other LED-light treatments.

The highest measurement on each sampling date compared to white light (control); 82R18B was 38.5% higher at 20 DAS. 69R24B7G was 31.2% higher at 30DAS and 22.1% higher at 40 DAS.

Trial two

Relative chlorophyll content at 20. 30 and 40 DAS were significantly (P<0.05) influenced by LED lights (Table 23). At 20 DAS sampling date, monochromatic 100R (43.16) obtained significantly (P<0.05) higher relative chlorophyll content compared other LED-light treatments but it was similar with the treatments 50R50B, 100B and 82R18B (43.12, 42.81 and 38.08). At 30 DAS all sampling date, treatment 50R50B (52.53) was the highest but was similar (P>0.05) to all LED-light treatments (52.33, 50.21, 49.18 and 48.67 for 82R18B, 100R, 100B and 69R24B7G respectively) except for White (control). While during 40 DAS sampling date, 50R50B (50.08) produced the higher relative chlorophyll content compared to other LED-light treatments but was no difference (P>0.05) towards 100R and 82R18B (49.07 and 46.26). White light (control) recorded the lowest height compared to other LED-light treatments.

The highest measurement on each sampling date compared to white light (control); 100R was 54.5% higher at 20 DAS. While 50R50B was 47.9% higher at 30DAS and 29% higher at 40 DAS.

Trial one and two combined

LED lighting had a significant (P<0.05) effect on the relative chlorophyll content at 20, 30, and 40 DAS (Table 24). At 20 DAS sampling date, 50R50B (43.46) obtained the higher measurement compared to other LED-light treatments but it was similar (P>0.05) to other LED-light treatments (43.24, 42.72,41.99 and 41.91 for 82R18B, 69R24B7G, 100B and 100R respectively) except for white (control). At 30 DAS

sampling date, 50R50B (53.99) gained the highest relative chlorophyll content but it has no significant difference (P<0.05) with other LED-light treatments (53.45, 52.28, 50.97 and 50.04 for 82R18B, 52.28, 100B and 100R respectively). While at 40 DAS sampling date, 50R50B (53.52) indicated the highest measurement but was similar (P>0.05) towards treatments (51.13, 51.05 and 49.58 for 100B, 82R18B and 69R18B7G respectively). White light (control) recorded the lowest relative chlorophyll content compared to other LED-light treatments.

The highest measurement on each sampling date compared to white light (control); 50R50B was 38.7% higher at 20 DAS, 38.2% higher at 30DAS and 25.2% higher at 40 DAS.

Cultivar x LED-Lights Interaction

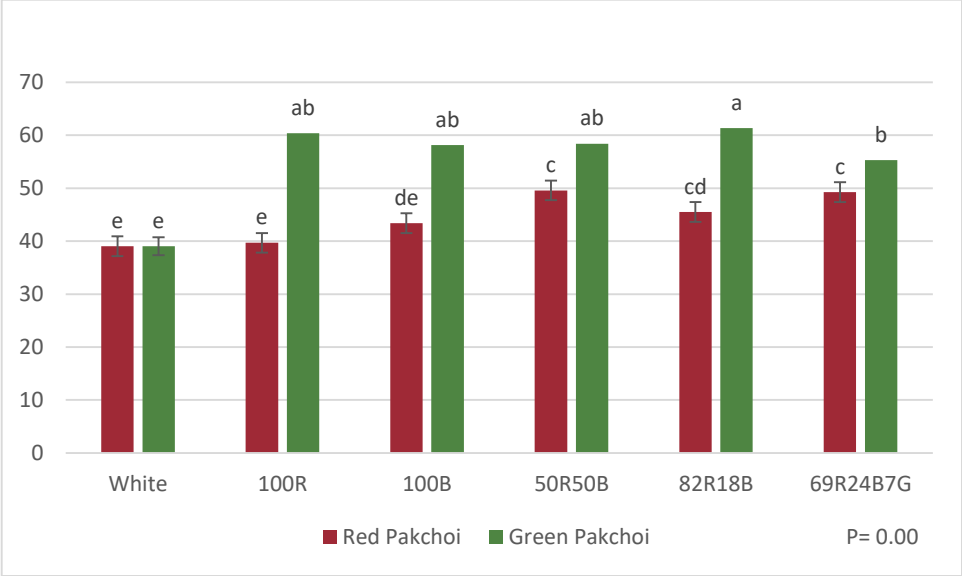


Figure 52 The interaction of chlorophyll content index at 30 DAS of green pakchoi and red pakchoi towards LED-light treatments. Means with different letters are significantly different at P= 0.05 by Duncan multiple comparisons test. Light treatment abbreviations as in Table 3.

Trial one and two combined

Only at 30 and 40 DAS sampling dates LED-lights have a significant (P<0.05) effect on the relative chlorophyll content of green and red pakchoi. While the LED-light treatments had no significant effect on the relative chlorophyll content at the 20 DAS sample date (Table 24). At 30 DAS sampling date (Figure 52), response to LED-light treatment was higher (P<0.05) in green pakchoi than red pakchoi in all LED-light treatments except under the treatment white light (control). The highest relative chlorophyll content was recorded on green pakchoi under the treatment 82R18B. The

lowest relative chlorophyll content measurement was found on the red pakchoi under the treatment white light (control). Similar result obtained during 40 DAS sampling date (Figure 53), response to LED-light treatment was higher (P<0.05) in green pakchoi than red pakchoi in all LED-light treatments except under the treatment white light (control). The highest relative chlorophyll content was recorded on red pakchoi under the treatment 100R. While, the lowest relative chlorophyll content measurement was found on the red pakchoi under the treatment white light (control).

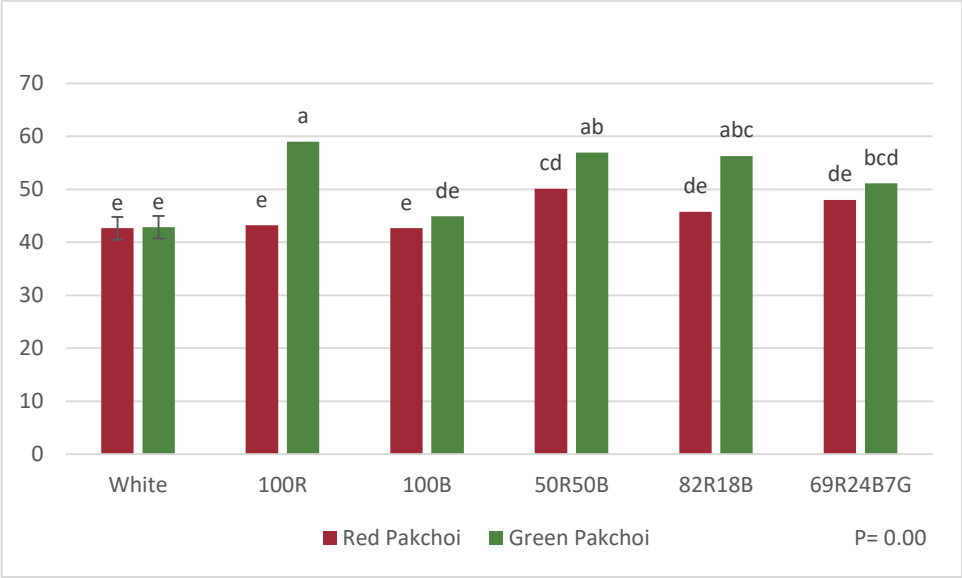


Figure 53 The interaction of chlorophyll content index at 40 DAS of green pakchoi and red pakchoi towards LED-light treatments. Means with different letters are significantly different at P= 0.05 by Duncan multiple comparisons test. Light treatment abbreviations as in Table 3.

4.11 Chlorophyll florescence (Fv/Fm)

Main effects of LED lights, cultivars and their interaction on the chlorophyll florescence at 20, 30 and 40 DAS in Trial 1 and 2 are presented in Table 25. While the main effects of LED lights, cultivars and their interaction on the plant height at 20, 30 and 40 DAS in Trial 1 and 2 combined are presented in Table 26.

Table 25 Chlorophyll florescence of green and red pakchoi plants at 20, 30 and 40DAS (Days after sowing) grown under different LED-light quality treatments in Trial 1 and Trial 2.

Treatment	Chlorophyll florescence (Fv/Fm)					
	Trial 1			Trial 2		
	20 DAS	30 DAS	40 DAS	20 DAS	30 DAS	40 DAS
Cultivar (C)						
Green Pakchoi	0.80 [a]	0.80 [a]	0.77 [a]	0.80 [a]	0.80 [a]	0.78 [a]
Red Pakchoi	0.74 [b]	0.75 [b]	0.76 [b]	0.76 [b]	0.76 [b]	0.76 [b]
SEM	0.002	0.003	0.003	0.002	0.003	0.002

P value	0.000	0.000	0.000	0.000	0.000	0.000
LED-Lights mixture (L)						
White	0.75 [b]	0.77 [a]	0.75 [bc]	0.76 [c]	0.77 [b]	0.75 [d]
100R	0.76 [ab]	0.78 [a]	0.78 [a]	0.78 [ab]	0.77 [ab]	0.79 [a]
100B	0.77 [ab]	0.77 [a]	0.74 [c]	0.79 [ab]	0.78 [ab]	0.78 [ab]
50R50B	0.77 [ab]	0.78 [a]	0.77 [ab]	0.79 [ab]	0.78 [ab]	0.77 [ab]
82R18B	0.76 [ab]	0.77 [a]	0.78 [a]	0.77 [bc]	0.79 [a]	0.77 [bc]
69R24B7G	0.77 [a]	0.78 [a]	0.77 [a]	0.79 [a]	0.79 [ab]	0.76 [cd]
SEM	0.004	0.005	0.005	0.004	0.005	0.004
P value	0.050	0.950	0.000	0.000	0.020	0.000
Interaction P values						
C x L	0.240	0.010	0.180	0.010	0.360	0.080

Means with the same letters across column are not significantly different using Tukeys at 5% level.

Table 26 Chlorophyll florescence (fv/fm) of green and red pakchoi plants at 20, 30 and 40DAS (Days after sowing) grown under different LED-light quality treatments in Trial 1 and Trial 2 combined.

Treatment	Chlorophyll florescence (Fv/Fm)		
	20 DAS	30DAS	40DAS
Cultivar (C)			
Green Pakchoi	0.80 [a]	0.80 [a]	0.78 [a]
Red Pakchoi	0.75 [b]	0.76 [b]	0.76 [b]
SEM	0.002	0.002	0.002
P value	0.000	0.000	0.000
LED-Lights mixture (L)			
White	0.76 [b]	0.77 [a]	0.75 [d]
100R	0.77 [a]	0.78 [a]	0.78 [a]
100B	0.78 [a]	0.78 [a]	0.76 [cd]
50R50B	0.78 [a]	0.77 [a]	0.77 [abc]
82R18B	0.77 [ab]	0.78 [a]	0.77 [ab]
69R24B7G	0.78 [a]	0.78 [a]	0.76 [bc]
SEM	0.003	0.004	0.003
P value	0.000	0.171	0.000
Interaction P values			
C x L	0.030	0.020	0.062

Means with the same letters across column are not significantly different using Tukeys at 5% level.

Cultivar

Trial one

Cultivar had significant (P<0.05) effect on the chlorophyll florescence (fv/fm) at all sampling stages (20, 30 and 40 DAS) (Table 25). Green pakchoi recorded significantly higher chlorophyll florescence measurement than red at 20 (0.80 for green and 0.74 for red pakchoi), 30 (0.80 for green and 0.75 for red pakchoi) and 40 DAS (0.77 for green and 0.76 for red pakchoi). This increase in chlorophyll florescence in green pakchoi compared to the red was 8.1% at 20 DAS, 6.7% at 30 DAS and 1.3% at 40 DAS.

Trial two

At all sample stages (20, 30 and 40 DAS), the cultivar had a significant (P<0.05) influence on chlorophyll florescence (fv/fm) (Table 25). Green pakchoi had considerably greater chlorophyll florescence (fv/fm) than red pakchoi at 20 (0.80 for green and 0.76 for red pakchoi), 30 (0.80 for green and 0.76 for red pakchoi) and 40 DAS (0.78 for green and 0.76 for red pakchoi). This increase in chlorophyll florescence (fv/fm) in green pakchoi compared to the red pakchoi was 5.3% at 20 DAS and 30 DAS and 2.6% at 40 DAS.

Trial one and two combined

At all sample stages (20, 30 and 40 DAS), the cultivar had a statistically significant (P<0.05) effect on the chlorophyll florescence (fv/fm) (Table 26). Green pakchoi recorded significantly higher chlorophyll florescence (fv/fm) than red at 20 (0.80 for green and 0.75 for red pakchoi), 30 (0.80 for green and 0.76 for red pakchoi) and 40 DAS (0.78 for green and 0.76 for red pakchoi). This increase of chlorophyll florescence (fv/fm) in green pakchoi compared to the red pakchoi was 6.7% at 20 DAS, 5.3% at 30 DAS and 2.6% at 40 DAS.

LED-Lights

Trial one

Chlorophyll florescence (fv/fm) at 20 and 30 DAS were not significantly (P>0.05) influenced by LED-light treatments, only at 40 DAS was significantly affected by the LED-light treatments (Table 25). At 40 DAS sampling date, monochromatic 100R and 82R18B both obtained 0.78 as the highest measurement respectively, but was similar to (P>0.05). 69R24B7G and 50R50B. Monochromatic 100B was recorded the lowest chlorophyll florescence compared to other LED-light treatments on the 40 DAS.

The highest measurement on each sampling date compared to white light (control); 69R724B7G was 2.7% higher at 20 DAS and 1.3% higher at 30DAS. While, 82R18B 4% higher at 40 DAS.

Trial two

LED lighting had a significant (P<0.05) effect on chlorophyll florescence (fv/fm) at 20, 30, and 40 DAS (Table 25). At 20 DAS sampling date, 69R24B7G (0.79) gained the higher chlorophyll florescence (fv/fm) among other LED-light treatments. However, there was no difference (P<0.05) between treatments 50R50B, 100B and 100R (0.79, 0.79 and 0.78). At 30 DAS sampling date, 82R18B (0.79) obtained the highest chlorophyll florescence (fv/fm) but similar to all the LED-light treatments (0.79, 0.78, 0.78 and 0.77 for 69R24B7G, 50R50B,100B and 100R respectively) except for white light (control). While at 40 DAS sampling date, monochromatic 100R (0.79) indicated the highest measurement but was similar to 100B and 50R50B (0.78 and 0.77). White light (control) recorded the lowest height compared to other LED-light treatments on every sampling dates.

The highest measurement on each sampling date compared to white light (control); 69R24B7G was 3.9% higher at 20 DAS, 82R18B was 2.6% higher at 30DAS and 100R was 5.3% higher at 40 DAS.

Trial one and two combined

Chlorophyll florescence (fv/fm) at 20 and 40 DAS were significantly (P<0.05) influenced by LED-light treatments. While at 30 DAS, Chlorophyll florescence (fv/fm) was not significanty (P>0.05) influenced by the LED-light treatments (Table 26). At 20 DAS sampling date, 69R24B7G (0.78) obtained the highest measurement compared other LED-light treatments but it was similar (P>0.05) towards other treatments except to white light (control). While at 40DAS sampling date, monochromatic 100R (0.78) obtained the higher measurement compared to other LED-light treatments. However, it was no significant different (P>0.05) to 82R18B and 50R50B (0.77 for both treatment). White light (control) recorded the lowest height compared to other LED-light treatments.

The highest measurement on each sampling date compared to white light (control); 100R was 87% higher at 20 DAS, 68% at 30DAS and 44% higher at 40 DAS.

Cultivar x LED-Lights Interaction

Trial one and two combined

The chlorophyll florescence (fv/fm) of green and red pakchoi was significantly (P<0.05) affected with LED-lights at 20 and 30 DAS sampling date. While at 40 DAS sampling date, the chlorophyll florescence (fv/fm) was not significantly (P>0.05) affected by the LED-light treatments (Table 26). At 20 DAS sampling date (Figure 54), response to LED-light treatment was higher (P<0.05) in green pakchoi than red pakchoi in all LED-light treatments. The highest relative chlorophyll florescence (fv/fm) was recorded on green pakchoi under the treatment 69R24B7G. The lowest chlorophyll florescence (fv/fm) measurement was found on the red pakchoi under the treatment white (control). At 30 DAS sampling date (Figure 55), response to LED-light treatment was still higher (P<0.05) in green pakchoi than red pakchoi in all LED-light treatments. The highest relative chlorophyll florescence (fv/fm) was recorded on green pakchoi under the treatment 82R18B. While, the lowest chlorophyll florescence (fv/fm) measurement was found on the red pakchoi under the treatment 50R50B.

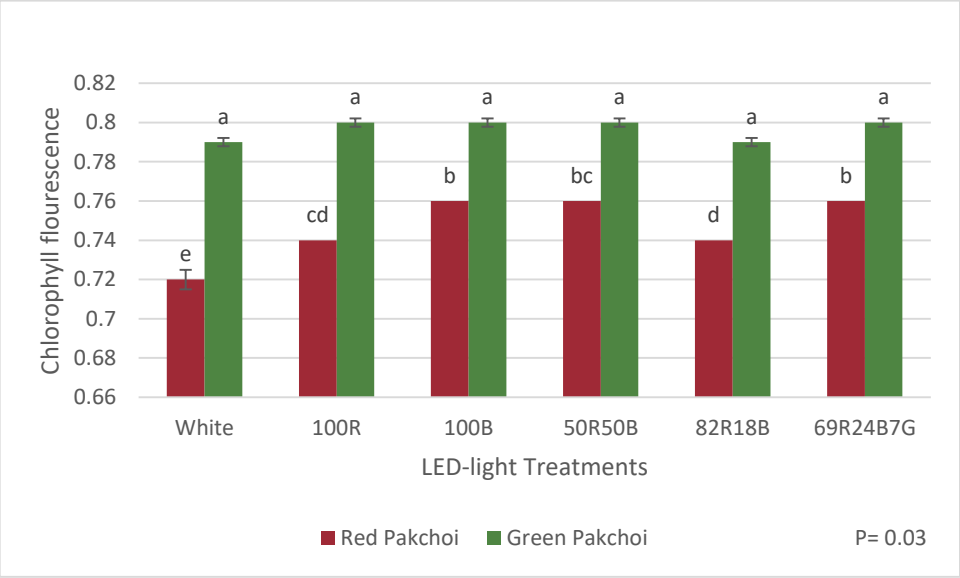


Figure 54 The interaction of chlorophyll fluorescence at 20 DAS of green pakchoi and red pakchoi towards LED-light treatments. Means with different letters are significantly different at P= 0.05 by Duncan multiple comparisons test. Light treatment abbreviations as in Table 3.

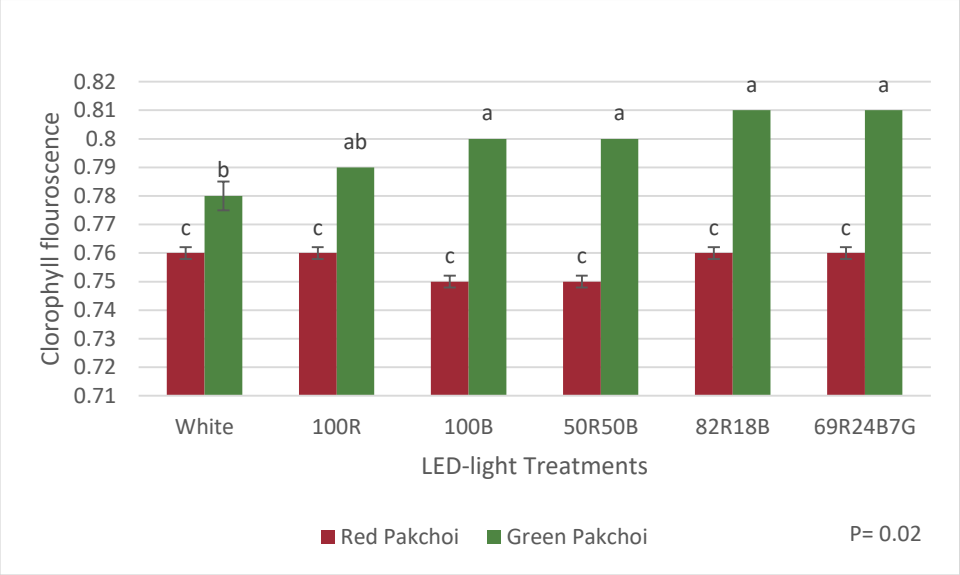


Figure 55 The interaction of chlorophyll fluorescence at 30 DAS of green pakchoi and red pakchoi towards LED-light treatments. Bars with different letters are significantly different at P= 0.05 by Duncan multiple comparisons test. Error bars are SEM values. Light treatment abbreviations as in Table 3.

4.12 Photosynthetic capacity

Main effects of LED lights, cultivars and their interaction on photosynthetic capacity; the photosynthesis rate (Pn), transpiration rate (E) and stomatal conductance (Gs) at 30 DAS are presented in Table 27. While the main effects of LED lights, cultivars and their interaction on the plant height at 30 DAS in Trial 1 and 2 combined are presented in Table 28.

Table 27 Photosynthetic capacity of green and red pakchoi plants at 30 DAS (Days after sowing) grown under different LED-light quality treatments in Trial 1 and Trial 2.

Treatment	Pn (µmol m^{-2} s^{-1})	E (mmol m^{-2} s^{-1})	Gs (mmol m^{-2} s^{-1})	Pn (µmol m^{-2} s^{-1})	E (mmol m^{-2} s^{-1})	Gs (mmol m^{-2} s^{-1})
	Trial 1			Trial 2		
	30 DAS					
Cultiv©(C)						
Green Pakchoi	18.21 a	5.05 a	186.98 a	16.84 a	5.68 a	176.31 a
Red Pakchoi	9.45 b	3.05 b	180.17 b	8.34 b	2.81 b	153.69 b
SEM	0.35	0.13	6.42	0.38	0.14	4.98
P value	0.000	0.000	0.000	0.000	0.000	0.000
LED-Lights mixture (L)						
White	11.51 c	1.53 d	107.14 c	11.39 c	1.53 c	123.86 de
100R	12.65 bc	3.26 c	121.86 c	10.87 c	3.73 b	109.71 e
100B	13.47 bc	4.53 b	219.93 ab	11.71 bc	5.58 a	175.36 bc
50R50B	16.25 a	4.71 b	182.57 b	11.79 bc	4.45 b	157.93 cd
82R18B	14.23 ab	5.74 a	237.21 a	14.13 ab	6.10 a	210.07 ab
69R24B7G	14.87 ab	4.52 b	232.21 a	15.64 a	4.09 b	213.07 a
SEM	0.61	0.23	11.13	0.66	0.25	8.62
P value	0.000	0.000	0.000	0.000	0.000	0.000
Interaction P values						
C x L	0.000	0.000	0.000	0.000	0.000	0.000

Means in a column followed by same letters are not significantly different using Tukeys test at 5% level.

Table 28 Photosynthetic capacity *of green and red pakchoi plants at 20, 30 and 40DAS (Days after sowing) grown under different LED-light quality treatments in Trial 1 and Trial 2 combined.*

Treatment	Pn (µmol m^{-2} s^{-1})	E (mmol m^{-2} s^{-1})	Gs (mmol m^{-2} s^{-1})
	30 DAS		
Cultivar (C)			
Green Pakchoi	17.52 [a]	5.37 [a]	181.64 [a]
Red Pakchoi	8.89 [b]	2.93 [b]	166.93 [b]
SEM	0.28	0.11	4.53
P value	0.000	0.000	0.020
LED-Lights mixture (L)			
White	11.45 [c]	1.53 [d]	115.5 [c]
100R	11.76 [c]	3.5 [c]	115.79 [c]
100B	12.59 [bc]	5.05 [b]	197.64 [ab]
50R50B	14.02 [ab]	4.58 [b]	170.25 [b]
82R18B	14.18 [ab]	5.92 [a]	223.64 [a]
69R24B7G	15.25 [a]	4.31 [b]	222.89 [a]
SEM	0.49	0.19	7.85
P value	0.000	0.000	0.000
Interaction P values			
C x L	0.000	0.000	0.000

Means in a column followed by same letters are not significantly different using Tukeys test at 5% level.

Cultivar

Trial one

Cultivar had significant (P<0.05) effect on the Pn, E and Gs at 30 DAS sampling stages (Table 27). Green pakchoi recorded significantly higher Pn (18.21 µmol m^{-2} s^{-1} for green and 9.45 µmol m^{-2} s^{-1} for red pakchoi), E (5.05 mmol m^{-2} s^{-1} for green and 3.05 mmol m^{-2} s^{-1} for red pakchoi) and Gs (186.98 mmol m^{-2} s^{-1} for green and 180.17 mmol m^{-2} s^{-1} for red pakchoi) than red pakchoi. This increase in green pakchoi compared to the red pakchoi was 92.7% for Pn, 65.6% for E and 3.8% for Gs.

Trial two

At 30 DAS sampling stage, there was a statistically significant (P<0.05) effect of cultivar on the Pn, E, and Gs (Table 27). Green pakchoi recorded significantly higher Pn than red (16.84 µmol m^{-2} s^{-1} for green and 8.34 µmol m^{-2} s^{-1} for red pakchoi), E (5.68 mmol m^{-2} s^{-1} for green and 2.81 mmol m^{-2} s^{-1} for red pakchoi) and Gs (176.31 mmol m^{-2} s^{-1} for green and 153.69 mmol m^{-2} s^{-1} for red pakchoi). This increase in green pakchoi compared to the red pakchoi was 101.9% for Pn, 102.1% for E and 14.7% for Gs.

Trial one and two combined

Cultivar had significant (P<0.05) effect on the Pn, E and Gs at 30 DAS sampling stages (Table 28). Green pakchoi recorded significantly higher photosynthesis rate Pn

(17.52 µmol m^{-2} s^{-1} for green and 8.89 µmol m^{-2} s^{-1} for red pakchoi), E (5.37 mmol m^{-2} s^{-1} for green and 2.93 mmol m^{-2} s^{-1} for red pakchoi) and Gs (181.64 mmol m^{-2} s^{-1} for green and 166.93 mmol m^{-2} s^{-1} for red pakchoi) than red pakchoi. This increase in green pakchoi compared to the red pakchoi was 97.1% for Pn, 83.3% for E and 8.8% for Gs.

LED-Lights

Trial one

The Pn, E and Gs at 30 DAS sampling stages were significantly (P<0.05) influenced by LED-light treatments (Table 27). Referring to the Pn, the treatment 50R50B (16.25 µmol m^{-2} s^{-1}) obtained significantly (P<0.05) higher Pn, compared other LED-light treatments. However, it was similar (P>0.05) to the treatments 69R24B7G and 82R18B (14.87 µmol m^{-2} s^{-1} and 14.23 µmol m^{-2} s^{-1}). The treatment white (control) (11.51 µmol m^{-2} s^{-1}) recorded the lowest Pn compared to other LED-light treatments. In the other hand, the E as significantly highest (P<0.05) under the treatment 82R18B (5.74 mmol m^{-2} s^{-1}) compared to other LED-light treatments. The monochromatic 50R50B (4.71 mmol m^{-2} s^{-1}) was the second highest measurement but was similar (P>0.05) towards treatments monochromatic 100B and 69R24B7G (4.56 mmol m^{-2} s^{-1} and 4.52 mmol m^{-2} s^{-1}). The white (control) (1.53 mmol m^{-2} s^{-1}) treatment indicated the significantly lowest (P<0.05) E compared to other LED-light treatments. For the Gs, the treatment 82R18B (237.21 mmol m^{-2} s^{-1}) obtained significantly (P<0.05) higher Gs compared other LED-light treatments. However, it was no difference (P>0.05) with the treatment 69R24B7G (232.21 mmol m^{-2} s^{-1}1) and monochromatic 100B (219.93 mmol m^{-2} s^{-1}). The white (control) (107.14 mmol m^{-2} s^{-1}) recorded the lowest Gs compared to other LED-light treatments.

The highest measurement on each sampling date compared to white light (control); 50R50B was 41.2% higher for Pn. While 82R18B was 275.2% higher for E and 121.4% higher for Gs.

Trial two

The Pn, E and Gs at 30 DAS sampling stages were significantly (P<0.05) influenced by LED lights (Table 27). The Pn, the treatment 69R24B7G (15.64 µmol m^{-2} s^{-1}) obtained significantly (P<0.05) higher Pn, compared other LED-light treatments.

However, it was similar (P>0.05) to the treatment 82R18B (14.13 µmol m^{-2} s^{-1}). The monochromatic 100R (10.87 µmol m^{-2} s^{-1}) recorded the lowest Pn compared to other LED-light treatments. In the other hand, the E was the highest under the treatment 82R18B (6.10 mmol m^{-2} s^{-1}) but it was similar (P>0.05) towards the treatment monochromatic 100B (5.58 mmol m^{-2} s^{-1}). The white (control) (1.53 mmol m^{-2} s^{-1}) treatment indicated the lowest E compared to other LED-light treatments. For the Gs, the treatment 69R24B7G (213.07 mmol m^{-2} s^{-1}) obtained significantly (P<0.05) higher Gs compared other LED-light treatments. However, it was no difference (P>0.05) with the treatment 82R18B (210.07 mmol m^{-2} s^{-1}). The monochromatic 100R (109.71 mmol m^{-2} s^{-1}) recorded the lowest Gs compared to other LED-light treatments.

The highest measurement on each sampling date compared to white light (control); 69R24B7G was 37.3% higher for Pn. While 82R18B was 298.7% higher for E and 69R24B7G was 72%% higher for Gs.

Trial one and two combined

The Pn, E and Gs at 30 DAS sampling stages were significantly (P<0.05) influenced by LED lights (Table 28). The Pn, the treatment 69R24B7G (15.25 µmol m^{-2} s^{-1}) obtained significantly (P<0.05) higher Pn, compared other LED-light treatments. However, it was similar (P>0.05) to the treatments 82R18B and 50R50B (14.18 µmol m^{-2} s^{-1} and 14.02 µmol m^{-2} s^{-1}). The white (control) (11.45 µmol m^{-2} s^{-1}) treatment recorded the lowest Pn compared to other LED-light treatments. In the other hand, the E was significantly highest (P<0.05) under the treatment 82R18B (5.92 mmol m^{-2} s^{-1}) towards other LED-light treatments. The white (control) (1.53 mmol m^{-2} s^{-1}) treatment indicated the lowest E compared to other LED-light treatments. For the Gs, the treatment 82R18B (223.64 mmol m^{-2} s^{-1}) obtained significantly (P<0.05) higher Gs compared other LED-light treatments but was similar (P>0.05) with the treatments 69R24B7G and 100B (222.89 mmol m^{-2} s^{-1} and 197.64 mmol m^{-2} s^{-1}). The white (control) (115.50 mmol m^{-2} s^{-1}) treatment recorded the lowest Gs compared to other LED-light treatments but similar (P>0.05) towards the treatment monochromatic 100R (115.79 mmol m^{-2} s^{-1}).

The highest measurement on each sampling date compared to white light (control); 69R24B7G was 33.2% higher at 20 DAS, 286.7% at 30DAS and 93.6% higher at 40 DAS.

Cultivar x LED-Lights Interaction

Trial one and two combined

The Pn of green and red pakchoi was significantly (P<0.05) affected with LED-lights (Table 28). The Pn (Figure 56) response to LED-light treatment was higher (P<0.05) in green pakchoi than red pakchoi in all LED-light treatments. The highest Pn was recorded on green pakchoi under the treatment 50R50B. The lowest chlorophyll florescence (fv/fm) measurement was found on the red pakchoi under the treatment white light (control).

While the E of green and red pakchoi was also significantly (P<0.05) affected with LED-lights (Table 28). The E (Figure 57) response to LED-light treatment was higher (P<0.05) in green pakchoi than red pakchoi in all LED-light treatments. The highest E was recorded on green pakchoi under the treatment 82R18B and the lowest E measurement was found on the red pakchoi under the treatment white light (control).

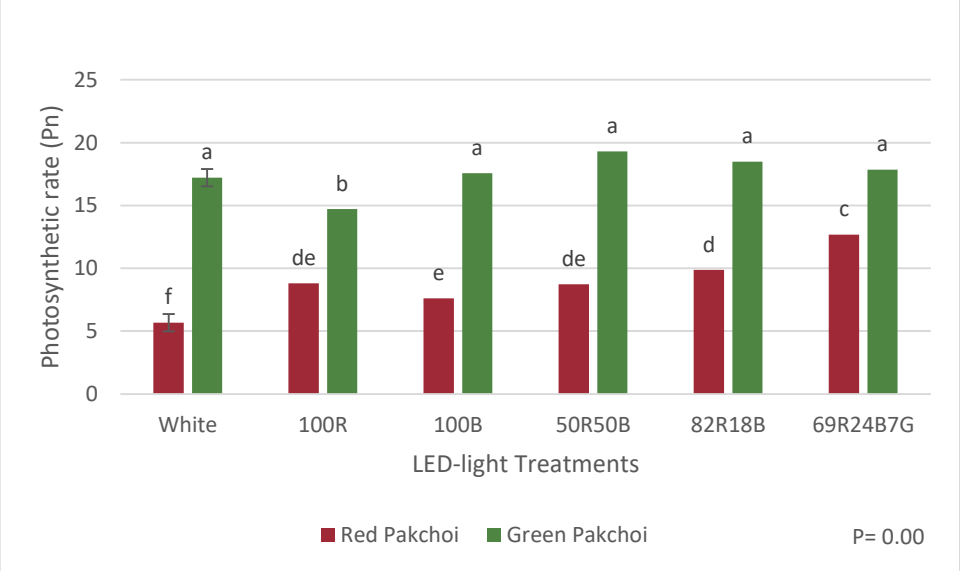


Figure 56 The interaction of photosynthesis rate (Pn) at 30 DAS of green pakchoi and red pakchoi towards LED-light treatments. Means with different letters are significantly different at P= 0.05 by Duncan multiple comparisons test. Light treatment abbreviations as in Table 3.

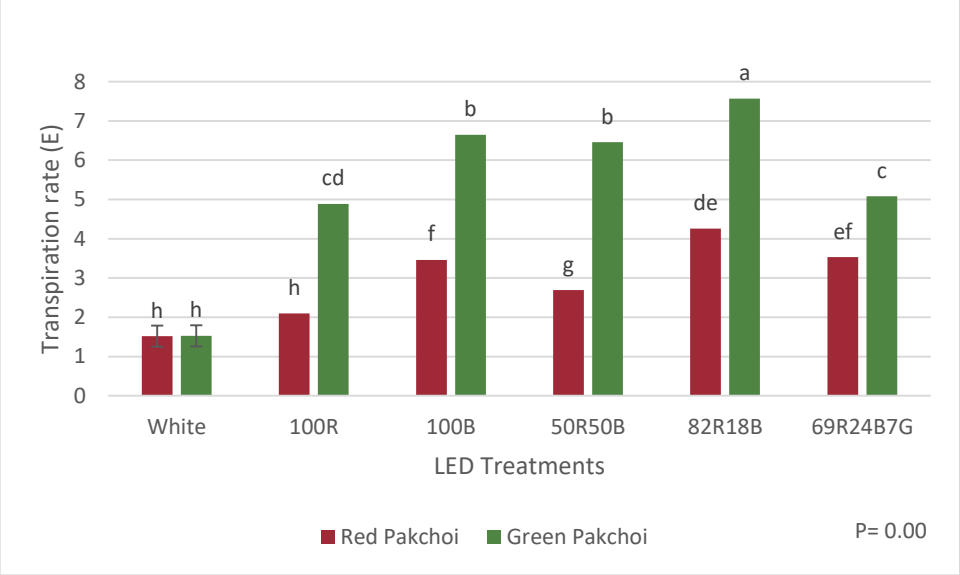


Figure 57 The interaction of transpiration rate (E) at 30 DAS of green pakchoi and red pakchoi towards LED-light treatments. Means with different letters are significantly different at P= 0.05 by Duncan multiple comparisons test. Light treatment abbreviations as in Table 3.

Then for the Gs of green and red pakchoi was also significantly (P<0.05) affected with LED-lights (Table 28). The Gs (Figure 58) response to LED-light treatment was higher (P<0.05) in green pakchoi than red pakchoi in all LED-light treatments except for the treatmentS 82R18B and 100B. The highest Gs was recorded on red pakchoi under the treatment 82R18B. While the lowest Gs measurement was found on the red pakchoi under the treatment white light (control).

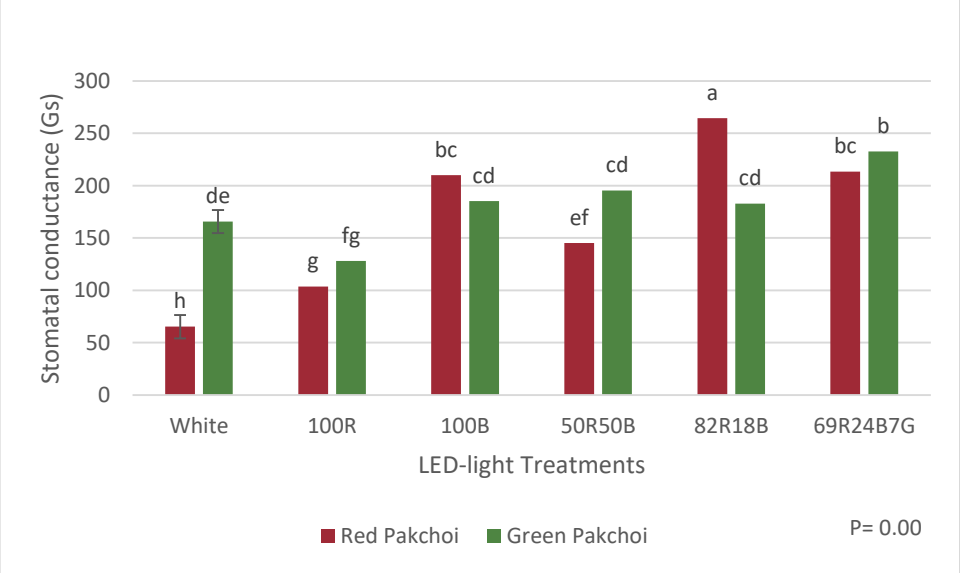


Figure 58 The interaction of stomatal conductance (Gs) at 30 DAS of green pakchoi and red pakchoi towards LED-light treatments. Means with different letters are significantly different at P= 0.05 by Duncan multiple comparisons test. Light treatment abbreviations as in Table 3.

4.13 Effects of LED-light treatment on root morphology

4.13.1 Visual observation on green pakchoi root system

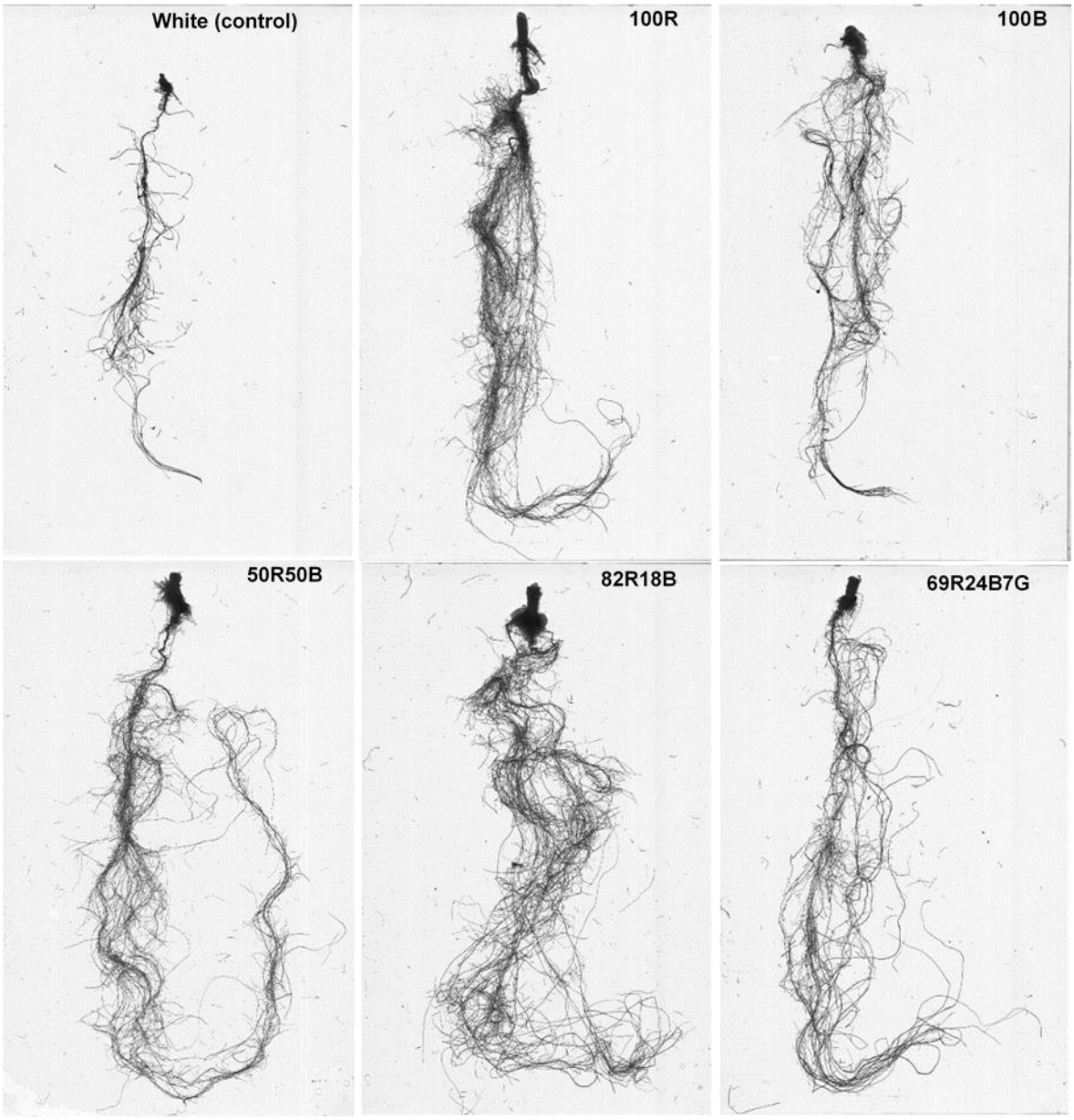


Figure 59 Scan images of the root systems of green pakchoi at 30 days after sowing (DAS) treated under different LED-light treatments. Light treatment abbreviations as in Table 3.

Figure 59 depicts the scanned images of one green pakchoi root system example replicate for all led-light treatments at 30 DAS. The root system was placed in the following order: W (control), 100R, 100B, 82R18B, 50R50B, and 69R24G7R. Among the LED-light treatments, the root system subjected to the white light (control) treatment observed to contain a small number of branches that are very sparse. The root system of plants treated to treatment 100R appear to be quite vigorous, with several branches and a considerable length. In contrast with the root of plants exposed

to 100B, the root system appears multi-branches and dense yet has a short length. Visual observation on the plants exposed to treatments 50R50B root system, the root condition much branched and lush. However, the root length was not as short as the 100B treatment and not as long as the treatment with a higher R light ratio. The observations also found that roots of plants exposed towards 82R18B light treatment had the largest root dispersion, which has many branches and long root length. For the roots of plants under treatment 62R24B7G was found to have a relatively moderate root area and branches. However, the root length is relatively long.

Through the observations from the naked eye, it can be said that the LED-light treatment of 82R18B produces the lushest root system in terms of branches and length. Whereas the white light (control) treatment produced fewer branches and sparse roots compared to other LED-light treatments.

4.13.2 Visual observation on red pakchoi root system

The scan images of one red pakchoi root system sample replicate for all led-light treatments at 30 DAS are shown in Figure 60. The root system was arranged as follows: W (control), 100R, 100B, 82R18B, 50R50B, and 69R24G7R. Among the LED-light treatments, the root system treated to the white light (control) treatment was found to have a limited number of sparse branches. Which similar pattern found in green pakchoi roots. The root system of plants treated with 100R appears to be quite robust, with numerous branches and a significant length. While the root of plants that exposed to 100B, the root system appears sparse and not dense. The length is moderate. This is quite different from the observations made on the green pakchoi. The roots under 100B treatment appear dense and short.

Visual inspection of the plants under treatments 50R50B root's revealed has moderate branching and coverage however it has the longest root length compared to other LED-light treatments. The findings also revealed that roots of the plants that subjected to the 82R18B LED-light treatment exhibited the greatest root dispersion, with many branches and a lengthy root length. While, the roots of plants treated to treatment 62R24B7G were observed to have a very moderate root coverage and branching. Additionally, the root length is not particularly long.

Similarly, with the green pakchoi root system, the naked eye inspection found the LED-light treatment of 82R18B results in the most vigorous root system in terms of branches and length. In comparison to other LED-light treatments, white light (control) produced fewer branches and sparse roots.

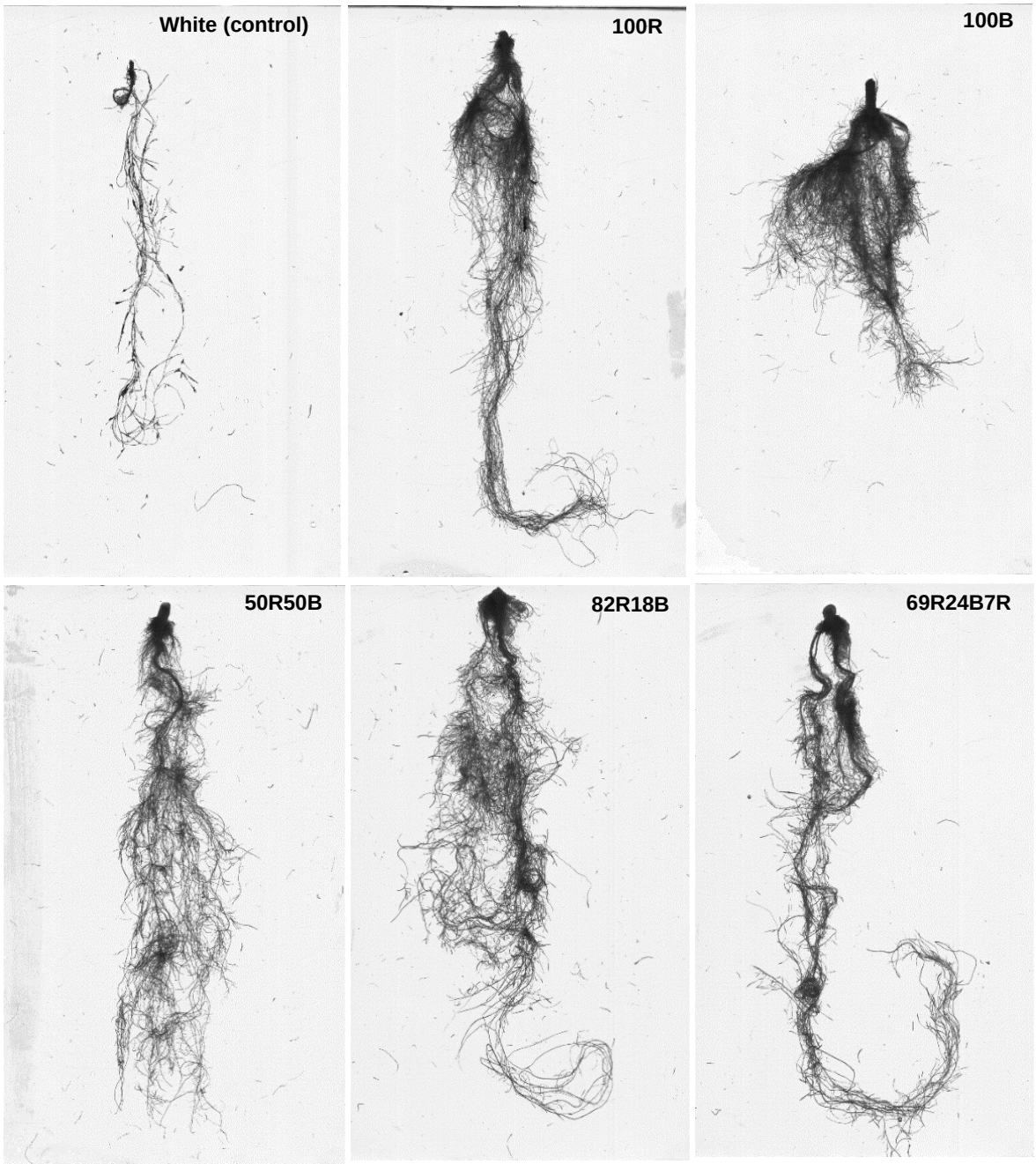


Figure 60 Scan images of the root systems of red pakchoi at 30 days after sowing (DAS) treated under different LED-light reatments. Light treatment abbreviations as in Table 3.

Main effects of LED lights, cultivars and their interaction on the root length, root diameter, root tips, root volume and root surface at 30 DAS are presented in Table 29.

Table 29 Root morphology of green and red pakchoi plants at 20, 30 and 40DAS (Days after sowing) grown under different LED-light quality treatments.

Treatment	Root length	Root diameter	Root tips	Root volume	Root surface area
			30 DAS		
Cultivar (C)					
Green Pakchoi	354.77 [a]	0.53 [a]	1933.94 [a]	2.25 [a]	155.83 [a]
Red Pakchoi	335.82 [a]	0.36 [b]	1379.39 [b]	0.84 [b]	92.12 [b]
SEM	10.92	0.01	118.13	0.11	7.16
P value	0.230	0.000	0.000	0.000	0.000
LED-Lights mixture (L)					
White	242.46 [d]	0.34 [c]	653.67 [c]	0.66 [c]	41.15 [c]
100R	345.11 [bc]	0.54 [a]	1938.83 [ab]	1.92 [ab]	129.64 [b]
100B	286.86 [cd]	0.47 [ab]	1466.00 [bc]	1.49 [b]	112.66 [b]
50R50B	365.01 [bc]	0.43 [bc]	1919.33 [ab]	1.53 [b]	137.77 [b]
82R18B	449.32 [a]	0.46 [ab]	2435.17 [a]	2.35 [a]	204.67 [a]
69R24B7G	383.02 [ab]	0.44 [abc]	1527.00 [bc]	1.36 [bc]	117.96 [b]
SEM	18.92	0.03	204.6	0.18	12.4
P value	0.000	0.000	0.000	0.000	0.000
Interaction P values	26.75	0.04	289.35	0.26	17.53
C x L	0.200	0.000	0.460	0.190	0.330

Means with the same letters across column are not significantly different using Tukeys at 5% level.

Cultivar

Cultivar had significant (P<0.05) effect on the root diameter, root tips, root volume and root surface. While on the root length, there was no significant (P>0.05) effect between the cultivars (Table 29). Green pakchoi recorded higher root length, eventhough there was no significant difference (354.77 for green and 335.82 for red pakchoi). Green pakchoi recorded significantly higher root diameter (0.53 for green and 0.36 for red pakchoi), root tips (1933.94 for green and 1379.39 for red pakchoi), root volume (2.25 for green and 0.84 for red pakchoi) and root surface (155.83 for green and 92.12 for red pakchoi) than red pakchoi. The increment in green pakchoi compared to the red pakchoi was 5.6% higher for root length, 47.2% higher for root diameter, 40.2% higher for root tips, 167.9% higher for root volume and 397.4% higher for root surface.

LED-Lights

The root length, root diameter, root tips, root volume and root surface at 30 DAS sampling stage were significantly (P<0.05) influenced by LED lights (Table 29). Referring to the root length, the treatment 82R18B (449.32) obtained higher root length

compared other LED-light treatments. However, it was similar (P>0.05) to the treatment 69R24B7G (383.02). The white (control) (242.46) treatment recorded the lowest root length compared to other LED-light treatments.

In the other hand, the root diameter was significantly (P<0.05) the highest under the treatment monochromatic 100R (0.54) compared to other LED-light treatments. However, it was similar (P>0.05) with the treatments monochromatic 100B, 82R18B and 69R24B7G (0.47, 0.46 and 0.44). The white (control) treatment indicated the lowest root diameter compared to other LED-light treatments. For the root tips, the treatment 82R18B (2435.17) obtained significantly (P<0.05) higher root tips compared other LED-light treatments but it was similar (P>0.05) with the treatments monochromatic 100R and 50R50B (1938.83 and 1919.33). The white (control) treatment recorded the lowest root tips compared to other LED-light treatments.

Results for the root volume, the treatment 82R18B (2.35) gained significantly (P<0.05) higher root volume compared other LED-light treatments but it was similar (P>0.05) with the treatments monochromatic 100R (1.92). The white (control) (0.66) treatment recorded the lowest root volume compared to other LED-light treatments. Moreover, for the root surface the treatment 82R18B (204.67) indicated significantly (P<0.05) higher root surface compared other LED-light treatments. The white (control) (41.15) treatment obtained the lowest root surface compared to other LED-light treatments.

The highest measurement on each sampling date compared to white light (control); 100R was 58.8% higher for root diameter. While the treatment 82R18B was 85.3% higher for the root length, 272.5% higher for root tips, 256.1% higher for root volume and 397.4% for root surface.

Cultivar x LED-Lights Interaction

The root diameter of green and red pakchoi was significantly (P<0.05) affected with LED-light treatments. While the other root morphology parameters; root length, root tips, root volume and root surface were not significantly (P>0.05) affected by the LED-light treatments (Table 29). The root diameter (Figure 61) response to LED-light treatment was higher (P<0.05) in green pakchoi than red pakchoi in all LED-light

treatments except for white (control) treatment. The highest root diameter was recorded on green pakchoi under the treatment monochromatic 100R. The lowest root diameter measurement was found on the green pakchoi under the treatment white light (control).

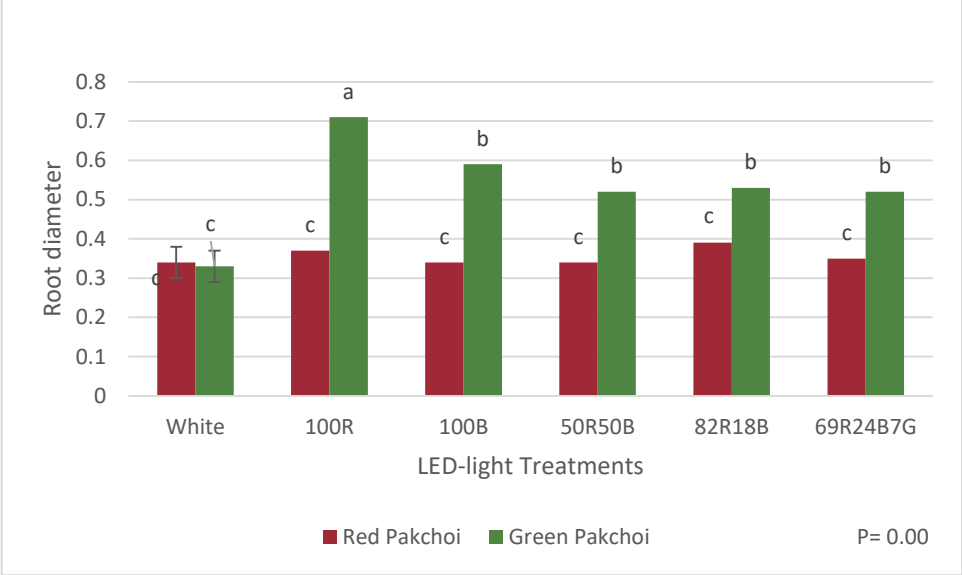


Figure 61 The interaction of root diameter at 30 DAS of green pakchoi and red pakchoi towards LED-light treatments. Means with different letters are significantly different at P= 0.05 by Duncan multiple comparisons test. Light treatment abbreviations as in Table 3.

4.14 Effects of LED-light treatments on phytochemical accumulation

4.14.1 Anthocyanin index

Main effects of LED lights, cultivars and their interaction on the anthocyanin index at 20, 30 and 40 DAS in Trial 1 and 2 are presented in Table 30. While the main effects of LED lights, cultivars and their interaction on the anthocyanin index at 20, 30 and 40 DAS in Trial 1 and 2 combined are presented in Table 31.

Table 30 Anthocyanin index of green and red pakchoi plants at 20, 30 and 40DAS (Days after sowing) grown under different LED-light quality treatments in Trial 1 and Trial 2.

Treatment	Anthocyanin index					
	Trial 1			Trial 2		
	20 DAS	30 DAS	40 DAS	20 DAS	30 DAS	40 DAS
Cultivar (C)						
Green Pakchoi	7.59 ^{b}	6.57 ^{b}	7.76 ^{b}	6.20 ^{b}	6.23 ^{b}	6.03 ^{b}
Red Pakchoi	12.98 ^{a}	97.28 ^{a}	116.54 ^{a}	17.82 ^{a}	83.62 ^{a}	145.42 ^{a}
SEM	0.46	4.59	4.37	0.66	3.13	25.04
P value	0.000	0.000	0.000	0.000	0.000	0.000

LED-Lights mixture (L)						
White	5.4 c	17.06 b	21.46 c	5.03 d	13.12 c	20.23 b
100R	12.24 ab	56.32 a	68.14 ab	22.07 a	46.69 b	67.84 ab
100B	11.11 ab	60.13 a	59.05 b	12.74 bc	46.74 b	47.89 ab
50R50B	12.92 a	60.73 a	96.96 a	13.27 b	79.73 a	207.84 a
82R18B	10.49 ab	74.30 a	76.51 ab	10.60 bc	45.69 b	66.19 ab
69R24B7G	9.55 b	43.00 ab	50.76 bc	8.36 cd	37.56 b	44.34 ab
SEM	0.79	7.96	7.57	1.15	5.41	43.37
P value	0.000	0.000	0.000	0.000	0.000	0.050
Interaction P values						
C x L	0.000	0.000	0.000	0.000	0.000	0.050

Means with the same letters across column are not significantly different using Tukeys at 5% level.

Table 31 Anthocyanin index of green and red pakchoi plants at 20, 30 and 40DAS (Days after sowing) grown under different LED-light quality treatments in Trial 1 and Trial 2 combined.

Treatment	Anthocyanin index		
	20 DAS	30DAS	40DAS
Cultivar (C)			
Green Pakchoi	6.89 b	6.4 b	6.9 b
Red Pakchoi	15.4 a	90.45 a	130.99 a
SEM	0.52	2.95	12.75
P value	0.000	0.000	0.000
LED-Lights mixture (L)			
White	5.22 d	15.09 c	20.85 b
100R	17.15 a	51.5 ab	68.00 ab
100B	11.93 bc	53.4 4 ab	53.47 b
50R50B	13.10 b	70.23 a	152.4 a
82R18B	10.55 bc	60.00 ab	71.35 ab
69R24B7G	8.95 c	40.28 b	47.55 b
SEM	0.89	5.10	22.08
P value	0.000	0.000	0.000
Interaction P values			
C x L	0.000	0.000	0.002

Means with the same letters across column are not significantly different using Tukeys at 5% level.

Cultivar

Trial one

Cultivar had significant (P<0.05) effect on the anthocyanin index at all sampling stages (20, 30 and 40 DAS) (Table 30). Red pakchoi recorded significantly higher anthocyanin index than green pakchoi at 20 (12.98 for red and 7.59 for green pakchoi), 30 (97.28 for red and 6.57 for green pakchoi), and 40 DAS (116.54 for red and 7.76 for green pakchoi), This increase in anthocyanin index in red pakchoi compared to the green pakchoi was 71% at 20 DAS, 1380.7% at 30 DAS and 1401.8% at 40 DAS.

Trial two

Cultivar had significant (P<0.05) effect on the anthocyanin index at all sampling stages (20, 30 and 40 DAS) (Table 30). Red pakchoi recorded significantly higher anthocyanin index than green at 20 (17.82 for red and 6.20 for green pakchoi), 30 (83.62 for red and 6.23 for green pakchoi) and 40 DAS (145.42 for red and 6.03 for green pakchoi). This increase in anthocyanin index in red pakchoi compared to the green pakchoi was 187.4% at 20 DAS, 1242.2% at 30 DAS and 2311.6% at 40 DAS.

Trial one and two combined

Cultivar had significant (P<0.05) effect on the anthocyanin index at all sampling stages (20, 30 and 40 DAS) (Table 31). Red pakchoi recorded significantly higher anthocyanin than green at 20 (15.40 for red and 6.89 for green pakchoi), 30 (90.45 for red and 6.40 for green pakchoi) and 40 DAS (130.99 for red and 6.90 for green pakchoi). This increase in anthocyanin index in red pakchoi compared to the green pakchoi was 123.5% at 20 DAS, 1313.3% at 30 DAS and 1798.4% at 40 DAS.

LED-Lights

Trial one

Anthocyanin index at 20, 30 and 40 DAS were significantly (P<0.05) influenced by LED lights (Table 30). At 20 DAS sampling date, 50R50B (12.92) recorded the highest anthocyanin index among other LED-light treatments but it was similar (P>0.05) towards monochromatic 100R, monochromatic 100B and 82R18B (12.24,11.11 and 10.49). White light (control) (5.40) recorded the lowest anthocyanin index compared to other LED lights. While on 30 DAS sampling date, 82R18B (74.30) indicated the highest anthocyanin index compared to other LED-light treatments. However, there was no significant difference (P>0.05) towards other LED-light treatments except for white (control). The white light (control) (17.06) recorded the lowest anthocyanin index compared to other LED lights. During 40 DAS sampling date, 50R50B (96.96) obtained the highest anthocyanin index among other LED-light treatments but it was similar (P>0.05) towards 82R18B and monochromatic 100R (76.51 and 68.14). White light (control) (21.46), as during 20 and 30 DAS sampling date results, still recorded the lowest anthocyanin index compared to other LED lights.

The highest measurement on each sampling date compared to white light (control); 50R50B was 139.3% higher at 20 DAS, 256% at 30DAS and 351.8% higher at 40 DAS.

Trial two

Anthocyanin index at 20 and 30 DAS were significantly ($P<0.05$) influenced by LED-light treatments, but 40 DAS was not significantly ($P>0.05$) influenced by the LED-light treatments (Table 30). At 20 DAS sampling date, monochromatic 100R (22.07) obtained significantly ($P<0.05$) higher anthocyanin index compared other LED-light treatments. The treatment 50R50B (13.27) was the second highest but was similar to ($P>0.05$) 100B and 82R18B (12.74 and 10.60). At 30 DAS, 50R50B (79.73) indicated the significantly ($P<0.05$) highest anthocyanin index among other LED-light treatments. The monochromatic 100B (46.74) was the second highest measurement but was similar ($P>0.05$) to 100R,82R18B and 69R24B7G (46.69, 45.69 and 37.56). White light (control) recorded the lowest anthocyanin index compared to other LED-light treatments.

The highest measurement on each sampling date compared to white light (control); 100R was 338.8% higher at 20 DAS. While 50R50B was 507.7% higher at 30DAS and 927.4% higher at 40 DAS.

Trial one and two combined

Anthocyanin index at 20. 30 and 40 DAS were significantly ($P<0.05$) influenced by LED lights (Table 31). At 20 DAS sampling date, monochromatic 100R (17.15) obtained significantly ($P<0.05$) higher anthocyanin index compared other LED-light treatments. Treatment 50R50B (13.10) was the second highest but was similar to ($P>0.05$) 100B and 82R18B (11.93 and 10.55). White light (control) recorded the lowest anthocyanin index compared to other LED-light treatments.

The highest measurement on each sampling date compared to white light (control); 100R was 228.5% higher at 20 DAS. While 50R50B was 355.4% higher at 30DAS and 630.9% higher at 40 DAS.

Cultivar x LED-Lights Interaction

Trial one and two combined

The anthocyanin index of green and red pakchoi was significantly (P<0.05) affected with LED-light treatments at all sampling dates (Table 31). At 20 DAS sampling date (Table 32), response to LED-light treatment was higher (P<0.05) in red pakchoi than green pakchoi in all LED-light treatments. The highest anthocyanin content was recorded on red pakchoi under the treatment monochromatic 100R. The lowest anthocyanin content measurement was found on the green pakchoi under the treatment white light (control). At 30 DAS the similar pattern was found (Table 34), red pakchoi were significantly (P<0.05) had higher anthocyanin index than green pakchoi with all the LED-light treatments. The highest anthocyanin index was recorded in red pakchoi with the treatment 50R50B and the lowest anthocyanin index measurement was obtained on green pakchoi exposed to white light (control) treatment. While at 40 DAS sampling date (Table 34), red pakchoi were significantly (P<0.05) had higher anthocyanin index than green pakchoi under all the LED-light treatments. The highest anthocyanin content was recorded in red pakchoi with the treatment 50R50B and the lowest anthocyanin content measurement was obtained on green pakchoi exposed to monochromatic 100R treatment.

Table 32 The interaction of anthocyanin index at 20, 30 and 40 DAS of green pakchoi and red pakchoi towards LED-light treatments in Trial 1 and 2 combined.

Cultivar x LED-light	Anthocyanin index					
	20 DAS		30 DAS		40 DAS	
	Red pakchoi	Green pakchoi	Red pakchoi	Green pakchoi	Red pakchoi	Green pakchoi
White (control)	6.03 ^{de}	4.40 ^{e}	24.91 ^{d}	5.27 ^{d}	35.72 ^{cd}	5.98 ^{d}
100R	27.05 ^{a}	7.26 ^{de}	97.67 ^{b}	5.34 ^{d}	130.31 ^{bc}	5.67 ^{d}
100B	15.06 ^{b}	8.79 ^{cd}	100.49 ^{b}	6.38 ^{d}	101.16 ^{bcd}	5.79 ^{d}
50R50B	17.63 ^{b}	8.56 ^{cd}	132.37 ^{a}	8.09 ^{d}	296.15 ^{a}	8.66 ^{d}
82R18B	15.28 ^{b}	5.82 ^{de}	113.71 ^{ab}	6.28 ^{d}	135.04 ^{b}	7.66 ^{d}
69R24B7G	11.36 ^{c}	6.54 ^{de}	73.52 ^{c}	7.04 ^{d}	87.49 ^{bcd}	7.62 ^{d}
SEM	1.26		7.22		31.23	
P value	0.00		0.00		0.002	

For each duration (DAS), means with different letters across rows and columns are significantly different at P<0.05 by Duncan multiple comparisons test. Light treatment abbreviations as in Table 3.

4.14.2 Phytochemicals content

Main effects of LED lights, cultivars and their interaction on the phytochemicals content; phenolic, carotenoid, vitamin C, protein, carbohydrate and crude fibre content at 30 DAS are presented in Table 33.

Table 33 Phenolic, carotenoid, vitamin C, protein, carbohydrate and crude fibre content of green and red pakchoi plants at 30 DAS (Days after sowing) grown under different LED-light quality treatments.

Treatment	Phenolic	Carotenoid	Vitamin C	Protein	Carbohydrate	Crude Fibre
	g/100g					
	30DAS					
Cultivar (C)						
Green Pakchoi	2.89 ^{a}	11.39 ^{b}	13.68 ^{a}	15.96 ^{a}	46.98 ^{b}	20.69 ^{a}
Red Pakchoi	1.62 ^{b}	22.39 ^{a}	13.37 ^{a}	13.54 ^{b}	47.9 ^{a}	13.81 ^{b}
SEM	0.05	0.23	0.18	0.07	0.12	0.13
P value	0.000	0.000	0.240	0.000	0.000	0.000
LED-Lights mixture (L)						
White	2.82 ^{a}	25.35 ^{a}	15.81 ^{a}	15.68 ^{a}	48.67 ^{b}	17.97 ^{b}
100R	1.92 ^{b}	14.66 ^{c}	13.32 ^{b}	12.85 ^{d}	50.15 ^{a}	19.07 ^{a}
100B	2.10 ^{b}	13.68 ^{c}	11.80 ^{c}	15.54 ^{a}	45.14 ^{c}	14.51 ^{c}
50R50B	2.10 ^{b}	14.4 ^{c}	12.48 ^{bc}	15.63 ^{a}	45.09 ^{c}	14.61 ^{c}
82R18B	1.99 ^{b}	14.98 ^{c}	12.9 ^{bc}	13.9 ^{c}	50.35 ^{a}	18.68 ^{ab}
69R24B7G	2.61 ^{a}	18.27 ^{b}	14.83 ^{a}	14.9 ^{b}	45.23 ^{c}	18.67 ^{ab}
SEM	0.08	0.40	0.31	0.12	0.20	0.22
P value	0.000	0.000	0.000	0.000	0.000	0.000
Interaction P values						
C x L	0.000	0.000	0.010	0.000	0.000	0.020

Means with the same letters across column are not significantly different using Tukeys at 5% level.

Cultivar

Cultivar had significant (P<0.05) effect on the phenolic, carotenoid, protein, carbohydrate and fibre content at 30 DAS sampling stages. While for the vitamin C, the cultivar had no significant effect (P>0.05) (Table 33). Green pakchoi recorded significantly phenolic content than red pakchoi (2.89 for green and 1.62 for red pakchoi). Whereas, red pakchoi recorded significantly higher carotenoid content than green pakchoi (22.39 for red and 11.39 for green pakchoi). This increase in green pakchoi compared to the red was 78.4% for phenolic content and 2.3% for Vitamin C. While the increase in red pakchoi compared to the green pakchoi was 96.6% for carotenoid.

Green pakchoi recorded significantly higher protein content (15.96 for green and 13.54 for red pakchoi) and fibre content (20.69 for green and 13.81 for red pakchoi) than red pakchoi. Whereas, red pakchoi recorded significantly higher

carbohydrate content than green pakchoi (47.90 for red and 46.98 for green pakchoi). The increase in green pakchoi compared to the red pakchoi was 17.9% for protein and 49.8% for fibre. While the increase of red pakchoi compared to the green pakchoi was 2% for the carbohydrate.

LED-Lights

The phenolic, carotenoid, vitamin C, protein, carbohydrate and crude fibre content at 30 DAS sampling stages were significantly ($P<0.05$) influenced by LED lights (Table 33). Referring to the phenolic content, the treatment white (control) (2.82) obtained higher phenolic content compared other LED-light treatments. However, it was similar ($P>0.05$) to the treatment 69R24B7G (2.61). The lowest phenolic content was recorded on the treatment monochromatic 100R (1.92). Similarly, on the carotenoid content, the white (control) (25.35) treatment obtained the significantly highest ($P<0.05$) measurement. The second highest was the treatment 69R24B7G (18.27) and significantly different with other LED-light treatments. The treatment 50R50B (14.40) produced the lowest carotenoid content among other LED-light treatments. The same pattern of results was also found on the vitamin C content. The treatment white (control) (15.81) indicated the highest vitamin C content among the LED-light treatments, but it was similar ($P>0.05$) towards the treatment 69R24B7G (14.83). The lowest vitamin C content was found on the monochromatic 100B (11.80) treatment.

Referring to the protein content, the treatment white (control) (15.68) obtained higher protein content compared other LED-light treatments. However, it was similar ($P>0.05$) to the treatments 50R50B and monochromatic 100B (15.63 and 15.54). The lowest protein content was recorded on the treatment monochromatic 100R (12.85). On the other hand, the carbohydrate content, the 82R18B (50.35) treatment obtained the highest measurement but it was the same ($P>0.05$) with the treatment monochromatic 100R (50.15). The treatment 50R50B (45.09) produced the lowest carbohydrate content among other LED-light treatments. While the results on the fibre content, the treatment white (control) (19.07) indicated the highest fibre content among the LED-light treatments, but it was similar ($P>0.05$) towards the treatment 82R18B and 69R24B7G (18.68 and 18.67). The lowest fibre content was found on the monochromatic 100B (14.51) treatment.

The highest measurement on each sampling date compared to white light (control); the treatment white light (control) was the highest measurement for phenolic, carotenoid, Vitamin C and protein content. While 82R18B was 3.5% higher for carbohydrate and 100R was 6.1% higher for fibre.

Cultivar x LED-Lights Interaction

The phenolic content was significantly (P<0.05) affected with LED-lights (Table 33). The phenolic content (Table 34) response to LED-light treatment was higher (P<0.05) in green pakchoi than red pakchoi in all LED-light treatments. The highest phenolic content was recorded on the green pakchoi under the treatment 69R24B7G. The lowest phenolic content measurement was found on the red pakchoi under the treatment monochromatic 100R.

While the carotenoid content of green and red pakchoi was also significantly (P<0.05) affected with LED-lights (Table 34). The carotenoid content (Table 34) response to LED-light treatment was higher (P<0.05) in red pakchoi than green pakchoi in all LED-light treatments. The highest carotenoid content was recorded on red pakchoi under the treatment white (control) and the lowest carotenoid content measurement was found on the green pakchoi under the treatment monochromatic 100B.

Table 34 The interaction of phenolic, vitamin A and vitamin C content at 30 DAS of green pakchoi and red pakchoi towards LED-light treatments.

Cultivar x LED-light	30 DAS					
	Phenolic content (g/100g)		Carotenoid (g/100g)		Vitamin C (g/100g)	
	Red pakchoi	Green pakchoi	Red pakchoi	Green pakchoi	Red pakchoi	Green pakchoi
White (control)	2.63 ^{b}	3.00 ^{ab}	30.90 ^{a}	19.79 ^{cd}	14.49 ^{bc}	17.13 ^{a}
100R	1.14 ^{d}	2.71 ^{b}	20.01 ^{cd}	9.31 ^{f}	13.14 ^{cd}	13.49 ^{bcd}
100B	1.30 ^{d}	2.90 ^{ab}	18.34 ^{d}	9.02 ^{f}	12.14 ^{de}	11.46 ^{e}
50R50B	1.30 ^{d}	2.89 ^{ab}	19.43 ^{cd}	9.37 ^{f}	12.84 ^{de}	12.11 ^{de}
82R18B	1.20 ^{d}	2.78 ^{ab}	20.24 ^{c}	9.73 ^{ef}	12.76 ^{de}	13.03 ^{d}
69R24B7G	2.14 ^{c}	3.08 ^{a}	25.41 ^{b}	11.13 ^{e}	14.83 ^{b}	14.83 ^{b}
SEM	0.11		0.57		0.44	
P value	0.00		0.004		0.009	

Means with different letters across rows and columns are significantly different at P<0.05 by Duncan multiple comparisons test. Light treatment abbreviations as in Table 3.

Whereas for the vitamin C content of green and red pakchoi was also significantly (P<0.05) affected with LED-lights (Table 34). The vitamin C content (Table 34) response to LED-light treatment was higher (P<0.05) in green pakchoi than red pakchoi in white (control), monochromatic 100R and 82R18B LED-light treatments. The response towards the LED-light treatments was higher (P<0.05) in red pakchoi for the treatments, 50R50B and monochromatic 100B. While the treatment 69R24B7G the vitamin C content response towards the LED-light treatment was similar (P>0.05) between both cultivars. The highest vitamin C content was recorded on green pakchoi under the treatment white (control). While the lowest vitamin C content measurement was found on the green pakchoi under the treatment monochromatic 100B.

Table 35 The interaction of protein, carbohydrate and fibre content at 30 DAS of green pakchoi and red pakchoi towards LED-light treatments.

Cultivar x LED-light	30 DAS					
	Protein (g/100g)		Carbohydrate (g/100g)		Crude Fibre (g/100g)	
	Red pakchoi	Green pakchoi	Red pakchoi	Green pakchoi	Red pakchoi	Green pakchoi
White (control)	13.74 ^{d}	17.62 ^{a}	50.81 ^{a}	46.54 ^{c}	15.12 ^{d}	20.81 ^{b}
100R	12.34 ^{e}	13.37 ^{d}	49.45 ^{b}	50.84 ^{a}	15.67 ^{d}	22.46 ^{a}
100B	14.53 ^{c}	16.55 ^{b}	45.51 ^{de}	44.76 ^{e}	10.57 ^{e}	18.44 ^{c}
50R50B	14.79 ^{c}	16.48 ^{b}	45.36 ^{de}	44.82 ^{de}	10.73 ^{e}	18.48 ^{c}
82R18B	13.52 ^{d}	14.28 ^{c}	50.53 ^{a}	50.18 ^{ab}	15.46 ^{d}	21.9 ^{a}
69R24B7G	12.32 ^{e}	17.48 ^{a}	45.71 ^{cd}	44.74 ^{e}	15.32 ^{d}	22.02 ^{a}
SEM	0.18		0.29		0.32	
P value	0.00		0.00		0.02	

Means with different letters across rows and columns are significantly different at P<0.05 by Duncan multiple comparisons test. Light treatment abbreviations as in Table 3.

The protein content was significantly (P<0.05) affected with LED-lights (Table 33). The protein content (Figure 35) response to LED-light treatment was higher (P<0.05) in green pakchoi than red pakchoi in all LED-light treatments. The highest protein content was recorded on the green pakchoi under the treatment white (control). The lowest protein content measurement was found on the red pakchoi under the treatment 69R24B7G.

While the carbohydrate content of green and red pakchoi was also significantly (P<0.05) affected with LED-lights (Table 33). The carbohydrate content (Table 35)

response to LED-light treatment was higher ($P<0.05$) in red pakchoi than green pakchoi in all LED-light treatments except for the treatment monochromatic 100R. The highest carbohydrate content was recorded on green pakchoi under the treatment monochromatic 100R and the lowest carbohydrate content measurement was found on the green pakchoi under the treatment 69R24B7G.

Whereas for the fibre content of green and red pakchoi was also significantly ($P<0.05$) affected with LED-lights (Table 33). The fibre content (Table 35) response to LED-light treatment was higher ($P<0.05$) in green pakchoi than red pakchoi in all LED-light treatments. The highest fibre content was recorded on green pakchoi under the treatment monochromatic 100R. While the lowest fibre content measurement was found on the red pakchoi under the treatment monochromatic 100B.

4.15 Correlation coefficient evaluation between morphological, physiological and secondary metabolites parameters at 30 days after Sowing (DAS)

Trial one and two combined

The relationship between the morphological, physiological and secondary metabolites parameters in Table 36 were determined using Pearson's correlation. There was a significant positive correlation ($P<0.01$) between plant height towards other morphological parameters; plant width ($R^2= 0.89$) (Figure 62), leaf number ($R^2= 0.72$), leaf area ($R^2= 0.90$), fresh yield ($R^2= 0.78$), dry yield ($R^2= 0.72$), NAR ($R^2= 0.72$) and AGR ($R^2= 0.59$), Furthermore, there was also a significant positive correlation ($P<0.01$) between plant height towards root morphology parameters; root length ($R^2= 0.40$), root surface ($R^2= 0.65$), root diameter ($R^2= 0.73$), root volume ($R^2= 0.75$) (Figure 63) and root tips ($R^2= 0.83$). While for the correlation between the morphological and physiological, the plant height was significantly positive correlated ($P<0.05$) with chlorophyll florescence ($R^2= 0.54$) and photosynthesis rate ($R^2= 0.41$). Plant height was positive correlated ($P<0.01$) towards transpiration rate ($R^2= 0.74$). The correlation between the morphological and secondary metabolites, the plant height was positive correlated ($P<0.01$) towards phenolic content ($R^2= 0.49$) and fibre content ($R^2= 0.74$). On the other hand, the plant height was negative correlated ($P<0.01$) towards anthocyanin content ($R^2= -0.53$) and carotenoid content ($R^2= -0.82$).

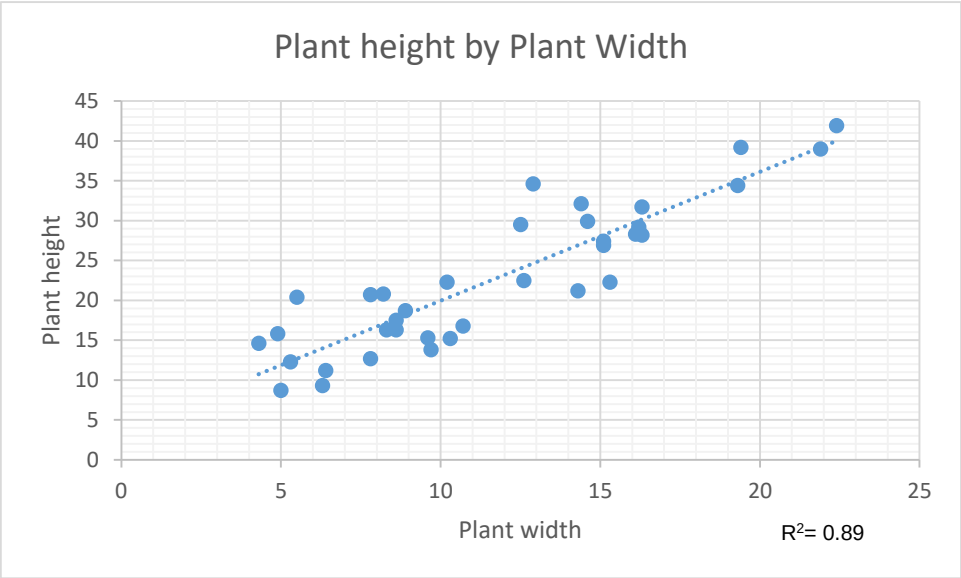


Figure 62 Relationship between plant height and plant width of pakchoi at 30 days after sowing (DAS).

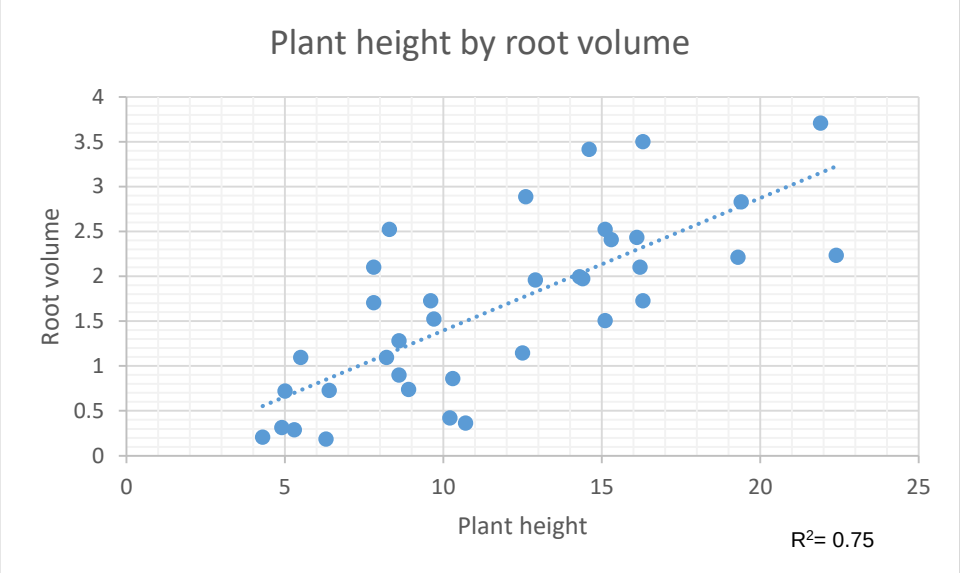


Figure 63 Relationship between plant height and root volume of pakchoi at 30 days after sowing (DAS).

There was a significantly positive correlation ($P<0.01$) between plant width towards leaf number ($R^2= 0.61$), leaf area ($R^2= 0.86$), fresh yield ($R^2= 0.79$), dry yield ($R^2= 0.70$), NAR ($R^2= 0.54$) and AGR ($R^2= 0.51$), Furthermore, there was also a significant positive correlation ($P<0.01$) between plant width towards root morphology parameters; root length ($R^2= 0.45$), root surface ($R^2= 0.58$), root diameter ($R^2= 0.65$), root volume ($R^2= 0.68$) and root tips ($R^2= 0.53$). While for the correlation between the morphological and physiological, the plant width was significantly positive correlated ($P<0.01$) with chlorophyll florescence ($R^2= 0.57$), photosynthesis rate ($R^2= 0.46$) and

transpiration rate (R^2= 0.61). The correlation between the morphological and secondary metabolites, the plant width was positive correlated (P<0.01) towards phenolic content (R^2= 0.56) and fibre content (R^2= 0.81). On the other hand, the plant width was negative correlated (P<0.01) towards anthocyanin content (R^2= -0.61) and carotenoid content (R^2= -0.65).

The result showed significantly positive correlation (P<0.01) between leaf number towards leaf area (R^2= 0.76), SLA (R^2= 0.61) and AGR (R^2= 0.56). While significantly positive correlation at (P<0.05) towards fresh yield (R^2= 0.41). There was also a significant positive correlation (P<0.01) between leaf number towards root morphology parameters; root diameter (R^2= 0.73) and root volume (R^2= 0.59). While significantly positive correlation at (P<0.05) towards root surface (R^2= 0.42) and root tips (R^2= 0.41). While for the correlation between the morphological and physiological, the leaf number was significantly positive correlated (P<0.01) with chlorophyll florescence (R^2= 0.43) and transpiration rate (R^2= 0.81). The correlation between the morphological and secondary metabolites, the leaf number was positive correlated (P<0.01) towards phenolic content (R^2= 0.55) and fibre content (R^2= 0.51). While significantly positive correlation at (P<0.05) towards protein (R^2= 0.34). On the other hand, the leaf number was negative correlated (P<0.01) towards anthocyanin content (R^2= -0.48) and carotenoid content (R^2= -0.71). Significantly negative correlation at (P<0.05) towards vitamin c (R^2= -0.34).

A significantly positive correlation (P<0.01) between leaf area towards fresh yield (R^2= 0.84) (Figure 64), dry yield (R^2= 0.72) and NAR (R^2= 0.53). While significantly positive correlation at (P<0.05) towards AGR (R^2= 0.60). There was also a significant positive correlation (P<0.01) between leaf area towards root morphology parameters; root surface (R^2= 0.53), root diameter (R^2= 0.76) (Figure 65), root volume (R^2= 0.68) and root tips (R^2= 0.49). While for the correlation between the morphological and physiological, the leaf area was significantly positive correlated (P<0.01) with chlorophyll florescence (R^2= 0.59) and transpiration rate (R^2= 0.72). Significantly positive correlation at (P<0.05) towards photosynthesis rate (R^2= 0.40). The correlation between the morphological and secondary metabolites, the leaf area was positive correlated (P<0.01) towards phenolic content (R^2= 0.58) and fibre content

(R^2= 0.77). On the other hand, the leaf area was negative correlated (P<0.01) towards anthocyanin content (R^2= -0.56) and carotenoid content (R^2= -0.80).

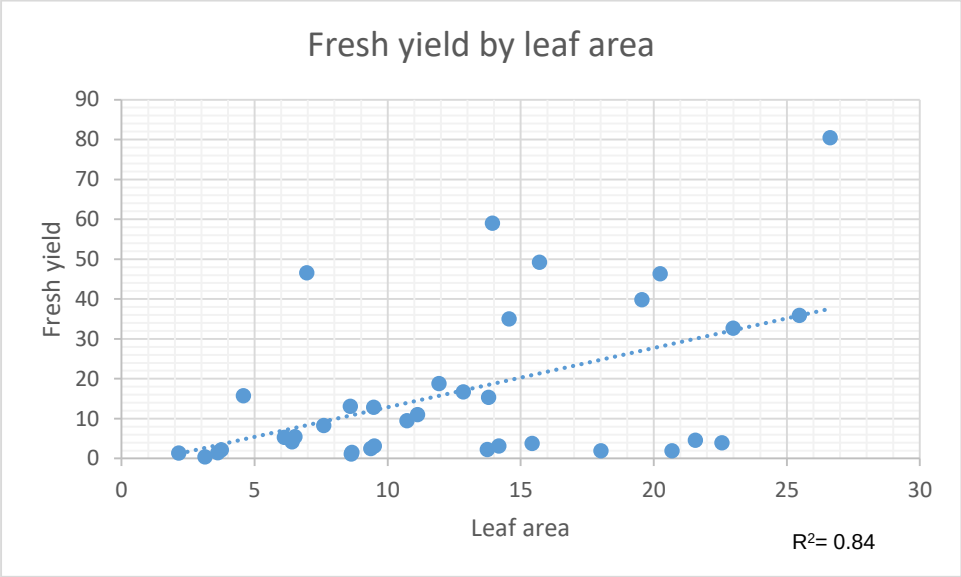


Figure 64 Relationship between fresh yield and leaf area of pakchoi at 30 days after sowing (DAS).

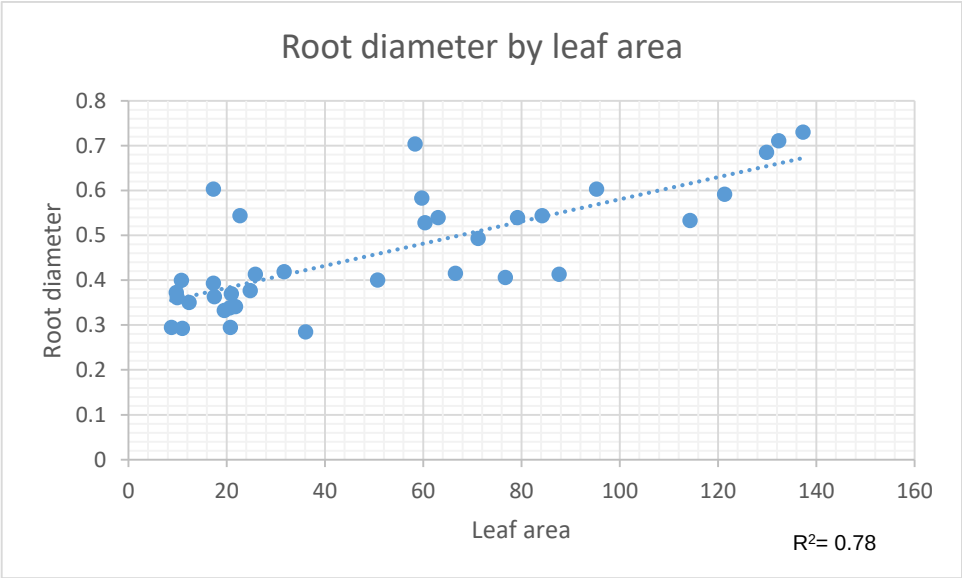


Figure 65 Relationship between root diameter and leaf area of pakchoi at 30 days after sowing (DAS).

A significantly positive correlation (P<0.01) between fresh yield towards other morphological parameters; dry yield (R^2= 0.89), NAR (R^2= 0.67) and AGR (R^2= 0.53). There was also a significant positive correlation (P<0.01) between fresh yield towards root morphology parameters; root surface (R^2= 0.54), root diameter (R^2= 0.61), root volume (R^2= 0.58) and root tips (R^2= 0.44). A significant positive correlation (P<0.05) between fresh yield towards root length (R^2= 0.40). While for the correlation between

the morphological and physiological, the leaf area was significantly positive correlated ($P<0.01$) with chlorophyll florescence ($R^2= 0.57$), photosynthesis rate ($R^2= 0.46$) and transpiration rate ($R^2= 0.55$). The correlation between the morphological and secondary metabolites, the fresh yield was positive correlated ($P<0.01$) towards phenolic content ($R^2= 0.51$) and fibre content ($R^2= 0.74$). On the other hand, the fresh yield was negative correlated ($P<0.01$) towards anthocyanin content ($R^2= -0.51$) and carotenoid content ($R^2= -0.65$).

A significantly positive correlation ($P<0.01$) between dry yield towards other morphological parameters; NAR ($R^2= 0.68$) and AGR ($R^2= 0.50$). A positive correlation ($P<0.05$) between dry yield towards LAI ($R^2= 0.38$). There was also a significant positive correlation ($P<0.01$) between dry yield towards root morphology parameters; root length ($R^2= 0.45$), root surface ($R^2= 0.66$), root diameter ($R^2= 0.53$) and root volume ($R^2= 0.54$). A significantly positive correlation ($P<0.05$) between dry yield towards root tips ($R^2= 0.42$). While for the correlation between the morphological and physiological, the leaf area was significantly positive correlated ($P<0.01$) with chlorophyll florescence ($R^2= 0.52$) and transpiration rate ($R^2= 0.51$). A significantly positive correlation ($P<0.05$) between dry yield towards photosynthesis rate ($R^2= 0.40$). The correlation between the morphological and secondary metabolites, the dry yield was positive correlated ($P<0.01$) towards fibre content ($R^2= 0.57$). On the other hand, the fresh yield was negative correlated ($P<0.01$) towards anthocyanin content ($R^2= -0.34$), carotenoid content ($R^2= -0.57$) and vitamin c ($R^2= -0.64$).

A significantly positive correlation ($P<0.01$) between NAR towards root morphology parameters; root surface ($R^2= 0.49$) and root volume ($R^2= 0.55$). A significantly positive correlation ($P<0.05$) between NAR towards root tips ($R^2= 0.36$). While for the correlation between the morphological and physiological, the NAR was significantly positive correlated ($P<0.01$) with chlorophyll florescence ($R^2= 0.62$), photosynthesis rate ($R^2= 0.76$), and transpiration rate ($R^2= 0.48$). The correlation between the morphological and secondary metabolites, the NAR was positive correlated ($P<0.01$) towards protein ($R^2= 0.58$), phenolic ($R^2= 0.68$) and fibre content ($R^2= 0.75$). On the other hand, the fresh yield was negative correlated ($P<0.01$) towards anthocyanin content ($R^2= -0.62$) and carotenoid content ($R^2= -0.64$).

A significantly positive correlation (P<0.01) between LAI towards other morphological parameters; AGR (R^2= 0.81) and RGR (R^2= 0.47). A significantly positive correlation (P<0.01) between LAI towards root morphology parameters; root length (R^2= 0.52), root surface (R^2= 0.59), root volume (R^2= 0.47) and root tips (R^2= 0.47). The correlation between the morphological and secondary metabolites, the LAI was positive correlated (P<0.01) towards anthocyanin content (R^2= 0.36).

A significantly positive correlation (P<0.01) between AGR towards root morphology parameters; root length (R^2= 0.52), root surface (R^2= 0.69), root diameter (R^2= 0.61), root volume (R^2= 0.70) and root tips (R^2= 0.57). While for the correlation between the morphological and physiological, the AGR was significantly positive correlated (P<0.01) with transpiration rate (R^2= 0.60). The correlation between the morphological and secondary metabolites, the AGR was positive correlated (P<0.01) towards carotenoid content (R^2= 0.62).

The correlation between the morphological and secondary metabolites, the RGR was positive correlated (P<0.05) towards anthocyanin content (R^2= 0.34). On the other hand, the RGR was negative correlated (P<0.05) towards carbohydrate (R^2= -0.37) and fibre (R^2= -0.36).

A significantly positive correlation (P<0.01) between root length towards other root morphology parameters; root surface (R^2= 0.78), root volume (R^2= 0.64) and root tips (R^2= 0.66). A significantly positive correlation (P<0.05) between root length towards root diameter (R^2= 0.38). While for the correlation between the root length and physiological parameters, the root length was significantly positive correlated (P<0.01) with transpiration rate (R^2= 0.43).

A significantly positive correlation (P<0.01) between root surface towards other root morphology parameters; root diameter (R^2= 0.63), root volume (R^2= 0.90) and root tips (R^2= 0.90). While for the correlation between the root surface and physiological parameters, the root length was significantly positive correlated (P<0.01) with chlorophyll florescence (R^2= 0.44) photosynthesis rate (R^2= 0.36) and transpiration rate (R^2= 0.67) (Figure 66). The correlation between root surface and secondary metabolites, the root surface was positive correlated (P<0.05) towards fibre

content (R^2= 0.38). On the other hand, the root surface was negative correlated (P<0.05) towards carotenoid (R^2= -0.69) and vitamin c (R^2= -0.41).

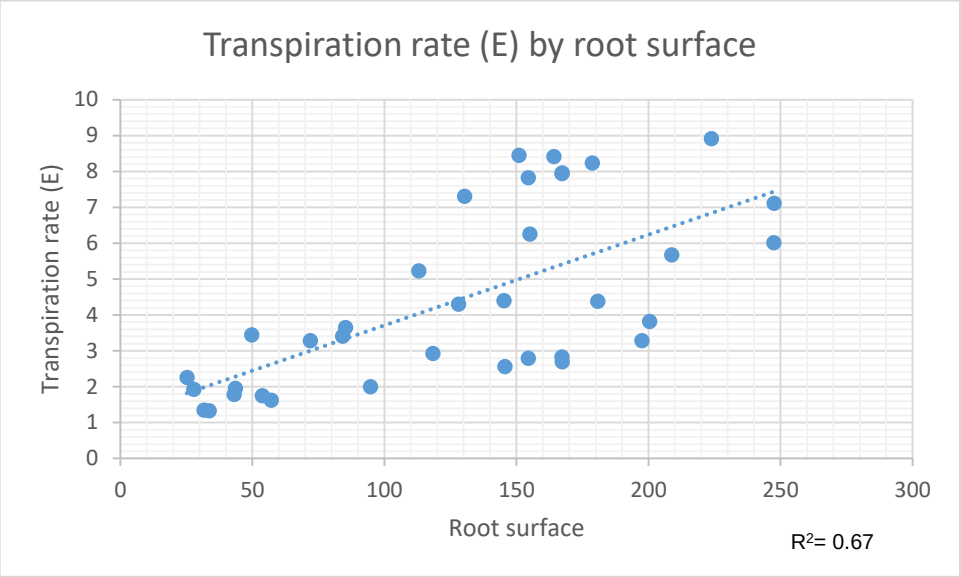


Figure 66 Relationship between transpiration rate (E) and root surface of pakchoi at 30 days after sowing (DAS).

A significantly positive correlation (P<0.01) between root diameter towards other root morphology parameters; root volume (R^2= 0.80) and root tips (R^2= 0.53). While for the correlation between the root diameter and physiological parameters, the root diameter was significantly positive correlated (P<0.01) with chlorophyll florescence (R^2= 0.43) and significantly positive correlated (P<0.05) towards transpiration rate (R^2= 0.68). The correlation between root diameter and secondary metabolites, the root diameter was positive correlated (P<0.01) towards fibre content (R^2= 0.46) and significantly positive correlated (P<0.05) towards phenolic content (R^2= 0.33). On the other hand, the root diameter was negative correlated (P<0.05) towards carotenoid (R^2= -0.70) and vitamin c (R^2= -0.36).

A significantly positive correlation (P<0.01) between root volume towards root root tips (R^2= 0.80). While for the correlation between the root volume and physiological parameters, the root volume was significantly positive correlated (P<0.01) with chlorophyll florescence (R^2= 0.50), photosynthesis rate (R^2= 0.48) (Figure 67) and transpiration rate (R^2= 0.68). The correlation between root volume and secondary metabolites, the root volume was positive correlated (P<0.01) towards fibre

content (R^2= 0.53). On the other hand, the root volume was negative correlated (P<0.01) towards carotenoid (R^2= -0.77).

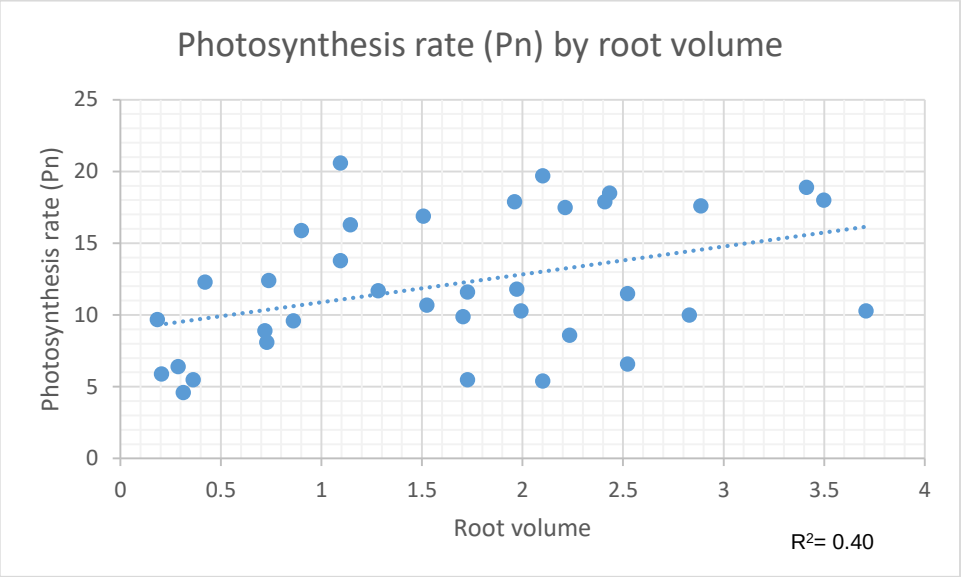


Figure 67 Relationship between photosynthesis rate (Pn) and root volume of pakchoi at 30 days after sowing (DAS).

The correlation between the root volume and physiological parameters, the root tips was significantly positive correlated (P<0.01) with transpiration rate (R^2= 0.56). The correlation between root volume and secondary metabolites, the root tips was positive correlated (P<0.05) towards fibre content (R^2= 0.36). On the other hand, the root volume was negative correlated (P<0.01) towards carotenoid (R^2= -0.63) and vitamin c (R^2= -0.38).

A significantly positive correlation (P<0.01) between chlorophyll florescence towards photosynthesis rate (R^2= 0.58) and transpiration rate (R^2= 0.56). The correlation between chlorophyll florescence and secondary metabolites, the chlorophyll florescence was positive correlated (P<0.01) towards protein (R^2= 0.48), phenolic content (R^2= 0.61) and fibre content (R^2= 0.64). On the other hand, the root volume was negative correlated (P<0.01) towards carotenoid (R^2= -0.58).

A significantly positive correlation (P<0.01) between chlorophyll content towards anthocyanin index (R^2= 0.54). However, the chlorophyll content was negative correlated (P<0.01) towards phenolic content (R^2= -0.63) and fibre content (R^2= -0.43).

There are positive correlation (P<0.01) between photosynthesis rate towards transpiration rate (R^2= 0.56) (Figure 68). The correlation between photosynthesis rate and secondary metabolites, the photosynthesis rate was positive correlated (P<0.01) towards protein (R^2= 0.58), phenolic content (R^2= 0.59) and fibre content (R^2= 0.67). However, the photosynthesis rate was negative correlated (P<0.01) towards anthocyanin index (R^2= -0.56) and carotenoid (R^2= -0.52).

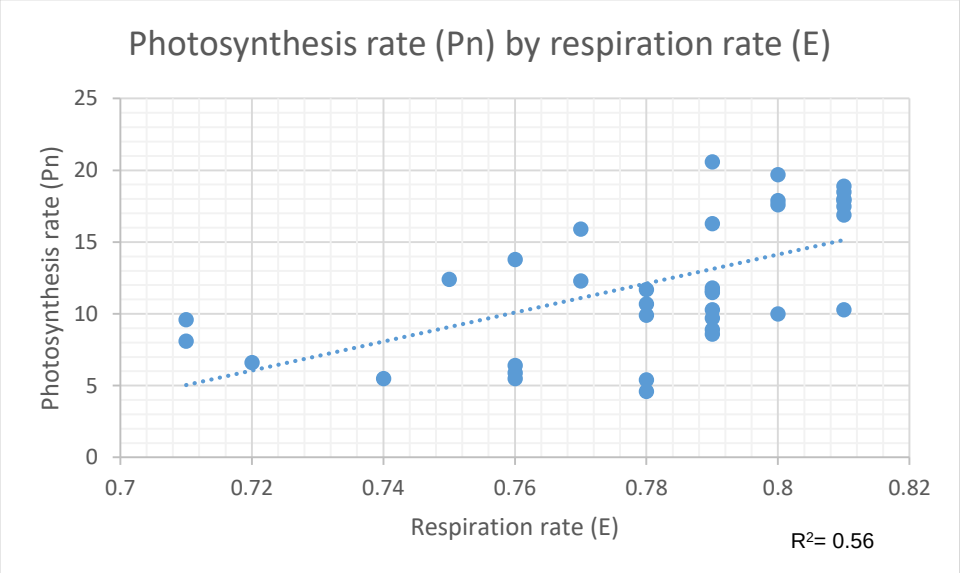


Figure 68 Relationship between photosynthesis rate (Pn) and respiration rate (E) of pakchoi at 30 days after sowing (DAS).

A significantly positive correlation (P<0.05) between transpiration rate towards phenolic content (R^2= 0.40) and fibre content (R^2= 0.42). However, the transpiration rate was negative correlated (P<0.01) towards anthocyanin index (R^2= -0.44).

A significantly positive correlation (P<0.05) between stomatal conductance towards protein content (R^2= 0.35). A significantly positive correlation (P<0.05) between anthocyanin index towards vitamin c (R^2= 0.41). The anthocyanin index was negative correlated (P<0.01) towards phenolic content (R^2= -0.78), fibre content (R^2= -0.84) and carotenoid content (R^2= -0.84). A significantly negative correlation (P<0.05) between anthocyanin index and protein (R^2= -0.40).

A significantly positive correlation (P<0.01) between protein towards phenolic content (R^2= 0.58) and fibre content (R^2= 0.38). Protein was negatively correlated

(P<0.01) towards carbohydrate (R^2= -0.60) (Figure 69) and carotenoid (R^2= -0.45). The anthocyanin index was negative correlated (P<0.01) towards phenolic (R^2= -0.78), fibre (R^2= -0.84) and carotenoid content (R^2= -0.84). A significantly positive correlation (P<0.05) between phenolic content towards fibre content (R^2= 0.78) (Figure 70). The phenolic content was negative correlated (P<0.05) towards carotenoid content (R^2= -0.42). The fibre content was negative correlated (P<0.01) towards carotenoid content (R^2= -0.58). The carotenoid content was negative correlated (P<0.05) towards vitamin c (R^2= -0.39).

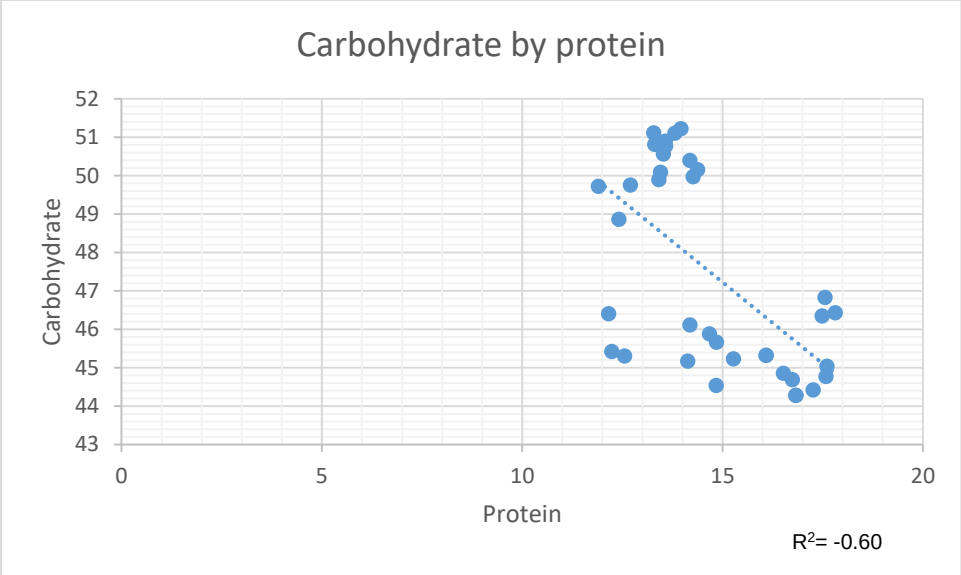


Figure 69 Relationship between carbohydrate) and protein of pakchoi at 30 days after sowing (DAS).

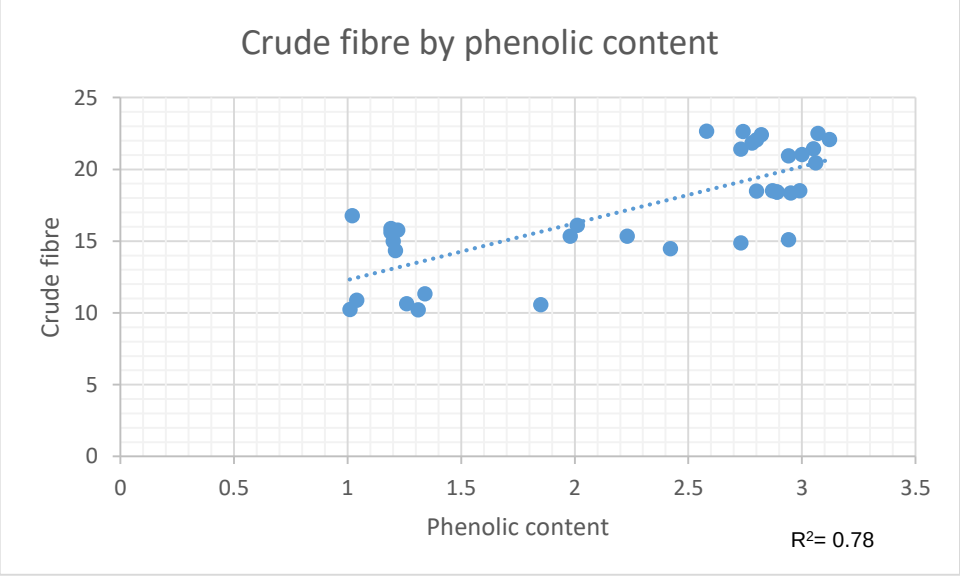


Figure 70 Relationship between crude fibre and phenolic content of pakchoi at 30 days after sowing (DAS)

Table 36 Correlation coefficient evaluation between morphological, physiological and secondary metabolites parameters at 30 days after Sowing (DAS).

Traits	GROWTH MORPHOLOGY															PHYSIOLOGY					PHYTOCHEMICAL						
	Plant height	**Plant width**	**Leaf number**	**Leaf area**	**Specific leaf area**	**Fresh yield**	**Dry yield**	**NAR**	**LAI**	**AGR**	**RGR**	**Root length**	**Root surface**	**Root diameter**	**Root volume**	**Root tips**	**Chlorophyll florescence**	**Chlorophyll content**	**Photosynthesis rate (Pn)**	**Transpiration rate (E)**	**Stomatal conductance (Gs)**	**Anthocyanin index**	**Protein**	**Carbohydrate**	**Phenolic**	**Fibre**	**Caroteoid**	**Vitamin C**
Plant height	1	0.89**	0.72**	0.90**	0.33	0.78**	0.72**	0.53**	0.21	0.59**	-0.27	0.40*	0.65**	0.73**	0.75**	0.63**	0.54*	-0.21	0.41*	0.74**	0.07	-0.53**	0.18	0.11	0.49**	0.74**	-0.82**	-0.18
Plant width		1	0.61**	0.86**	0.30	0.79**	0.70**	0.54*	0.18	0.51**	-0.24	0.45**	0.58**	0.65**	0.68**	0.53**	0.57**	-0.36	0.46**	0.61**	0.13	-0.61**	0.17	0.21	0.56**	0.81**	-0.65**	0.54
Leaf number			1	0.76**	0.61**	0.41*	0.29	0.30	0.01	0.56**	-0.08	0.17	0.42*	0.73**	0.59**	0.41*	0.43**	-0.33	0.24	0.81**	0.14	-0.48**	0.34*	-0.19	0.55**	0.51**	-0.71**	-0.34*
Leaf area				1	0.11	0.84**	0.72**	0.53**	0.18	0.60*	-0.18	0.32	0.53**	0.76**	0.68**	0.49**	0.59**-	0.26	0.40*	0.72**	0.05	-0.56**	0.29	0.07	0.58**	0.77**	-0.80**	-0.13
SLA					1	0.10	-0.16	0.13	-0.19	0.17	-0.08	-0.05	0.09	0.33*	0.28	0.20	0.29	-0.36*	0.26	0.38*	0.26	0.36*	0.25	0.09	0.40*	0.42*	0.28	-0.03
Fresh yield						1	0.89**	0.67**	0.32	0.53**	-0.18	0.40*	0.54**	0.61**	0.58**	0.44**	0.57**	-0.22	0.46**	0.55**	-0.01	-0.51**	0.21	0.16	0.51**	0.74**	-0.65**	-0.02
Dry yield							1	0.68**	0.38*	0.50**	-0.16	0.45**	0.66**	0.53**	0.54**	0.42*	0.52**	-0.03	0.40*	0.51**	0.04	-0.34*	0.20	0.06	0.32	0.57**	-0.57**	-0.64**
NAR								1	0.16	0.30	-0.25	0.32	0.49**	0.32	0.55**	0.36*	0.62**	-0.22	0.76**	0.48**	0.19	-0.62**	0.58**	-0.11	0.68**	0.75**	-0.64**	0.16
LAI									1	0.81**	0.47**	0.52**	0.59**	0.25	0.47**	0.47**	0.10	0.23	0.08	0.23	0.22	0.36*	-0.10	-0.14	-0.12	-0.09	-0.29	-0.24
AGR										1	0.31	0.52**	0.69**	0.61**	0.70**	0.57**	0.32	-0.23	0.17	0.60**	0.22	-0.02	0.15	-0.15	0.22	0.27-	0.62**	-0.33
RGR											1	0.00	-0.06	-0.08	-0.08	-0.16	-0.13	-0.05	-0.06	-0.10	0.11	0.34*	0.03	-0.37*	-0.03	-0.36*	-0.18	-0-0.03
Root length												1	0.78**	0.38*	0.64**	0.66**	0.18	0.08	0.22	0.43**	0.24	0.02	-0.27	0.19	-0.04	0.25	-0.33	-0.22
Root surface													1	0.63**	0.90**	0.90**	0.44**	0.09	0.36**	0.67**	0.29	-0.13	0.09	0.05	0.11	0.38*	-0.69**	-0.41*
Root diameter														1	0.80**	0.53**	0.43**	-0.23	0.18	0.68*	0.04	-0.24	0.18	-0.02	0.33*	0.46**	-0.70**	-0.36*
Root volume															1	0.80**	0.50**	-0.10	0.40**	0.68**	0.23	-0.26	0.22	0.03	0.31	0.53**	-0.77**	-0.26

Traits	Plant height	Plant width	Leaf number	Leaf area	Specific leaf area	Fresh yield	Dry yield	NAR	LAI	AGR	RGR	Root length	Root surface	Root diameter	Root volume	Root tips	Chlorophyll florescence	Chlorophyll content	Photosynthesis rate (Pn)	Transpiration rate (E)	Stomatal conductance (Gs)	Anthocyanin index	Protein	Carbohydrate	Phenolic	Fibre	Caroteoid	Vitamin C
Root tips																1	0.32	0.12	0.26	0.56**	0.23	-0.14	0.00	0.11	0.05	0.36*	-0.63*	-0.38*
Chlorophyll florescence (Fv/Fm)																	1	-0.31	0.58**	0.56**	0.30	-0.56	0.48**	-0.07	0.61**	0.64**	-0.58**	-0.00
Chlorophyll content																		1	-0.31	-0.12	0.30	0.54**	-0.14	-0.31	-0.63**	-0.43**	-0.04	-0.27
Photosynthesis rate (Pn)																			1	0.56**	0.30	-0.56**	0.58**	0.296	0.59**	0.67**	-0.52**	0.20
Transpiration rate (E)																				1	0.28	-0.44**	0.25	0.09	0.40*	0.42*	-0.28	-0.02
Stomatal conductance (Gs)																					1	0.00	0.35*	-0.32	-0.03	0.10	-0.28	-0.10
Anthocyanin index																						1	-0.40*	-0.15	-0.78**	-0.84**	-0.84**	0.41*
Protein																							1	-0.60**	0.58**	0.38**	-0.45**	0.17
Carbohydrate																								1	-0.15	0.17	0.23	0.06
Phenolic																									1	0.78**	-0.42*	0.29
Fibre																										1	-0.58**	0.31
Caroteoid																											1	0.39*
Vitamin C																												1

and indicate level of significance at P<0.05 and P<0.01, respectively. The values without * are not statistically significant.*

CHAPTER 5

DISCUSSION

Chapter overview

This chapter will discuss the findings obtained from the study. The discussion content is organised into two major topics; morphology & physiological measurements and phytochemical measurements. This is to aid the comprehension of the parameters explained and described.

5.1 Morphology and physiology measurements

5.1.1 Effects of light treatments on plant height and diameter

Light is one of the most critical environmental elements for plant growth, development, and the accumulation of plant metabolites. Light of certain wavelengths has specific impacts on plants. Plants absorb and utilise mostly visible light with wavelengths ranging from 400 to 700 nm (Landi et al., 2020). Referring to green pakchoi, the tallest plants were samples exposed to monochromatic 100R light, while the shortest plants were found in samples exposed to white light (control). The similar results were found for the red pakchoi. The diameter of green pakchoi exposed to monochromatic 100R light produced the widest plants, whereas green pakchoi exposed to white light (control) produced the smallest plant diameter. As in the plant height, the red pakchoi shown the same results as the green pakchoi for the plant diameter. The result was consistent with previous research done on cucumber and basil, which reported that plant size and leaf area decreased with increasing of B proportion from 10% to 75% (Hernández and Kubota, 2016). Also, an almost similar finding was recorded on lettuce, in which the leaf length and width decreased with the increment of B proportion from 0% to 30% (Kang et al., 2016). Red wavelength is intercepted through phytochromes, which the wavelength most absorbed in red/far-red area (665nm-730nm).

Phytochromes detect and transduce light information, such as light intensity and duration, in order to assist plants in every cycle of their development (Tripathi et al., 2019). Phythochromes are classified into two types; Type I phythochromes, which

absorb far-red light and have particular downstream molecular targets which govern discrete processes after illumination with far-red light (≈730 nm). It is important in later stage of plant life, such as controlling the flowering (Valverde *et al.*, 2004). Whereas the Type II phytochromes, absorbed and triggered by the photons of red light (≈660 nm). Resulting in a variety of downstream alterations in gene expression and cellular responses. It is crucial for long-term responses to light and play roles from shade avoidance responses to participation in flowering control (Folta and Carvalho, 2015a).

In this study the red light coverage was between 600nm to 700nm and the peak was at 660nm, which stimulates phytochrome type I absorption towards R wavelength. When phytochromes are activated by light, cytoplasmic and nucleus processes begin. Phytochrome regulation has an impact on a wide range of plant activities, from plant height control to the foundations of gene expression (Folta and Carvalho, 2015b). These pigments are sensitive to red and far red light, but they also absorb blue/near-ultraviolet light. Light-induced stimulation of phytochrome pigments begins a cascade of actions in the cytoplasm and nucleus. The active photosensors modify protein phosphorylation in the cytoplasm and also localise to the nucleus, these are connected to hormonal changes. These actions are associated with variations in the levels of gibberellins (Feng et al., 2008) and auxins (Tao et al., 2008), two plant growth hormones. As a result, the R wavelengths stimulated the growth of the plant's extension such as stem and shoot elongation and leaf expansion. The outcome of this interaction can explain the findings obtained in the study conducted, monochromatic 100R produced the highest plant height and diameter among other LED-light treatments.

In the other hand, the B wavelength is intercepted via cryptochrome photoreceptors, and the absorption coverage is between 340nm to 520 nm. In this particular study the B wavelength range was between 400 nm to 480 nm and the peak was at 440 nm. The cryptochrome receptors (cry1 and cry2) that sense B wavelength were discovered because they have a dramatic influence on seedling growth and flowering (Ahmad et al., 2002; Guo et al., 1998). When cryptochromes photoreceptors are exposed to the B wavelength, they transmit signals to cry1 to upregulate the gibberellic acid biosynthesis pathway. As a result, the B wavelength has a compacting effect on plants and reduces stem elongation (Chatterjee et al.,

2006). As the B wavelength increased, it is possible that cryptochrome will become overstimulated, resulting in a substantial reduction in plant growth.

The plant height and diameter of green and red pakchoi indicated almost the similar increasing pattern with the increment of R wavelength proportion in the LED-light treatment. In contrast, the plant size decreased with increasing of B wavelength proportion. This indicated that, the treatment containing higher R wavelength enhance the plant elongation, and by doing otherwise, increasing the B wavelength inhibited the plant extension. Which clearly observed in the treatment 82R18B, 69R24B7G, 50R50B and 100B, which the height and diameter of plant is shrinking in response to an increase in the B ratio. In addition, it was found that green pakchoi cultivar had a higher growth interaction than red pakchoi cultivar due to finding in this study the green pakchoi had higher chlorophyll content, photosynthetic capacity and photosynthetic energy quantum than red pakchoi, which as a result of this can contribute to promote photosynthesis efficiency and lead to promote growth (Goins et al., 1997). Such effect was significantly dependent on the cultivar of the pakchoi.

Furthermore, two LED-light treatments with G wavelength were used in this investigation. That is a 69R24B7G and white (control) treatment. The content of the G wavelength ratio differs between these two treatments. The control treatment had a greater G wavelength concentration than the 69R24B7G treatment. The inclusion of G wavelength at the combination of 69R24B7G in both green and red pakchoi resulted the plant height and diameter almost the same size with the plant under treatment 82R12B. However, when the G proportion increased from 7% to 35% in white (control) treatment, the plant size significantly decreased. The inclusion of G wavelength at a high proportion in the light treatment might reduce the photon flux of R and B wavelengths, which may resulted negative effects on plant growth (Folta and Maruhnich, 2007). This statement parallel with the current study, but contradict with lettuce crop, the leaf expansion is often enhanced when G wavelength added to R and B or full-spectrum lighting (Kim et al., 2004; Mickens et al., 2019).

The photoreceptors that are specialised for G wavelengths have not yet been discovered. There is evidence that green wavebands have impacts on discrete plant processes that are independent of recognised photosensors (Folta and Carvalho,

2015). The G wavelength effects have numerous characteristics in that they generally oppose the activity of R or B wavelength-regulated plant activities. The utilisation of G wavelength, on the other hand, may be crucial in controlling plant height and has a function in influencing pigmentation (Zhang et al., 2011). Meanwhile, previous observation on the effect of plant response on G wavelength was recorded mixed results. Some reported inhibition of growth when receiving G wavelength and the other reported increased of growth. The inhibiting effects of G wavelength was reported on the tomato seedlings cultivated under varied fluence rates of red and blue light will achieve a particular dry weight. Plants growing under visible light with a green component had reduced dry mass, regardless of how much the overall fluence rate was raised. When a lavender filter was applied, no inhibition was detected, indicating that the G wavelength component was opposing the B and R wavelengths (Went, 1958). Furthermore, the G wavelength's effect in plant development has also been investigated by NASA researchers. G wavelength was found to reduce stomatal conductance, leaf size, and thickness (Kim et al., 2004). On the contrary, G wavelength was found to induce shade avoidance symptoms and influenced the leaf growth (Zhang et al., 2011). Early stem development has also been found to be accelerated by G wavebands (Folta, 2004).

According to the current study, G wavelength has a favourable influence on the plant height and diameter of green and red pakchoi at a low ratio. This is due to the fact that when the G wavelength ratio is raised, the inhibitory impact on the green and red pakchoi is quite substantial, as demonstrated in the white (control) treatment. This finding may also help to explain why plants exposed to the white (control) treatment are smaller in height and diameter than plants exposed to other LED-light treatments. Most likely, the rate of G wavelength ratio in LED-lighting combinations has a substantial influence in plant's growth, and explained the mixed results of previous reported findings. In addition, according to the findings the 82R18B and 69R24B7G treatments may produce height and diameter of green and red pakchoi that are more balanced and presentable for market demand. On the 30 DAS, the crop under such treatment likewise achieves the ideal average commercial height for harvest, which is between 12-17 cm (Wellgrow Malaysia, 2021).

This study also discovered that combining multiple wavelengths results can produce more balanced and marketable plant shape compared to monochromatic wavelength. In the same way, it has long been recognised that wavelength combinations act additively and synergistically on plants. The reaction of plants requires the engagement of many sensory photoreceptors systems (Mohr, 1994). Cryptochromes interact physically and functionally with phytochromes to govern a significant number of photoreceptors activities, therefore mechanistically defining the phenomenon of "coaction." The term "coaction" refers to the functional interaction of light-sensory circuits that have been engaged (Folta and Carvalho, 2015). Multiple photosensory systems can be activated to provide enhanced degrees of trait control. Numerous research has described the possibility of coaction phenomenon through the use of lighting systems with numerous independently controlled emitters (Yano and Fujiwara, 2012). Furthermore, there was a strong positive association between plant height and plant diameter, indicating that growth in height on the pakchoi is directly tied to growth in diameter.

5.1.2 Effects of light treatments on leaf number

It was found that the cultivar of the pakchoi is highly dependent on the light treatments, where it was observed that the response of green pakchoi to LED-light treatment had a consistent trend compared to red pakchoi whose response appeared to be mixed. Observed at the beginning of growth both cultivars had the highest number of leaves under 50R50B treatment. While at the end of the growth cycle (40DAS) there was little difference between the two cultivars, green pakchoi had more leaves under the treatment of 69R24B7G while red pakchoi produced more leaves under the treatment of 82R18B. This clearly shows that the influenced of light treatments towards number of leaves depends on the type of cultivar. This is parallel with the findings reported by Naznin and Lefsrud (2019) , where the effect of varying percentages of R and B LEDs on the number of leaves varied by plant species. This referred to their observation on spinach and basil, a significantly higher leaf number was observed under the treatment of 91% R with 9% B LEDs than the treatment of 100% R LEDs. While in pepper, a significantly higher leaf number was observed under the treatment of 95% R with 5% B LEDs in comparison with 100% R LEDs. In contrast,

they also reported there was no significant difference on the kale and lettuce (Naznin et al., 2019). Which was similar to the previous study that showed no differences in the leaf number in cucumber under different ratios of R and B wavelength (Hernández and Kubota, 2014).

In this study, it was found that high B wavelength ratio played role in increasing the number of leaves on pakchoi, especially at the beginning of growth as in the treatment 50R50B. While at the subsequent growth, the increment of R wavelength seems to beneficial towards the leaf numbers of green and red pakchoi. The role of B wavelength in increasing the leaf number might because it was mediated via both cryptochromes and phototropins, since phototropins are involved in leaf expansion (Christie, 2007). This synchronised with the previous findings, the larger fraction of B wavelength had increased the leaf numbers of plants (Macedo et al., 2011). Despite the positive effect of the B wavelength, several studies reported that B wavelength may suppress the number of leaves of lettuce compared to other monochromatic and multi-chromatic treatments (Tracy et al., 2004; Li and Kubota, 2009). To summarise, light is a critical regulator of leaf growth, however the effect of light quality varies by species (Hunter and Burritt, 2004). Besides that, there was a strong positive correlation between plant height and diameter towards the number of leaves. This suggests that the pakchoi plant's height and diameter strongly related with the leaf number.

5.1.3 Effects of light treatments on leaf area

Green pakchoi had a greater leaf area than red pakchoi nearly for all harvests in each trial. In terms of LED-light treatments, monochromatic 100R generated the largest leaf area size, but there was no difference on a specific harvest day between the 82R18B and 50R50B treatments. This study clearly showed that the LED-light treatments had significant interaction towards leaf area. However, such effect is highly dependent on the cultivar of the pakchoi, where it was found that the results obtained during the first, second and overall trials were different according to the type of cultivar. The reaction of leaf area towards LED-light treatments was found to be highly variable depending on the cultivar. For green pakchoi, it was discovered that monochromatic 100R produced a highest leaf area size at the beginning of the growth cycle compared to the other LED-light treatments. Then, it was identified that 82R18B and 50R50B

generated higher leaf area sizes at the end of the growth cycle. While the pattern is slightly different on the red pakchoi, it can be claimed that the treatment 82R18B consistently produce the largest leaf area size for each harvest. Additionally, it was found that the green pakchoi treated with 100R LED-light treatment produced the highest leaf area size in most of the harvest sessions conducted apart from the 50R50B and 82R18B led-light treatment. The red pakchoi treated with white (control) remained the smallest leaf area size throughout the harvest and in both trials, including a combination of the first and second trials' findings.

Growth parameter such as leaf area are affected by R wavelength through the phytochrome photoreceptors, which resulted in promoting the leaf area. For example, the R wavelength was found to increase the leaf area of cucumber (Trouwborst et al., 2010). However, the previous research, demonstrated that R wavelength alone was insufficient for seedling development by evaluating the subsequent growth (Johkan et al., 2010; Miao et al., 2016). Light quality signals acquired by plants at the seedling stage had a significant impact on subsequent growth and quality (Eskins, 1992; Lee et al., 2011). This might explain the finding in this study, which in the early growth stage the monochromatic 100R had a high leaf area but then at the mature stage the treatment of 82R18B and 50R50B produced larger leaf area. In addition, it was also found that after transplanting, monochromatic R wavelength reduced leaf growth and delayed blooming time in cucumber seedlings (Johkan et al., 2010). Johkan et al. (2010) also discovered similar findings in lettuce, indicating that mature lettuce had smaller leaf area and lower fresh weight when lettuce seedlings were grown under monochromatic R wavelength compared to those cultivated under mixed R and B wavelength. Seedlings exposed to blue-containing LED light would be beneficial for further growth since blue-containing LEDs resulted in more compact features (Johkan et al., 2010; Miao et al., 2016). The result from this study implied that the additional fraction of B wavelength in R wavelength were considered to be main factor in increasing the green and red pakchoi leaf’s area.

As in the plant height and plant diameter, the leaf area of green and red pakchoi indicated almost the same increasing pattern with the increment of R proportion in the

light treatment. In contrast, the leaf area decreased with increasing of B proportion. The effects of red and blue light on green and red pakchoi were similar with previous research, with a larger proportion of blue light resulting in smaller lettuce seedling leaves (Hernández and Kubota, 2014). This was most likely due to blue photonflux stimulating cryptochrome photoreceptors (Hernández and Kubota, 2016), and blue light causing a shade avoidance response (Snowden, 2015). While the inclusion of G at a high proportion in the light treatment might reduce the photon flux of R and B wavelengths, which may resulted negative effects on plant growth (Folta and Maruhnich, 2007). This statement parallel with the current study, the inclusion of G wavelength at the combination of 69R24B7G in both green and red brassicas resulted the plant height and width almost the same size with the plant under treatment 82R12B. However, when the G proportion increased from 7% to 35% in W treatment, the plant size significantly decreased. This finding contradicts with lettuce crop, the leaf expansion is often enhanced when G wavelength added to R and B or full-spectrum lighting (Kim et al., 2004; Mickens et al., 2019). The same pattern can be found in leaf area result for green brassica. However, the impact of G wavelength on red brassica seems did not provide a solid outcome. On the other hand, a significant positive association was seen between plant height and diameter and leaf area. Which suggests that the pakchoi plant's height and width are inversely proportional to its leaf area.

5.1.4 Effects of light treatments on specific leaf area (SLA)

The specific leaf area (SLA) defined as the ratio of total leaf area to total leaf dry mass, is one of the leaf attributes that can reflects plant growth (Gunn et al., 1999). The SLA measurement reflects the leaf thickness. The environmental factor, such as light and temperature were modifying the SLA. The findings for SLA obtained from the first, second, and overall trials were found to be inconsistent. The red pakchoi was found to have a greater SLA than green pakchoi for all harvests in each trial. It can be said that red pakchoi had thicker leaves than green pakchoi. The increase of SLA could have a positive impact on the density of chloroplast within the leaves or the proportion of incident light captured by the photosynthetic apparatus (He et al., 2015).

While for the LED-light treatments, there was no difference between the treatments at early growth (20 DAS) in all trials and the overall trials result. However, at the subsequent stage (30 DAS) monochromatic 100B treatment had the highest SLA but it was similar towards other treatments except towards 69R24B7G. While at the final growth stage (40 DAS), the white light (control) had the highest SLA and have no difference between other LED-light treatments. The effect of LED-light treatments on green and red pakchoi does not appear to follow a clear pattern. As a result, the LED-light treatments had no direct effect on the SLA of red and green pakchoi.

The SLA response to LED-light treatments was found to have a relatively less relationship between cultivars. Although the SLA reading on red pakchoi was found to be higher than the SLA at each harvest, there was no uniform pattern throughout the trials performed including the overall results of the trials. At 30 DAS of first trial, red pakchoi treated with monochromatic 100B produced the highest SLA. While the green pakchoi treated with 50R50B produced the lowest SLA. Then at 40 DAS, it was found that red pakchoi with white light (control) treatment had the highest SLA and green pakchoi with monochromatic 100R treatment had the lowest SLA measurement. Meanwhile, the second trial result showed the almost similar measurement for SLA among the treatments and the cultivars at 20 and 30 DAS. Furthermore, the overall results showed there was no interaction of SLA between the LED-light treatments and cultivars throughout the observation dates.

This finding indicated that the role of B wavelength and the inclusion of G wavelength in the light treatment does have positive impact on the SLA measurement especially on red pakchoi, which resulted in increasing the leaf thickness. The higher projected SLA under treatments with G wavelength is a good indicator of higher photosynthetic surface area per unit in leaf tissue, which is often associated with shade-type physiology (Hanba et al., 2002).

5.1.5 Effects of light treatments on fresh yield and dry yield

Fresh yield findings from observations in the first, second, and overall trials were nearly identical. On the other hand, there was significant interaction between the

LED-light treatments and cultivars towards the fresh yield. It was identified that both cultivars were affected by the LED-light treatments in similar pattern. However, the fresh yield of the green pakchoi was more affected by the LED-light treatments compared to the red pakchoi. This outcome similar as in the plant height and width, green pakchoi obtained the higher measurement compared to red pakchoi. The overall growth of green pakchoi was greater compare to the red pakchoi might due to the green pakchoi had greater relative chlorophyll content, photosynthetic capacity, and photosynthetic energy quantum than red pakchoi, which these factors; influenced the photosynthesis efficiency and growth (Goins et al., 1997).

It was identified that the green pakchoi treated with the treatment monochromatic 100R gained the highest fresh yield at the early stage of growth. The increase of fresh yield on plants treated with monochromatic 100R at early growth was due to the R wavelength triggered phytochrome photoreceptors that play an important role in early growth (Strasser et al., 2010). The phytochrome photoreceptor triggered under R wavelength (660nm) is Phytochrome II. Phytochrome II acts to govern the photomorphogenesis process in the plant life cycle, starting from induce seed germination and emergence to growth and survival (Milberg et al., 2000). While, at the subsequent stage the green pakchoi under treatment 69R24B7G and 82R18B obtained the highest fresh yield results. On the other hand, it was also understood that the fresh yield on red pakchoi increased the most under the treatment 82R18B. While, the red pakchoi exposed under white light (control) remained to have the lowest fresh yield throughout the harvest session on every trials. B wavelength in combination with R wavelength had showed positive effects on growth, physiological and nutritional characteristics on several horticulture crops (Bantis et al., 2018). The efficiency of R at 650–665nm wavelength on plant development is consistent with the absorption peak of chlorophyll and phytochrome; whereas the addition B wavelength demonstrated that the combination of RB wavelengths can mimic natural light for plant growth. Additionally, the mix of R and B wavelengths demonstrated a greater level of photosynthetic activity than monochromatic light (Sabzalian et al., 2014). The similar pattern was obtained in this study photosynthetic capacity and other growth parameters.

It is observed that the addition of B wavelength to R wavelength has a positive effect on fresh yield. The increase in the R wavelength ratio in the combination of red-blue light was clearly demonstrated to escalate fresh yield. Whereas, the opposite occurs when the B wavelength ratio increases. This finding was in parallel with the findings in tomatoes where B supplemented to R wavelength had positive effect on plant biomass besides increased the nutrients concentration (Bantis et al., 2016). In the other hand, the findings in cucumber shown a different result, which the monochromatic R wavelength suppressed the fresh and dry mass compared to the multiwavelength RB and RBG combination. While the B wavelength promoted the biomass production (Hernández and Kubota, 2016). The results suggested that high fraction of R wavelength combine with B wavelength at seedling stage was beneficial for its subsequent growth. Which similar with the previous studies, showed the R wavelength alone was not suitable for raising seedlings when observing the subsequent growth (Miao et al., 2016). Johkan (2010) also reported a similar trend found in lettuce, demonstrating that mature lettuce had smaller leaf area and fresh weight when grown under monochromatic W wavelength compared to the lettuce grown under mixed blue-red wavelength. Seedlings treated with addition of B wavelength would be useful for its subsequent growth led to compact characteristic (Johkan et al., 2010).

Moreover, in this study it was also observed that the addition of G wavelength did not affect the fresh yield measure. This can be seen at certain harvests, the fresh yield of plants treated with the treatment 69R24B7G had no difference with the 100R and 82R18B treatments. The addition of G wavelength at a little ratio of 7% for this study does not affect fresh yield. However, when the G wavelength ratio was increased to 35% (in white light), fresh yield was found to decrease. Similar finding was found that the addition of 1.7% to 10% of G wavelength in R and B wavelengths ratio did not affect lettuce growth (Kang et al., 2016), while the high fraction of G wavelength was energetically wasteful and reduced the growth of the lettuce (Kim et al., 2004). According to this study, at 35% of G wavelength had suppressed the growth of both pakchoi cultivars. This indicated that pakchoi responses towards G wavelength is highly dependent on the fraction of G wavelength.

In terms of dry yield results, both individual trials and the aggregate trial results are consistent. Throughout each trial's harvests, green pakchoi produced higher dry yield than red pakchoi. Among the LED-light treatments, treatment 50R50B generated highest dry yield at the early stage of growth (20 DAS). At the subsequent stage, at 30 and 40 DAS it was discovered that plants treated with 82R18B had the highest dry yield compared to the other LED-light treatments. It was discovered that the effect of LED-light interaction on dry weight is the same for both cultivars. Furthermore, it was identified that green pakchoi exposed under the monochromatic 100R gained the highest dry weight at the early growth stage, At the subsequent growth, green pakchoi treated by the treatment 82R18B produced the highest dry yield. This similar towards the red pak choi, which the highest dry weight in this particular cultivar was found under treatments 82R18B. While the lowest dry weight was identified on red pakchoi that exposed under white light (control) treatment.

This finding is similar to the findings obtained for fresh weight. Where, at the beginning of monochromatic growth R wavelength obtained highest dry weight, but for subsequent stage the RB wavelengths found to be had more effect on dry weight. Adding B wavelength to R wavelength has been reported numerously to be beneficial towards plant growth. The combination RB wavelengths reported can increase net photosynthetic rate, chlorophyll content, and plant dry weight in numerous plant species, including rice, spinach and cucumber (Ohashi et al., 2006; Ohashi et al., 2007). In addition, RB wavelengths also found to increase stomatal conductance and photosynthetic rates in wheat. Increased stomatal conductance was thought to boost photosynthetic rate, which was linked to an increase in dry yield (Goins et al., 1997). It can be concluded that R combined with B wavelength specifically 82R18B has a positive effect on both fresh and dry yield of pakchoi. Whereas with the addition of G wavelength in the blue-red ratio had no significant difference for all trials conducted and for the overall results of the dry yield.

Moreover, a positive correlation between plant height, diameter, and diameter and leaf area of the pakchoi plant are inversely related to the fresh and dry yields.

5.1.6 Effects of light treatments on growth indices

Growth indices are utilised to establish direct comparisons between cultivars and treatments. In this study, the following growth indices are calculated: Leaf area index (LAI), Absolute growth rate (AGR), Relative growth rate (RGR), and Leaf area index (LAI).

Leaf area index (LAI)

Leaf area index (LAI) is defined as the total of one sided leaf area leaf area per unit land area (Fang and Liang, 2008). This growth index indicates the pace at which leaf area increases, which indicates the rate at which photosynthetic capability increases in plants. LAI is the dominant factor in determining growth rates (Han and Chiba, 2009). Furthermore, the importance of vegetative growth is to produce a large enough photosynthetic factory to obtain maximum yields; therefore, the shoot fresh weight of the leafy vegetables can be used to determine the final yield (Brown, 2015). The total leaf number and LAI of leafy vegetables, on the other hand, might influence the final yield (Gil et al., 2012; Patil et al., 2018). The LAI on green pakchoi was higher compared to red pakchoi during the overall stage of growth. This might be due to the fact that green pakchoi has a higher vegetative growth than red pakchoi, which has an impact on the increment in photosynthetic capacity of green pakchoi, thus enhancing the final yield of green pakchoi. This is consistent with the study's findings on plant height, plant diameter, leaf area and fresh yield which were greater on green pakchoi.

In terms of LED light treatment, the LAI were significantly the highest when exposed under 69R24B7G, 100B and 50R50B throughout the harvest sessions. The role of B wavelength is important in improving the photosynthetic capacity of plants (Kraepiel and Miginiac, 1997; Lee et al., 2007). Where based on the findings of this experiment, it was also found that B has a positive effect on transpiration rate and stomatal conductance in pakchoi. However, it was known that the combination of B and R wavelength much more beneficial towards plants. R wavelength supplemented with B wavelength resulted in higher photosynthetic rates (Pn) as well as an increase in stomatal conductance in the leaves of the plants (Kim et al., 2004). The chlorophyll concentration, stomatal conductance, and Pn concentrations in cucumber were all positively linked with B wavelength in the range of 0% to 80% under combination R &

B wavelengths (Hogewoning et al., 2010; Hernández and Kubota, 2016). Combining R and B wavelengths improves plant photosynthetic capability by increasing chlorophyll content, stomatal density, and enzyme activity (Bugbee, 2016).

Additionally, this research discovered that 50R50B increased the number of leaves on the pakchoi, and that the treatment 69R24B7G; the G wavelength fraction able to enter the leaves' lower mesophyll, and activating the chloroplast and increasing photosynthetic capacity. Because of these factors, it is likely that the light treatments increase the value of LAI. It is understood that a plant with vigorous vegetative development can absorb more light energy for photosynthesis (Lin et al., 2013). Thus, the increase in the LAI is reliant on the amount of light intercepted, the temperature, the availability of water, and the nutrition (Hernández, 2012). In this study, it can be stated that the B and R wavelength plays the most important function in the increment of LAI, with the inclusion of the G wavelength, it was also plays a significant role on the LAI measurement.

Absolute Growth Rate (AGR)

AGR is the increment in total dry weight per unit time (Hunt, 1990). This growth index is used specifically to quantify growth of single plant such as in pot experiments where the components of a crop spread over a given land area is absent. Green pakchoi had a greater AGR than red pakchoi for all harvests. This was to be expected given that the size of green pakchoi is larger than that of red pakchoi. In terms of LED-light treatments, 50R50B and 82R18B had the highest AGR throughout the planting period. These findings are consistent with those obtained in terms of morphology and physiology for the beneficial effects of the combination of R and B wavelengths; in particular, the 82R18B treatment has the greatest influence on the most of parameters recorded. Which, as a result of the combination of in the B and R wavelengths, results in changes in photosynthetic performance, having an effect on growth and development (Ouzounis et al., 2015). The effect of the reaction between the R and B wavelengths can definitely raise the AGR of the pakchoi. Furthermore, it was identified the AGR showed a slow ascent 30 DAS and then showed an accelerated increase until reaching its maximum value at 40 DAS. The slow pattern to start its acceleration, reflecting less accumulation of dry mass in leaves (Rafael et al., 2016). This is in line with the results obtained for dry weight, which increased when approaching to 40 DAS.

Relative Growth Rate (RGR)

RGR is the increment of total dry weight per unit time per unit existing total dry weight (Hunt, 1990). The RGR expresses the dry weight increase in a time interval in relation to the initial weight (Gardner, 1986). This allows more equitable comparisons than an absolute growth rate (AGR). The current study showed green and red pakchoi had no significant difference on the AGR. While in in terms of LED light treatment, it was identified that the plants exposed under treatment 82R18B had the highest RGR. The higher RGR indicated that the plants were provided with enough resources to grow successfully without any forms of stress. The treatment 82R18B provide the optimal wavelength for pakchoi to grow optimally. Similar results were reported in previous study, indicating that a stable RGR was achieved when enough resources (light, nutrients, water) were available for plants to grow successfully (Blackman, 1969).

Nett Assimilation Rate (NAR)

NAR is the increment of total dry weight per unit time per unit leaf area. It defines the efficiency of biomass production specifically in terms of the amount of photosynthetic tissue (Konings, 1989). Since the PPF in this study was constant at either 250 $\mu molm^{-2}s^{-1}$, net assimilation rate provides a relative measure of photosynthetic efficiency. Green pakchoi had a greater NAR than red pakchoi nearly for all harvests. This finding might become one of the factor to explain the growth of green pakchoi which was greater than red pakchoi. Probably because the attributes of the green pakchoi having a higher relative chlorophyll content, photosynthetic capacity, and photosynthetic energy quantum than red pakchoi, all of which lead to the affected photosynthesis efficiency and growth (Goins et al., 1997). Apart from that, it was found that the NAR measurement especially in the green pakchoi was highest at 30 DAS. It was found that the pattern of NAR measurement started low at 20 DAS, increased at 30 DAS and decreased again at 40 DAS. In general, a drop in NAR was linked to increasing foliage in the plants, lowering the amount of light intercepted (Poorter, 1997).This is likely at 30 DAS the plants at the optimal growth conditions, since at 25 to 30 days after sowing is the best harvest time for pakchoi (Wellgrow Malaysia, 2021) . Therefore, it can be said that at 30 DAS is the NAR time at the most optimal rate.

In terms of LED-light treatments, 50R50B, 69R24B7G and 82R18B had the highest NAR which can be seen clearly in green pakchoi compared to red pakchoi. This finding was parallel towards the morphology and physiological findings, which the treatments 82R18B and 69R24B7G have the highest measurement in almost all the parameters. The NAR variable is directly related to the leaf area, layout and age of the leaves and also has an effect on the plant's internal metabolism as a reaction to external influences via the respiration process (Torres et al., 2016). The results highlight the relationship that the LED-light treatments, especially 69R24B7G and 82R18B could increase the photosynthetic efficiency of the pakchoi and lead to increase the growth.

5.1.7 Effects of light treatments on relative chlorophyll content (a+b)

Chlorophyll is the green pigment found in the chloroplasts of plants. Chlorophyll measurements can be used to quantify and assess subtle changes in plant health, and are often estimated using a SPAD meter (Yuan et al., 2016). The chlorophyll content is affected by the light quality (Sæbø et al., 1995). The relative chlorophyll content (SPAD measurement) on green pakchoi was higher compared to red pakchoi. The similar results were obtained in the second and overall trials. While for the LED-light treatments, the early growth stage result was not uniform which is found that 82R18B, 100R and 50R50B had the highest chlorophyll content from the trials results. However, at 30 and 40 DAS a uniform pattern was identified. The treatment 69R24B7G, 82R18B and 50R50B obtained the highest chlorophyll content in the harvest sessions during the 1st and 2nd trials. However, there was no difference between the LED-light treatments. While for the overall result, the treatment 50R50B consistently increased the chlorophyll content throughout the harvest sessions. Even though, it was similar towards other LED-light treatments except to the white light (control) it was observed that the chlorophyll content increased under the multi-wavelength treatments compared to the monochromatic treatments. Many research found that supplementing R with B wavelengths improved plant photosynthetic capacity by boosting chlorophyll content, stomatal density, and enzyme activity (Bugbee, 2016). It was also reported that, under combination R & B wavelengths the chlorophyll concentration, stomatal conductance, and Pn concentrations in cucumber

were all positively correlated with B wavelength in the range of 0% to 80%. (Hogewoning et al., 2010; Hernández and Kubota, 2016).

It was also found that the effect of LED-light interaction on the relative chlorophyll content is the same for both cultivars. However, the findings were not uniform between the first, second and overall results. During the first trial the interaction was only at 40 DAS, and it was found that 82R18B produced a greater relative chlorophyll content in green pakchoi, while red pakchoi treated with white light (control) had the lowest relative chlorophyll content. While at the second cycle green pakchoi treated with 100R shown the highest relative chlorophyll content in most of the harvest session. While green pakchoi treated with white light (control) had the lowest relative chlorophyll content throughout the harvest. The data obtained from every harvest in overall trial found the treatment 82R18B produced the highest relative chlorophyll content in green pakchoi, while red pakchoi treated with white light (control) had the lowest relative chlorophyll content. It was observed that the green pakchoi was more influenced by the LED-light treatments. In the most harvest of all trials the green pakchoi treated with the 82R18B and monochromatic 100R gained the highest chlorophyll content. While the lowest chlorophyll content also found in green pakchoi, which exposed towards the monochromatic 100B and white light (control). In addition, the red pakchoi interaction pattern towards the LED-light treatments was almost similar with the green pakchoi. Chlorophyll content directly influences the photosynthetic potential as well as the primary production of the plants (Curran et al., 1995). This can be related to the findings on the growth of pakchoi green which is larger than red pakchoi. As well as in terms of photosynthetic capacity, green pakchoi is higher than red pakchoi. This is because the higher chlorophyll content in green pakchoi has increased the rate of photosynthetic capacity and might lead to boost the growth of green pakchoi.

From the observation it was understood that R wavelength can increase the relative chlorophyll content in pakchoi. While by adding B wavelength is also found to help increase the accumulation of relative chlorophyll content. The combination R & B wavelength could boost the chlorophyll content, specifically 82R18B. Similar results has been reported, an 11% increase in chlorophyll content of mustard grown with a light ratio mixed of RB wavelengths. R and B wavelengths are related with distinct

mechanisms of chlorophyll production. R wavelength promotes chlorophyll synthesis, while the B wavelength inhibits chlorophyll accumulation (Landi et al., 2020).

It was also understood that the light treatments with the combination of RB wavelengths were gained high chlorophyll content and some had no difference towards treatment 82R18B. While the result on monochromatic 100B was found to be relatively low reading, which can be said that the B wavelength at high ratios does not greatly help the accumulation of chlorophyll content. Which similar with previous finding, the continuous exposure of plants towards monochromatic B wavelength has been found to reduce the photosynthetic pigments due to chloroplast escape reactions and damage to mesophyll cells (Landi et al., 2020). However, there was also a contradict report found that the B wavelength could increase the chlorophyll content (Sæbø, Krekling and Appelgren, 1995a). This suggests that plant interactions on light quality might vary by species.

On the other hand, the addition of G wavelength at a small ratio 7% as in the treatment 69R24B7G was found not decreasing even seen as potentially improving the chlorophyll content readings. However, when a high ratio of 35% as in white light is found to decrease the accumulation of chlorophyll content. B and G wavelengths can be said to help in the accumulation of chlorophyll content at a certain and not too high ratio. When the ratio is elevated B and G potentially lowers the chlorophyll content. This might due to the alterations in the intracellular structure of mesophyll tissues as a result of exposure to B and G wavelength-enriched environments (Mickens et al., 2019). While for the addition of G wavelength in light fraction situation, the leaf morphology may change to allow for more light transmission into deeper level (Massa et al., 2015).

5.1.8 Effects of light treatments on chlorophyll florescence (Fv/Fm)

Chlorophyll fluorescence (Fv/Fm) is often used to indicate the quantum efficiency of the electron transport in Photosystem II (Maxwell and Johnson, 2000) and it is also defined as the maximum photochemical yield of photosystem II in the dark-adapted state (Wojciechowska et al., 2013). Chlorophyll fluorescence (Fv/Fm) characteristics are one of the most essential elements in photosynthetic control and plant responses

to environmental conditions (Dai et al., 2009). Chlorophyll fluorescence (Fv/Fm) can indicate some of a plant's photosynthetic capabilities, and the efficiency of PSII photochemistry (PSII) can be utilised to show a plant's physiological status; often in relation to plant development and stress (Furbank et al., 2009).Healthy and non-stressed plant samples have the Fv/Fm value measurement between 0.81-0.85 (Murchie and Lawson, 2013). The decreasing of Fv/Fm values represent the stress of plants from the external environment or phytochemical efficiency of photosystem II (Maxwell and Johnson, 2000). From the recent study, most of the measurement for green and red pakchoi was around 0.77-0.80 (green pakchoi) and 0.74-0.76 (red pakchoi). Which may indicate that plants were stressed compared to the non-stressed measurement (0.81-0.85) with the external condition or it may also be due to other natural factors. On the other hand, at the 40 DAS of harvest, the data clearly showed the decrement of Fv/Fm value, which may indicate that the plants were not in the optimum condition due to overgrown. Since the optimum harvest time for pakchoi is at 25 to 30 days after sowing (Wellgrow Malaysia, 2021).

The results for chlorophyll florescence (Fv/Fm) derived from observations in the first, second, and overall trials were almost uniform. For all harvest session in both trials and the overall results showed that green pakchoi had a greater chlorophyll florescence (Fv/Fm) than red pakchoi. This is likely due to higher anthocyanin pigments and lower chlorophyll pigments in red pakchoi. In terms of LED-light treatments, both trials showed the 62R24B7G treatment produced the highest chlorophyll florescence (Fv/Fm) at the early stage of the trial (20 DAS). Then the subsequent growth stage, the treatments 82R18B and monochromatic 100R was observed to have the highest chlorophyll florescence (Fv/Fm). A similar pattern of observation was found in the overall result, however there was no significant difference among the treatments except towards the white light (control). The higher chlorophyll florescence (Fv/Fm) under treatments 82R18B and 100R at subsequent growth possibly due that the R wavelength is more efficient in performing photosynthesis. The R wavelength is considered to be the most efficient for photosynthesis (McCree, 1971). The higher the R wavelength makes the chlorophyll florescence (Fv/Fm) increase. In the other hand, the addition of fraction B also helps in the process of photosynthesis and at the same time increases chlorophyll florescence (Fv/Fm). The relative quantum efficiency of R wavelength was greater than that of B wavelength

because fractional B wavelength was absorbed by flavonoids in vacuoles and pigments (anthocyanins) that did not function for photosynthesis in chloroplasts or were less efficient in transferring energy to the reaction centres (McCree, 1971).

There was no clear pattern for the relationship of the LED-light treatments on the accumulation of chlorophyll florescence (Fv/Fm) in the cultivars. The interaction was only significant at selected harvest session at the trials done. However, most of the results obtained portrayed the green pakchoi exposed towards 82R18B, 69R24B7G and 100R had higher chlorophyll florescence (Fv/Fm). While the red pakchoi exposed under white light (control), 69R24B7G and 50R50B had the lowest measurement. However, the data obtained from red brassica indicated the lower measurement compared to green brassica, in which the range of Fv/Fm in red brassica was 0.74-0.76; around 5% lower than Fv/Fm level in green brassica which indicated 0.77-0.80. The lower Fv/Fm result on red brassica than green brassica might be due to the leaves' pigment colours. The absorption pattern and the consequent of leaves are affected by the pigment composition (Inada, 1980). Chlorophylls are the green pigments known to contribute the most to the harvesting of light-energy used for photosynthesis (Gates et al., 1965). In red brassica contained higher anthocyanin pigments concentration, which is less efficient in excitation energy transfer than chlorophyll (Terashima et al., 2009). This factor may lead to lower reading on quantum yield efficiency than green brassica.

The chlorophyll florescence (Fv/Fm) increase with the increase in the R wavelength ratio, whereas it decreases with the increase in the B and G wavelength ratios. Apart from that, the combination of RB wavelengths also has a positive effect on chlorophyll florescence (Fv/Fm). This was similar with previous report found that the RB treatment had increased the chlorophyll florescence (Fv/Fm) in sweet pepper (Li et al., 2020). The greater chlorophyll florescence (Fv/Fm) demonstrated that combined R and B wavelengths enhanced the PSII openness and electron transport efficiency, allowing more electrons to be absorbed, collected, and transported. This showed that the leaves' energy conversion of combined R and B wavelengths into chemical energy was exceptionally efficient, since this proportion of visible light had by far the highest quantum yield for CO^2 fixation when compared to other light

treatments. While the addition of a fraction of G wavelength also identified helps optimise the chlorophyll florescence (Fv/Fm).

Results obtained for the chlorophyll florescence (Fv/Fm) was nearly identical with the results found on the chlorophyll content and photosynthetic capacity. The treatments 82R18B and 69R24B7G obtained the highest readings for photosynthesis rate (Pn) and stomatal conductance (Gs). Which is directly connected to the high chlorophyll and stomata content in the treated plants, has resulted in enhancing the photosynthetic capacity of the plants. Increased photosynthetic capacity is usually associated with an increased flow of electrons through Photosystem II (quantum yield) which lead to increase the plant's growth (Yao et al., 2017). This is even more convincing when relate with the positive correlation between the growth parameters; plant height, diameter, leaf area, fresh yielad and dry yield towards the chlorophyll florescence (Fv/Fm). Which implies that the stated growth parameters of the pakchoi plant are inversely related to the chlorophyll florescence (Fv/Fm) measurement.

5.1.9 Effects of light treatments on photosynthesis rate (Pn), transpiration rate (E) and stomatal conductance (Gs).

A consistent result was obtained for photosynthesis rate, transpiration rate and stomatal conductance.for both the trial and the whole trial. Photosynthesis is the formation of carbohydrates from CO^2 and a source of hydrogen (as water) in the chlorophyll-containing tissues of plants exposed to light. Photosynthetic rate (Pn) is determined by measuring CO^2 before and after it enters the leaf chamber to calculate the rate of CO^2 assimilation by a known leaf area. Transpiration is the movement of water vapor from leaf tissue into the atmosphere. Transpiration rate (E) is determined by measuring water vapor before and after it enters the leaf chamber to calculate the rate of water vapor flux per one-sided leaf area. Stomatal conductance refers to the openness of the leaf stomata determines the rate of CO2 assimilation into the leaf and water vapor exits the leaf through the stomata. Stomatal conductance (Gs) is calculated by measuring transpiration rate as a function of leaf temperature (CID Bio-science, 2021)

The green pakchoi had a greater photosynthesis rate (Pn), transpiration rate (E) and stomatal conductance (Gs) compared to red pakchoi for all harvests in each trial. This was due to higher chlorophyll content in green pakchoi compared to red pakchoi. While the red pakchoi was higher in anthocyanin pigments in the leaves; which affect the photosynthetic process by restricting light absorption within the uppermost palisade mesophyll cells (Gould et al., 2000). The lower photosynthetic capacity in red leaves compared the green leaves plants species has been reported severally (Burger and Edwards, 1996; Gould et al., 2000). Chlorophyll is the primary catalyst for photosynthesis (Terashima and Inoue, 1985; Kirk, 2003; Mandal and Dutta, 2020). The pigment is found in green leaves plants' specialised cellular organelle called the chloroplast, which is the only compartment in the cell where photosynthesis occurs (Terashima and Inoue, 1985; Maclachlan and Zalik, 2011). Due to the higher chlorophyll content in green leaves, they photosynthesize at a higher pace than purple and red leaves plants. This is one of the reasons why the growth and yield of the green pakchoi is higher than the red pakchoi.

5.1.10 Photosynthesis rate

While for the LED-light treatments, 82R18B was found to increase the highest photosynthesis rate (Pn) compared to other LED-light treatments. However, it was similar towards the treatments 69R24B7G and 50R50B. It was realised that monochromatic treatments (100R and 100B) and white light (control) treatment had lower photosynthesis rate (Pn) compared to LED-light treatments that had a combined blue-red ratio. B and R wavelengths are the most effectively utilised wavelengths for plants photosynthesis as absorption spectrum of photosynthetic pigments mainly focus on blue (400–500 nm) and red light spectrum (600–700 nm) (Miao et al., 2016). This was similar with finding reported by Goins et al. (1997), wheat plants grown under R wavelength supplemented with B wavelength and reported increased photosynthesis rates (Pn) as well as an increase in stomatal conductance in the plants' leaves (Kim et al., 2004). By raising the B wavelength percentage in red wavelength, the lettuce plant's photosynthetic ability significantly enhanced (Miao et al., 2016). Rice (Matsuda et al., 2004) and cucumber seedlings (Hernández and Kubota, 2016) exhibit similar tendencies. Plants grown under a combination of R and B wavelength sustained higher photosynthetic rates than plants grown under monochromatic

wavelength (Ohashi et al., 2006). The changes in B and R wavelength regions stimulate the photosynthetic performance, influencing growth and development (Ouzounis et al., 2015).

The LED-light treatments had significant interaction towards the photosynthetic pigments and cultivar. However, such effect is highly dependent on the cultivar of the pakchoi. Green pakchoi was found to have higher photosynthetic capacity readings than red pakchoi. Referring to photosynthesis rate (Pn), it was observed that green pakchoi treated under 50R50B and 69R24B7G treatments had the highest measurements and red pakchoi treated under white light (control) had the lowest measurements. It was realised that, there was a difference in the effect of G wavelength addition in the LED-light treatments between green and red pakchoi, the addition of 7% fraction G wavelength was found to have a positive effect on photosynthesis rate (Pn) of green pakchoi. In contra with red pakchoi, it was found that a high percentage of G wavelength lowers the photosynthetic rate (Pn). This is likely from the higher amount of chloroplast contained in green pakchoi than in red pakchoi, making the absorption of G wavelength more efficient.

The experimental results also found that the stomatal content on 69R24B7G is among the highest of the LED-light treatments, which indicates a high content of chloroplast distribution on the leaves. Due to its high chloroplast content and high PPFD provided by the LED-light in this study (200-210 $mmolm^2s^{-1}$) the G wavelength it is capable of being penetrated to the lower mesophyll and activate the chloroplast and lead to the higher photosynthesis rate. At low PPFD, R wavelength is more efficient than G wavelength, but at high PPFD light energy collected by the topmost chloroplasts tends to be lost as heat, whereas penetrating G wavelength improves photosynthesis by activating chloroplasts deep in the mesophyll (Terashima et al., 2009). Even though in the previous researches the G wavelength is widely argued to be inefficient for photosynthesis in green leaves (Nishio, 2000; Singh et al., 2015). There are several absorbance spectra recorded with the G wavelength have shown clearly that green leaves of terrestrial plants absorb a substantial fraction of G wavelength (McCree, 1971; Inada, 1976). It also found that, once the G wavelength absorbed by the leaves, it will stimulate photosynthesis with great efficiency (McCree, 1971; Inada, 1976). This may explain why G wavelength is more efficient on green

pakchoi compared to the red pakchoi. Apart from the findings about the efficiency of the combination of red-blue wavelengths in increasing the rate of photosynthesis in pakchoi cultivars. Combination of R and B wavelengths has been proved to be effective in driving photosynthesis (Wang et al., 2016). Additionally, there is a positive link between the chlorophyll florescence (Fv/Fm) and the rate of photosynthesis. Which means that the pakchoi plant's chlorophyll florescence (Fv/Fm) value is inversely linked to the chlorophyll florescence (Fv/Fm) value measured. This is parallel with the previous research that the increased photosynthetic capability is frequently accompanied by an increase in electron flow through Photosystem II (quantum yield) in chlorophyll florescence (Yao et al., 2017).

5.1.11 Transpiration rate

In the other hand, the transpiration rate (E) readings were found consistently to be highest in plants subjected to 82R18B LED-light treatment. Which is a very similar pattern observation with the photosynthetic rate (Pn). In addition, it was identified that the treatment monochromatic 100B increased the transpiration rate (E) and similar towards 69R24B7G. However, it was found that plants treated with the monochromatic 100R and white light (control) produced the lowest measurement. It was found that green pakchoi exposed towards treatments 82R18B and 100B had the highest measurements. While, red pakchoi which received white light (control) had the lowest measurement. It is clear that B wavelength plays an important role in the transpiration rate (E) and the addition of the R wavelength with B wavelength further increases the transpiration rate (E). The cumulative effect of R and B wavelength on transpiration rate (E) may be due to the fact that R wavelength inhibits stomatal differentiation (Lee et al., 2007). The absence of cryptochromes and phototropins, which work in tandem with blue light to stimulate stomatal development and opening, explains why differentiation of stomata is impaired in the presence of R wavelength (Kang et al., 2009).

On the other hand, the similar findings as in the photosynthesis rate, there was positive correlation between the chlorophyll florescence (Fv/Fm) and transpiration rate. Which means that the pakchoi transpiration rate value is increased together with the chlorophyll florescence (Fv/Fm) value.

5.1.12 Stomatal conductance

Stomata are small pores in the leaf epidermal that allow gas exchange between the plant and the environment. Stomatal development is influenced by the light quality which it will lead to influence the stomatal conductance (Gs) of air through the leaf mesophyll and stomata (Zheng and Van Labeke, 2017). B wavelength is well known to affect the stomatal opening through the photoreceptors phototropin and cryptochrome (Liscum et al., 2003). The role of B wavelength in the opening of stomata has been underlined by several studies (Kraepiel and Miginiac, 1997). B wavelength was identified to increase the stomatal density in chrysanthemum (Kim et al., 2004). In this study, based on the observation, it was found that the 82R18B produced the highest measurement of stomatal conductance. However, it was similar towards the treatments 69R24B7G and monochromatic 100B. Similar with the respiration rate (E), the stomatal conductance (Gs) was found lowest under the treatments monochromatic 100R and white light (control). In addition, it is observed that red pakchoi had a higher stomatal conductance (Gs) than green pakchoi. The highest was in the plants exposed to 100B and 82R18B treatments. However, red pakchoi that received white light (control) treatment had the lowest stomatal conductance (Gs) measurements. It was found that B wavelength increased the stomatal conductance more than R wavelength. This was parallel with research on *Xanthium Strumarium*, found that the B wavelength induces stomatal conductance 10 to 20 times more than B wavelength (Sharkey and Raschke, 1981).

However, in this study it was also found that the addition of R wavelength to the monochromatic 100B light recipe produced better stomatal conductance (Gs) on pakchoi than monochromatic 100B. The very notable influence of light quality on stomatal aperture is R and B wavelength promote stomatal opening, which leads to stomatal conductance (Gs) through several processes altering guard cell turgor pressure (Lawson, 2009). Phototropins detect B wavelength directly and initiate a signalling cascade that leads in rapid stomatal opening in the presence of background R. (Shimazaki et al., 2007). The long-term impacts of light quality can be just as prominent Gs, including effects on stomata size, quantity, and distribution on the top and lower surfaces of leaves (Franks and Beerling, 2009). This reaction may explain why 82R18B has higher Gs compared to other light treatments, especially the

monochromatic 100B. Besides that, according to (Karlsson, 1986), B and R wavelength promote stomatal opening more than other light wavelengths, which can contribute to an increase in dry matter production. Moreover, B wavelength added to proportion of R wavelength determined have a positive effect on the stomatal conductance of *Ficus benjamina* and *Sinningia speciosa* (Zheng and Van Labeke, 2017). This clearly shows that the addition of R fraction in B wavelength is very effective in increasing green and red pakchoi stomatal conductance (Gs).

5.1.13 Effects of light treatments on root morphology

Root morphology refers to the active ability of nutrient and water uptake of plant roots, and it is determined by the respiratory function (Xu et al., 2019). Based on the observations conducted, it was found that green pakchoi had a higher measurement than red pakchoi for all root morphology parameters taken; root length, root diameter, root tips, root volume and root surface. The aggressive root systems lead to higher water and nutrient absorption, directly increasing the vegetative production of green pakchoi, such as growth and fresh weight, as compared to red pakchoi. This is one of the reasons the green pakchoi gained higher measurement in terms of growth and fresh weight than the red pakchoi.

While for LED-light treatments, it was found that 82R18B produced the highest reading for root length but no difference with 69R24B7G, root tips but no difference with 50R50B and 100R, root volume but no difference with 100R and root surface. For root diameter, monochromatic 100R was found to produce the highest reading compared to other treatments. white light (control) was found to produce the lowest readings for all parameters taken. Only root diameter parameters have interaction with LED-light and cultivar. It was found that green pakchoi had a higher reading than red pakchoi for almost all LED-light treatments except white light (control). Green pakchoi under 100R monochromatic LED-light treatment produced the highest root diameter, while green pakchoi under white light treatment (control) produced the lowest root diameter.

The previous study done by Li et al.(2010) stated R wavelength has the highest root activity in *Gossypium hisutum,* however R with an additional large number of B

wavelength could make the roots larger and healthier (Li et al., 2010). Furthermore, the combination of R and B wavelength have been identified to promote root growth of *Doritaenopsis sp.* (Johkan et al., 2010). The finding in this study indicated a similar trend with the previous research, whereas in both green and red brassicas showed a better root activity under treatment 82R12B compared to monochromatic 100R. Which this may show that, high proportion of R with the inclusion of a specific proportion of B could enhance the root growth and activity in green and red pakchoi. Light promotes root development by supplying carbohydrates and auxin to the developing root. Especially R and B wavelengths, in particular, have a beneficial influence on root elongation (Sweere et al., 2001; Costigan et al., 2011). Auxin is a multifunctional phytohormone that regulates physiological and developmental responses, with the induction of lateral and adventitious roots being one of its most essential functions (Tiwari et al., 2020). This is consistent with the increased carbohydrate build-up observed in treatments with a high R wavelength, as well as in combination R and B wavelengths treatments. The high carbohydrate content of this treatment might promotes auxin for root growth and development. Which due to higher root growth will lead to a more extensive root absorption area that increases the root absorption capacity, and this affected to promote the plant growth into vigour plants. This can be attributed to vegetative growth such as plant height, width, leaf area and biomass which can be seen in treatments that have a combination of R and B wavelengths especially on the treatment 82R18B.

The G wavelength has the same positive effect on the roots as it does on the shoots. However, when the G proportion increased from 7% to 35% in W treatment, the root morphology result significantly decreased. This demonstrates that the G wavelength contributes to root development in the pakchoi only in a minor fraction relative to the light formulation. G wavelength are crucial for photosynthetic activities, despite the fact that plants have a low need for the G wavelength composition. Supplementing R and B wavelengths with G wavelength may aid in the delivery of photosynthates to roots, hence promoting root development (Xu et al., 2019) . Furthermore, it was discovered that the vegetative growth parameters; plant height, plant diameter, leaf number and leaf area were positively correlated with the root morphology results; root length, root surface, root diameter, root volume and root tips. That is to say, the absorption of light wavelengths in the vegetative component and

active root systems were closely linked. It causes greater water and nutrient absorption, which boosts vegetative development. Additionally, photosynthesis and transpiration rates are positively correlated with root surface and root volume. Whereas root length and diameter both correlate positively with transpiration rate. This shows that when combined with active root systems, the plant's photosynthetic capacity is increased while vegetative development is accelerated. The strong relationship between these three components demonstrates the critical role of the optimal combination of light's wavelength in crop development.

5.2 Phytochemicals measurements

5.2.1 Effects of light treatments on anthocyanin index

Anthocyanin are the plant pigments from the group of flavonoid compounds, which is important as biological functions in protecting plants against various biotic and abiotic stresses and also proven to be very useful in protecting human health against numerous disease, including cancer (Harborne and Williams, 2000; Folta and Carvalho, 2015). The results for anthocyanin index derived from observations in the first, second, and overall trials were almost consistent. The red pakchoi had a greater anthocyanin index than green pakchoi for all harvests in each trial. This similar with the total anthocyanin content in red cabbage and lettuce, which are higher than green cabbage and lettuce (Balacheva et al., 2008). While for the LED-light treatments, it was identified on 20 DAS the treatment monochromatic 100R increased the anthocyanin index at trial 2 and overall trial results. While during the trial 1, the treatment 50R50B had the highest anthocyanin index. Meanwhile, at 30 and 40 DAS it was found that the plants received 50R50B treatment had the highest readings for all harvest series in all trials except for the first trial of 82R18B treatment had the highest anthocyanin readings. Meanwhile, the plants treated with white light (control) showed the lowest readings consistently throughout the trials done.

The treatment 50R50B found to be the most effective treatment to increase the anthocyanin content. However, it was realised that at early stage of growth the treatment monochromatic 100R had the highest anthocyanin index compared to other LED-light treatments. While at the subsequent stage, the treatment 50R50B indicated the highest anthocyanin index. It was also observed that the treatment 82R18B was

similar towards the treatment 50R50B in almost every harvest in all trials. Although the previous studies found the R wavelength alone had a minor effect on anthocyanin accumulation (Takeda and Abe, 1992), in this research showed that anthocyanin formation was greatly enhanced with the combination of R and B wavelength. Which can be said that the combination of R and B wavelength is needed to enhance the anthocyanin level.

Besides that, it was also realised that the addition of G wavelength in the light combination might decreased the anthocyanin content. Which clearly can be seen in the treatments 69R24B7G and white light (control). This similar pattern with previous research that reported, increasing of G wavelength the amount of anthocyanin in Arabidopsis decreased compared to the level present in plants grown under combination R and B wavelength (Zhang et al., 2011). The principal driver of anthocyanin synthesis is the B wavelength (Meng et al., 2015). The cryptochromes efficiently absorbed the B wavelength through the leaves, which is the primary driver of anthocyanin production (Vastakaite et al., 2015). As referred to previous studies, B wavelength positively influenced carotenoid and anthocyanin of lettuce and tomato (Giliberto et al., 2005). However, the percentage of G wavelength in white light (control) & 69R24B7G inhibits the synthesis of anthocyanin. G wavelength has been shown to inhibit several chryptochrome-mediated reactions, including anthocyanin synthesis (Folta and Carvalho, 2015).

The LED-light treatments had significant interaction towards anthocyanin index. It was found that the accumulation of anthocyanin index towards LED-light treatments was found to be higher in red pakchoi. However, at early stage of growth the interaction towards the LED-light treatments almost similar in both cultivars. It was found the red pakchoi treated with monochromatic 100R had the highest anthocyanin index during the early stage of growth. Later at the subsequent growth stage (30 and 40 DAS) it was observed the red pakchoi exposed towards 50R50B had the highest anthocyanin index. In the meantime, the green pakchoi treated with white light (control) had the lowest anthocyanin index throughout the trials done. It was understood that the increased of G wavelength in the light treatments could reduce the anthocyanin content of both cultivars. This is likely because the G wavelength is frequently enriched under leaf shade and anthocyanin-rich leaves strongly attenuate the transmission of

B wavelength to underlying leaves (Zhang et al., 2011; Mickens et al., 2019). It is possible that the plants treated with G wavelength fraction responded to G enrichment by suppressing anthocyanin accumulation to allow deeper light penetration into the canopy, which may be more efficient than putting energy into leaf expansion (Poorter, 1997). These results indicate that the B wavelength had a significant influence in anthocyanin accumulation. Additionally, the light spectrum may be altered to increase the anthocyanin content and associated benefits of pakchoi.

5.2.2 Effects of light treatments on phenolic content

Phenolic are secondary metabolites produced by plants and exhibit a wide variety of bioactivities. As plant secondary metabolites, phenolic compounds may have a function in cardiovascular health protection, anti-carcinogenic, anti-viral, antimicrobial, anti-inflammatory, anti-mutagenic, and anti-diabetic properties (Bucić-Kojić et al., 2020). It has been shown that the quality of light regulates the metabolism of higher plants. Additionally, earlier research has established that light has the potential to boost the phenolic content of sprouts (Pas´kopas´ko et al., 2009). Light increases the total phenolic content by enhancing photosynthesis and the enzyme pathway, both of which are involved in the production of phenolic compounds (Qian et al., 2016).

In this research, green pak choi has a greater phenolic content than red pak choi. While for the LED-light treatments, white light (control) treatment obtained the greatest reading and similar towards 69R24B7G, whereas red pakchoi treated with monochromatic 100R recorded the lowest result. This result are in agreement in previous study, when compared to a dark environment control, blue, white, and yellow light greatly increased the phenolic content in pea sprout, while red light dramatically lowered it (Liu et al., 2016). However, Liu et al. concluded that B wavelength is the most optimal light for pea sprout although from the results there is no significant difference with white light. This is because B wavelength was found to increase significantly all of the individual phenolic contents when compared to the other light treatments (Liu et al., 2016).

G wavelength has similar impacts on plant growth and development as blue light (Swartz et al., 2001). B and G wavelength have been shown to have similar favourable impacts on plant development, such as photosynthetic capability and phytochemical synthesis, in a variety of plants (Baroli et al., 2008). B wavelength causes CO_2 fixation largely in the top palisade mesophyll, but G wavelength penetrates deeper and stimulates CO_2 fixation in the lower palisade and upper spongy mesophyll (Sun et al., 1998). G wavelength isn't directly engaged in photosynthesis, although it can influence plant growth and endogenous chemical production (Cui et al., 2009). This might be the reason white light (in which there is a fraction of G wavelength) has a similar effect with B wavelength on accumulation phytochemicals, including the phenolic content.

In the other hand, this finding contradicts with the previous reports where green (G) and yellow (Y) wavelengths were originally emitted by white light emitting diodes were in the similar light region (500-600 nm). This might lead towards similar effect on plants between the G and Y wavelength. The addition of white light to B and R wavelength resulted in a decrease in total flavonoids in *Anoectochilus roxburghii,* as compared to the BR wavelength treatment (Gam et al., 2020). It was also reported that Y wavelength decreased the total phenolic of *A. roxburghii* (Ye et al., 2017). Similarly, Wang et al. discovered that the yellow light reduced total flavonoid concentration (Wang et al., 2018). The phenomena of distinct growth responses to the wavelengths reflects plants' capacity to respond to changes in the light environment in order to complete their life cycle, as well as the various activities of phytochrome, cryptochrome and phototropins photoreceptors (Fiorucci and Fankhauser, 2017). This suggests that each plant has a different interaction towards light.

The pattern of results obtained found that the addition of G wavelength in the light treatment was effective to increase the phenolic content in pakchoi. However, it was found that there was no difference between the 7% and 35% G wavelength ratio which were exist in the treatment 69R24G7B and white light (control). The addition of G wavelength ratio could increase the phenolic content in green and red pakchoi compared to monochromatic and blue-red light treatments.

5.2.3 Effects of light treatments on carotenoid

Carotenoids are pigments that are yellow, orange, and red that are produced by plants. Investigations into the control of carotenoid composition in vegetables are of particular interest, because a diet high in carotenoids can benefit human health by guarding against cardiovascular disease, some forms of cancer, eye illnesses, and light-induced skin damage (Fiedor and Burda, 2014). One of the most important environmental elements affecting colouring and carotenoid concentration is light (Lado et al., 2019). According to the observation, red pakchoi has a higher carotenoid content than green pakchoi. This is obviously due to the high red colour pigment in the red pakchoi. The highest measurement was found in red pakchoi treated with white light (control), whereas the lowest measurement found in green pakchoi treated with monochromatic 100B.

In comparison to monochromatic light and blue-red light, similar with the phenolic content the pattern of findings revealed that LED-light treatments with a G wavelength ratio might also enhance the carotenoid content. The previous study reported the similar finding, the addition of G wavelength at 520 nm increased on blue-red light combination the amount of carotenoid on lettuce (Brazaityte et al., 2016). In addition, higher carotenoid content was observed in *lactuca sativa* when G wavelength added in R and B wavelength (Liu and Van Lersel, 2021). The combination of white light with monochromatic R and B wavelength also found to maximise the accumulation of carotenoid (Chen et al., 2016). White light had the greatest total carotenoid concentrations, whereas B and R wavelength had somewhat lower total carotenoid concentrations in *Brassica rapa chineensis* (pakchoi) (Frede et al., 2018) . The same condition demonstrated in *Lactuca sativa* 'Redfire' and *Brassica campestris* 'Komatsuna' (Ohashi-kaneko et al., 2007). However, a contradict recorded result which the combination of R and B wavelength increased the carotenoid of lettuce compared to the white light. While the other lettuce cultivars *Lactuca sativa* 'Banchu Red Fire' and spinach *Spinacia oleracea* 'Okame' demonstrated a rise in carotenoid levels under blue light (Amoozgar et al., 2016). These findings support the species-dependent characteristics of carotenoid production and subsequent metabolism. Moreover, in this current research it was found that there was significant difference on

the G wavelength ratio. The higher percentage of G wavelength ratio might produce the higher carotenoid content.

5.2.4 Effects of light treatments on vitamin C

Vitamin C is a significant antioxidant found in *Brassica* vegetables that protects cells from oxidative damage by scavenging free radicals and hence enhances human health (Podsedek, 2007). In the present study, it was identified that the green pak choi has a higher vitamin C content than red pakchoi. However, there was no difference between the cultivars. Regarding the LED-light treatments, the white light (control) treatment recorded the highest reading and was similar to the treatment 69R24B7G. The greater vitamin C levels under white light LEDs may be due to the role of vitamin C in photoprotection (Smirnoff et al., 2003). When broccoli sprouts were exposed to white light, a similar effect was found (Pérez-Balibrea et al., 2008). According to the findings, white light LED was more favourable to vitamin C enrichment than LED light, which is consistent with the findings (Wu et al., 2006).

The vitamin C content and cultivar had been significantly affected by the LED-light treatments. Depending on the LED-light treatment, the vitamin C content of green pakchoi and red pakchoi differed. In the treatments white light (control), monochromatic 100R, and 82R18B, green pakchoi had the most vitamin C content compared to red pakchoi. In contrast, the red pakchoi had the highest measurement for the other LED-light treatments. Green pakchoi exposed to white light (control) had the greatest vitamin C measurement, whereas green pakchoi exposed to monochromatic 100B had the lowest value. The pattern of data indicated that LED-light treatments with a G wavelength ratio may increase vitamin C concentration when compared to monochromatic light and blue-red light. Plant grown under R and B wavelength look like purplish to human eyes, and when combined with G wavelength the LED light appears white, as in this study two treatments comprised G wavelength; white light (control) with 35% of G wavelength ratio and 69R24B7G with 7% of G wavelength ratio. The addition of the G wavelength fraction into the red-blue wavelength combination is a major factor in the increase of vitamin C in pakchoi. This finding is similar to the previous report, the addition of a 7.4% ratio of G to R improves the quality of lettuce in terms of yield and nutritional values (Yan et al., 2019).

In addition, the increment of B wavelength significantly suppressed the Vitamin C. Which this finding contradicted with the result found in broccoli, R wavelength was significantly suppressed the accumulation of ascorbic acid compared to B wavelength (Ma et al., 2014). The response to the light spectrum and the accumulation of vitamin C in plants is dependent on the type of species. The regulatory effects of R and B wavelength on vitamin C accumulation have been intensively researched in several species, with the results frequently convoluted and mixed (Li and Kubota, 2009; Qian et al., 2016).

5.2.5 Effects of light treatments on carbohydrate and crude fibre

Carbohydrate and crude fibre made up of the sweetness and crispness of vegetables are affected by soluble sugars; primarily fructose, glucose, and sucrose (Chadwick et al., 2016). The total sweetness index (TSI) of vegetables is determined by the concentration of each soluble sugar (Beckles, 2012). Light quality and duration can increase soluble carbohydrate content in plants by altering CO_2 absorption. The carbohydrate quantity and composition of vegetables influence both their flavour and quality (Chen et al., 2017). In the present study, it was found that the red pakchoi has a higher carbohydrate content than green pakchoi. As for the LED-light treatments, the treatment 82R18B recorded the highest measurement but similar towards monochromatic 100R treatment. Previously, R and B wavelengths were shown to have an influence on carbohydrate accumulations and compositions, which govern both the flavour and quality of vegetables (Yang et al., 2013). The interaction between the cultivar was mixed, green pakchoi had the highest carbohydrate under the treatment 100R. While the red pakchoi had the highest carbohydrate content under the treatment white light (control). However, it can be said that the R fraction has high influence on the accumulation on carbohydrate in pakchoi.

For the crude fibre, green pakchoi had higher crude fibre content reading than red pakchoi for all LED-light treatments. It was also found that the green pakchoi treated with monochromatic 100R had the highest crude fibre content, whereas red pakchoi treated with monochromatic 100B recorded the lowest crude fibre content. This finding was similar with previous research, found that the fresh weight and concentrations of fructose, glucose, crude fibre, and TSI in lettuce were dramatically

increased by monochromatic R treatment as compared to plants treated with RB (Chen et al., 2019).The pattern of data of crude fibre indicated the similar pattern with the carbohydrate content, the LED-light treatments with a higher R wavelength ratio may increase crude fibre when compared to higher B wavelength ratio.

R wavelength stimulates carbohydrate production and increases the expression of associated genes (Yuan et al., 2020). This was similar towards previous studies, the highest contents of fructose, glucose, soluble sugar and TSI were observed in lettuce treated with monochromatic R treatment (Chen et al., 2017). Increased carbohydrate levels have also been seen when cabbage, soybean, and rapeseed exposed to the R wavelength (Wang et al., 2009; Lin et al., 2013). While a contradict effects observed in monochromatic B, which inhibited the sucrose formation in strawberry compared with those under R or RB. This was similar with the finding in this study, where R wavelength seems to increase the carbohydrate and crude fibre while, B inhibit the carbohydrate and crude fibre accumulation.

Furthermore, R wavelength is essential for photosynthetic apparatus growth and starch accumulation, whereas B wavelength is necessary for chlorophyll production, chloroplast development, and stomatal opening (Wu et al., 2007). In the other hand, the accumulation of carbohydrate in leaves can be an impact factor for photosynthesis rate (Pn). The reports from the previous studies showed that the increase of sucrose and starch content under R treatment resulting from restriction of export of photosynthetic products out of the leaves (Sæbø et al., 1995), which was not conducive to photosynthesis (Bondada and Syvertsen, 2003). Down-regulated photosynthesis rate (Pn) by carbohydrate accumulation in source leaves was a response to limited sink demand (Franck et al., 2006). The result was similar with the recent study that the higher starch (carbohydrate) content, along with a lower photosynthesis rate (Pn) observed in plants treated under R wavelength treatment.

5.2.6 Effects of light treatments on protein

Proteins are nitrogen-containing substances that are formed by amino acids. They serve as the major structural component of muscle and other tissues in the body (Hoffman and Falvo, 2004). In the recent study, it was found that the green pak choi

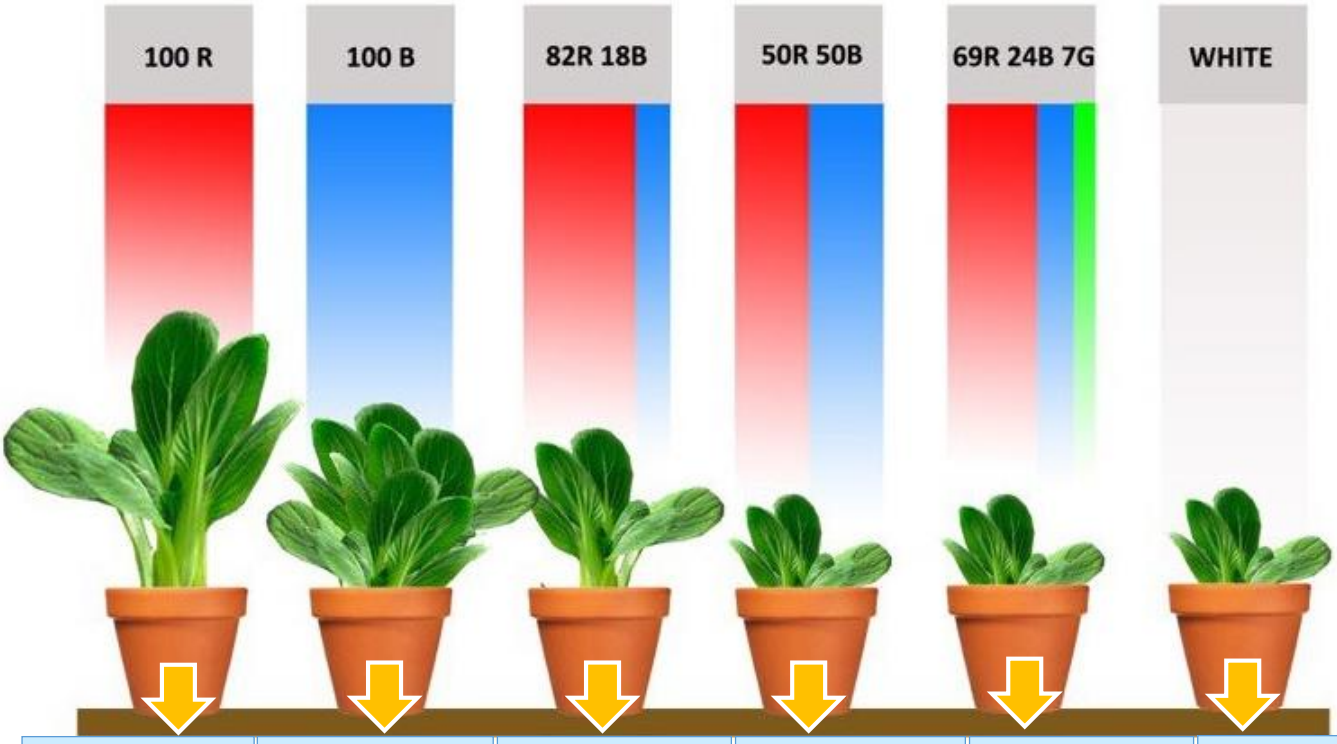
had a higher protein content than red pak choi. As for the LED-light treatments, the treatment white light (control) recorded the highest measurement but similar towards monochromatic 100B and 50R50B treatments. White light (control) is found to be more efficient in protein accumulation than other LED-light treatments, presumably because the white light's contained G wavelength in the ratio of 35% enhance the photosynthesis. This is due to the G wavelength's ability to penetrate deeper into leaf tissues allowing it to evenly excite the chloroplast while driving photosynthesis and increasing CO^2 assimilation (Sun et al., 1998; Nishio, 2000; Terashima et al., 2009). G wavelength has been shown to be effective in carrying out photosynthesis at high PPFDs (Liu and Van Lersel, 2021), such as the PPFD (200-210 $\mu molm^2s^{-1}$) used in this work. The addition of G wavelength in the RB combination wavelengths can be considered to be effective in leaf photosynthesis due to more equal light dispersion across the leaf which enhancing the CO^2 assimilation in pakchoi (specifically, green pakchoi). The increase of the CO^2 assimilation increased amino acid biosynthesis throughout the photosynthetic process (da Fontoura Prates et al., 2020). The results of this study, are quite closely related to the previous findings which found that the accumulation of amino acids appeared to be higher in the G wavelength treatment compared to the white light (full spectrum) treatment (Ajdanian et al., 2020). It is likely, the high G wavelength fraction in the LED-light treatment plays a major role in protein accumulation. Yet this is somewhat speculative, given that between white light (control) towards 100B and 50R50B treatments there was no significant difference. Furthermore, the interactions between G and R & B wavelength combinations are difficult to anticipate, but they are known to be mediated through photosensory pathways since phytochromes, phototropins, and cryptochromes also absorb the G wavelength (Folta and Maruhnich, 2007; Zhang and Folta, 2012). Further studies can be carried out after this to study the potential of G in increasing the protein content.

B wavelength was also identified to increase protein accumulation in grown plants, while R wavelength increased glucose accumulation (Barro et al., 1989).
B wavelength increased the protein accumulation might be related to the stimulation of protein biosynthesis, which results in a decrease in carbohydrate content owing to carbohydrate breakdown by helping the production of amino acids and proteins. Additionally, it has been reported that B wavelength transforms carbon dioxide to amino acids and organic acids under photosynthetic process, whereas R wavelength

promotes the stability of starch and sucrose (Ajdanian et al., 2020). These findings are very much in line with the results of carbohydrate content, for which treatments with high fraction of R wavelength were found to be able to increase carbohydrate content. While B wavelength was shown to have less impact on carbohydrate accumulation, it does have a major role in protein accumulation. For instance, B wavelength has been shown to activate and stimulate enzyme syntheses which resulting in the creation of more organic acids and hence an increase in amino acid synthesis (Barro et al., 1989). This is consistent with the research finding indicated a negative correlation between proteins and carbohydrate. Therefore, if carbohydrate level decreases, protein content increases and vice versa.

On the other hand, the LED-light treatments had significantly influenced the protein content and the cultivar. It was also found that the green pakchoi treated with white light (control) had the highest result, whereas red pakchoi treated with 69R24B7G recorded the lowest result. The pattern of data indicated that the LED-light treatments gave the contradict effect towards the cultivars, which the treatments white light (control) and 69R24B7G produced the highest protein in green pakchoi. However, the treatments produced the lowest protein in red pakchoi. The disparities in findings between green and red brassica demonstrated that light regulates protein accumulation in a species-dependent way. This is due to the green leaves absorb a large amount of G. The typical absorbance values at 550 nm vary from 50% in lettuce to 90% in evergreen broad-leaved trees (Inada, 1976).

The Figure 71 depicts a summary visual diagram of the effects of 6 LED-light treatments on the morphology, physiology and phytochemicals of green and red pakchoi. The parameters shown beneath each LED-light treatments are the ones that are increased as a result of the treatment.



100 R	100 B	82R 18B	50R 50B	69R 24B 7G	WHITE
Morphology - Plant height - Plant diameter - Leaf area - Fresh yield - Dry yield - Root length - Root diameter **Physiological** - Chlorophyll florescence **Phytochemical** -Carbohydrate -Fibre	**Physiological** -Transpiration rate **Phytochemicals** -Protein	**Morphology** - Plant height, - Plant diameter - Leaf area, - Fresh yield - Dry yield - Root length **Physiological** -Chlorophyll content -Chlorophyll florescence -Photosynthesis rate -Stomatal conductance **Phytochemicals** - Carbohydrate -Fibre	**Morphology** - Leaf number - Root length. **Physiological** - Chlorophyll content - Chlorophyll florescence - Photosynthesis rate **Phytochemicals** - Anthocyanin - Protein	**Morphology** -Plant height -Fresh yield -Dry yield **Physiological** -Chlorophyll content -Chlorophyll florescence -Photosynthesis rate -Respiration rate -Stomatal conductance **Phytochemicals** -Phenolic -Carotenoid	**Phytochemicals** - Phenolic - Carotenoid - Vitamin c (only in green pakchoi)

Figure 71 The effects of assigned LED-light treatments on green and red pakchoi. The overall effects were similar between the two cultivars only different at certain parameters. The parameters stated under every LED-light treatment are the parameters that are enhanced under the treatment.

CHAPTER 6

CONCLUSIONS

Global climate change has already had an impact on the environment. Adaptation is an important factor in preventing the magnitude of future climate change effects on food production. Furthermore, the projected population expansion by 2050, with 70% of the population living in cities, necessitates a major solution of current efforts on food security and the ways to achieve it. Vertical farms in controlled environment will be an essential feature of future crops production due to environmental and geographical constraints in heavily populated regions. Although the problem of food security is significantly more complex than simply hunger or undernourishment, proactive initiatives should be taken to find solutions through whatever means are felt as solution towards the urban food production.

Significant advancements in lighting for controlled-environment plant production have occurred in recent years, especially due to significant advancements in light-emitting diode (LED) technology. LEDs are currently one of the most critical tool in controlled environment agriculture for plant production due to their high conversion efficiency, long operating life, miniature size, low thermal radiation, solid-state, and absence of toxic mercury. Compared with traditional arc-discharge lamps, LEDs have exceptionally long operational life expectancies. Furthermore, LEDs operate at lower temperatures, emit comparably little long wave radiation and intrinsically safer from a workplace safety perspective. Apart from increased energy efficiency, LEDs enable the spectrum provided to a crop to be customised. The ability to tailor the spectrum delivered to plants, has open the potential to optimize various aspects of growth and metabolism in crops.

It is critical to understand how these specific wavebands are absorbed by plant tissue in order to improve systems in a controlled environment for plant production. Providing optimal light quality in a controlled environment for plant production in vertical farming set-up is the primary impediment to realising the full economic and research potential of vertical farms in a controlled environment. Light is the energy source for plants as it drives photosynthesis. Light quality drive major developmental

changes such as photomorphogenesis, photoperiodic induction of flowering, phototropism, and shade avoidance. Plants have a variety of photoreceptors that control many different aspects of plant life, including root development. Different light wavelengths are associated with various effects in plant development, and plants have a range of photoreceptors to detect these wavelengths. UVR8 is sensitive to UV-B light, cryptochromes and phototropins detect UV-A and blue light, and phytochromes sense red and far-red light. Plants are capable of absorbing photons throughout the photosynthetically active radiation *(*PAR*)* waveband but it is having long been understood that strong absorption in the blue and red regions is due to the presence of chlorophyll. The ability to control light quality will be vital to grow vegetable for food production in vertical farm in controlled environment. As in this research is to determine the effect of different wavelengths of LED-lighting combination ratio (red, blue and green) by evaluating morphological changes, physiological responses and secondary metabolites accumulation in green and red pakchoi under controlled environment vertical hydroponic farm.

According to the findings in this study, R wavelength has a significant effect on the growth of green and red pakchoi, while B wavelength has a greater effect on the photosynthetic efficiency and physiology of the plants. R and with supplemented of B wavelength achieved the optimum of growth in term of shoot and root, physiology and secondary metabolism in green and red brassica. The treatment 82R18B seems the best proportion of wavelength compared to higher B proportion and monochromatic R and B wavelength. This demonstrates that R and B wavelengths work in tandem to satisfy the morphological and physiological needs of green and red pakchoi, respectively. The inclusion of G in the proportion of the light treatment does have a positive impact on the growth, physiology, and phytochemical of green and red pakchoi. Even though, the result showed that the plants were the most optimum condition under 82R18B, the data indicated that addition of G could increase the chloroplast on the leaf, which lead to better photosynthetic efficiency on plants. However, greater G proportion could decrease the growth, physiology and secondary metabolism in green and red pakchoi which can be seen under treatment W (full-spectrum). This may be explained why the full-spectrum LED-light (white light) is less efficient to be used as growth light. This is because when the G wavelength is present at a high ratio, such as 35% in the white (control) treatment, the growth of green and

red pakchoi is observed to decrease growth and physiology. However, at small fraction as the 7% G wavelength, as in the treatment 69R24B7G is quite beneficial for satisfying the growth requirements of green and red pakchoi.

In addition, for the accumulation of secondary metabolites, it was shown that high G wavelength levels can enhance the content of specific nutrients in green and red pakchoi, especially phenolic, carotenoid and vitamin c. In terms of R & B wavelength, it was discovered that by increasing the R wavelength ratio may boost carbohydrates accumulation, while increasing the B wavelength ratio enhanced the protein content in green and red pakchoi. It can be concluded that for the accumulation of secondary metabolites, each wavelength has a relatively specific role towards the accumulation of specific phytochemicals.

The optimal light spectrums for green and red pakchoi in terms of morphology, growth and phytochemical accumulation are 82R18B and 69R24B7G, respectively. Although the growth rate under 69R24B7G is less than that under 82R18B, the impact of these two lights is comparable. The G wavelength has the potential to be included in the light ratio in order to enhance the plants' quality. The inclusion of a small proportion of G wavelength in the growth light sources could provide a better and pleasant condition for the indoor vertical farming environment without reducing the yield, quality, and phytochemical contents of green and red pakchoi. G wavelength was discovered to be capable of enhancing certain phytochemicals in pakchoi. Thus, these two light compositions may be employed as the basis for vegetable crops, particularly pakchoi, grown in vertical farm in controlled environments. G wavelengths were discovered to be equally as crucial for plants as R and B wavelengths. Green and red pakchoi benefit from the treatment in terms of morphology, physiology, and secondary metabolites. However, further studies needed to determine the optimal G proportions that needed to be added on R and B wavelengths, besides to evaluate other variety of potential vegetables that can be produced in indoor vertical farming. Apart from that, it was discovered that the interaction between the light wavelength combination and the cultivar, even within the same plant species, varied according to the cultivar, as observed with the green and red pakchoi.

Finally, it can be concluded that light spectral can be used as a method to produce vegetables that are high quality, safe and specially tailored to high in certain nutrients such as vegetables high in carbohydrates, protein or vitamins by providing light treatment according to specific wavelength to improve those phytochemicals. The ability to manipulate light quality is important for achieving improved production or nutritional quality of commercial crops in controlled-environment vertical farm. Even though the effective light quality treatment varies depending on the plant species, the knowledge gained may be used to produce for current or even future food production that is both safer and more nutritious.

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