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Investigation of optimal Light Environments for Crops in EDEN LUNA

Bachelor's Thesis

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Abstract

To return to and to build a long-term base on the Moon and other celestial bodies, a multitude of difficulties regarding life support need to be addressed, one of which is the provision of food. With the EDEN LUNA project, the DLR develops Controlled Environment Agriculture technologies to be used in planetary space stations to provide Astronauts with fresh produce. To maximise the growth of crops in the EDEN LUNA future exploration greenhouse (FEG) and to minimise the energy input, the development of individualized light environments for two crops (lettuce and cucumber) was attempted in this thesis. These light environments were determined by literary research for general use and adapted for the use in the EDEN LUNA FEG. The light environment for lettuce was evaluated and adapted experimentally. Power consumption of the light environments were estimated by taking snap-reading and extrapolating over the whole growth period.

It could be shown that lettuce requires a light intensity of about 220 to 230 $\frac{\mu mol}{m^2 s}$. A higher blue light ratio led to a denser growth of the lettuce, while red and far red light made the lettuce spread out more. Green light might allow the lettuce to grow denser as it increases the photosynthesis in the lower layered leaves of the plant. A sensory analysis showed that the new light environment produced sweeter lettuce with higher crispness if the light intensity was between about 220 to 230 $\frac{\mu mol}{m^2 s}$. The developed light recipe did not lead to a higher yield than the control. It was estimated that the experiment consumed slightly more (~3%) energy than the control.

Zusammenfassung

Für die Rückkehr zum Mond und zu anderen Himmelskörpern und den Aufbau einer langfristigen Basis auf diesen müssen eine Vielzahl von Problemen der Lebenserhaltung gelöst werden, darunter auch die Versorgung mit Nahrungsmitteln. Im Rahmen des Projekts EDEN LUNA entwickelt das DLR Technologien für die kontrollierte Landwirtschaft (Controlled Environment Agriculture), die in planetarischen Raumstationen eingesetzt werden können, um Astronauten mit frischen Lebensmitteln zu versorgen. Um das Wachstum von Nutzpflanzen im EDEN LUNA Future Exploration Greenhouse (FEG) zu maximieren und den Energieaufwand zu minimieren, wurde in dieser Arbeit versucht, individualisierte Lichtumgebungen für zwei Nutzpflanzen (Kopfsalat und Gurke) zu entwickeln. Diese Lichtumgebungen wurden durch Literaturrecherche für den allgemeinen Gebrauch ermittelt und für den Einsatz im EDEN LUNA FEG angepasst. Die Lichtumgebung für Kopfsalat wurde experimentell evaluiert und angepasst. Der Stromverbrauch der Lichtumgebungen wurde anhand von Momentaufnahmen und einer Extrapolation über die gesamte Wachstumsperiode geschätzt.
Es konnte gezeigt werden, dass Salat eine Lichtintensität von etwa 220 bis 230 $\frac{\mu mol}{m^2 s}$ benötigt. Ein höherer Anteil an blauem Licht führte zu einem dichteren Wachstum des Salats, während rotes und weit rotes Licht den Salat stärker ausbreiten ließ. Grünes Licht könnte den Salat dichter wachsen lassen, da es die Photosynthese in den unteren Blattschichten der Pflanze erhöht. Eine sensorische Analyse ergab, dass die neue Lichtumgebung einen süßeren und knackigeren Salat hervorbrachte, wenn die Lichtintensität zwischen etwa 220 und 230 $\frac{\mu mol}{m^2 s}$ lag. Das entwickelte Lichtrezept führte nicht zu einem höheren Ertrag als die Kontrolle. Es wurde geschätzt, dass der Versuch etwas mehr (~3%) Energie verbrauchte als die Kontrolle.

Declaration of Authorship

I hereby declare that the thesis submitted is my own, unaided work, completed without any external help. Only the sources and resources listed were used. All passages taken from the sources and aids used, either unchanged or paraphrased, have been marked as such.
Where generative AI tools were used, I have indicated the product name, manufacturer, the software version used, as well as the respective purpose (e.g. checking and improving language in the texts, systematic research). I am fully responsible for the selection, adoption, and all results of the AI-generated output I use.
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I further declare that I have not submitted the thsis in the same or similar form to any other examination authority.

Lea Antonia Behnke ([redacted])

Berlin, den 28.10.2024

Exposé

Investigation of optimal Light Environments for Crops in EDEN LUNA

The Artemis campaign shall bring humans back to the Moon's surface and launch humanities first lunar space station (NASA, 2024). Prolonged manned missions to the Moon offer a multitude of difficulties regarding life support, one of which is the continuous wellbeing – mental and physical – of Astronauts. Fresh vegetables not only provide important nutrients, but have also been shown to improve mental wellbeing in Astronauts (Bartsev et al. 1997). The projects of the Planetary Infrastructure Group at the German Aerospace Center in Bremen therefore develop Controlled Environment Agriculture (CEA) technologies for greenhouses to be used in planetary space stations on Moon and Mars to provide Astronauts with fresh produce and on terrestrial challenging environments.

Growth parameters for plants, like temperature, nutrients, and illumination, have to be closely monitored for CEA greenhouses like EDEN LUNA. As the effect of discreet wavelengths on plants could only be tested since the invention of LEDs, the development of individual light recipes for plants will optimise vertical faming technologies: The correct lighting can affect total biomass, fruiting, nutrient contents, and taste of the crops (Massa et al., 2008, Olle & Viršilė, 2013, Hasan et al., 2017).

The aim of this work is to define targets for the light recipes and to develop these for plants used in the EDEN LUNA project for the time from seeding to harvest. The light recipe shall provide the plants with the necessary intensities at the in EDEN LUNA available wavelengths during their life time. As the illumination will be more individualised, the energy requirement of the lighting is likely to decrease. This energy would therefore be available for other subsystems in a future flight model of the EDEN greenhouse.

Objectives

- Clustering the plants used in EDEN LUNA into groups with similar or the same illumination needs
- Define the assumptions under which the light recipes are developed
- Define the goals for the light recipes
- Develop light recipes for max. 3 plants in mono- and polyculture using evaluation matrix developed above
- Conduct experiment to test growth of lettuce with designed light recipe
- Conduct experiment to measure power consumption of designed light recipe for lettuce
- Calculate estimated power consumption for other light recipes
- Write program for lettuce light recipe or suggest recommendations for changes in the EDEN LUNA light set-up for space missions

Possible variation of parameters and objectives are established in collaboration with the supervisor of this thesis.

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Contents

Abstract . . . . . **iii**

Zusammenfassung . . . . . **iv**

List of Figures . . . . . **x**

List of Tables . . . . . **xi**

Nomenklatur . . . . . **xii**

1 Introduction **1**

2 Scientific Background **2**
2.1 Life-Support Systems 2
2.2 Moon Programmes 3
2.3 Controlled Environment Agriculture (CEA) 4

3 Materials and Methods **9**
3.1 Development of Light Recipes 9
3.2 Programming 9
3.3 Experimental Verification 9
3.4 Statistical Analysis 15

4 Light Recipes **16**
4.1 Definition of Goals for Light Recipes 16
4.2 Assumptions 16
4.3 Development of Light Recipes 16

5 Results **31**
5.1 Experiments with Lettuce (*L. sativa*) 31
5.2 Expected Power Consumption 40

6 Discussion **42**
6.1 Discussion of Experiment 1 42
6.2 Discussion of Experiment 2 44
6.3 Problems regarding measurement equipment 45
6.4 Practical Application of Light Recipes in EDEN LUNA 47
6.5 Summary 49
6.6 Future Studies 51

References . . . . . **XIII**

Appendix . . . . . **XVIII**

List of Figures

2.1 Light absorption for photosynthesis in plants. 5
2.2 Heliospectra lamp used in EDEN LUNA 8
3.1 Test Stand for Spectrometer Test 10
3.2 Test Stand for Spectrometer Test during Use 10
3.3 Nursery for Seedlings 11
3.4 Plant Test Set-Up 12
4.1 Spectrum of 120 W Lamp used in EDEN LUNA 17
4.2 Calculation of Lamp Settings 21
4.3 Seedling and Vegetative Stages of Lettuce 23
4.4 Height of Lettuce plants during Pretest 24
4.5 Growth of Lettuce during Pretest 24
4.6 Life Cycle of Cucumber 27
5.1 Average height of Lettuce plants in first Experiment 31
5.2 Average area of Lettuce plants in first Experiment 32
5.3 Leaves counting after harvest 32
5.4 Roots on Day of Harvest in first Experiment 33
5.5 Experiment 1 on the Day of Harvest 34
5.6 Experiment 2 on the Day of Harvest 36
5.7 Roots of Experiment 2 after Harvest 38
5.8 Sensory Analysis of second Experiment 39
5.9 Average Height of plants in the second Experiment 39
6.1 Comparison of PPFD-meters 46
6.2 Comparison of PPFD-meters by Colour Ranges 46
6.3 Optimal Light Recipe for Lettuce 50
6.4 Optimal Light Recipe for Cucumber 50
J.1 Set Up of Plant Trays in EDEN LUNA XLIV

List of Tables

3.1 Environmental Parameters in Experiments 1 and 2 . . . 11
3.2 Nutrient Solution . . . 12
3.3 Light Environment Experiment 1 . . . 13
3.4 Light Environment Experiment 2 . . . 14
3.5 Overview Power Measurements . . . 15
4.1 Start Settings for Lettuce in vegetative stage in EDEN laboratory . . . 26
4.2 Start Settings for Lettuce Seedlings - 120 W lamp - 87 cm . . . 27
4.3 Cucumber light environment in EDEN ISS . . . 27
4.4 Start Settings for Cucumber Seedlings in EDEN LUNA . . . 29
4.5 Start Settings for Cucumber during the Vegetative Stage in EDEN LUNA . . . 30
5.1 Results of Experiment 1 . . . 33
5.2 Colouring of the Leaves in Experiment 1 . . . 33
5.3 Results of Experiment 2 . . . 35
5.4 Power Consumption during Experiment 2 . . . 40
5.5 Estimated Power Consumption for Lettuce in EDEN LUNA . . . 40
5.6 Estimated Power Consumption for Cucumber in EDEN LUNA . . . 41
6.1 Results of Experiment 1 without plants on position 3 . . . 43
6.2 Settings for Lettuce in EDEN LUNA - 120 W lamp - 38.5 cm - 220 PPFD . . . 47
6.3 Settings for Lettuce in EDEN LUNA - 120 W lamp - 50 cm - 220 PPFD . . . 48
6.4 Settings for Lettuce in EDEN LUNA - 240 W lamp - 38.5 cm - 220 PPFD . . . 48
6.5 Settings for Lettuce in EDEN LUNA - 240 W lamp - 50 cm - 220 PPFD . . . 48
6.6 Objectives of this thesis . . . 51
A.1 Growth of Lettuce Plants under Control Conditions in retest . . . XVIII
D.1 Settings in Experiment 1 . . . XXIII
D.2 Settings in Experiment 2: 100% . . . XXIII
D.3 Settings in Experiment 2: 80% . . . XXIV
D.4 Settings in Experiment 2: 70% . . . XXIV
E.1 Lettuce - Vegetative Stage - 120 W lamp - 38.5 cm - 270 PPFD . . . XXV
E.2 Lettuce - Vegetative Stage - 120 W lamp - 38.5 cm - 220 PPFD . . . XXV
E.3 Lettuce - Vegetative Stage - 120 W lamp - 38.5 cm - 200 PPFD . . . XXV
E.4 Lettuce - Vegetative Stage - 120 W lamp - 50 cm - 270 PPFD . . . XXVI
E.5 Lettuce - Vegetative Stage - 120 W lamp - 50 cm - 220 PPFD . . . XXVI
E.6 Lettuce - Vegetative Stage - 120 W lamp - 50 cm - 200 PPFD . . . XXVI
E.7 Lettuce - Vegetative Stage - 240 W lamp - 38.5 cm - 270 PPFD . . . XXVII
E.8 Lettuce - Vegetative Stage - 240 W lamp - 38.5 cm - 220 PPFD . . . XXVII
E.9 Lettuce - Vegetative Stage - 240 W lamp - 38.5 cm - 200 PPFD . . . XXVIII
E.10 Lettuce - Vegetative Stage - 240 W lamp - 50 cm - 270 PPFD . . . XXVIII
E.11 Lettuce - Vegetative Stage - 240 W lamp - 50 cm - 220 PPFD . . . XXIX
E.12 Lettuce - Vegetative Stage - 240 W lamp - 50 cm - 200 PPFD . . . XXIX
E.13 Lettuce - Vegetative Stage - 120 W lamp - 38.5 cm - Control . . . XXX
E.14 Lettuce - Vegetative Stage - 120 W lamp - 50 cm - Control . . . XXX
E.15 Lettuce - Vegetative Stage - 240 W lamp - 38.5 cm - Control . . . XXX
E.16 Lettuce - Vegetative Stage - 240 W lamp - 50 cm - Control . . . XXX
E.17 Lettuce - Seedling Stage - 120 W lamp - 87 cm . . . XXXI
E.18 Lettuce - Seedling Stage - 240 W lamp - 87 cm . . . XXXI
E.19 Cucumber - Vegetative + Reproductive Stages - 240 W lamp - 198 cm - 166 PPFD . . . XXXI
E.20 Cucumber - Seedling Stage - 120 W lamp - 87 cm . . . XXXII
E.21 Cucumber - Seedling Stage - 240 W lamp - 87 cm . . . XXXII

Nomenklatur

Abbreviations

AMS	Atmosphere Management System
BLSS	Bio-regenerative Life-Support System
CEA	Controlled Environment Agriculture
cv.	cultivar
DAS	Days after Seeding
DAT	Days after Transplanting
DHCS	Data Handling and Control System
DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V.
DW	dry weight
EDEN	Evolution & Design of Environmentally-Closed Nutrition-Sources
ESA	European Space Agency
FDIR	Fault Detection, Isolation and Recovery
FEG	Future Exploration Greenhouse
FW	fresh weight
ISS	International Space Station
LCS	Lighting Control System
LED	Light-emitting diode
LLS	Life-Support System
NDS	Nutrient Delivery System
spp	species
TCS	Thermal Control System

Symbols

λ	Wavelength, in nm
Φ	Photon flux density
c	Speed of Light, in $\frac{m}{s}$
$E_{Photon,\lambda}$	Energy per Photon, in J
h	Plancks constant, in Js
I	Intensity
N_A	Avogadro constant, in $\frac{1}{mol}$
P	Power, in W
p	Percentage, in $\%$
t_{photo}	Photoperiod, in $\frac{h}{d}$
W_{total}	Work, in Wh
d	day, in d
DLI	Dalyight Integral, in $\frac{mol}{m^2 \cdot d}$
PAR	Photosynthetically active radation, in $\frac{\mu mol}{m^2 \cdot s}$
PPF	Photosynthetic photon flux, in $\frac{\mu mol}{m^2 \cdot s}$
PPFD	Photosynthetic photon flux density, in $\frac{\mu mol}{m^2 \cdot s}$

1 Introduction

The Artemis campaign shall bring humans back to Moon's surface and launch humanity's first lunar space station [1]. Prolonged crewed missions to the Moon offer a multitude of difficulties regarding the engineering required, one of which is the continuous well-being - mental and physical - of astronauts. Fresh vegetables not only provide important nutrients, but have also been shown to improve mental well-being in Astronauts [2]. The projects of the Planetary Infrastructure Group at the German Aerospace Center in Bremen are therefore currently developing Controlled Environment Agriculture (CEA) technologies for greenhouses to be used on terrestrially challenging environments and in planetary space stations on Moon and Mars to provide Astronauts with fresh produce.

The EDEN LUNA project is a part of the EDEN (Evolution & Design of Environmentally-Closed Nutrition-Sources) initiative. The initiative's focus lies on the research of Bio-regenerative Life Support Systems (BLSS), especially greenhouse modules, and their integration into future space habitats. The EDEN LUNA project develops a greenhouse module (Future Exploration Greenhouse, FEG) that will be part of the ESA-DLR LUNA (European Space Agency and Deutsches Zentrum für Luft- und Raumfahrt respectively), an analogue moon facility for the simulation of a lunar environment with robotic and astronautic activity [3].

Growth parameters for plants, like temperature, nutrients, and illumination, have to be closely monitored for CEA plant growth facilities like EDEN LUNA. The effect of discreet wavelengths on plants could only be tested since the invention of LEDs. The development of individual light recipes for plants will optimise vertical farming technologies: The correct lighting can affect photosynthesis, total biomass, fruiting, nutrient contents, and taste of the crops [4–9].

The aim of this work is to define performance targets for the light recipes and to develop these for plants used in the EDEN LUNA project for the time from germination to harvest. The light recipe shall provide the plants with the necessary intensities at the in EDEN LUNA available wavelengths during their life time. As the illumination will be more individualised, the energy demands of the lighting is likely to decrease. A lower energy demand would therefore lower the overall energy demand of a future flight model of the EDEN greenhouse.

Our newly developed light recipe for lettuce (*Lacutca Sativa*) is tested in two experiments. Both experiments test the reaction of lettuce growth to different light environments against the same control. The second experiment also tests the growth under different intensities to find the lowest required light intensity and therefore lowest required power input. The power input of the light recipes was then measured.

Chapter 2 will summarize the scientific background of BLSS and the role of lighting in Controlled Environment Agriculture systems like EDEN LUNA. The used materials and methods will be shown in Chapter 3. In Chapter 4 the development of the light recipes will be discussed. Chapter 5 will give the results of the lettuce and power experiments. Results will be discussed in Chapter 6 and the thesis will be summarized and an outlook on possible future studies will be given.

2 Scientific Background

This chapter gives an overview over all subjects relevant for this thesis. Section 2.1 explores the needs and uses for Life-Support Systems (LLS) in general and BLSS in particular. Subsequently, section 2.2 gives a short overview over current and planned Moon programs like the Artemis, in which NASA plans to return humans to the moon. Section 2.3 examines Controlled Environment Agriculture.

2.1 Life-Support Systems

Human presence in space can significantly improve flexibility of research. Humans can interact with payloads, repair systems, and perform tasks that have not been fully defined before the mission. But space is not a human-friendly environment. The development of life-support systems is therefore a necessary part of any manned space mission. Life-support systems provide "an environment and resources which preserve human life in health and safety for the duration of a mission" [10, P. 418]. The classic functions of a life-support system include

- Water management and regeneration of urine
- Atmosphere control
  - Oxygen supply
  - CO_2 removal
  - Control of trace contaminants
  - Humidity control
  - Control of temperature
  - Pressure control
- Provision of food
- Fire detection and suppression
- Waste management
- Extravehicular services [11, P. 113 f.].

Currently used life-support systems for space stations such as the International Space Station (ISS) consist of both regenerative and non-regenerative systems [12]. An example for a non-regenerative system is the food provisioning. Besides small test plant growth facilities, like Veggie, food has to be delivered in full [13]. Oxygen on the other hand is produced via the regenerative Sabatier process [14], in which carbon dioxide (CO_2) reacts with hydrogen (H_2) to form methane (CH_4) and water (H_2O). The water will then be split into molecular hydrogen and oxygen (O_2) via electrolysis [15, P. 441]:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \tag{2.1}$$

$$2H_2O \rightarrow O_2 + 2H_2 \tag{2.2}$$

In non-regenerative systems, also called open-loop system, provisions have to be delivered regularly. They represent additional risks, especially for long-term missions to other planets

like Mars, and are expensive. As of 2018, delivering 1 kg to the ISS costs $23 300 [16]. During such long-term missions, higher autonomy of a space station is therefore necessary. The EDEN initiative aims to transition to regenerative LLS in regards to food production by providing a greenhouse. These will add to the caloric intake of astronauts as well as fulfill their requirements for micronutrients and reduce diet fatigue [17]. It has also been shown that fresh vegetables can significantly improve astronaut's mental health [18]. Additionally, plants produce O_2 and remove CO_2 from the atmosphere [19]. The goal of a BLSS is therefore the support of long-term autonomous existence of humans in space by providing oxygen, storing carbon dioxide, purifying water, and providing food.
Different forms of BLSS have been researched: systems with bacteria, algae, mushrooms, higher plants or mixtures between those. Comparing these BLSS, Bartsev et al. concluded that a BLSS using higher plants offers higher reliability and comfort than the other options, when combining the LSS-criteria minimum mass, maximum safety, and maximum quality of life [2].
BLSS are also relevant for missions to the Moon, which is regarded as a stepping stone to Mars. As such, technology that is necessary for missions to Mars will be developed and used for missions to the Moon as for example planned for the Artemis-Programme [20].

2.2 Moon Programmes

The Artemis-programme is NASA's plan to return humans to the moon and build long-term stations both in orbit and on the surface [1]. During the first phase, Artemis-I, -II, and -III, the first manned landings in more than 50 years will be prepared and conducted, when two astronauts will land near the lunar south pole [20, 21]. In the second phase, a space station is to be build in lunar orbit: the Lunar Gateway. The Gateway will be designed to house four astronauts for up to 90 days [21, 22]. The long-term goal is a permanent presence on the moon to facilitate exploration and finally the development of an Artemis Base Camp on the lunar surface [23]. The base camp shall provide the facilities and mobility systems required for exploration of the lunar south pole and support habitation by astronauts [24]. The surface habitat is planned for housing up to four crew and must therefore provide food for them via both deliveries and locally produced produce.
The lunar village is a concept that was introduced by the ESA in 2015. The goal is a long-term lunar settlement with both private and public international members. Every member would have and conduct their "self-determined operations at a common location on the Moon" [12]. Like all other human settlements, a lunar village will require nourishment. As the concept of a lunar village might lead to one or multiple permanent settlements of 10^3 to 10^6 citizens with a biological life-support system [12].
One 25 year old male of 75 kg body weight requires 0.64 kg of dry mass of food every day. This means, for a mission like the Lunar Gateway with four astronauts, $0.64\ kg \cdot 4 = 2.56\ kg$ dry mass need to be available every day [11, P. 137 f.]. With $23 300 per kg, just for dry food, $59 648 are spent every day to provide food to four astronauts on the ISS. For a moon programme, this number is not sufficient, as transport costs are higher. EDEN ISS, the precursor project to EDEN LUNA, produced an edible biomass of 168 kg during an experiment phase of nine months (mid-February to mid-November 2018) [19]. Thus, the EDEN container was able to produce

24% of the required biomass in the experimental phase. For a mission with four astronauts, a greenhouse of the same dimensions as EDEN LUNA will therefore have the potential to save nearly a quarter of transport costs for food.

2.3 Controlled Environment Agriculture (CEA)

The key elements of the EDEN LUNA greenhouse can be ascribdd to CEA. Here, all needs and environmental requirements of the crops are artificially created: the air is conditioned and pressurized and humidity and temperature are defined. Nutrients can be customized and illumination is provided through Light-Emitting Diodes (LEDs) which can be controlled to emit wavelengths and intensities required for different crops. This can lead to higher productivity and can withstand climate change [25, 26]. CEA is used among others in urban farming to combat food insecurities and in greenhouse modules for manned space stations [18, 25, 27, 28].

2.3.1 Growth Parameters of Crops

Plants, like all other organisms, are subject to certain environmental parameters. Only within the borders laid by the evolutionary developed parameters can a plant survive, grow, and reproduce. For a crop, these growth parameters are among others [27, 29]

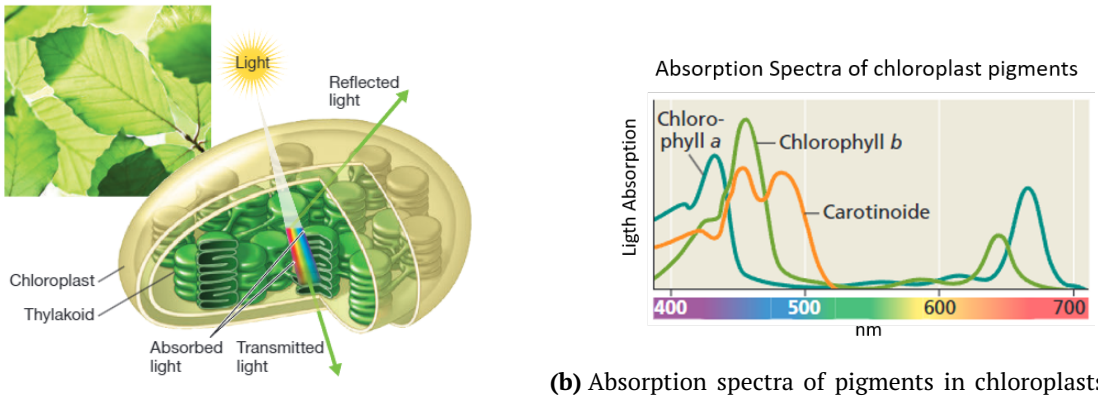
- Nutrient availability
- Water availability
- Humidity
- Temperature
- CO_2 availability
- Illumination.

Water availability is an important factor for plants. Water makes up a big part of the mass of plants and transports solved nutrients into the plants via the root system [30, P. 45 f.]. Capillary forces and transpiration raise water and nutrients through the Xylem, the water transport channels inside the plants [30, P. 50 ff.]. Transpiration is a passive process, in which water evaporates through the wall of the mesophyll cells and the stomata in the leaves. Nutrient supply is therefore dependent on humidity. With high humidity, water will be slower to evaporate which might lead to a deficit of nutrients [31, P. 1051 ff.].
CO_2 is necessary for photosynthesis: the transformation of carbon dioxide and water into carbohydrates and oxygen by binding light energy into chemical energy [31, P. 154]. Photosynthesis is a multi-stage process whose balance can be summarised by the following chemical formula:

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2 \tag{2.3}$$

In plants, this process takes place in the chloroplasts. Mostly red and blue light is absorbed by the plants and converted into chemical energy, while green light is mostly reflected - leaves appear green - or transmitted through the leaves (cf. 2.1a).

Within the chloroplasts, chlorophyll a and b can be found: pigments which are responsible for the absorption of light energy with absorption peaks at 660 and 460 nm respectively. The absorption spectra can be found in figure 2.1b.



(a) Light absorption in chloroplasts [32, P. 158]

(b) Absorption spectra of pigments in chloroplasts [31, P. 260]

Figure 2.1: Light absorption for photosynthesis in plants.

Light is not only required as an energy source but also as an external signal, which regulates physiological processes like sex expression [33, 34]. It has been shown that changes in light (spectrum and intensity) lead to high physiological, morphological, and anatomical plasticity in plants [4, 35–37].

Therefore, for plant growth to be effective, the plant needs access to CO_2, water, and light of the correct intensity and wavelengths. This thesis will focus on the illumination of crops.

Plant Life Cycle

The growth parameters may change over the life cycle of a plant. During its life time, a plant goes through multiple stages. The life cycle of a flowering plant is introduced shortly.

In germination, the seedling grows from its seed using resources stored in the seed. With the cotyledons, photosynthesis is first applied for the production of sugars. After the growth of the first real leaves, the vegetative stage is entered in which the plant growths exponentially. Finally, the plant moves into the reproductive stage, in which first flowers and than, in case of fertilisation, fruits develop [31, P. 1093].

The duration of the life cycle depends on the plant itself and on environmental factors, like light or the availability of nutrients [31, 38, P. 1144]. Generally, in hydroponic horticulture, the seedling stage is shortened in contrast to traditional cultivation methods [29, P. 211]. Flowering is mostly induced by environmental factors, since all members of a species should flower simultaneously [39], and can be induced by stressors like high-intensity light [38].

2.3.2 Illumination in CEA

In CEA, several different type of lamps are used to illuminate the plants. These can for example be flourescent lamps, high pressure sodium lamps, or LEDs [5, 36]. Besides the wavelengths and intensity, the power consumption is an important factor which has to be considered. Here, LED's have a noted advantage. They are energy efficient and in comparison to other artificial light sources only produce little heat. They are lightweight and small, which means they can be mounted closer to the plants. It is also possible to irradiate in discreet wavelengths instead of

a full spectrum. This allows certain wavelengths to be selected, which can save power in those wavelength ranges where no photons are required [40, P. 120].
In LEDs, current is supplied to two semi-conductor plates: an anode and a cathode. Electrons move towards the positively charged semi-conductor, releasing energy in the form of photons when they cross a band gap. The wavelength of the photons - and therefore their colour - is dependent on the material of the semi-conductors and the energy necessary for the electrons to cross the band gap [40, P. 120].
The intensity of light used for growing crops is given as either Photosynthetically Active Radiation (PAR), the Photosynthetic Photon Flux (PPF), or the Photosynthetic Photon Flux Density (PPFD). Historically, PAR derives from the total energy that radiated upon an area and therefore has the units $\frac{W}{m^2}$. PPF originated when it became clear that not the total energy determines plant growth, but the number of photons. The units of PPF were therefore $\frac{\mu mol}{m^2 s}$. Over time, PPFD replaced PPF using the same units, while in some publications the units $\frac{\mu mol}{s}$ started to be used for PPF. In today's literature, PAR, PPFD and PPF might be used interchangeably with the units $\frac{\mu mol}{m^2 s}$ and describe the number of photons in Micromoles that the plant can use for photosynthesis per square meter and second. In this thesis, PPFD will be used [41].
Not only the light intensity at the moment is important for the development of the light environment, but also the accumulated light intensity over an entire day. This is where the Daylight Integral (DLI) comes into play, which links the PPFD to the length of daylight per day. DLI is calculated using the light intensity PPFD and the photoperiod t_{photo} in daylight hours per day [33]:

$$DLI = PPFD \cdot t_{photo} \cdot 3.6 \cdot 10^{-3} \tag{2.4}$$

Please note that t_{photo} is a unit-less quantity.

2.3.3 Effects of Different Wavelengths and Light Intensities on Crops

Light intensity and photoperiod are two important environmental factors affecting plant growth [33]. Both too low and too high light intensity affects growth negatively. If the light intensity is too low, the light does not offer enough energy for photosynthesis. This negatively affects growth and development and, should the light be dangerously low, make it impossible for the plant to grow at all. Too high intensity may lead to a decrease in photochemical activity resulting in photoinhibition, where photosynthesis activity declines due to a saturation of the reaction centre of the photosystems [33]. To high intensity can also lead to sunburn or starvation, when the photosynthesis rate is increased and the stomata open to ingest more CO_2. This leads to a high evaporation rate that may not be countered by the water intake of the root system [42].
Even beside the photosynthetic activity, the wavelength can have a strong impact on the development of a plant. Red light can lead to stem elongation and changes in plant anatomy and might inhibit flowering, while blue light inhibits stem elongation and thus compresses the plant. This is important especially in CEA, where vertical space is limited. It also boosts the chlorophyll biosynthesis and photosynthesis [5, 43]. Green light supplemental to red and blue

light has been shown to increase plant growth, if it is available in ratios of 24% or higher. Data about the effect of green light is controversial though, as some studies report reductions in growth, leaf number, internode length, and a delay in flower induction in merigold, tomato, corn, and bean plants [28, 44]. It could be shown that UV light decreased growth and development in cucumber [44, 45], lettuce [46], and oat and canola [47].

2.3.4 Light Installation in EDEN LUNA

In EDEN LUNA, each light source illuminates one or two trays, which each hosts between one and twelve plants. Distance to the light source and number of plants per tray depend on the space requirements of the plant. The distances between tray and light source are

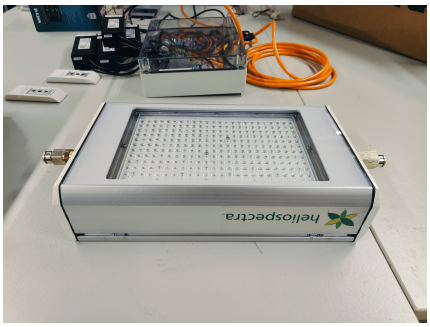
- 198 cm: for rack R3 with two trays for every light source (tall growing plants)
- 87 cm: for rack R4 with two trays for every light source (medium hight growing)
- 52 cm: for rack R1 with two trays per shelf and three shelves
- 49 cm: for rack R1 with two trays per shelf and three shelves
- 38.5 cm: four rack R2 with two trays per shelf and four shelves

Appendix J gives an overview over the potential set up of the plant trays and their illumination in the container. As the distances between the lights and the trays are variable, the light settings must be customized not only for each plant but also for its placement inside the container.
Two types of LED-lamps are used to illuminate the crops: the LX601 and the LX602 with C-Plates using a water cooling system. The data sheets of the air cooled version can be found in Appendix B and Appendix C respectively. Both lamp types have four LED types that irradiate blue, red, far red, or white light:

- 450 nm LEDs: OSRAM LD CQDP-2U3U-W5-1
- 660 nm LEDs: OSRAM LH CPDP-3T4T-1
- 730 nm LEDs: OSRAM GF CSHPM1.24-3S4S-1
- 5700 K LEDs: OSRAM LCW CRDP.PC-LRLT-5F7G-1-R18

LX601 can use up to 120W, while LX602 can use up to 240W.
The channels can be controlled via Wifi or ethernet. The software can be accessed by communicating with the lamps IP-address. The four channels can each be set between 0 and 1000 and function on a per mille basis: 0 means the LEDs are off, while 1000 means the LEDs of that channel are on to their maximum capacity. The intensity in per mille of each channel will in this thesis be described as Setting. Figure 2.2 shows a photo of the lamps.

(a) LED plate



(b) Lamp including connections to water cooling system

Figure 2.2: Heliospectra lamp used in EDEN LUNA

The light spectrum of the lamps can be found in Section 4.3.1.

3 Materials and Methods

This chapter gives an overview of the materials used and methods applied in this thesis. First, in Section 3.1, the process for the development of the light recipes is described. Section 3.2 gives an overview over the programming tools used in this thesis. In Section 3.3 all methods and materials are described that were applied in the experimental verification of the lettuce light recipe. At the end of this Chapter, in Section 3.4, the statistical methods are described.

3.1 Development of Light Recipes

The development of the light recipes was conducted via literary research and using the foundations of the light recipe used in EDEN ISS, which is presented in Chapter 4. Research about required wavelengths was only used when it was conducted using completely artificial light sources. Artificial light sources supplemental to natural light was not incorporated into the development of light environments here, as no daylight will be available during EDEN LUNA or in space stations on the moon. In terms of light intensity, however, literary resources with natural light were consulted when necessary.

3.2 Programming

Calculations of the ratios of the light colours (wavelengths) and the lamp settings were done by programming, as were the statistical analysis of the experiments and their graphical representation. All programming was done using the Python language Python language (3.12.4) [48] using the following packages:

- NumPy [49]
- pandas [50]
- array
- Matplotlip [51]
- ScipPy [52]
- statistics

3.3 Experimental Verification

To test the designed light environment for *L. sativa*, a pretest and two experiments were conducted. In the pretest, the height and illuminated area of plants were measured under control conditions to derive expected growth rate and harvest weight of the lettuce plant. The first experiment tested a designed light environment against a control, which is currently in use in the EDEN Laboratory, while the second experiment tested a different designed light environment at 100%, 80%, and 70% intensity against the control. The light concentrations are shown in sections 3.3.4 and 3.3.5 respectively.

3.3.1 Experimental Equipment

For the experiment the lettuce cultivar (cv.) Salanova EXPERTISE (79-27) from Rijk Zwaan Welver GmbH was used. To measure the spectrum of the EDEN LUNA Heliospectra lamps, the Spectro 320 (D) R5 Optical Scanning Spectrometer in the ranges 390 to 800 nm at a distance of 90 cm to the light source was used. The test set-up can be seen in Figures 3.1 and 3.2. To measure light intensity during the experiments, two PPFD-meters from Apogee Instruments, Inc. were used: (1) MQ-200 with a spectral range of 400 to 700 nm and (2) MQ-610 with a spectral range of 380 to 760 nm. Weight was scaled using the KERN PCB 10000-1 scale. Height was measured using a ruler. Area was estimated by calculating the area of an ellipses, which encompasses all leaves of the plant with the major-axis a and minor-axis b (cf. Fig. 3.4b):

$$A = \frac{a}{2} \cdot \frac{b}{2} \cdot \pi \tag{3.1}$$

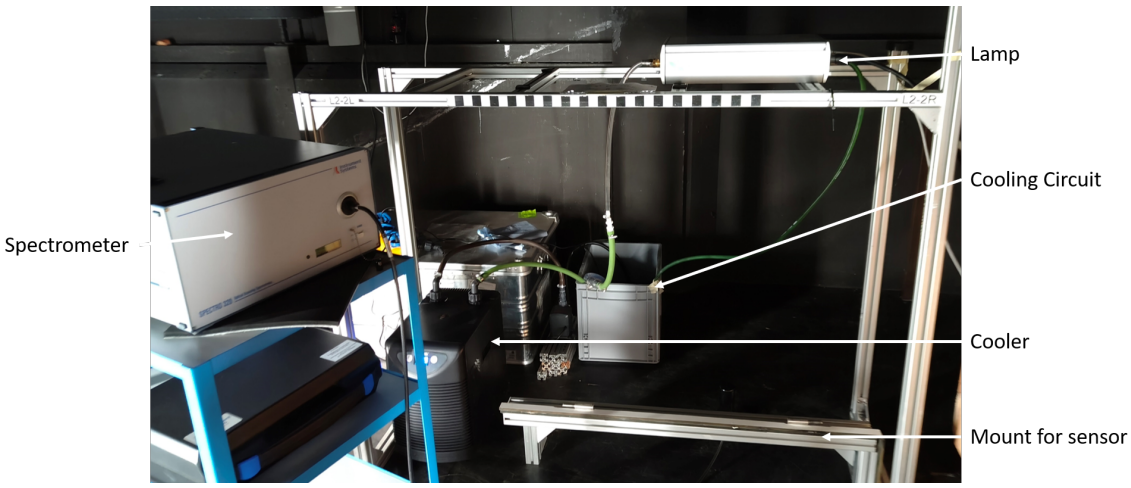


Figure 3.1: Test Stand for Spectrometer Test

Figure 3.2: Test Stand for Spectrometer Test during Use

Power consumption of the lamps was measured using the Voltcraft SEM45000. Regular pictures were taken using the HIKVISION Exir Fixed Dome Network Camera and the HIKVISION IR Mini Dome Network Camera, as well as a mobile phone camera.
The Data Handling and Control System (DHCS) in the EDEN laboratory can only process light settings with an accuracy of 10 per mille.

3.3.2 Environmental Parameters

Besides the light environment during vegetative stage, both experiments were conducted under the same environmental parameters, which are summarized in Table 3.1. The photoperiod consisted of 19 h light and 5 h dark.

Table 3.1: Environmental Parameters in Experiments 1 and 2

Parameter	Value
Day temperature [°C]	between 23 and 26
Night temperature [°C]	between 18.5 and 20
Day Humidity [%]	between 48 and 60
Night Humidity [%]	between 48 and 60
CO_2-level [ppm]	between 550 and 750
Space per plant [cm^2]	336 cm^2

Seeds were germinated hydroponically by planting them in rock wool soaked in water. During seedling stage, the seedlings were grown in a nursery within a nutrient solution and with a light intensity of $150\ \frac{\mu mol}{m^2 s}$ (measured using PPFD-meter No. 2). Figure 3.3 shows the nursery. During the vegetative stage, the nutrient solution was delivered via a pump system through diffusers onto the root system every 7 minutes. The contents of the nutrient solution can be found in Table 3.2.

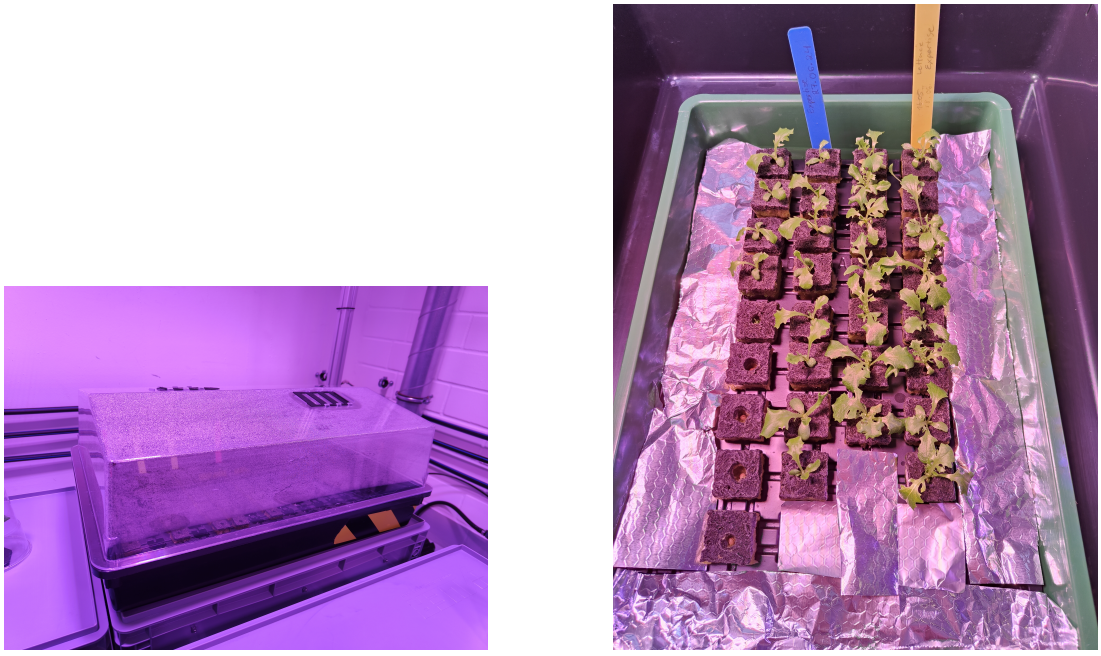
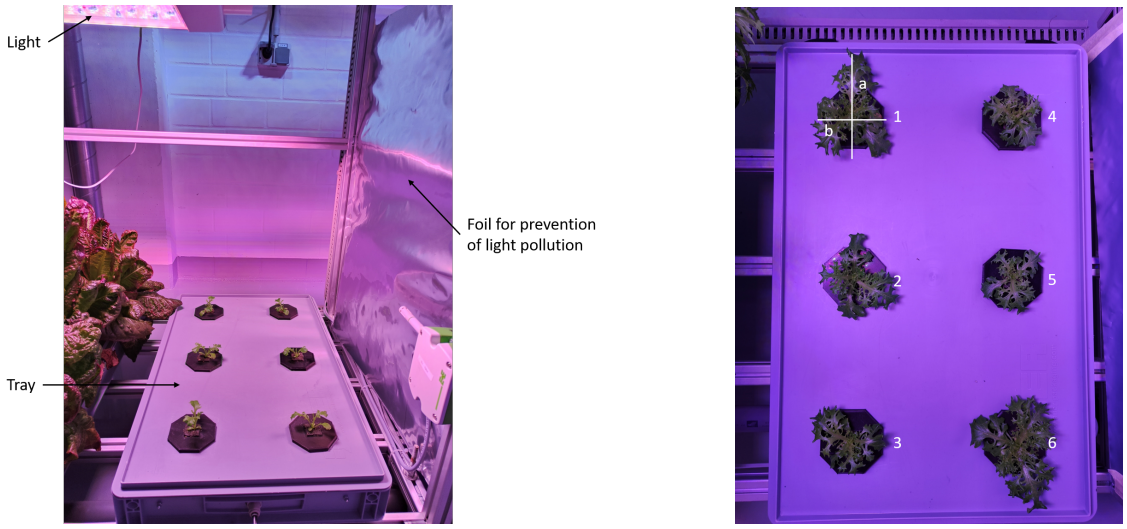


Figure 3.3: Nursery for Seedlings

Table 3.2: Nutrient Solution

Substance	Amount for 150 l nutrient solution
$CA(NO_3)_2 - 4H_20$	70.848
KNO_3	45.495
$MgSO_4 - 7H_20$	36.972
$NH_4H_4PO_4$	8.672
Folicin DP11%	2.468
Micronutrients added to 0.15 l H_20:	
H_3BO_3	0.2145 g
$MnCl_2 - 4H_2O$	0.13575 g
$ZnSO_4 - 7H_2O$	0.0165
$CuSO_4 - 5H_2O$	0.006
H_2MoO_4	0.0015 g

In both experiments, every group consisted of a sample size of 6 plants, grown in one tray with a distance of 66 cm to the middle of the lamp. Silver foil was used to prevent light pollution by shielding the trays from neighbouring lights (cf. Fig. 3.4).



(a) Test Set-Up **(b)** Labelling of Experiment Tray

Figure 3.4: Plant Test Set-Up

3.3.3 Pretest

The pretest was conducted under control conditions of experiments 1 and 2. The plants were in vegetation stage during the whole test with measurements starting at 21 Days After Seeding (DAS) and harvest at 47 DAS. Height and area were measured regularly to derive the expected growth rate of *L. sativa* cv. Expertise.

3.3.4 Experiment 1

In experiment 1, the plants were transferred from the nursery to the tray at 13 DAS and stayed under transparent plastic cups below control light conditions for 2 days, before the light environment of the experiment tray was changed. The light environment of the experiment at 15 DAS and control tray are summarized in Table 3.3.

Table 3.3: Light Environment Experiment 1

Light Colour	Control		Experiment	
	Setting	Light Ratios	Setting	Light Ratios
White (5700 K)	310	-	1000	-
Blue (390 - 500 nm)	680	21.6 %	80	12.59 %
Green (501 - 600 nm)	-	12.24 %	-	17.69 %
Red (601 - 700 nm)	310	62.04 %	750	69.11 %
Far Red (701 - 800 nm)	900	4.12 %	0	0.6 %

The light intensity of the experiment tray was changed regularly in 3 or 4 day increments (twice per week) to follow the growth of the plants and assure the same light intensity at canopy height during the whole growth. The settings during the whole experiment can be found in Appendix D. During the vegetative stage, the number of leaves were counted (until 29 DAS), and height (until 40 DAS) and area (from 27 DAS) were measured. Harvest was conducted at 40 DAS at which point height, area, shoot fresh and shoot dry weight (FW, DW), root FW and root DW, and leaf colour were measured. Shoot DW was measured after drying the leaves at 80°C for 19h in a drying oven. Roots were dried at 80°C for 24h. The number of leaves of each lettuce was counted by cutting each leave from the plant.

3.3.5 Experiment 2

In experiment 2, four trays were installed: a Control, a developed light recipe at high intensity (100%), at medium intensity (~80%), and at low intensity (~70%). The light settings and ratios at the start of the experiment are summarized in Table 3.4. For the 100%, 80%, and 70% trays, the light intensity was lowered in 3 to 4 day increments (twice per week) to achieve a constant light intensity at canopy height. It is to be noted, that while the control, 100%- and 80%-trays were illuminated with a 120 W lamp, the 70%-tray used a 240 W lamp. The settings during the whole experiment can be found in Appendix D. A more detailed description of the light environment can be found in section 4.3.3. The seedlings of the 100% and control trays were transferred into the trays at 20 DAS, while the 80% and 70% seedlings were transferred at 14 DAS. This assured the seedlings were at the same growth status, even though it was discovered that the nutrient solution of the 100% and control seedlings had a low pH, which inhibited their development. Harvest was conducted at 47 DAS for the 100% and Control plants and at 40 DAS for the 80% and 70% plants. This means that plants were harvested 27 or 26 Days After Transplanting (DAT). During the vegetative stage, the number of leaves were counted (until 41 and 35 DAS respectively) and height and area were measured (until harvest at 47 and 40 DAS respectively). After harvest, height, area, shoot FW and shoot DW, root FW and root DW, and

leaf colour were measured. Shoot DW was measured after drying the leaves at 80°C for 19h in a drying oven. Roots were dried at 80°C for 24h. The number of leaves of each lettuce was counted. Additionally, a sensory analysis with between 10 and 13 untrained consumer panelists aged 24-39 was conducted. The panelists were asked to scale the lettuce samples on four criteria: shape, crispiness, colour, and sweetness on a scale of 0 - 6, following an adapted sensory analysis protocol by Lin et al. [53]. 0 was considered very bad or very bitter, while 6 represented very good or very sweet.

- **Shape:** Were the shape and look of the lettuce leaves appetizing? Did they entice the proband?
- **Crispiness:** Did the lettuce feel crispy when bitten into? Was the feeling satisfactorily?
- **Colour:** Was the colour satisfactorily? Was it appetizing?
- **Sweetness:** How sweet or bitter was the taste?

Table 3.4: Light Environment Experiment 2

Light Colour	**Control**		**Experiment 100%**	
	Setting	Light Ratios	Setting	Light Ratios
White (5700 K)	310	-	800	-
Blue (390 - 500 nm)	680	21.60 %	900	29.30 %
Green (501 - 600 nm)	-	12.24 %	-	23.80 %
Red (601 - 700 nm)	310	62.04 %	260	46.09 %
Far Red (701 - 800 nm)	900	4.12 %	0	0.91 %
Light Colour	**Experiment 80%**		**Experiment 70%**	
	Setting	Light Ratios	Setting	Light Ratios
White (5700 K)	850	-	140	-
Blue (390 - 500 nm)	950	29.30 %	160	29.30 %
Green (501 - 600 nm)	-	23.80 %	-	23.80 %
Red (601 - 700 nm)	280	46.09 %	50	46.09 %
Far Red (701 - 800 nm)	0	0.91 %	0	0.91 %

3.3.6 Power Measurements

Power consumption was measured twice: power meters were connected to the 100%- and Control-lamps of Experiment 2 during the vegetative stage to measure the complete power usage during the experiment. As was mentioned in section 2.3.4, the light installation in the EDEN LUNA differs from the light installation in the lab, in which the experiments were conducted. Therefore, the lamp settings were calculated for the lamps and distances for the EDEN LUNA container. Power input was measured for each setting and extrapolated for the growth period by multiplying each power input with the time it is used for, as can be seen in Equation 3.2. W_{total} is the total power consumption in Watthours, P is the power input in Watts, $\frac{h}{d}$ are the hours per day the lamps are used, and d are the number of days of the growth period.

$$W_{total} = \sum P \cdot \frac{h}{d} \cdot d \tag{3.2}$$

The power measurements were done for different combinations of distance between tray and lamp and power of lamp. They are listed in Table 3.5.

Table 3.5: Overview Power Measurements

Crop	Life Phase	Distance [cm]	Lamp
Lettuce	Vegetative	38.5	120 W
Lettuce	Vegetative	50	120 W
Lettuce	Vegetative	38.5	240 W
Lettuce	Vegetative	50	240 W
Lettuce	Seedling	87	120 W
Lettuce	Seedling	87	240 W
Cucumber	Vegetative	189	240 W
Cucumber	Seedling	87	120 W
Cucumber	Seedling	87	240 W

The lamps were not able to reach the target intensities in all combinations. In these cases, the highest possible setting, which does not change the light ratios, was kept until the crops would be tall enough to receive target intensity at canopy height. After this, the intensity was reduced every three days to follow the growth of the crops. This means, that for some combinations (e.g. Lettuce - Vegetative - 50 - 270 PPFD) the settings do not change over the complete vegetative stage. All settings for all power measurements can be found in Appendix E.

3.3.7 Heliospectra Lamps

For the experiments, Heliospectra Lamps LX601 and LX602 with a C-plate and an air cooling system were used. The technical specifications can be found in Appendix B and Appendix C. Like the water-cooled version, the air-cooled LX601 has 4 frequency band channels, which can be controlled independently:

- 450 nm
- 660 nm
- 730 nm
- 5700 K white light

The lamp is controlled via LAN through the laboratory's DHCS.

3.4 Statistical Analysis

For statistical analysis, the Python packages *scipy.stats* and *statistics* and excel were used. For the t-tests, a significance niveau of 0.05 was set. Plots were done using the Python package *matplotlib*.

4 Light Recipes

In this chapter the light recipes are developed. First in Section 4.1, goals for the light recipes will be defined and in Section 4.2, the assumptions under which they are developed explained. The light recipes for lettuce and cucumber are developed in Section 4.3 by first determining the characteristics of the lamps and then a literary research into the light requirements of the crops.

4.1 Definition of Goals for Light Recipes

In space systems, a restricted power budget is allocated to each subsystem. Energy is a valuable commodity that is determined by external conditions such as the yield of solar panels and the strength of solar radiation. Therefore, one goal of the light recipes is to reduce the necessary input of energy without loss of yield by individualizing the light intensities.
Another limited resource is growing space with racks that are limited in terms of height. This is especially important for plants like cucumber that grow in vines and of which only a small part - the fruits - are edible. It is desirable that the plants grow compressed and that as much of the biomass as possible is edible.
As already discussed in Chapter 1 fresh vegetables lead to higher mental well-being and lower diet-fatigue. Diet-fatigue occurs when the same or similar foods are eaten over a longer period leading to loss of appetite. To magnify these effects to their possible maximum, the crops should be tasty and leave a nice feeling when consumed. The vegetables should be appetizing.

4.2 Assumptions

For the development of the light environments, some assumptions have to be made: environmental factors, like humidity, temperature, and nutrient solution are constant and optimal for the plant. All that can change the light requirements of a plant. For example, too little nutrient solution drastically reduces the need for light in the plant as transpiration and photosynthesis continue with light, lower light intensities and darkness will prevent starvation of the plant [31, 42, P. 1057].
It is also assumed that one tray is filled with only one species of plant and all plants are seeded and harvested simultaneously. Only this allows for the correct light environment for each plant and the correct changes during the plants life time. In future, however, it should also be possible to create a mixed culture in which the light settings are as optimal as possible for all plants. This will save space.

4.3 Development of Light Recipes

In this thesis, light recipes for two crops were developed: for lettuce (*Lactuca sativa*) and cucumber (*Cucumis sativus*).
Lettuce was chosen, as it is often used as a model organism in the research around CEA [9, 54].

It has a short life cycle of only about six weeks until harvest, which quickens research, and it is relatively small in contrast to other crops like tomatoes [55]. Since much research has gone into the requirements of lettuce, enough sources regarding the light requirements of lettuce are available. Its short life also allows the realisation of experiments in the scope of this thesis. Cucumber was chosen, because it is a warm-dwelling crop and is a vegetable with one of the highest yields in the world. This means, considerably research has gone into the upbringing of cucumber in greenhouses under artificial lighting [29, 33, P. 211].

4.3.1 Intensity of discreet Wavelengths in the Heliospectra lamps

The spectrum of the 120V-lamps used in EDEN LUNA can be seen in Figure 4.1.

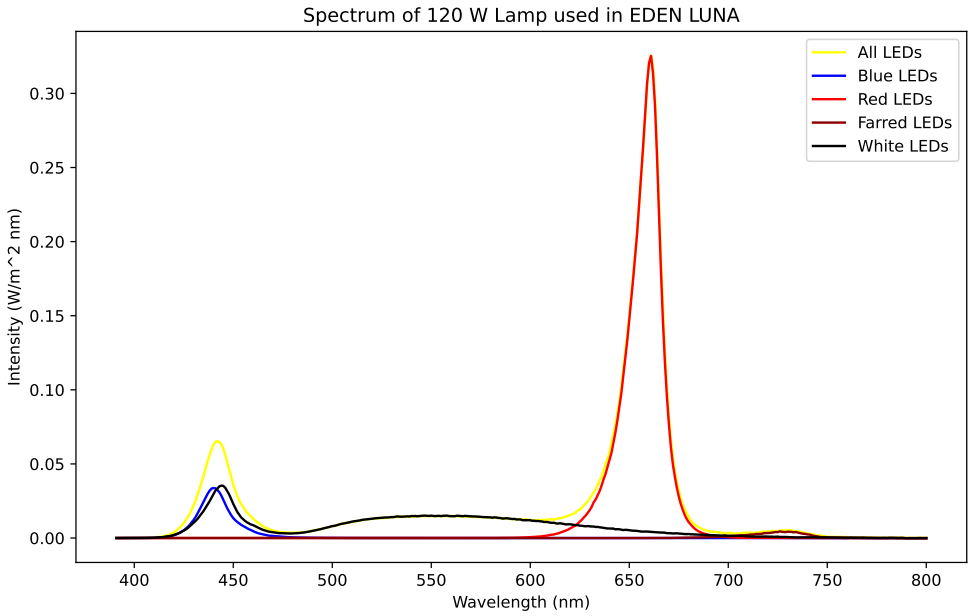


Figure 4.1: Spectrum of 120 W Lamp used in EDEN LUNA

To calculate the maximum PPFD expected of the lamp, the energy per photon $E_{Photon,\lambda}$ for every wavelength λ was calculated using the Planck's constant h and the speed of light c.

$$E_{Photon,\lambda} = \frac{h \cdot c}{\lambda \cdot 10^{-9}} \tag{4.1}$$

The measured intensity I_λ of that wavelength was then divided by the energy per photon to obtain the number of photons of this wavelength Φ.

$$\Phi_\lambda = \frac{I_\lambda}{E_{Photon,\lambda}} \tag{4.2}$$

By dividing this by the Avogadro constant N_A and multiplying it by $1e6$, the power per area is given as number of photons per area and second (PPFD) in $\frac{\mu mol}{m^2 \cdot s}$.

$$PPFD_\lambda = \frac{\Phi}{N_A} \cdot 10^6 \tag{4.3}$$

By summing over all wavelengths, the total PPFD at a distance of 90 cm to the lamp can be calculated:

$$PPFD = \sum_{\lambda=390nm}^{800nm} PPFD_\lambda = 50.44 \frac{\mu mol}{m^2 s} \tag{4.4}$$

This calculation was done using Python. The code can be found in Appendix F. Using the inverse-square law, where I_i is the intensity measured at distance d_i,

$$\frac{I_1}{I_2} = \frac{d_2^2}{d_1^2} \tag{4.5}$$

the expected PPFD can be calculated for the distances available in the container as can be found in Section 2.3.4. The intensity I_1 is the result of Equation 4.4, d_1 is the distance at which the measurement was performed, and d_2 are the distances available in the container. The expected intensity at 198 cm is $I_{198\,cm} = 10.42\ \frac{\mu mol}{m^2 s}$, at 87 cm $I_{87\,cm} = 53.98\ \frac{\mu mol}{m^2 s}$, at 50 cm $I_{50\,cm} = 163.43\ \frac{\mu mol}{m^2 s}$ and at 38.5 cm $I_{38.5\,cm} = 275.64\ \frac{\mu mol}{m^2 s}$.
Following the same process, the expected PPFD for all distances can be calculated for the 240 W lamp.

$$PPFD_{240\,W} = 231.6 \frac{\mu mol}{m^2 s} \tag{4.6}$$

$$I_{198\,cm} = 47.9\ \frac{\mu mol}{m^2 s} \tag{4.7}$$

$$I_{87\,cm} = 247.8\ \frac{\mu mol}{m^2 s} \tag{4.8}$$

$$I_{50\,cm} = 750.4\ \frac{\mu mol}{m^2 s} \tag{4.9}$$

$$I_{38.5\,cm} = 1265.6\ \frac{\mu mol}{m^2 s} \tag{4.10}$$

As can be seen in Figure 4.1 and is explained in Section 2.3.4, the lamp contains 4 different LED-types: blue, red, far red and white. White light itself is a mixture of multiple wavelengths with different intensities (cf. black graph in Figure 4.1). To design a light environment the intensities of the different colours need to be ascertained. For this, all wavelengths of the spectrum were allocated to a colour [56]:

- Blue: 390 nm - 500 nm
- Green: 501 nm - 600 nm
- Red: 601 nm - 700 nm
- Far Red: 701 nm - 800 nm

The sum of the intensities of all wavelengths within one colour were calculated using Python. λ_{start} and λ_{end} are the boundaries mentioned above: for example blue light has the start wavelength $\lambda_{start} = 390\ nm$ and end wavelength $\lambda_{end} = 500\ nm$.

$$I_{Colour} = \sum_{\lambda_{colour}=\lambda_{start}}^{\lambda_{end}} I_{\lambda_{colour}} \tag{4.11}$$

The code can be found in Appendix G.
By dividing the colour intensities by the total intensity, the percentage of each colour was calculated:

$$p_{Blue} = 31.15\% \tag{4.12}$$
$$p_{Green} = 46.9\% \tag{4.13}$$
$$p_{Red} = 19.9\% \tag{4.14}$$
$$p_{FarRed} = 1.6\% \tag{4.15}$$

Using these percentages and the discreet blue, red, and far red LEDs, the light environments were designed in the Sections 4.3.3 and 4.3.4.

4.3.2 Calculation of Light Settings for EDEN LUNA

The light recipes require percentages of specific wavelength ranges that have to be produced with the available LEDs. Since reducing or increasing one LED-type, e.g. the red LEDs, changes the ratio of the other colours, an optimum analysis had to be conducted to calculate the light settings for EDEN LUNA. Since the optimum analysis requires many iterations, a program was written using Python. Figure 4.2 shows the structure of that program. The Python-code for the calculations can be found in Appendix H.
The user specifies both start settings and target ratios. From the start settings, the colour ratios are calculated. Four loops exist within each other: one for each wavelength range that is important for the development of the light recipe (blue, green, red, and far red). Each loop adjusts the ratio of one colour. Using the start settings and their colour ratios, the first loop is entered: green. The difference between the actual (meaning the currently existing green light ratio) and the target green light concentration is calculated normalized to the white light intensity. This difference is than used to adjust the white LED setting. Should the difference between the actual and the target green light concentration be above 0.01 (1%), the calculation will be repeated. If the difference is less than 0.01, the blue light loop is entered.
Again, the concentration difference between the actual and the target blue light concentration is calculated and the difference used to adjust the blue LED setting. If the difference between the actual and the target blue light concentration is above 0.01, the green light loop is entered again. If the difference is less than 0.01, the red light loop is entered.
The red light loop, and then the far red light loop are structured in the same way.
When all light ratios are within 1% of the target ratios or if a loop has repeated 10 000 times,

the program ends and prints the LED settings and the achieved ratios.

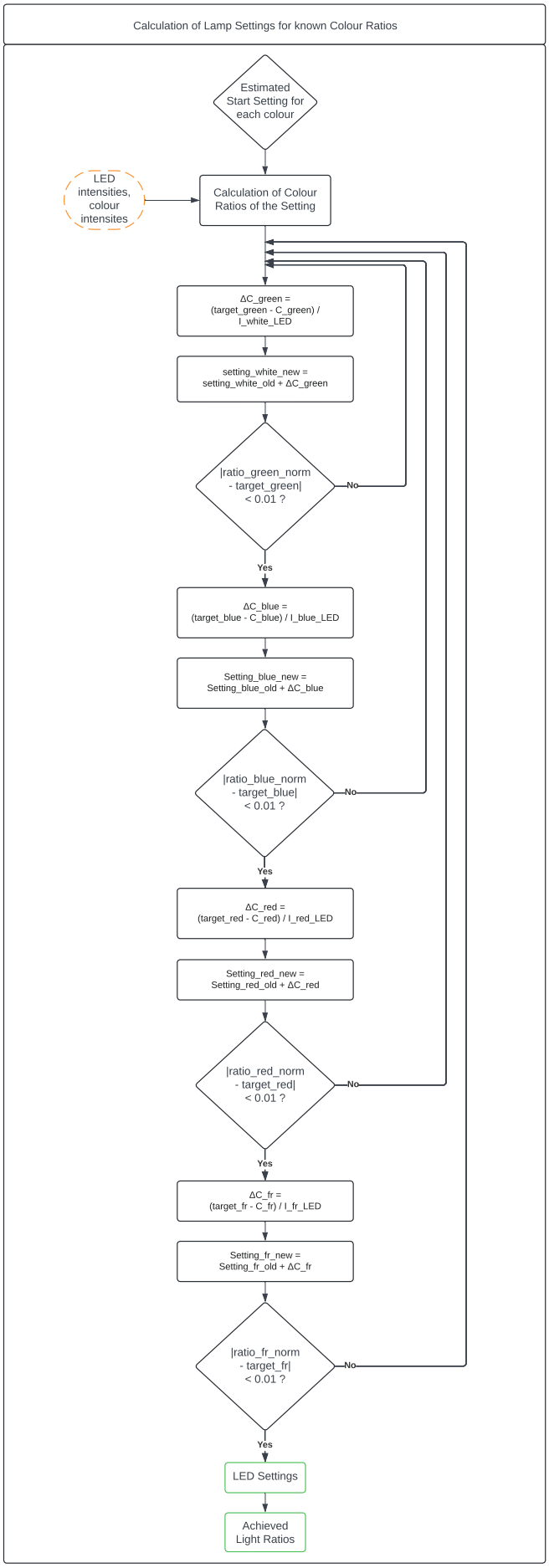


Figure 4.2: Calculation of Lamp Settings

For everyday operations of EDEN LUNA, it might be necessary to calculate the light ratios from the light settings. For this an additional program was written, which can be found in Appendix I. The goal is therefore the relative intensity of each colour $I_{color,rel}$ in the current setting.
First, the relative intensity of white LEDs of the setting I^w_{rel} is calculated by multiplying the setting of the white LEDs $Setting_w$ with the relative intensity of white LEDs, when all LEDs are turned on to 100% $I^w_{rel,100}$.

$$I^w_{rel} = 0.001 \cdot Setting_w \cdot I^w_{rel,100} \tag{4.16}$$

Then, the intensity of each colour in white light I^w_{colour} is calculated by multiplying the $I^w_{colour,rel}$ with I^w_{rel}. $I^w_{colour,rel}$ describes the amount of each coloured light in the white light. As an example, the colour blue is used here.

$$I^w_b = I^w_{b,rel} \cdot I^w_{rel} \tag{4.17}$$

By adding the intensity of the coloured light from the white LEDs I^w_{colou} to the intensity of the coloured light to the coloured LEDs I^{colour}_{colour}, the intensity of all colours and from all LEDs is obtained.

$$I_b = I^b_b + I^w_b \tag{4.18}$$
$$I_r = I^r_r + I^w_r \tag{4.19}$$
$$I_{fr} = I^{fr}_{fr} + I^w_{fr} \tag{4.20}$$

The intensity of green light only has one summand, as there is no green LED. All green light stems from the white LEDs:

$$I_g = I^w_g \tag{4.21}$$

Finally, the intensities of all lights are added together to obtain the total intensity. By dividing each intensity by the total intensity, the relative intensities $I_{colour,rel}$ can be calculated. Again, blue light is used as an example:

$$I_{total} = I_b + I_g + I_r + I_{fr} \tag{4.22}$$
$$I_{b,rel} = \frac{I_b}{I_{total}} \tag{4.23}$$

4.3.3 Lettuce (*Lactuca sativa*)

Lettuce is a leaf vegetable of which the leaves are eaten instead of fruits or flowers. Harvest is therefore conducted before flowering, which leaves two stages of life for which a light recipe

should be created: the seedling stage and the vegetative stage. Besides the general goals for light recipes mentioned in section 4.1, in lettuce and other leafy greens the flowering should take place as late as possible. Lettuce exists in many different cultivars and can have green (for example cultivar (cv.) Expertise) or red leaves (for example cv. Outredgous). Due to the different colouring, a different light recipe may be necessary for green and red leafy greens. This light recipe was developed for green leafed lettuce.
As a crop, two phases of life are interesting in lettuce: the seedling or germination phase, which starts with the germination of the seed. This phase lasts for about 11 to 14 days, in which first the cotyledons and then the first real leaves grow. Following the seedling stage is the vegetative stage, in which the plant grows exponentially. This phase lasts for about 30 days, at which point the plant should be harvested. If the plant is not harvested, it will now produce flowers and move into the reproductive stage [57, 58]. Since at this point the plant puts more energy into the reproduction and less into the production of biomass in the form of leaves, this is to be avoided. This is summarised in Figure 4.3.

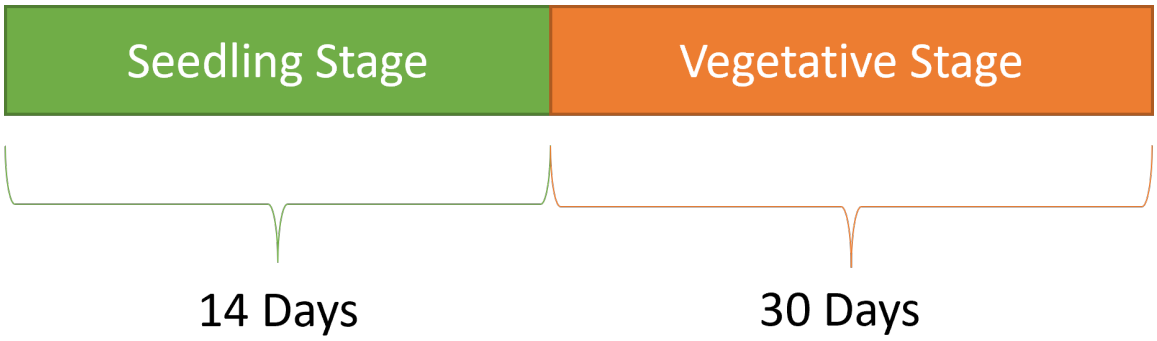


Figure 4.3: Seedling and Vegetative Stages of Lettuce

In this section, the results of the pretest will be disclosed to determine the growth rate of lettuce in the vegetative stage. Afterwards, a light recipe for lettuce in mono culture is developed through literary research and then adapted to EDEN LUNA using the results of the pretest.

Pretest

To provide the correct light intensities during the vegetative state of the plants, the average growth rate over time is necessary. The growth rate was first established during a pretest with six plants. The height of each plant was measured over time, starting at 21 DAS. The lighting conditions were the same as in control group of the experiment as can be found in Chapter 3. Figure 4.4 shows the height of the plants from 21 DAS to harvest on 47 DAS.

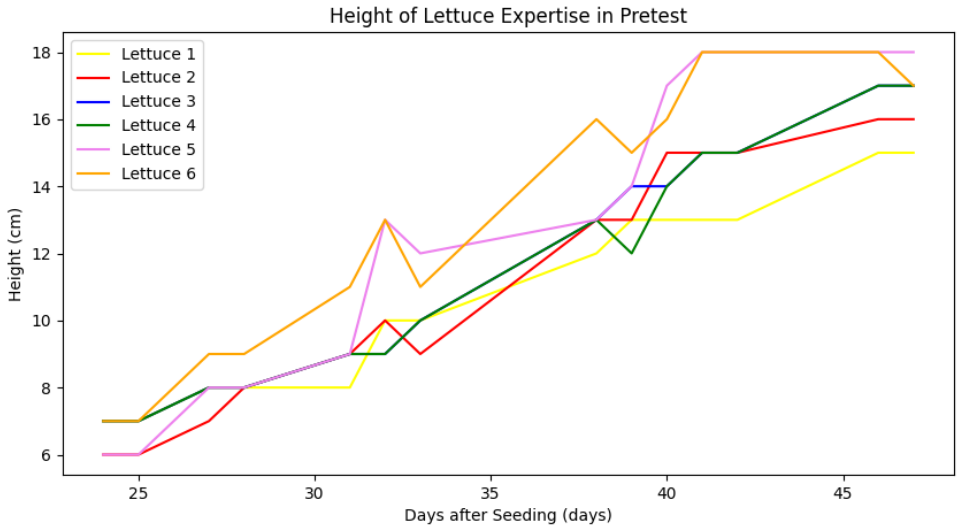


Figure 4.4: Height of Lettuce plants during Pretest

The average growth of the lettuce plants at every time is calculated by calculating the growth on each day and taking the average of all six plants for every day:

$$G = H_{i,d+1} - H_{i,d} \tag{4.24}$$

where G is the growth during one time period, $H_{i,d}$ is the height of a plant i on day d, and $H_{i,d+1}$ the height of the same plant on the following day. As can be seen in Figure 4.5, this approach did not yield any useful results as no mathematical function for the growth of lettuce in the EDEN lab was found. Therefore, the growth was assumed linear with a daily growth of 0.45 cm. The data has been added to the Appendix A.

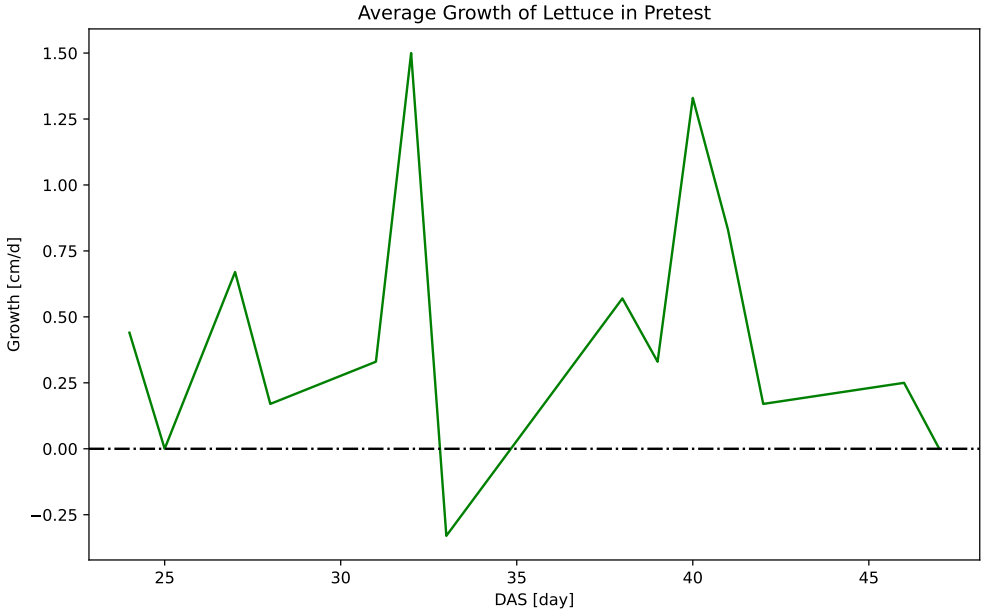


Figure 4.5: Growth of Lettuce during Pretest

Optimal Light Recipe for Lettuce

The seedling phase lasts for about 14 days after germination. For this time, the seedlings live in a nursery. Dependent on their health, they will be transplanted into their trays at about 14 DAS, after which a familiarisation phase of about 2 days follows. Afterwards, the plants enter the vegetative stage.

Testing the quality of lettuce at harvest after different light intensities and photoperiods during the seedling stage, Yan et al. found highest shoot fresh weight in lettuce that were grown under a PPFD of 200 $\frac{\mu mol}{m^2 s}$ for 16 $\frac{h}{d}$ for different red to blue ratios of light. A red to blue ratio of 2.2 had the added benefit of a higher vitamin C content than a ratio of 1.2 [59].

For the vegetative stage, Kang et al. found that photoperiod and light intensity influence the growth of leaf lettuce when they tested four light intensities and three different photoperiods. High light intensities of 290 $\frac{\mu mol}{m^2 s}$ showed stronger growth than lower intensities. They found photoperiods of 18 h light and 6 h dark or 6 h light and 2 h dark increased plant growth [60]. Using Equation 2.4, a DLI of 18.79 $\frac{mol}{m^2 d}$ can be calculated. Koontz and Prince found a 30% to 50% increase of biomass if photoperiod was increased from 16 h daylight to 24 h [61]. While there is some discrepancy between the studies, some found higher shoot dry weights even for higher light intensities of 932 $\frac{\mu mol}{m^2 s}$ for fluorescent and incandescent illumination for some lettuce cultivars [8]. Fu, Li and Wu found a range of 400 to 600 $\frac{\mu mol}{m^2 s}$ to be optimal for the production of lettuce [62].

Chang and Chang tested different combinations of light recipes for seedling and vegetative stage. They found the highest dry biomass at a combination of red, cyan and blue light (RCB) at 42.8%, 30%, and 27.2% respectively during the seedling stage and a combination of light red and light blue light (LrLb) at 61.5% and 38.5% respectively during vegetative stage. At this combination however they also found a high nitrate content of 3500 ppm, which might have negative effects as it is considered a carcinogen [63]. To combat this, an inverse light recipe of LrLb light during the seedling stage and RCB light during the vegetative stage was recommended, which showed a nitrate content of only 3000 ppm [9]. The addition of cyan light was found to increase chlorophyll content, while 24% green light of wavelengths between 500 and 600 nm supplemental to red and blue light increase plant growth. It was speculated that due to not being primarily absorbed by chlorophyll a and b, green and cyan light can shine deeper through the leaves and thus increase photosynthesis in the deeper leaf levels [9, 28]. A study comparing growth of lettuce under only green light to lettuce under white light found an increased shoot growth for green light (510 nm) at 300 $\frac{\mu mol}{m^2 s}$ [64]. This, too, is uncertain, as there have also been studies showing less growth or a decreased photosynthetics rate with the supplementation of green light to red and blue for seedlings [65] and in the vegetative stage respectively [66].

In some studies, plant growth increased with UV light treatments, while others found a decreased growth [9, 46].

For the seedling stage, the light should be a combination of 68.75% red and 31.25% blue light (a ratio of 2.2:1). The PPFD should be 200 $\frac{\mu mol}{m^2 s}$ with a photoperiod of 16 hours. This results in a DLI of 11.52 $\frac{mol}{m^2 d}$.

For the vegetative stage, the light should be combined from 29.5% blue, 24% green (510 nm) and 46.5% red light with a photoperiod of 24 hours. The PPFD should be at 220 $\frac{\mu mol}{m^2 s}$ to reach

a DLI of 19 $\frac{mol}{m^2 d}$.

Light Recipe for Lettuce for EDEN LUNA

It is not possible to directly control the percentage of green light which is irrigated upon the plants. But light of the wavelengths humans see as green are part of the 5700 K white light as shown in Chapter 4.3.1.
The necessary intensity of green light has to be delivered completely by white light, while red and blue light can be subsidized by the red and blue LEDs. Therefore, the use of

- White: 774
- Blue: 1000
- Red: 259
- Far Red: 0

produces a light mix near the target:

- Blue: 30.26%
- Green: 23.01%
- Red: 45.55%
- Far Red: 0.78%.

The target DLI is 19 $\frac{mol}{m^2 d}$, which is produced by a PPFD 220 $\frac{\mu mol}{m^2 s}$ for a photoperiod of 24 hours. Due to other plants requiring a dark period for metabolism processes, this photoperiod is not possible to achieve in EDEN LUNA, where all crops are grown in the same space. The EDEN LUNA greenhouse has a day cycle of 19 hours light and 5 hours darkness. To achieve a DLI of 19 at a photoperiod of 19h, the required PPFD can be calculated using equation 2.4:

$$PPFD = \frac{DLI \cdot \frac{1}{h}}{3.6 \cdot 10^{-3}} = \frac{19 \ \frac{mol}{m^2 d} \cdot \frac{1}{19h}}{3.6 \cdot 10^{-3}} \tag{4.25}$$

$$PPFD = 277.89 \ \frac{\mu mol}{m^2 s} \approx 280 \ \frac{\mu mol}{m^2 s} \tag{4.26}$$

With the developed light mix, the output of the lamps in the EDEN laboratory are at most $180 \frac{\mu mol}{m^2 s}$ at tray level, when measured with the PPFD-meter (1) MQ-200. Additionally, the accuracy of the lamp settings lie at 1%. To reach the target intensity of 220 $\frac{\mu mol}{m^2 s}$, the settings for the lamps of the EDEN laboratory at lowest plant height are therefore as can be found in Table 4.1, the settings during the seedling stage are listed in Table 4.2.

Table 4.1: Start Settings for Lettuce in vegetative stage in EDEN laboratory

LED	Setting	Light Ratio
White (5700 K)	770	-
Blue (450 nm)	900	29.30%
Green (501 - 600 nm)	-	23.80%
Red (660 nm)	260	46.09%
Far Red (730 nm)	0	0.91%

Table 4.2: Start Settings for Lettuce Seedlings - 120 W lamp - 87 cm

Colour	Setting	Light Ratio
White (5700 K)	0	-
Blue (450 nm)	1000	31.26%
Green (501 - 600 nm)	-	0%
Red (660 nm)	236	68.74%
Far Red (730 nm)	0	0%

4.3.4 Cucumber (*Cucumis sativus*)

In contrast to lettuce, in cucumber the fruits are eaten instead of the leaves. Therefore, not only seedling and vegetative stage are of interest for a light recipe, but also the reproductive stage. Here, the plant first forms flowers and than the fruits, which are harvested. Finally, the quantity and quality of fruits will decrease due to old age. Figure 4.6 shows the stages of the life cycle of cucumber [67].

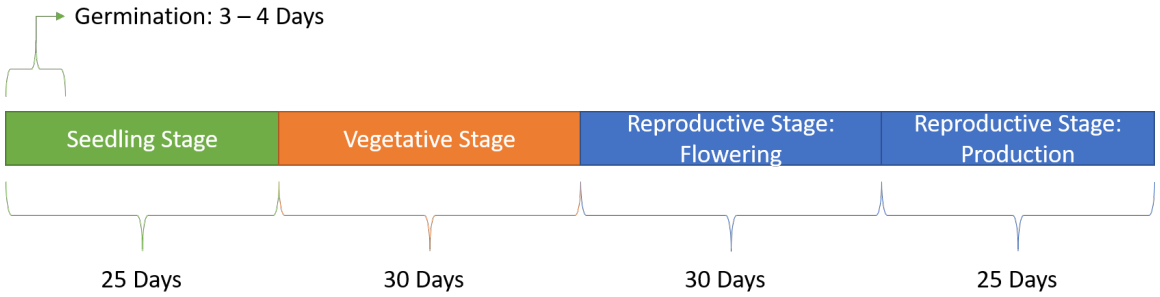


Figure 4.6: Life Cycle of Cucumber

Based on experience, the cucumber plants cv. Picowell in the EDEN lab grow in linear fashion with a rate of 6.9 $\frac{cm}{d}$ with the growth declining after day 20 oft the production stage. As for lettuce, the growth rate is necessary to reduce the light settings regularly, allowing the light intensity at canopy height to stay constant.
During EDEN ISS, a cucumber light environment was developed, which showed a high yield. Table 4.3 shows the settings and the corresponding light ratios of EDEN ISS, which produced a PPFD of 300 $\frac{\mu mol}{m^2 s}$. Based on these lessons learned and incorporating literature, a light recipe was developed here.

Table 4.3: Cucumber light environment in EDEN ISS

Colour	Setting	Light Ratio
White (5700 K)	440	-
Blue (390 - 500 nm)	1000	24.72%
Green (501 - 600 nm)	-	13.7%
Red (601 - 700 nm)	360	57.87%
Far Red (701 - 800 nm)	1000	3.71%

Optimal Light Recipe for Cucumber

Much research has gone into the light requirements of cucumber seedling in greenhouses under artificial light as a high quality of seedlings is necessary for a high yield. Growing different cultivars of cucumbers under different DLI for 23 days, Ji et al. concluded that a DLI of 14.4 $\frac{mol}{m^2 d}$ lead to the best health for two of the cultivars, while one cultivar showed the highest health index under 17.3 $\frac{mol}{m^2 d}$ [33]. In a study by Yan et al. testing the responses of seedlings to different photoperiods and light intensities under the same DLI a photoperiod of 16 hours daylight was concluded to be enough, while longer photoperiods of 19 and 22 hours per day did not increase dry or fresh weight [68].

Hogewoning et al. tested the response of cucumber seedling to different blue to red ratios. They concluded that blue light is necessary to prevent dysfunctional photosynthesis and photosynthesis and biomass increases with an increasing blue light ratio of up to 50%. CO_2 fixation was highest for blue light ratios between 7% and 30% [69]. In another study by de Silva et al. it was shown that for cucumber, sweet pepper, and lettuce seedlings, the red and blue light significantly increased the number of leaves and lead to higher root length and root dry matter in cucumber seedlings compared to cool-white light from fluorescent bulbs [43]. This suggests that a red and blue light should appear in ratios of 70% to 30% in the light environment for cucumber seedlings.

UV-B light was shown to dwarf seedlings and lead to a sturdier phenotype without affecting yield. It was irradiated for 4 h (10 am to 2 pm) per day with an intensity of 1.23 $\frac{kJ}{m^2 s}$ from the moment the first true leave - the first leave grown after the cotyledons - reached a diameter of 5 cm. This was done until the end of the seedling stage [70]. The first true leaves appear at 5 - 6 DAS [71].

In a study conducted by Brazaitytė et al. green light of 520 nm and orange light of 622 nm supplemental to 447, 638, 669, and 731 nm LEDs accelerated growth in transplants and lead to earlier flowering and fruiting of adult plants [45]. It is noted that other research contradicts the positive effect of orange light by showing slower growth [72]. A mix of blue, red, and far red light should therefore be supplemented with green light.

According to Ji et al., cucumbers should receive light for a photoperiod of 16 h per day during their seedling stage. With a DLI of 14.4 $\frac{mol}{m^2 d}$, the PPFD can be calculated using Equation 2.4 to 250 $\frac{\mu mol}{m^2 s}$. While Ji et al. did not test the cultivar planned for EDEN LUNA (*C. sativus* cv. Picowell), it is assumed that this light intensity is adequate. The light should consist of 28.2% blue light, 6% green light (520 nm), and 65.8% red light. Additionally, starting the moment, the first leave reaches a diameter of 5 cm, UV-B light should be irradiated for four hours per day at an intensity of 1.23 $\frac{kJ}{m^2 s}$.

Haque, Hasanuzzaman and Rahman found that while there is no significant variation in main stem length under different light intensities, there was a shorter internode at 75% PPFD from their full sunlight conditions (100%). As shorter internodes contribute to shorter plants, this is of interest in vertical farming. Chlorophyll concentration was also highest at 75%. Most other factors that were tested (number of leaves, leaf area, leaf weight) were significantly reduced at with reduced PPFD. Yield was highest, though not significantly so, at 100% PPFD, as was individual fruit weight [73]. It can be concluded that while slight reductions in light intensity

do not reduce yield significantly (70%) and can actually be of benefit in a vertical farming by reducing internode length, should the reduction be too high (50%), yield suffers significantly. Hogewoning found that the light mix should contain a ratio of 70% red and 30% blue light. For humans to correctly see the leaves as green and therefore be able to account for plant health, the share of green light should be at least at 10%.
Far red light was found to induce photosynthesis by equalizing the excitation of chlorophyll b and a and therefore the photosystems I and II. It was found that adding 50 $\frac{\mu mol}{m^2 s}$ of far red light to a mix of 200 $\frac{\mu mol}{m^2 s}$ blue and red light was enough to reach this effect [74]. This is a share of 20% far red light.
A light environment for cucumbers in the vegetative stage should therefore be comprised of 24% blue, 10% green, 57% red, and 9% far red light at an intensity of 250 $\frac{\mu mol}{m^2 s}$ for a photoperiod of 16 h.
By inducing flowering at the end of the vegetative stage, the harvest is more synchronized and might be easier to plan for. As mentioned in Chapter 2, flowering can be induced by stressing the plant. Stressors can be both high- and low-intensity lights [38]. Therefore, on 52 DAS, the light intensity should be turned up significantly for three days.

Light Recipe for Cucumber for EDEN LUNA

As was the case for lettuce, EDEN LUNA does not have green LEDs at it's disposal. Therefore, the green light needs to be supplied by the white LEDs. Since the daytime in EDEN LUNA is 19 h, to obtain a DLI of 14.4 $\frac{mol}{m^2 d}$, the PPFD must be 166 $\frac{\mu mol}{m^2 s}$ (cf. Equation 4.4). Table 4.4 shows a general light settings at highest intensity. Since the measured intensity at 87 cm, which is the distance from the light in the nursery, is only 109 $\frac{\mu mol}{m^2 s}$, the highest settings are thus used.

Table 4.4: Start Settings for Cucumber Seedlings in EDEN LUNA

Colour	Setting for 240 W lamp - 87 cm	Light Ratio
White (5700 K)	101	-
Blue (390 - 500 nm)	1000	28.78%
Green (501 - 600 nm)	-	5.14%
Red (601 - 700 nm)	270	65.91%
Far Red (701 - 800 nm)	0	0.18%

At the time of transplanting (after 25 days) the cucumber plants have a height of about 33.5 cm. The start settings for cucumbers after transplanting can be found in Table 4.5. Calculating the ratios from EDEN ISS in Table 4.3, the red to blue ratio of 70% to 30% was achieved:

$$0.2442 + 0.5787 = 0.8259 \tag{4.27}$$

$$c_{blue} = \frac{24.42}{82.59} = 0.299 \tag{4.28}$$

$$c_{red} = \frac{57.87}{82.59} = 0.701 \tag{4.29}$$

Since the lamps in EDEN LUNA have a very low output in the far red range (701 - 800 nm),

the share of 9% cannot be reached without turning the other LEDs down drastically. The target ratios for the light environment were therefore adjusted to a lower far red target ratio of 4%.

Table 4.5: Start Settings for Cucumber during the Vegetative Stage in EDEN LUNA

Colour	General Setting	Setting for 240 W lamp - 198 cm	Light Ratio
White (5700 K)	313	313	-
Blue (390 - 500 nm)	1000	1000	25.72%
Green (501 - 600 nm)	-	-	11.36%
Red (601 - 700 nm)	320	320	58.75%
Far Red (701 - 800 nm)	1000	1000	4.17%

Using the settings for cucumber during the vegetative stage, the PPFD was measured. Because the test stand was limited in size, the measurements could not be conducted at a distance of 198 cm. The PPFD was therefore measured at a distance of 50 cm and the result extrapolated using the inverse-square law (c.f. Equation 4.5). Hence, the expected achievable PPFD at 198 cm is:

$$I_{198} = \frac{(50\ cm)^2 \cdot 459 \frac{\mu mol}{m^2 s}}{(198\ cm)^2} = 29.3 \frac{\mu mol}{m^2 s} \tag{4.30}$$

The intensity does not reach the target intensity of 166 $\frac{\mu mol}{m^2 s}$. To reach that intensity, the red and white channels can either be turned up or during the first weeks, the intensity is not turned down. The first option - turning up the red and white channels - would lead to a higher percentage of red light, which might lead to internode elongation and thus lengthen the plant. In the second option, the plants do not receive the target PPFD until they have grown enough.

5 Results

This chapter presents the results of the experimental verification of the lettuce light recipe in Section 5.1. Afterwards, the expected power consumption of the light recipes for EDEN LUNA is calculated in Section 5.2.

5.1 Experiments with Lettuce (*L. sativa*)

The experiment was planned in two runs. In the first, a light recipe was carried out according to Section 3.3.4, in the second, the light recipe developed in Chapter 4 was evaluated at three different intensities incorporating the results of the first experiment. Additionally, a power measurement was carried out to estimate the power usage of the light recipes.

5.1.1 Run 1

The control plants were significantly taller than the experiment plants ($p<0.5$) with a height of on average 13.92 cm, while the experiment plants had an average height of 12 cm. As can be seen in Figure 5.1 the experiment plants started a little taller on average. On 19 DAS the growth rate of the control plants exceeded the growth rate of the experiment plants. By 20 DAS the control plants were on average taller than the experiment plants.

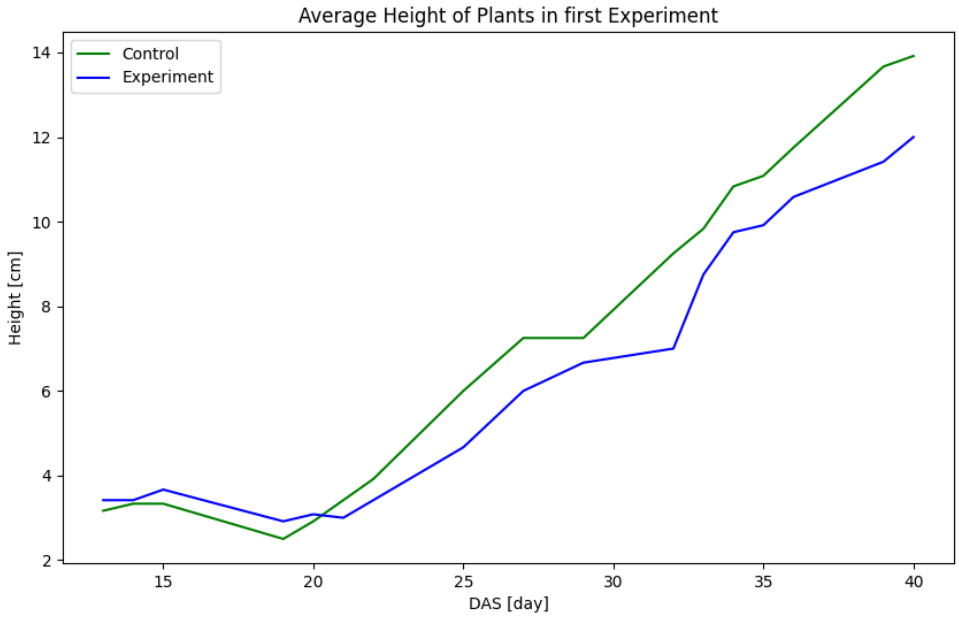


Figure 5.1: Average height of Lettuce plants in first Experiment

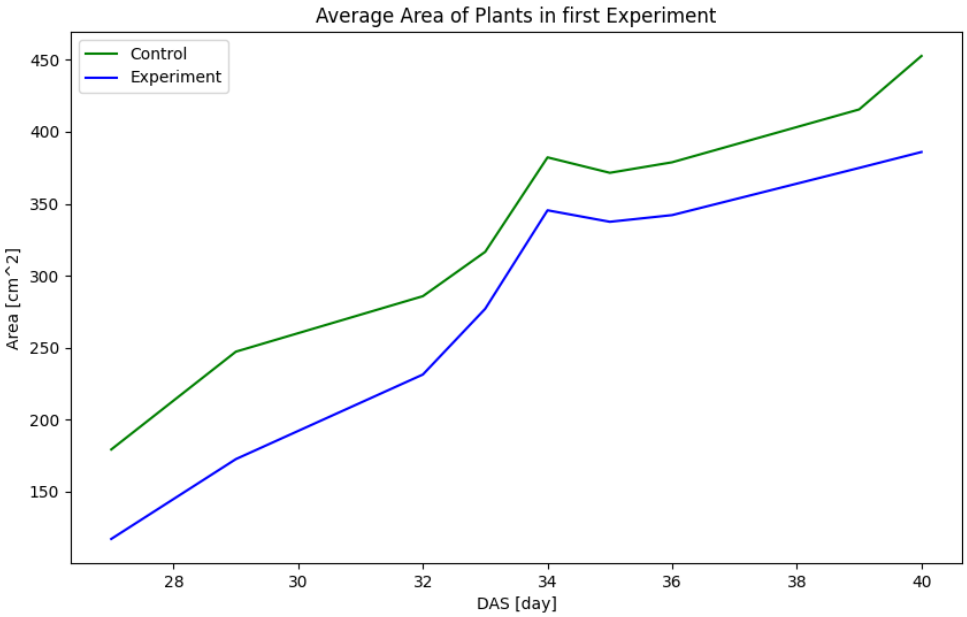
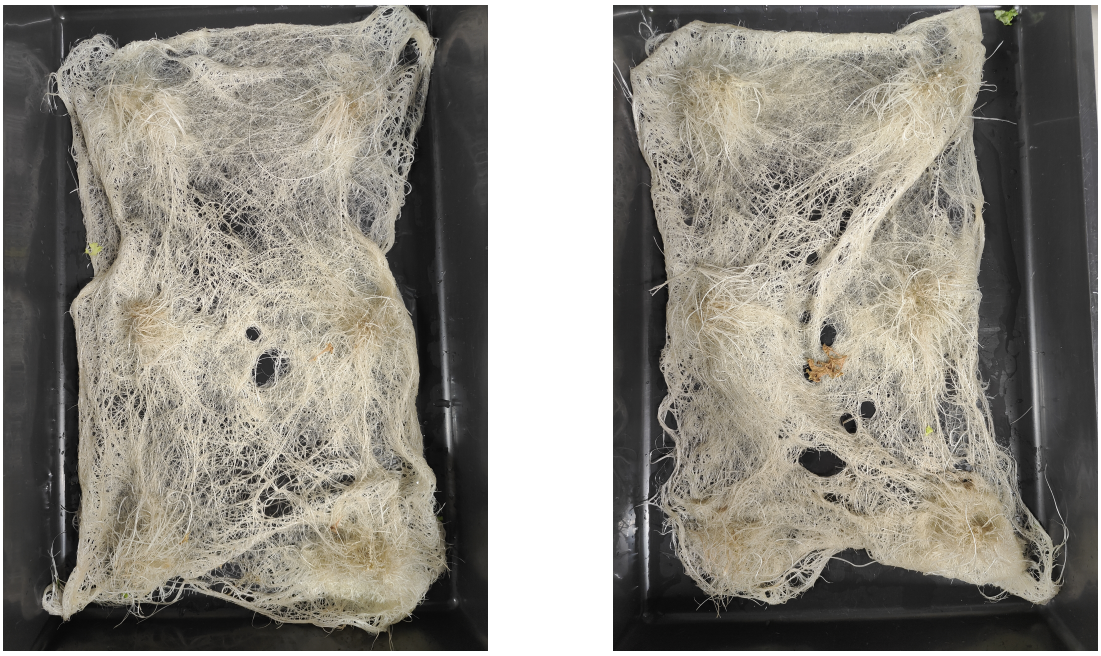


Figure 5.2: Average area of Lettuce plants in first Experiment

While the control plants covered a larger area on average, the difference was not significant ($p>0.5$). In contrast, the experiment plants had more leaves on average ($p>0.5$).

Figure 5.3: Leaves counting after harvest

Both shoot FW and shoot DW and root FW and root DW were higher in experiment plants. Since the roots of the plants grew together (cf. fig 5.4a), it was impossible to derive the root weights of individual plants and therefore impossible to use statistical tests to ascertain significance.



(a) Control Tray **(b)** Experiment Tray

Figure 5.4: Roots on Day of Harvest in first Experiment

The differences of shoot weight (fresh and dry) were not significant (p>0.5). The results have been summarised in Table 5.1.

Table 5.1: Results of Experiment 1

	Experiment	Control	Significance
Ø Height [cm]	12 ± 1.26	13.92 ± 1.46	significant ($p = 0.035$*)
Ø Area [cm^2]	385.96 ± 75.35	452.72 ± 67.32	not significant ($p = 0.137$)
Ø No. of leaves	39.17 ± 12.09	27.17 ± 6.34	not significant ($p = 0.057$)
Ø Shoot fresh weight [g]	135.33 ± 38.69	131.63 ± 43.05	not significant ($p = 0.879$)
Ø Shoot dry weight [g]	8.7 ± 1.31	8.0 $\pm 1.81\pm$	not significant ($p = 0.601$)
Ø Fresh-Dry Shoot Ratio	17.58 ± 1.5	19.86 ± 0.59	not significant ($p = 0.058$)
Root fresh weight [g]	26.3	20.55	not applicable
Root dry weight [g]	4.6	3.7	not applicable

The leaves of the experiment plants had a stronger red and green coloring and less blue, though the difference was not significant (cf. Table 5.2). Figure 5.5 shows the control and experiment trays on the day of harvest.

Table 5.2: Colouring of the Leaves in Experiment 1

	Experiment	Control	Significance
Red	41.4%	39.6	not significant ($p = 0.28$)
Blue	7.1%	10.8%	not significant ($p = 0.47$)
Green	51.4%	49.6%	not significant ($p = 0.60$)

The light intensity of the experiment was always higher than the control. Target intensity was

(a) Control Tray **(b)** Experiment Tray

Figure 5.5: Experiment 1 on the Day of Harvest

270 $\frac{\mu mol}{m^2 s}$. In this first experiment, light intensity was measured with the MQ-200. The target intensity was never measured, probably due to the PPFD-meter being insensitive due to age. This is further discussed in Section 6.3. The light intensity of the experiment was always between 160 and 198 $\frac{\mu mol}{m^2 s}$, while the light intensity of the control was between 123 and 155 $\frac{\mu mol}{m^2 s}$. Light intensity of the experiment was also more variable than that of the control, while the control's light intensity mostly increases over time and with the plant's growth.

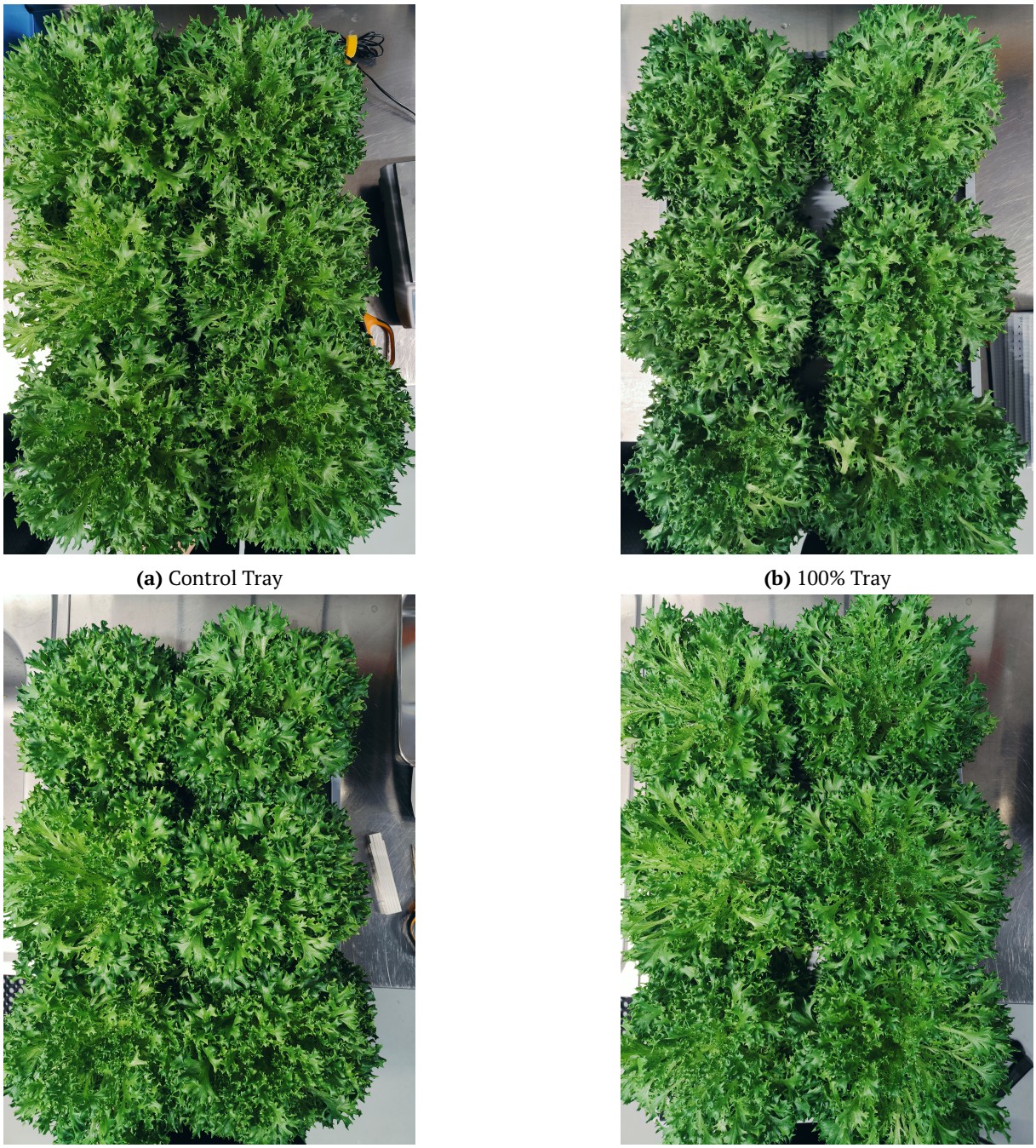
5.1.2 Run 2

The second experiment compared the growth of three different intensities of the developed light environment against the control. As many studies reported beneficial results for higher light intensities (cf. section 4.3.3), the 100%-intensity was determined to be at 270 $\frac{\mu mol}{m^2 s}$ at canopy height. Lower intensities were at a similar intensity to the control (220 $\frac{\mu mol}{m^2 s}$) and at a lower intensity (200 $\frac{\mu mol}{m^2 s}$). The results can be found in Table 5.3.

Table 5.3: Results of Experiment 2

	Control	100%	80%	70%
Ø Height [cm]	14.5 ±0.76	12.17 ±0.75	13 ±0.76	11.5 ±0.65
Ø Area [cm^2]	431.84 ±64.38	397.87 ±28.54	426.46 ±63.34	388.25 ±31.88
Ø No. of leaves	22.82 ±3.18	26.33 ±5.15	22.2 ±2.32	21.83 ±2.67
Ø Shoot fresh weight [g]	143.72 ±29.98	106.80 ±16.47	118.70 ±20.82	80.45 ±14.93
Ø Shoot dry weight [g]	7.67 ±1	6.5 ±1	6.37 ±0.12	4.47 ±0.59
Ø Fresh-Dry Shoot Ratio	19.92 ±3.16	19.39 ±0.38	21.35 ±0.75	20.25 ±0.65
Root fresh weight [g]	88.4	90.3	92.4	72.4
Root dry weight [g]	2.4	1.5	1.2	2.3

Figure 5.6 shows the trays right before harvest.



(a) Control Tray

(b) 100% Tray

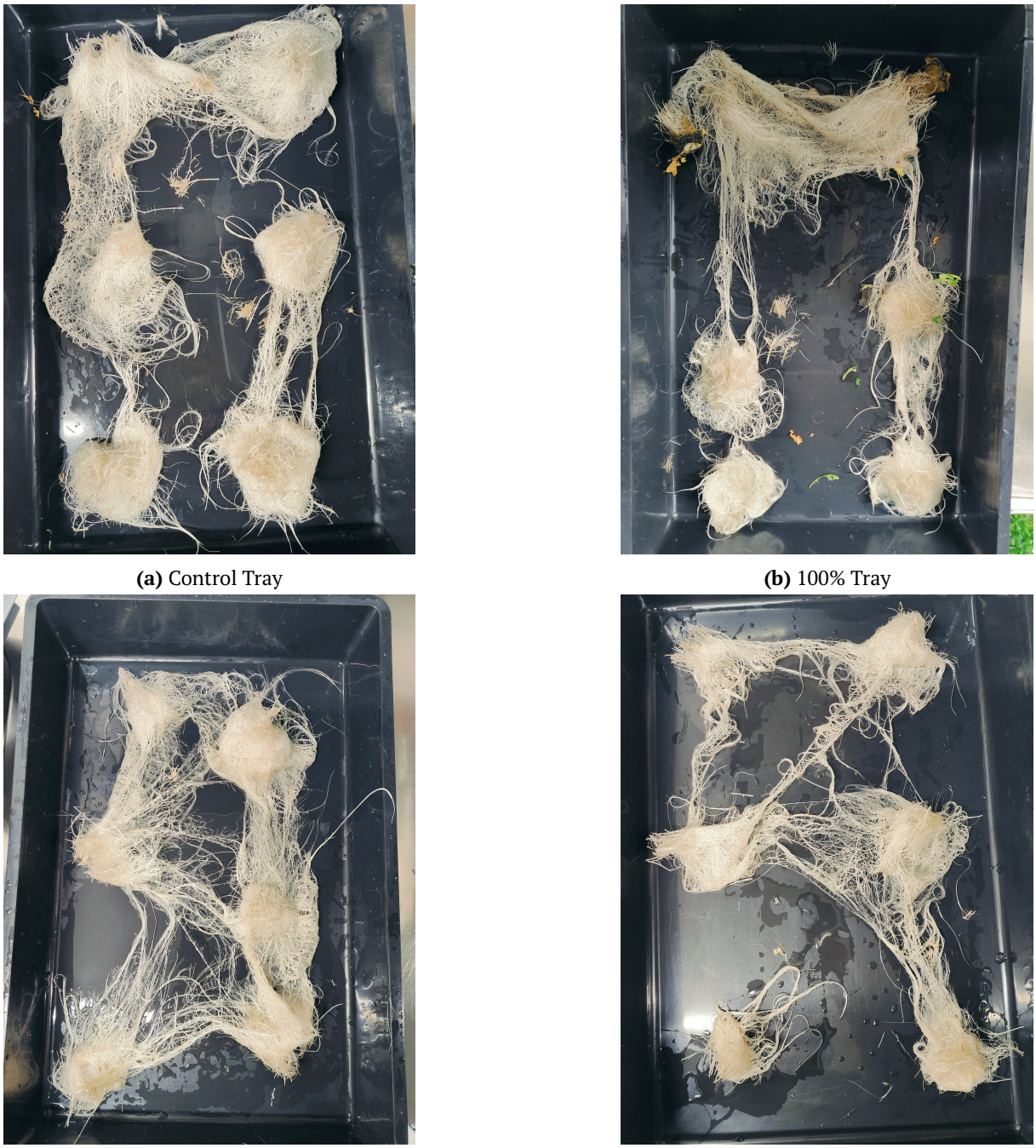
(c) 80% Tray

(d) 70% Tray

Figure 5.6: Experiment 2 on the Day of Harvest

With 14.5 ± 0.76 cm for the control plants, the difference in height to the 100%-plants ($p<0.001$) with 12.17 ± 0.75 cm and the 70%-plants ($p<0.001$) with 11.5 ± 0.65 cm was highly significant. The control plants were significantly taller than the 80%-plants ($p<0.05$) with 13 ± 0.76 cm. The differences between 100%-plants and both 80%- and 70%-plants were not significant with $p=0.111$. The difference in height between the 80%- and 70%- plants was very significant.
While the growth area of the control plants was biggest with 431.84 cm^2 (cf. Table 5.3), the differences to 100%- (397.87 ± 28.54 cm^2), 80%- (426.46 ± 63.34 cm^2) and 70%-plants (388.25 ± 31.88 cm^2) are not significant.
With on average 26.33 ± 5.15 leaves, the 100%-plants had most leaves at the time of harvest.

This is however not a significant difference to the other light settings.
The control plants showed the highest shoot FW, with the 80%-plants following. The difference between control and 100% and control and 70% are significant. The 100%-plants and 80%-plants are significantly heavier than the 70%-plants.
In the measurement of the shoot DW, a mistake had been made and one data point of the 100%-plants had to be discarded. Here, only two data points were available for statistical analysis. On average, the control plants had the highest shoot DW with 7.67 $\pm$ 1 g. This is significantly more than the 70%-plants ($p<0.05$). The 80%-plants came after with 6.37 $\pm$ 0.12 g, which is significantly heavier than the 70%-plants ($p<0.05$).
The fresh-dry shoot weight ratio was highest for the 80%-plants, meaning that per dry biomass the 80%-plants store most water. However, this was not significant.
The root FW was biggest for the 80%-plants with 92.4 g for all six plants combined. Pictures of the roots can be found in Figure 5.7.
The root dry weight of the control plants was highest, with the 70%-plants following closely (2.4 g and 2.3 g respectively). The 80%-plants had the lowest root dry weight with 1.2 g.



(a) Control Tray

(b) 100% Tray

(c) 80% Tray

(d) 70% Tray

Figure 5.7: Roots of Experiment 2 after Harvest

The results of the sensory analysis are shown in Figure 5.8. In general, the sweetness of the lettuce was considered to be medium in contrast to the lived experience on other lettuce of the probands. In the colour no big difference was perceived between the types with all types having been awarded between 3.7 and 4.05 points on average. The 80%-plants were awarded the most points in all evaluation criteria with the largest difference in sweetness. The 100%-plants were evaluated worst for shape and crispness and next to last for colour and sweetness. The control plants were evaluated worst for colour and sweetness and next to last for shape and crispness. This leaves the 70%-plants as second best in all categories.

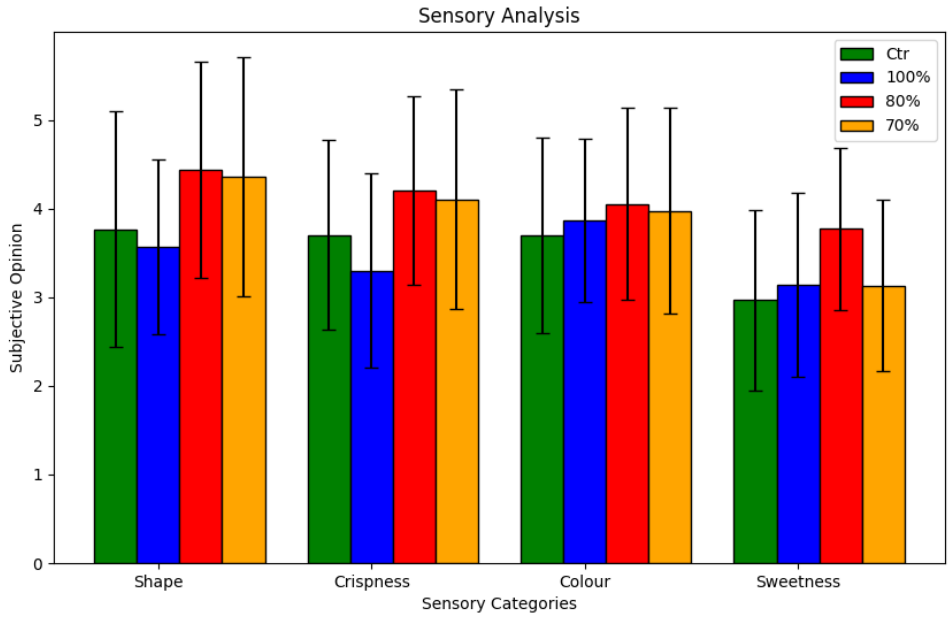


Figure 5.8: Sensory Analysis of second Experiment

Figure 5.9 shows the average height of the lettuce during the vegetative stage measured every day after transplanting: Days After Transplanting (DAT). As can be seen, the lettuce seedlings start on 0 DAT at a bit over 2 cm on average, with the 80%-plants being a bit smaller at 1.8 cm on average. This difference is equalized by day 2. The growth rate is similar for all plants during most of the vegetative state. After day 14 the 100%-plants are consistently smaller than the other plants until day 25, when the 70%-plants may be overtaken in height. Although it is impossible to say if this would have held up as the 70%-plants were harvested on day 25.

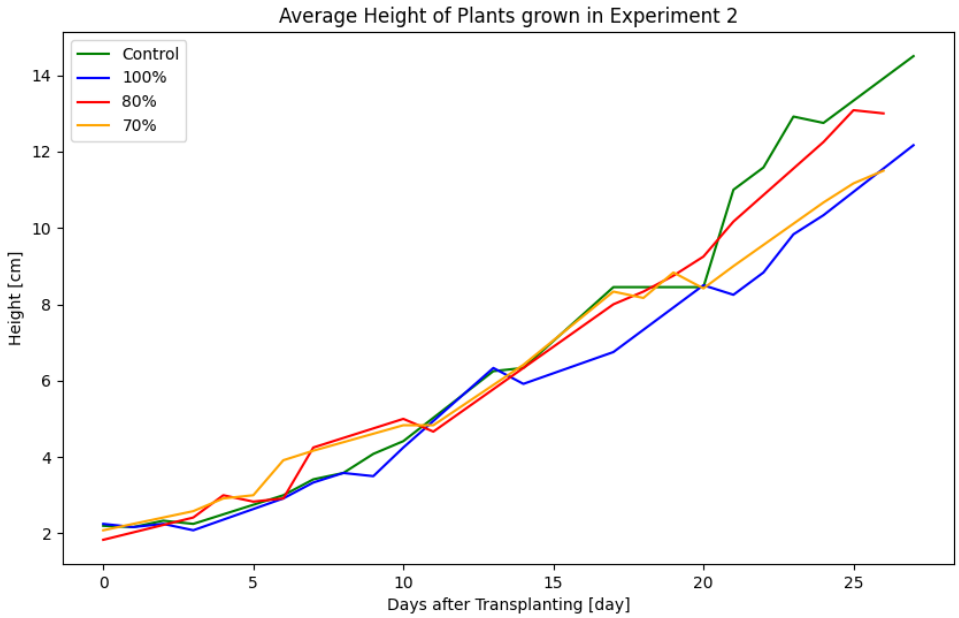


Figure 5.9: Average Height of plants in the second Experiment

The light intensity was measured using the MQ-610. The light intensity of the 70%-plants was for the most part lower than all other light intensities in a range between 157 and 221 $\frac{\mu mol}{m^2 s}$. The intensity at canopy height of the 80%-plant was mostly lower than the control plants. The control intensity was highest for most of the growth period.

5.2 Expected Power Consumption

To estimate the expected power consumption of the different light environments, power meters were used during the second experiment to measure the power consumption of the control and the 100%-lamps. It was found, that the 100%-lamp used 126% of the control-lamp's power. The power consumption can be found in Table 5.4.

Table 5.4: Power Consumption during Experiment 2

100%	Control
156.300 kWh	124.219 kWh
1.26	1

To estimate the power consumption in EDEN LUNA, the light recipes were recalculated for the distances and lamps used in the EDEN LUNA FEG and instantaneous measurements were carried out. These were then extrapolated to an entire growth cycle. The results can be found in Table 5.5.

Table 5.5: Estimated Power Consumption for Lettuce in EDEN LUNA

	Seedling	Control	100% (270 PPFD)	80% (220 PPFD)	70% (200 PPFD)
120 W - 38.5 cm	-	28.567 kWh	32.931 kWh	29.444 kWh	28.284 kWh
120 W - 50 cm	-	28.567 kWh	34.177 kWh	34.177 kWh	34.177 kWh
240 W - 38.5 cm	-	37.701 kWh	24.207 kWh	20.750 kWh	18.843 kWh
240 W - 50 cm	-	48.162 kWh	40.506 kWh	32.676 kWh	30.072 kWh
120 W - 87 cm	8.057 kWh	-	-	-	-
240 W - 87 cm	28.701 kWh	-	-	-	-

In the seedling stage, the 120 W lamp uses only 28% of the power usage of the 240 W lamp. During the vegetative stage, it is probable, that the 120 W with a distance of 38.5 cm will be used for lettuce in EDEN LUNA. The 70%-lamp used least power, though the difference to the control-lamp is small. Most energy was used by the 100%-lamp with 33 kWh. The difference between the control and the 80%-lamp is 3%. The energy used by the 240 W lamp for the same distance is 32% higher than for the 120 W lamp. The 240 W-lamp used most energy using the control light settings and less for 100%-, 80%-, and 70%-light settings in that order.
The cucumber seedlings will be planted with a distance of 87 cm to the 240 W-lamp, and will then be transferred to trays with a distance of 189 cm to a 240 W-lamp. As for lettuce, calculations were done for the cucumber light recipe in Table 5.6.

Table 5.6: Estimated Power Consumption for Cucumber in EDEN LUNA

	Seedling	Vegetative	Reproductive: Flowering	Reproductive: Production
240 W - 189 cm	-	96.216 kWh	96.216 kWh	45.833 kWh
120 W - 87 cm	16.863 kWh	-	-	-
240 W - 87 cm	58.188 kWh	-	-	-

The total power costs for one cucumber plant would therefore be 296.5 kWh assuming that only one cucumber seedling and one transplant would grow under the same lamp. The actual power cost would be lower as many seedlings can be grown under the same light and two cucumber plants of the vegetative and reproductive stages can grow under one light. Therefore, in EDEN LUNA, the power consumption for one cucumber plant would be halved. In larger productions with specific nurseries for different crops, the power consumption per plant would decrease further.

6 Discussion

This following chapter discusses the results of both experiments in Sections 6.1 and 6.2. Additionally, in Section 6.3 problems arising from measurement equipment are discussed and the errors are estimated. Subsequently, in Section 6.4.1, suggestions are given for the practical application of light recipes in EDEN LUNA and for changes to the light setup in follow-up projects. A summary of the work is given in Section 6.5 and future studies are suggested in Section 6.6.

6.1 Discussion of Experiment 1

The control plants were significantly taller than the experiment plants. This probably stems from the control light being less intensive. The experiment plants were packed densely, so that a smaller part of the leaves was exposed to direct light. The effect might also stem from missing far red light. The lack of far red light compresses the plants, which might normally be positive in vertical farming, but was extreme here, where biomass was reduced. During harvest it was found that some of the nutrient nozzles of the experiment tray were plugged. This might have lead to a reduced uptake of nutrients and water and thus prevented the formation of biomass. Reduced nutrients and water have an especially negative effect, if the light intensity is strong. Here, transpiration is increased to deliver the necessary nutrients for photosynthesis by the opening of the stomata, which also leads to a higher need for water. In extreme cases, this may lead to starvation. While the experiment plants were a little taller at the start of the experiment, this had no effects on the results of the experiment, as the control plants growth caught up by DAS 20 (c.f. Figure 5.1). The discrepancy is probably due to the seedlings having been slightly taller at the time of transplanting.
As with the height, the control plants took up a significantly larger area than the experiment plants. This, too, might stem from the lower light intensity and the higher share of far red light. While the experiment plants became densely packed to circumvent the light and prevent starvation, the control plants spread out to receive more light.
The fresh shoot weight of the experiment plants was higher. In combination with the smaller area, this means the plants under the experiment light conditions grew more biomass per area. It was hypothesized by Kim, Goins, Wheeler, and Sager that green light can shine into deeper leave layers, as it is not directly absorbed by the upper layers, and thus increase photosynthesis there [28]. The green light might have allowed the lettuce to be packed densely by preventing the lower layered leaves from degenerating.
The shoot dry weight of the experiment plants was also higher and the fresh-dry ratio of the shoot weight slightly lower. Thus, the water content of the control plants was higher in relation to their mass and the nutrient content was higher in experiment plants. While a positive effect (more calories and other for astronauts necessary nutrients), a lower water content might also negatively affect sensory satisfaction while eating. A lower water content means a less fresh and crunchy eating experience. This is also confirmed by a softer feeling to the touch during harvesting.
The fresh root weight of the experiments was higher, probably due to the higher green light

concentration [64], but might also stem from the plugged nozzle. The plants might have had need for longer roots to grow into areas in which more nutrient solution was supplied [75].
It can be concluded that a lower intensity than during this experiment is to be preferred. The intensity should be so low that the plant does not need to start countermeasures to protect itself from the light (like leaf curling) but not so low that the plants photosynthesis is significantly reduced and the leaves elongate to reach areas of higher intensities. While far red light increases photosynthesis and therefore biomass, too much elongates the leaves. In CEA, densely packed plants are preferred. Therefore, a "sweet spot" must be found.
In both experiment and control trays, the plant on position 3 (cf. Figure 3.4b) was smaller (experiment: p=0.001**, control: p=0.051) than the others on the same tray. It was hypothesized that this is due to the uneven distribution of nutrient solution within the trays. In contrast to Experiment 1, in Experiment 2 the plants on position 3 did not show a difference in size to other plants of the same tray. As the nozzle set-up was equal in both experiments, the hypothesis stated is unlikely to be true. No other explanation for the outlying data in Experiment 1 was not found.
Since it is an outlier in height, area and weight in both control and experiment plants, this may screw the significance of the results. While the difference of number of leaves is not significant considering all plants, it is significant (p=0.019*) if the plants on position 3 are not considered. Table 6.1 shows the results without the plant on position 3.

Table 6.1: Results of Experiment 1 without plants on position 3

	Experiment	Control	Significance
ØHeight [cm]	12.5 ± 0.35	14.4 ± 0.96	very significant (p=0.0032**)
ØArea [cm^2]	407.94 ± 58.94	472.34 ± 52.69	not significant (p=0.106)
ØNo. of leaves	42.8 ± 9.15	28.6 ± 5.75	significant (p=0.019*)
ØShoot fresh weight [g]	150.36 ± 13.35	146.34 ± 26.36	not significant (p=0.769)
ØShoot dry weight [g]	8.7 ± 1.31	8.0 $\pm 1.81\pm$	not significant (p>0.5)

The light intensity at canopy height during the experiment was far higher for the experiment tray than for the control tray, as the target intensity of 270 $\frac{\mu mol}{m^2 s}$ was to be achieved. The measurements were taken with the MQ-200, which due to old age was not sensitive enough. Hence, the highest measured intensity being 198 $\frac{\mu mol}{m^2 s}$. The light intensity of the experiment was also more variable than of the control. For the control, the light settings were constant over the growth period. The light intensity at canopy height therefore increased with the growth of the plants. The light settings of the experiment on the other hand were reduced over time to allow constant light intensity at canopy height. This was not successful. The light intensity jumps strongly from one day to the next. This points to the reductions being carried out in too large intervals. The resetting of the lamps should therefore be done more often and in smaller steps.

6.2 Discussion of Experiment 2

Until about 20 DAT, the three experiments, 100%, 80%, and 70% intensity, and the control had a similar growth. Only afterwards did the control plants growth increase relative to the experiment. The 80%-plants were significantly smaller than the control, but the lettuce was harvested while it was still in its growth phase. While it is impossible to say, if the smaller plants would have caught up to the control plants if longer growth times had been allowed, they were harvested at this point to allow for a comparison to the plants of experiment 1. The control and 100%-plants also started to feel rubbery to the touch at which point they stop growing and the quality declines. Both height and weight of the 80%-plants were increased relative to the 100%-plants. While other studies showed that high light intensities promoted growth in lettuce, this could not be confirmed neither here nor during the first experiment [8, 60]. Similarly, the 70%-plants showed significantly less mass and height than the 80%-plants. The leaves of the 70%-plants grew long and slim, which might be a sign for non-optimal light conditions in which the plant "searches" for light. A light intensity of 220 to 230 $\frac{\mu mol}{m^2 s}$ was therefore found to be optimal.
It was difficult to keep the same light intensity at canopy height. Especially the 100%-lamp did not reach the target intensity of 270 $\frac{\mu mol}{m^2 s}$. For this reason, the light settings were not reduced during the experiment even as the plants grew.
All roots of the second experiment showed a much lower dry mass than during the first experiment and comparing Figures 5.4 and 5.7, the roots of experiment 2 are underdeveloped. It is possible, that this effect was created by the experimenter: to compare root growth, the lids of the growth trays were lifted regularly. This might have stressed the roots and negatively influenced the root growth.
The control plants took up the most area, but the difference to the experiment plants was not significant. Still, it could be shown that the experiment plants grew more densely than the control plants, which is advantageous in vertical farming. This effect was probably created by the lower percentage of far red light and the higher percentage of blue light in the experiment.
The sensory analysis revealed a higher satisfaction with the 80%-plants in all categories. Due to the tasting being conducted on two days and with untrained testers, there might be some shift in the evaluation from one day to the next. This means, that comparing both days to each other might lead to some wrong conclusions. Comparing the 80%- to the 70%-plants (which were harvested on the same day), the 80%-plants were considered better in all categories. Doing the same for the control and 100%-plants, the control plants were evaluated as having a higher crispness and better shape than the 100%-plants while the colour was considered better for the 100%-plants. Additionally, the sweetness was rated higher for the 100%-plants. From this it can be derived, that the lettuce grown under the developed light recipe was sweeter than the lettuce grown under the control settings even at high light intensities of the developed light recipe. One participant noticed that it was at times difficult to define the sweetness and bitterness of the sample as "the lettuce was rather bitter and became sweet in the aftertaste."

6.2.1 Expected Power Consumption

The control lamp had a strongly reduced power consumption in contrast to the 100%-lamp. This is not surprising as for most of the experiment, the intensity of the 100%-lamp was higher at canopy level. This only changed at about DAS 42 (five days before harvest). Extrapolating the expected power consumption for a growth cycle in EDEN LUNA, the power consumption was lowest for the control plants for a distance between tray and lamp of 38.5 cm and using a 120 W lamp. The PPFD received on the tray from the control settings was only 101 $\frac{\mu mol}{m^2 s}$ at the highest possible intensity. In contrast, the 80% reached 112 $\frac{\mu mol}{m^2 s}$ and the target intensity of 220$\frac{\mu mol}{m^2 s}$ at 20 DAT. Experiment 2 showed that a reduced light intensity inhibits growth significantly. It is therefore recommended to apply the developed light recipe or to reduce the ratio of far red light of the currently used control settings and thus be able to increase the settings of the other LEDs. The power consumption of the 120 W lamp at a distance of 50 cm was the same for all three target PPFDs. This is explained by the lamp not being able to provide the target PPFDs 200 $\frac{\mu mol}{m^2 s}$, 220 $\frac{\mu mol}{m^2 s}$, or 270 $\frac{\mu mol}{m^2 s}$ at this distance. As explained in Chapter 3, the settings are kept at their highest during the whole vegetative stage. In this case, the power consumption was measured at the highest setting and than extrapolated for 30-day vegetative stage.

6.3 Problems regarding measurement equipment

As specified in chapter 3, three measurement devices were used to determine the intensity and the spectrum of the lights: a spectrometer to determine the spectrum of the lamps and two PPFD-meters to measure light intensity during the experiment.
With the help of the spectrum, the light recipes for the first were developed. During the evaluation of the results, it became clear that some of the values were wrong and led to a different light environment than expected during the first experiment. A second measurement of the lamps with a 3° instead of a 35° sensor delivered a correct spectrum. This was used to correct the light environment for the second experiment. The calculation of the correct light settings for the second experiment was facilitated by the development of a code as can be found in Appendix H.
During the first experiment, the PPFD-meter (1) MQ-200 with a spectral range of 400 to 700 nm was used. By comparing these measurements with the measurement with the (2) MQ-610 with a spectral range of 380 to 760 nm, it became clear that the first PPFD-meter has a significantly lower sensitivity than the second. As the MQ-200 is older, it was concluded that this might be due to wear and a slightly smaller detection range. Figure 6.1 shows the results of a comparison test between both PPFD-meters. It can be seen that while the measurements with the MQ-610 were always much higher than those of the MQ-200, both show a new linear growth with a receding distance from the lamp. Further tests have shown, that the MQ-610 has high sensitivity in the red and far red light ranges and low sensitivity in the blue light range. It is also possible that the sensitivity of the MQ-610 towards green light is lower as well. Due to the lack of green LEDs in the tested lamps, this could not be proven.
The light intensity readings of the first experiment are therefore lower than in the second experiment.

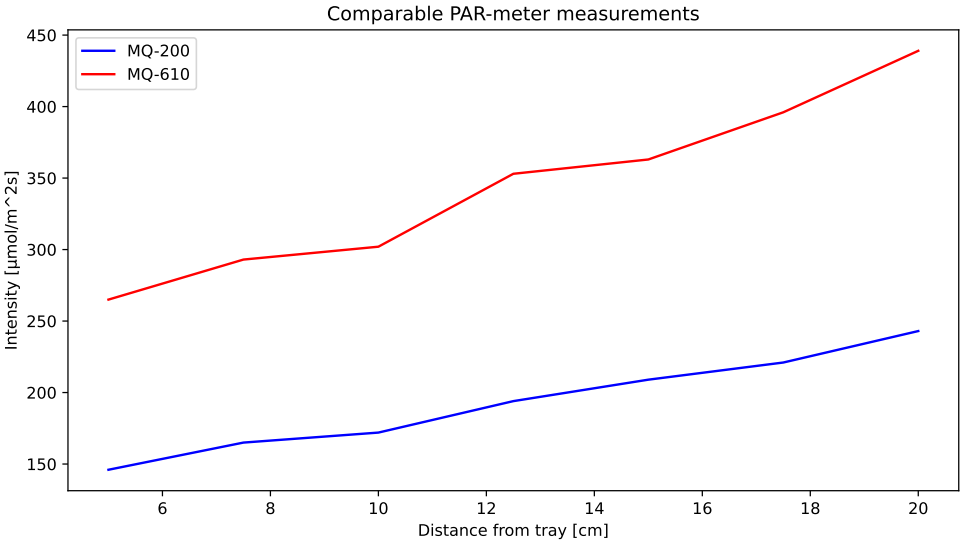


Figure 6.1: Comparison of PPFD-meters

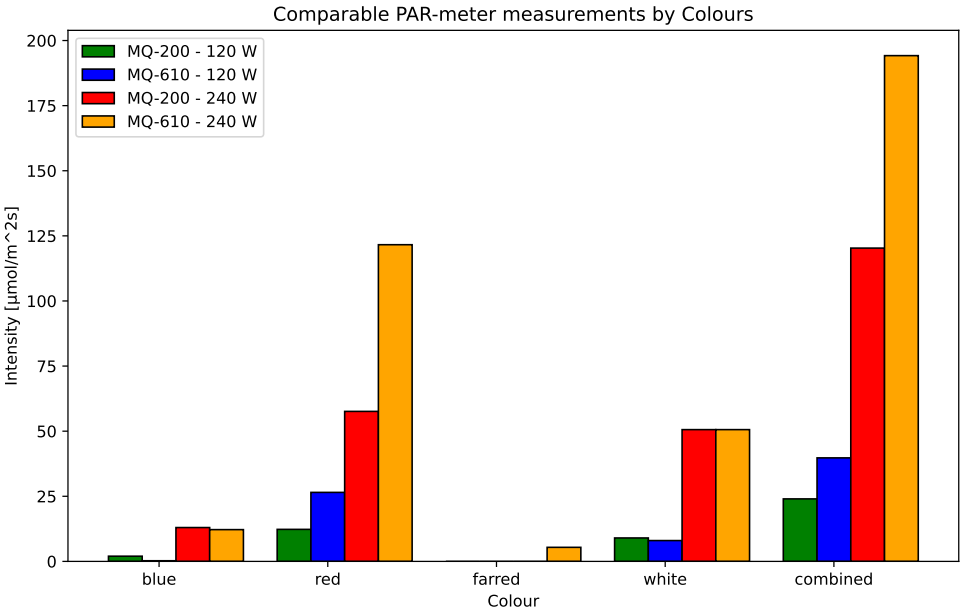


Figure 6.2: Comparison of PPFD-meters by Colour Ranges

As can be seen in Figure 6.2, the MQ-200 (green and red bars) has a vastly reduced sensitivity to red and far red light in comparison to the MQ-610 (blue and orange bars). In contrast in the blue range, the sensitivity of the MQ-200 is higher. The measured light intensity of the 120 W-lamps is stronger when measured by the MQ-200, since the 5700 K-light has a large blue and green part and only little red and far red light. The strong difference in sensitivity to red light can also be seen in the measurements of the white light of the 240 W-lamps, which is nearly equal for both PPDF-meters. Here, the MQ-610's sensitivity to red light is balanced by the MQ-200's sensitivity to blue light, which is in larger abundance in 5700 K-light.
The different sensitivities to different wavelengths between the PPDF-meters means, that in

the first experiment, when light intensity was measured using the MQ-200, the share of red light was not adequately measured. Since the first experiment had a larger share of red light (69.11%) than the second experiment (46.09%) it is probable, that the light intensity was far higher than expected and intended: the MQ-610 measures a PPFD of about twice as high in the red range than the MQ-200, with 12.3 $\frac{\mu mol}{m^2 s}$ and 26.5 $\frac{\mu mol}{m^2 s}$ respectively for the 120 W lamp and 57.7 $\frac{\mu mol}{m^2 s}$ and 121.6 $\frac{\mu mol}{m^2 s}$ respectively for the 240 W lamp. This difference could not be equalized by the blue light, as the blue light's share in the first experiment was lower than in the second experiment, with 12.59% and 29.3% respectively.

6.4 Practical Application of Light Recipes in EDEN LUNA

Possible problems from the practical application of light recipes in EDEN LUNA arise from the compact build of the container. Light pollution between the trays will change the light received by plants. As was described in Chapter 2, specific wavelengths can have detrimental effects on plants by stressing them. Blue light can for example promote flowering, which is to be avoided in certain plants like lettuce. The light pollution could be prevented by inserting foils between the trays. As an added benefit, this would increase the PPFD at canopy height due to reflection and thus save energy. A problem arising from this approach is a reduced air flow between the tays. This might lead to overheating and prevent CO_2 from reaching the plants.
Since the plants grow over time especially during the vegetative stage, the light intensity needs to be reduced regularly. Table 6.2 shows the light settings for lettuce in the vegetative stage with intensity reductions every three days for lettuce grown under the 120W lamps with a distance of 38.5 cm from the lamp. The harvest is on day 45 DAS or 30 DAT. The settings shall be changed on the day mentioned after transplanting. Tables 6.2, 6.3, 6.4, and 6.5 show the settings in different combinations of lamp power (120 W and 240 W) and distance between lamp and plants (38.5 cm and 50 cm) over time in days after transplanting. In EDEN LUNA, lettuce will probably be grown under 120 W lamps with a distance of 38.5 cm. Table 6.2 is the corresponding time table. Since the start settings produce only 112 $\frac{\mu mol}{m^2 s}$ at a distance of 38.5 cm, the settings need to stay constant until the plants have grown to reach their target intensity of 220 $\frac{\mu mol}{m^2 s}$ at canopy height. This will be about 20 days after transplanting. At day 21, the first reduction will be conducted.

Table 6.2: Settings for Lettuce in EDEN LUNA - 120 W lamp - 38.5 cm - 220 PPFD

Light Colour	**Settings**			
Days after Transplanting	1 - 21	21 - 24	24 - 27	27 - 30
White (5700 K)	888	858	759	643
Blue (450 nm)	1000	966	855	724
Red (660 nm)	288	278	246	208
Far Red (730 nm)	0	0	0	0

Table 6.3: Settings for Lettuce in EDEN LUNA - 120 W lamp - 50 cm - 220 PPFD

Light Colour	**Settings**					
Days after Transplanting	1 - 16	16 - 19	19 - 22	22 - 25	25 - 28	28 - 30
White (5700 K)	888	868	805	734	656	568
Blue (450 nm)	1000	978	906	827	739	640
Red (660 nm)	288	282	261	238	656	184
Far Red (730 nm)	0	0	0	0	0	0

Table 6.4: Settings for Lettuce in EDEN LUNA - 240 W lamp - 38.5 cm - 220 PPFD

LED	**Settings**				
Days after Transplanting	1 - 2	2 - 5	5 - 8	8 - 11	11 - 14
White (5700 K)	183	179	165	154	137
Blue (450 nm)	207	202	186	174	155
Red (660 nm)	59	58	53	50	44
Far Red (730 nm)	0	0	0	0	0
LED	**Settings**				
Days after Transplanting	14 - 17	17 - 20	20 - 23	23 - 26	26 - 30
White (5700 K)	118	96	71	43	10
Blue (450 nm)	133	109	81	49	12
Red (660 nm)	38	31	23	14	3
Far Red (730 nm)	0	0	0	0	0

Table 6.5: Settings for Lettuce in EDEN LUNA - 240 W lamp - 50 cm - 220 PPFD

LED	**Settings**					
Days after Transplanting	1 - 2	2 - 5	5 - 8	8 - 11	11 - 14	14 - 17
White (5700 K)	266	261	246	229	210	190
Blue (450 nm)	300	294	277	258	237	215
Red (660 nm)	86	84	79	74	68	62
Far Red (730 nm)	0	0	0	0	0	0
LED	**Settings**					
Days after Transplanting	17 - 20	20 - 23	23 - 26	26 - 29	29 - 30	
White (5700 K)	168	144	117	88	55	
Blue (450 nm)	190	163	132	99	62	
Red (660 nm)	54	47	38	28	18	
Far Red (730 nm)	0	0	0	0	0	

6.4.1 Recommendations for EDEN LUNA

To better benefit from light recipes, only the same plant should be grown under one light. Not only will this maximise the effect of a light recipe, it will also prevent shadowing of smaller plants by their neighbours.
While it was long assumed that green light was unnecessary for the growth of crops and only used to facilitate plant health monitoring and enhance the mental well-being effect of plants in humans, it has since been shown that both lettuce and cucumber benefit from green light. This should be considered when buying new lamps in the future. It is recommended the lamps have a green channel to facilitate the additions of green light. This is probable to save power in contrast to the light recipes for EDEN LUNA developed in this thesis as the green light had to be added by turning up the white light.
For cucumber, the far red ratio for an optimal light environment could not be reached with the Heliospectra lamps available for EDEN LUNA. In the future purchased lamps should therefore have stronger far red lighting abilities to reach a ratio of 10% far red light as specified in Chapter 4.
Intra-canopy lighting is interesting for multiple reasons: by using lower-hanging lamps during the early stages of the tall-growing plants like cucumber, the light intensity given off by the lamps can be lower while still reaching the target intensity at canopy height, thus saving on energy. It has also been shown that supplemental blue light inside the canopy can increase plant biomass and reduce the internode length. However, some studies reported the detrimental effect of reducing fruit yield [5, 76].
For EDEN LUNA, it might also be beneficial to review the number of plants grown per tray. Especially on trays with 6 or more individuals, the plants take each others space and light. This leads to less light reaching the lower leaves and them degenerating and becoming inedible. Tests with fewer plants per tray might prove the possible maximum edible biomass of each plant.

6.5 Summary

The development of individualised light environments for crops is of interest to both the space industry - to be able to efficiently provide fresh produce to astronauts on long-term missions - and terrestrial food production. With rising numbers of people that need to be fed on earth and a changing climate, CEA technologies can help secure food production. By individualising the light environment for each crop, food production may rise while lowering the power consumption of CEA. In this thesis, light recipes were developed for two crops: lettuce (*Lactuca sativa*) and cucumber (*Cucumis sativus*).
The optimal light recipe for lettuce is summarized in Figure 6.3.

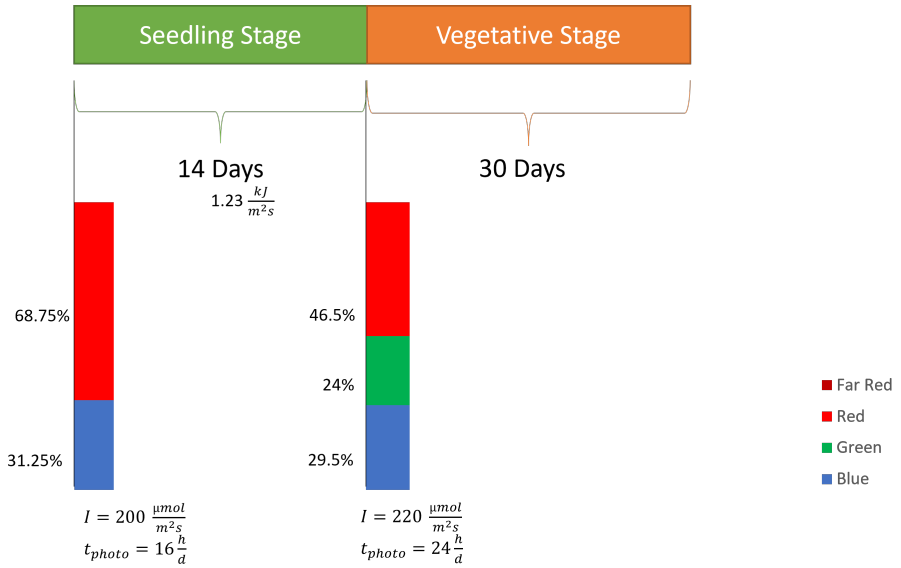


Figure 6.3: Optimal Light Recipe for Lettuce

The optimal light recipe for cucumber is summarized in Figure 6.4.

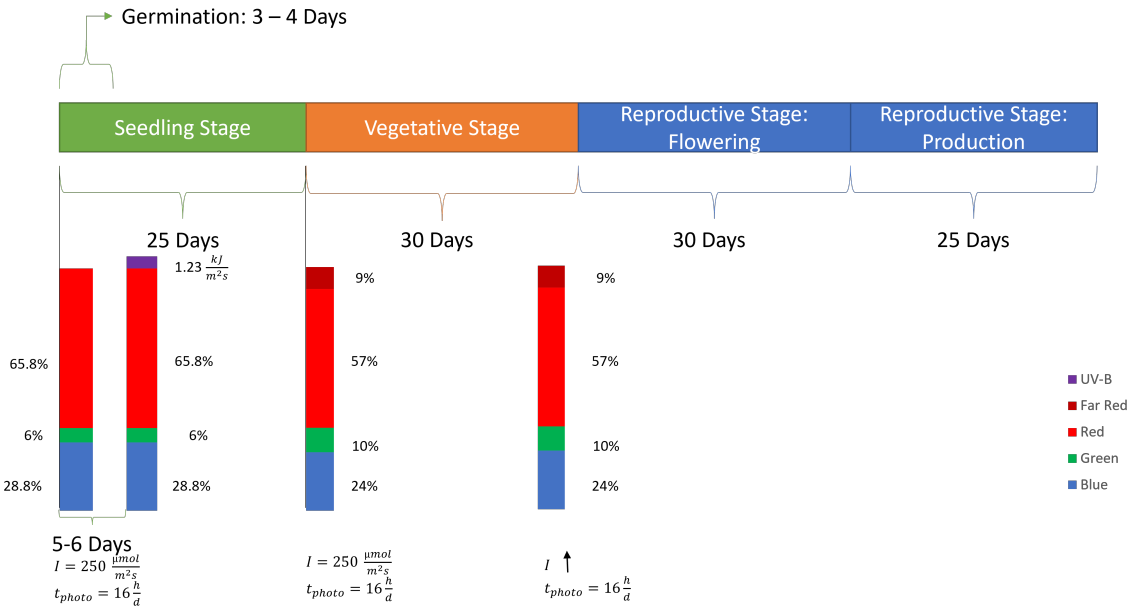


Figure 6.4: Optimal Light Recipe for Cucumber

These light recipes were then adapted for the light set-up used in the EDEN LUNA project of the EDEN initiative and the lettuce light recipe was tested in the EDEN laboratory in two experiments. It could be shown that an intensity of about 230 $\frac{\mu mol}{m^2 s}$ at canopy height is optimal for lettuce in the vegetative phase. A higher blue light ratio and a lower far-red ratio leads to a more compact build of the lettuce plants, which is advantageous in vertical farming, where space is scarce. A higher green light ratio might contribute to that by allowing the lower layered leaves of the lettuce to receive light and to photosynthesize. The developed light recipe did not lead to a higher yield than the control.

In an additional experiment the power consumption of the light recipe was measured using the lamps for the FEG. The power consumption of the 80%-lamp was slightly (~3%) higher than the control for the 120 W lamp and much lower (~32%) for the 240 W lamp. In combination with

the slightly better growth results of the 80%-plants, it is recommended to use that Light Recipe with the in Sections 6.2 and 6.4.1 mentioned adjustments.
Table 6.6 summarizes the objectives of this thesis as listed in the Exposé that can be found at the top of the work and if they were fulfilled.

Table 6.6: Objectives of this thesis

Objectives	
Clustering the plants used in EDEN LUNA into grouped with similar or the same illumination needs	not fulfilled
Define assumptions under which the light recipes are developed	fulfilled
Define the goals for the light recipes	fulfilled
Develop light recipes for max. 3 plants in mono- and polyculture using evaluation matrix developed above	fulfilled for 2 plants
Conduct experiment to test growth of lettuce with designed light recipe	fulfilled
Conduct experiment to measure power consumption of designed light recipes for lettuce	fulfilled
Calculate estimated power consumption for other light recipes	fulfilled
Write program for lettuce light recipe or suggest recommendations for changes in the EDEN LUNA light set-up for space missions	recommendations were suggested

Additional work included:

- Write program for the definition of lamp settings for EDEN LUNA from light recipes
- Write program for the calculation of light ratios from lamp settings in EDEN LUNA
- Preparation of a template for the future development of light recipes

6.6 Future Studies

This study developed light recipes for lettuce and cucumber. These should be further tested, especially in regards to factors which were outside the scope of this thesis, like nutrient content. The sensory analysis should be repeated with a larger number of participants to account for the subjectiveness of taste. Besides that, light recipes for the other crops selected for EDEN LUNA should be developed. This can be done using the template that can be found in Appendix K.
To facilitate the use of light recipes in poly cultures, the crops should be grouped according to their illumination requirements as more light recipes are developed. This will allow plants with similar light requirements to be grown under one light source.
To be able to further develop light environments for crops, more in-depth research into the effect of light intensities and wavelengths on plants must be conducted. Not only is the general effect interesting, but also how plants react to changing light conditions over each photoperiod and over their life time. This way, food producers can offer light exactly as it is needed by the

plant. This might also facilitate planning: as mentioned in Chapter 2, flowering can be induced using stressors like high light intensity. By actively inducing flowering harvest may be easier to predict.
In the future, the development of an adaptive system will be interesting. A system containing a camera, which monitors the plants growth and health, and changes the light settings to accommodate the plants needs. For example, if the plant were to shoot up, the system could recognise this and increase the blue light ratio.

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Appendix

Appendix A Growth of Lettuce during Pretest

Table A.1: Growth of Lettuce Plants under Control Conditions in retest

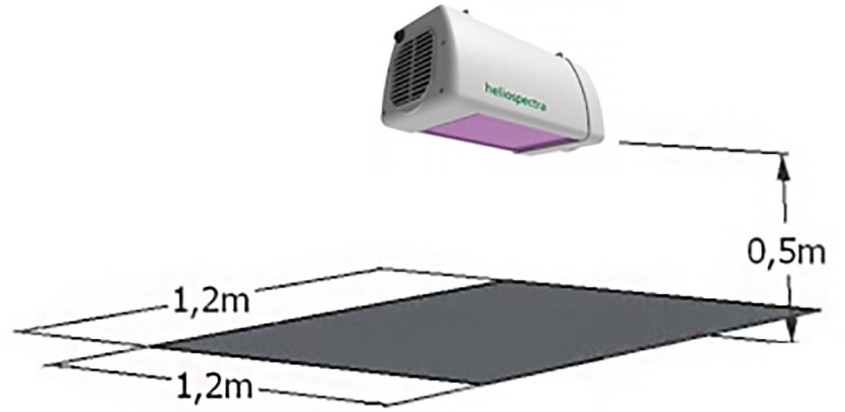
DAS	1 [$\frac{cm}{d}$]	2 [$\frac{cm}{d}$]	3 [$\frac{cm}{d}$]	4 [$\frac{cm}{d}$]	5 [$\frac{cm}{d}$]	6 [$\frac{cm}{d}$]	No. days b/w measurements	average growth [$\frac{cm}{d}$]
24	3	1	2	0	0	2	3	0.44
25	0	0	0	0	0	0	1	0.00
27	1	1	1	1	2	2	2	0.67
28	0	1	0	0	0	0	1	0.17
31	0	1	1	1	1	2	3	0.33
32	2	1	0	0	4	2	1	1.50
33	0	-1	1	1	-1	-2	1	-0.33
38	2	4	3	2	1	5	5	0.57
39	1	0	1	0	1	-1	1	0.33
40	0	2	0	2	3	1	1	1.33
41	0	0	1	1	1	2	1	0.83
42	0	0	1	0	0	0	1	0.17
46	2	1	2	1	0	0	4	0.25
47	0	0	0	1	0	-1	1	0.00

Appendix B Product Leaflet Heliospectra LX601

heliospectra
intelligent light for efficient growth

Product Leaflet

Heliospectra LX601



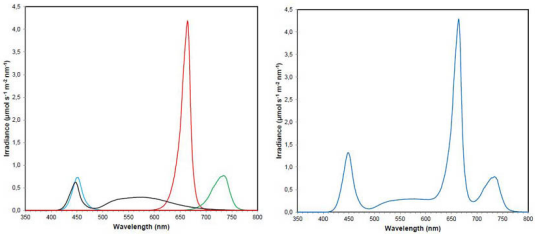
Heliospectra LX601 is the markets premier product for indoor (sole-source) lighting applications. The optical distribution is ideal for the light to be close to the plant - either for higher intensities or due to space constraints - while maintaining a wide, uniform light distribution

Recommended Applications

- Controlled environments agriculture
- Commercial horticulture
- Research greenhouses
- Hobby/indoor gardening

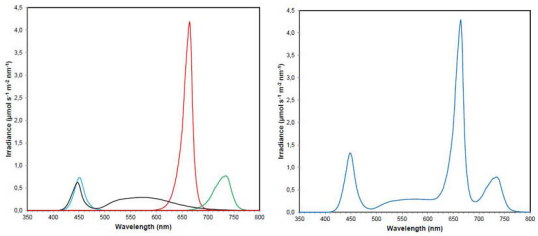
Spectral & Full Spectrum Output Options

C-Plate
Wavelength (nm)
450
5700K
660
735



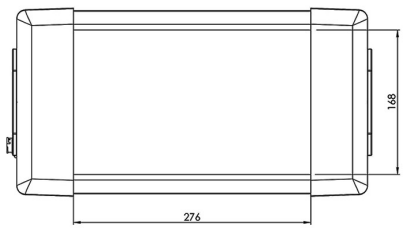
Optics: C-Plate

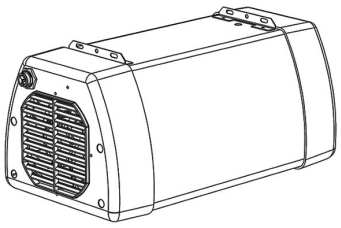
G-Plate
Wavelength (nm)
450
5700K
660

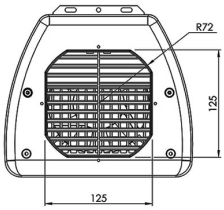


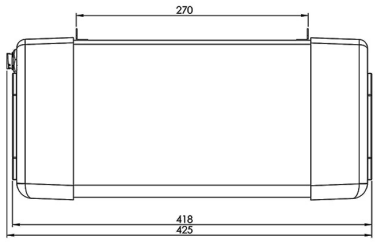
Optics: G-Plate

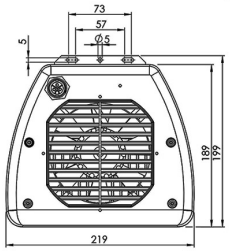
Measurements:
LX601

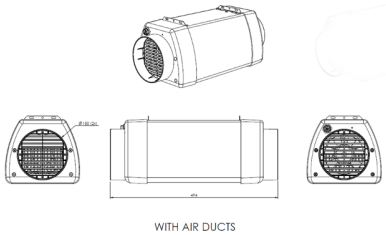


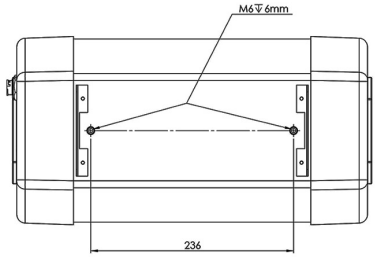












What's in the box?

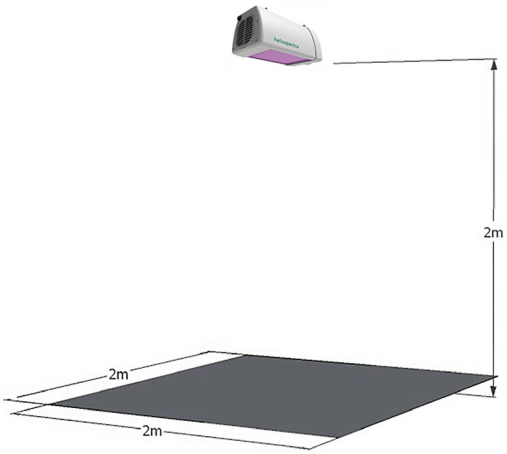
- Your LX601 LED grow light
- 2 m (6 ft) power cable with EU or North American plug type
- 2 m (6 ft) Ethernet cable
- V-hook mounting hardware
- Quick install guide

Appendix C Product Leaflet Heliospectra LX602

heliospectra
intelligent light for efficient growth

Product Leaflet

Heliospectra LX602



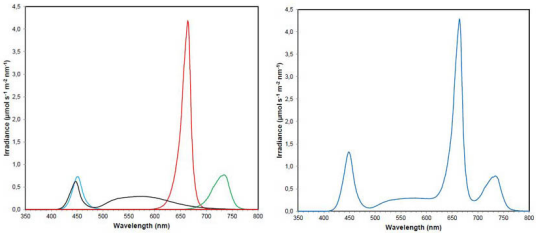
Heliospectra LX602 is the most advanced LED grow light for horticulture crop production. Growers who are serious about quality use the LX602 as an essential tool in their grow operations. The LX602 optical distribution is ideal for greenhouses when the light needs to be mounted at a distance from the plant, while still maintaining a wide, uniform light distribution.

Recommended Applications

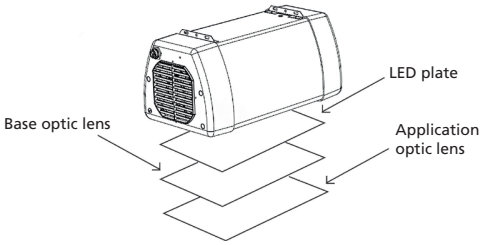
- Controlled environments agriculture
- Commercial horticulture
- Research greenhouses
- Hobby/indoor gardening

Spectral & Full Spectrum Output Options

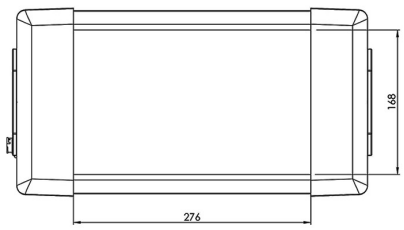
G-Plate
Wavelength (nm)
450
5700K
660

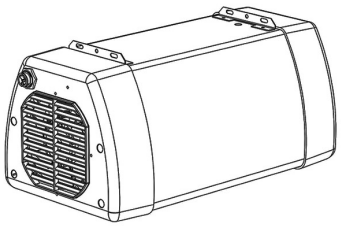


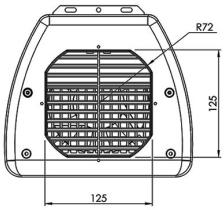
Optics: G-Plate

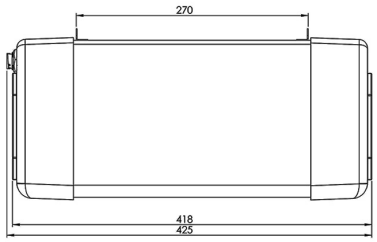


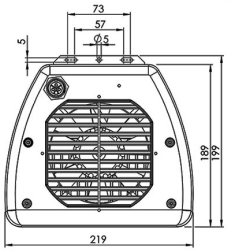
Measurements:
LX602

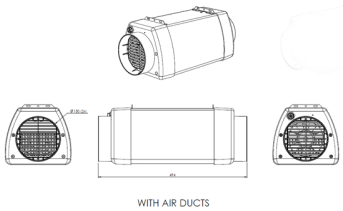


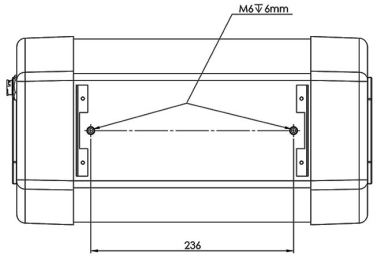












What's in the box?

- Your LX602 LED grow light
- 2 m (6 ft) power cable with EU or North American plug type
- 2 m (6 ft) Ethernet cable
- V-hook mounting hardware
- Quick install guide

Appendix D Settings during Lettuce Light Recipe Evaluation

Table D.1: Settings in Experiment 1

	Light Ratio	**Setting 31.05.24**	**Setting 06.06.24**	**Setting 10.06.24**	**Setting 14.06.24**
White	-	1000	950	920	900
Blue	12.59%	80	70	70	70
Green	17.69%	-	-	-	-
Red	69.11%	750	710	690	680
Far Red	0.6%	0	0	0	0
	Light Ratio	Setting 17.06.24	Setting 21.06.24	Setting 24.06.24	Setting 27.06.24
White	**-**	**880**	**850**	**830**	
Blue	12.59%	70	60	60	
Green	17.69%	-	-	-	
Red	69.11%	660	640	630	
Far Red	0.6%	0	0	0	

Table D.2: Settings in Experiment 2: 100%

	Light Ratio	**Setting 09.07.24**	**Setting 12.07.24**	**Setting 15.07.24**	**Setting 19.07.24**
White	-	800	780	760	860
Blue	29.34%	900	880	860	970
Green	23.81%	-	-	-	-
Red	46.03%	260	250	250	280
Far Red	0.81%	0	0	0	0
	Light Ratio	Setting 22.07.24	Setting 26.07.24	Setting 29.07.24	Setting 02.08.24
White	**-**	**860**	**860**	**860**	**860**
Blue	29.34%	970	970	970	970
Green	23.81%	-	-	-	-
Red	46.03%	280	280	280	280
Far Red	0.81%	0	0	0	0

Table D.3: Settings in Experiment 2: 80%

	Light Ratio	**Setting 12.07.24**	**Setting 15.07.24**	**Setting 19.07.24**	**Setting 22.07.24**
White	-	850	830	800	770
Blue	29.14%	950	920	890	860
Green	23.72%	-	-	-	-
Red	46.34%	280	270	260	250
Far Red	0.81%	0	0	0	0
	Light Ratio	Setting 26.07.24	Setting 29.07.24	Setting 02.08.24	Setting 05.08.24
White	**-**	**740**	**720**	**690**	**660**
Blue	29.14%	830	800	770	740
Green	23.72%	-	-	-	-
Red	46.34%	240	240	230	220
Far Red	0.81%	0	0	0	0

Table D.4: Settings in Experiment 2: 70%

	Light Ratio	**Setting 12.07.24**	**Setting 15.07.24**	**Setting 19.07.24**	**Setting 22.07.24**
White	-	140	130	130	120
Blue	28.48%	160	150	150	140
Green	22.95%	-	-	-	-
Red	47.79%	50	50	50	50
Far Red	0.79%	0	0	0	0
	Light Ratio	Setting 26.07.24	Setting 29.07.24	Setting 02.08.24	Setting 05.08.24
White	**-**	**110**	**100**	**90**	**80**
Blue	28.48%	120	110	100	90
Green	22.95%	-	-	-	-
Red	47.79%	40	40	30	30
Far Red	0.79%	0	0	0	0

Appendix E Settings for EDEN LUNA

Appendix E.1 Lettuce

Table E.1 lists the settings for a growth period of lettuce, using the 120 W lamp, a 38.5 cm distance, and for a target intensity of 270 $\frac{\mu mol}{m^2 s}$. Reached intensity at experiment start is 112 $\frac{\mu mol}{m^2 s}$. The target intensity at canopy height is received by the plant on day 26.

Table E.1: Lettuce - Vegetative Stage - 120 W lamp - 38.5 cm - 270 PPFD

Light Colour	Settings	
Days after Transplanting	1 - 27	27 - 30
White (5700 K)	888	855
Blue (450 nm)	1000	963
Red (660 nm)	288	277
Far Red (730 nm)	0	0

Table E.2 lists the settings for a growth period of lettuce, using the 120 W lamp, a 38.5 cm distance, and for a target intensity of 220 $\frac{\mu mol}{m^2 s}$. Reached intensity at experiment start is 112 $\frac{\mu mol}{m^2 s}$. The target intensity at canopy height is received by the plant on day 20.

Table E.2: Lettuce - Vegetative Stage - 120 W lamp - 38.5 cm - 220 PPFD

Light Colour	Settings			
Days after Transplanting	1 - 21	21 - 24	24 - 27	27 - 30
White (5700 K)	888	858	759	643
Blue (450 nm)	1000	966	855	724
Red (660 nm)	288	278	246	208
Far Red (730 nm)	0	0	0	0

Table E.3 lists the settings for a growth period of lettuce, using the 120 W lamp, a 38.5 cm distance, and for a target intensity of 200 $\frac{\mu mol}{m^2 s}$. Reached intensity at experiment start is 112 $\frac{\mu mol}{m^2 s}$. The target intensity at canopy height is received by the plant on day 17.

Table E.3: Lettuce - Vegetative Stage - 120 W lamp - 38.5 cm - 200 PPFD

Light Colour	Settings				
Days after Transplanting	1 - 18	18 - 21	21 - 24	24 - 27	27 - 30
White (5700 K)	888	860	766	657	529
Blue (450 nm)	1000	968	862	739	596
Red (660 nm)	288	279	248	213	172
Far Red (730 nm)	0	0	0	0	0

Table E.4 lists the settings for a growth period of lettuce, using the 120 W lamp, a 38.5 cm distance, and for a target intensity of 270 $\frac{\mu mol}{m^2 s}$. Reached intensity at experiment start is 77 $\frac{\mu mol}{m^2 s}$. The target intensity at canopy height is received by the plant on day 47. As harvest is at

day 35, the highest intensity settings are used during the whole growth vegetative stage.

Table E.4: Lettuce - Vegetative Stage - 120 W lamp - 50 cm - 270 PPFD

Light Colour	Settings
Days after Transplanting	1 - 30
White (5700 K)	888
Blue (450 nm)	1000
Red (660 nm)	288
Far Red (730 nm)	0

Table E.5 lists the settings for a growth period of lettuce, using the 120 W lamp, a 38.5 cm distance, and for a target intensity of 220 $\frac{\mu mol}{m^2 s}$. Reached intensity at experiment start is 77 $\frac{\mu mol}{m^2 s}$. The target intensity at canopy height is received by the plant on day 41. As harvest is at day 35, the highest intensity settings are used during the whole growth vegetative stage.

Table E.5: Lettuce - Vegetative Stage - 120 W lamp - 50 cm - 220 PPFD

Light Colour	Settings
Days after Transplanting	1 - 30
White (5700 K)	888
Blue (450 nm)	1000
Red (660 nm)	288
Far Red (730 nm)	0

Table E.6 lists the settings for a growth period of lettuce, using the 120 W lamp, a 38.5 cm distance, and for a target intensity of 200 $\frac{\mu mol}{m^2 s}$. Reached intensity at experiment start is 77 $\frac{\mu mol}{m^2 s}$. The target intensity at canopy height is received by the plant on day 37. As harvest is at day 35, the highest intensity settings are used during the whole growth vegetative stage.

Table E.6: Lettuce - Vegetative Stage - 120 W lamp - 50 cm - 200 PPFD

Light Colour	Settings
Days after Transplanting	1 - 30
White (5700 K)	888
Blue (450 nm)	1000
Red (660 nm)	288
Far Red (730 nm)	0

Table E.7 lists the settings for a growth period of lettuce, using the 240 W lamp, a 38.5 cm distance, and for a target intensity of 270 $\frac{\mu mol}{m^2 s}$. Reached intensity at experiment start is 271 $\frac{\mu mol}{m^2 s}$. The target intensity at canopy height is received by the plant on day 1.

Table E.7: Lettuce - Vegetative Stage - 240 W lamp - 38.5 cm - 270 PPFD

Light Colour	**Settings**					
Days after Transplanting	1 - 2	2 - 5	5 - 8	8 - 11	11 - 14	14 - 17
White (5700 K)	226	221	203	184	162	138
Blue (450 nm)	255	249	229	208	183	156
Red (660 nm)	72	70	65	57	52	44
Far Red (730 nm)	0	0	0	0	0	0
Light Colour	**Settings**					
Days after Transplanting	17 - 20	20 - 23	23 - 24	24 - 25	25 - 26	26 - 30
White (5700 K)	110	79	43	30	26	2
Blue (450 nm)	125	89	48	34	30	2
Red (660 nm)	35	25	14	10	8	1
Far Red (730 nm)	0	0	0	0	0	0

Table E.8 lists the settings for a growth period of lettuce, using the 240 W lamp, a 38.5 cm distance, and for a target intensity of 220 $\frac{\mu mol}{m^2 s}$. Reached intensity at experiment start is 222 $\frac{\mu mol}{m^2 s}$. The target intensity at canopy height is received by the plant on day 1.

Table E.8: Lettuce - Vegetative Stage - 240 W lamp - 38.5 cm - 220 PPFD

Light Colour	**Settings**				
Days after Transplanting	1 - 2	2 - 5	5 - 8	8 - 11	11 - 14
White (5700 K)	183	179	165	154	137
Blue (450 nm)	207	202	186	174	155
Red (660 nm)	59	58	53	50	44
Far Red (730 nm)	0	0	0	0	0
Light Colour	**Settings**				
Days after Transplanting	14 - 17	17 - 20	20 - 23	23 - 26	26 - 30
White (5700 K)	118	96	71	43	10
Blue (450 nm)	133	109	81	49	12
Red (660 nm)	38	31	23	13	3
Far Red (730 nm)	0	0	0	0	0

Table E.9 lists the settings for a growth period of lettuce, using the 240 W lamp, a 38.5 cm distance, and for a target intensity of 200 $\frac{\mu mol}{m^2 s}$. Reached intensity at experiment start is 198 $\frac{\mu mol}{m^2 s}$. The target intensity at canopy height is received by the plant on day 1.

Table E.9: Lettuce - Vegetative Stage - 240 W lamp - 38.5 cm - 200 PPFD

Light Colour	**Settings**				
Days after Transplanting	1 - 2	2 - 5	5 - 8	8 - 11	11 - 14
White (5700 K)	165	161	148	139	123
Blue (450 nm)	186	182	167	156	139
Red (660 nm)	53	52	48	45	40
Far Red (730 nm)	0	0	0	0	0
Light Colour	**Settings**				
Days after Transplanting	14 - 17	17 - 20	20 - 23	23 - 26	26 - 30
White (5700 K)	106	85	63	37	7
Blue (450 nm)	119	97	71	42	9
Red (660 nm)	34	28	20	12	2
Far Red (730 nm)	0	0	0	0	0

Table E.10 lists the settings for a growth period of lettuce, using the 240 W lamp, a 50 cm distance, and for a target intensity of 270 $\frac{\mu mol}{m^2 s}$. Reached intensity at experiment start is 268 $\frac{\mu mol}{m^2 s}$. The target intensity at canopy height is received by the plant on day 1.

Table E.10: Lettuce - Vegetative Stage - 240 W lamp - 50 cm - 270 PPFD

Light Colour	**Settings**					
Days after Transplanting	1 - 2	2 - 5	5 - 8	8 - 11	11 - 14	14 - 17
White (5700 K)	359	352	331	309	284	257
Blue (450 nm)	403	396	372	347	319	289
Red (660 nm)	117	115	108	101	93	84
Far Red (730 nm)	0	0	0	0	0	
Light Colour	**Settings**					
Days after Transplanting	17 - 20	20 - 23	23 - 26	26 - 29	29 - 30	
White (5700 K)	228	195	159	119	75	
Blue (450 nm)	255	219	179	134	24	
Red (660 nm)	74	64	52	39	24	
Far Red (730 nm)	0	0	0	0	0	

Table E.11 lists the settings for a growth period of lettuce, using the 240 W lamp, a 50 cm distance, and for a target intensity of 220 $\frac{\mu mol}{m^2 s}$. Reached intensity at experiment start is 217 $\frac{\mu mol}{m^2 s}$. The target intensity at canopy height is received by the plant on day 1.

Table E.11: Lettuce - Vegetative Stage - 240 W lamp - 50 cm - 220 PPFD

Light Colour	**Settings**					
Days after Transplanting	1 - 2	2 - 5	5 - 8	8 - 11	11 - 14	14 - 17
White (5700 K)	266	261	246	229	210	190
Blue (450 nm)	300	294	277	258	237	215
Red (660 nm)	86	84	79	74	68	62
Far Red (730 nm)	0	0	0	0	0	
Light Colour	**Settings**					
Days after Transplanting	17 - 20	20 - 23	23 - 26	26 - 29	29 - 30	
White (5700 K)	168	144	117	88	55	
Blue (450 nm)	190	163	132	99	62	
Red (660 nm)	54	47	38	28	18	
Far Red (730 nm)	0	0	0	0	0	

Table E.12 lists the settings for a growth period of lettuce, using the 240 W lamp, a 50 cm distance, and for a target intensity of 200 $\frac{\mu mol}{m^2 s}$. Reached intensity at experiment start is 201 $\frac{\mu mol}{m^2 s}$. The target intensity at canopy height is received by the plant on day 1.

Table E.12: Lettuce - Vegetative Stage - 240 W lamp - 50 cm - 200 PPFD

Light Colour	**Settings**					
Days after Transplanting	1 - 2	2 - 5	5 - 8	8 - 11	11 - 14	14 - 17
White (5700 K)	239	235	221	206	189	172
Blue (450 nm)	270	265	249	233	214	194
Red (660 nm)	77	76	71	66	61	55
Far Red (730 nm)	0	0	0	0	0	
Light Colour	**Settings**					
Days after Transplanting	17 - 20	20 - 23	23 - 26	26 - 29	29 - 30	
White (5700 K)	152	131	107	81	51	
Blue (450 nm)	172	147	121	91	58	
Red (660 nm)	49	42	34	26	17	
Far Red (730 nm)	0	0	0	0	0	

Table E.13 lists the settings for a growth period of lettuce, using the 120 W lamp, a 38.5 cm distance, and for the control. Reached intensity at experiment start is 101 $\frac{\mu mol}{m^2 s}$.

Table E.13: Lettuce - Vegetative Stage - 120 W lamp - 38.5 cm - Control

Light Colour	Settings
Days after Transplanting	1 - 30
White (5700 K)	344
Blue (450 nm)	755
Red (660 nm)	344
Far Red (730 nm)	1000

Table E.14 lists the settings for a growth period of lettuce, using the 120 W lamp, a 50 cm distance, and for the control. Reached intensity at experiment start is 61 $\frac{\mu mol}{m^2 s}$.

Table E.14: Lettuce - Vegetative Stage - 120 W lamp - 50 cm - Control

Light Colour	Settings
Days after Transplanting	1 - 30
White (5700 K)	344
Blue (450 nm)	755
Red (660 nm)	344
Far Red (730 nm)	1000

Table E.15 lists the settings for a growth period of lettuce, using the 240 W lamp, a 38.5 cm distance, and for the control. Reached intensity at experiment start is 235 $\frac{\mu mol}{m^2 s}$.

Table E.15: Lettuce - Vegetative Stage - 240 W lamp - 38.5 cm - Control

Light Colour	Settings
Days after Transplanting	1 - 30
White (5700 K)	97
Blue (450 nm)	209
Red (660 nm)	97
Far Red (730 nm)	279

Table E.16 lists the settings for a growth period of lettuce, using the 240 W lamp, a 50 cm distance, and for the control. Reached intensity at experiment start is 227 $\frac{\mu mol}{m^2 s}$.

Table E.16: Lettuce - Vegetative Stage - 240 W lamp - 50 cm - Control

Light Colour	Settings
Days after Transplanting	1 - 30
White (5700 K)	138
Blue (450 nm)	298
Red (660 nm)	138
Far Red (730 nm)	399

Table E.17 lists the settings for a seedling stage of lettuce, using the 120 W lamp, and at a 87 cm distance. Reached intensity is 9 $\frac{\mu mol}{m^2 s}$.

Table E.17: Lettuce - Seedling Stage - 120 W lamp - 87 cm

Light Colour	Settings
Days after Seeding	1 - 14
White (5700 K)	0
Blue (450 nm)	1000
Red (660 nm)	236
Far Red (730 nm)	0

Table E.18 lists the settings for a seedling stage of lettuce, using the 240 W lamp, and at a 87 cm distance. Reached intensity is 93 $\frac{\mu mol}{m^2 s}$.

Table E.18: Lettuce - Seedling Stage - 240 W lamp - 87 cm

Light Colour	Settings
Days after Seeding	1 - 14
White (5700 K)	0
Blue (450 nm)	1000
Red (660 nm)	236
Far Red (730 nm)	0

Appendix E.2 Cucumber

Table E.19 lists the settings for a growth period of cucumber, using the 240 W lamp, a 198 cm distance, and for a target intensity of 166 $\frac{\mu mol}{m^2 s}$. Expected reached intensity at canopy hegiht after transplantion is 42 $\frac{\mu mol}{m^2 s}$.

Table E.19: Cucumber - Vegetative + Reproductive Stages - 240 W lamp - 198 cm - 166 PPFD

Light Colour	Settings				
Days after Transplanting	1 - 72	72 - 73	73 - 74	75 - 85	
White (5700 K)	313	254	176	71	4
Blue (450 nm)	1000	811	562	227	14
Red (660 nm)	320	259	180	73	4
Far Red (730 nm)	1000	811	562	227	14

Table E.20 lists the settings for a seedling stage of cucumber, using the 120 W lamp, and at a 87 cm distance. Reached intensity is 11 $\frac{\mu mol}{m^2 s}$.

Table E.20: Cucumber - Seedling Stage - 120 W lamp - 87 cm

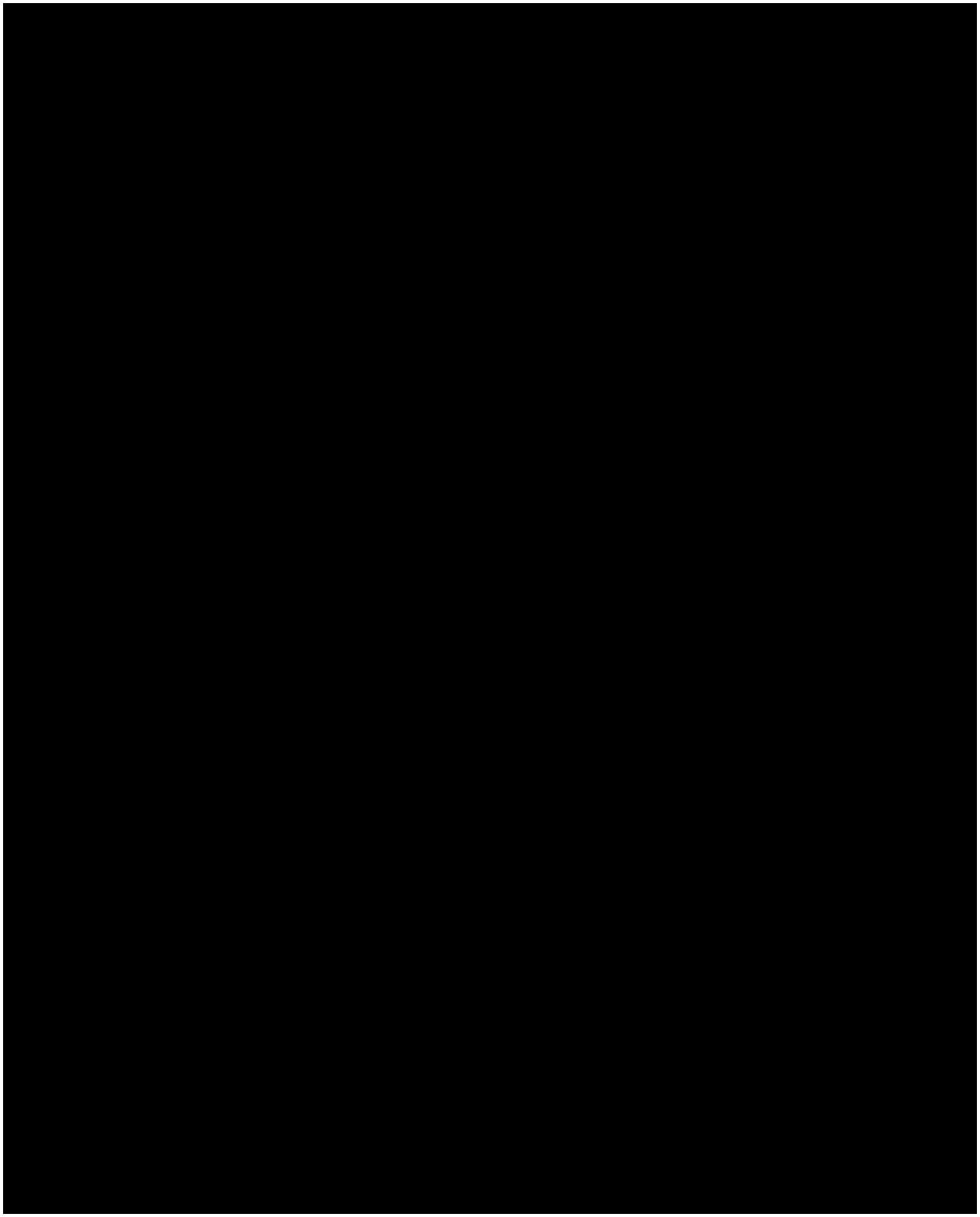
Light Colour	Settings
Days after Seeding	1 - 14
White (5700 K)	0
Blue (450 nm)	1000
Red (660 nm)	270
Far Red (730 nm)	0

Table E.21 lists the settings for a seedling stage of cucumber, using the 240 W lamp, and at a 87 cm distance. Reached intensity is 109 $\frac{\mu mol}{m^2 s}$.

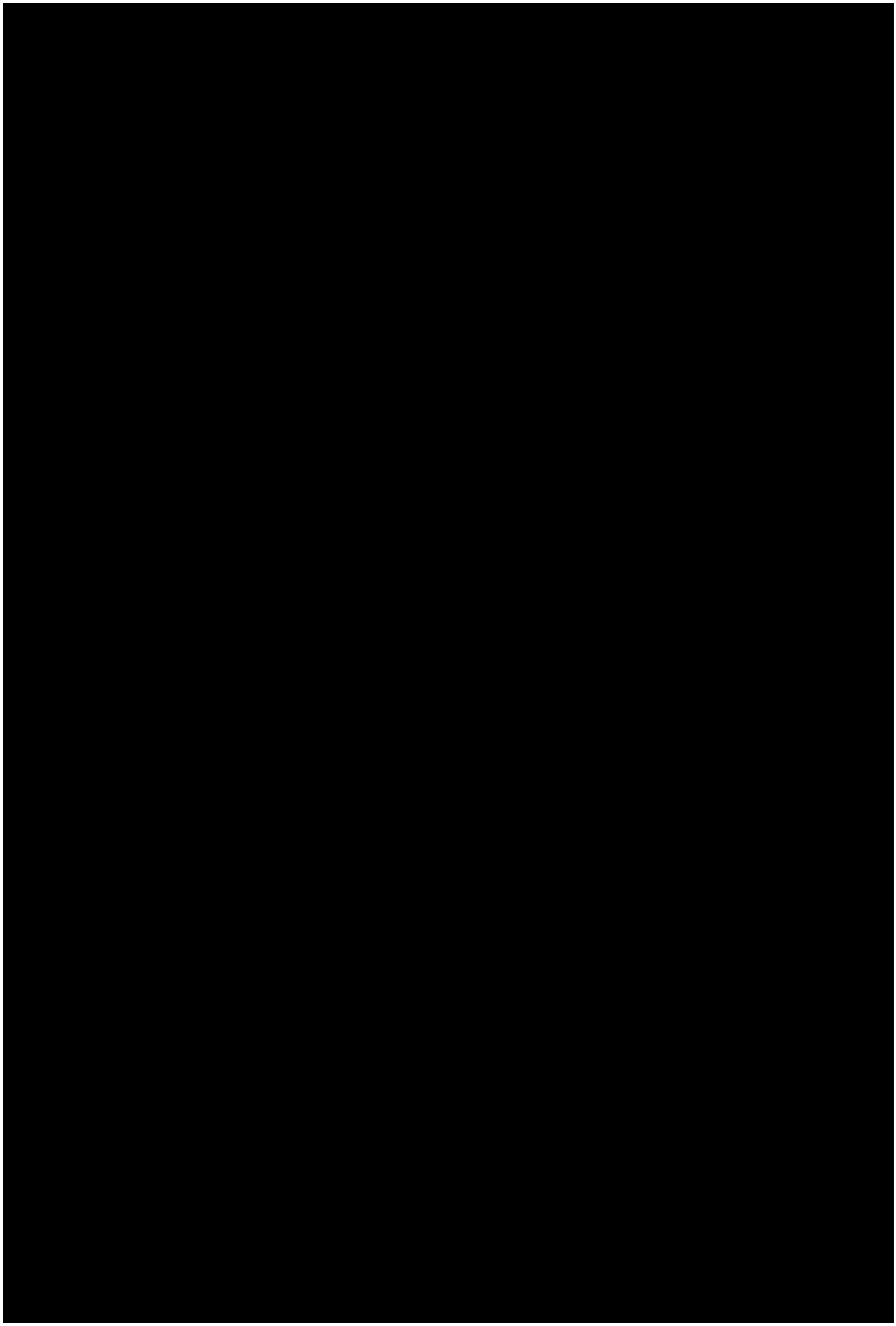
Table E.21: Cucumber - Seedling Stage - 240 W lamp - 87 cm

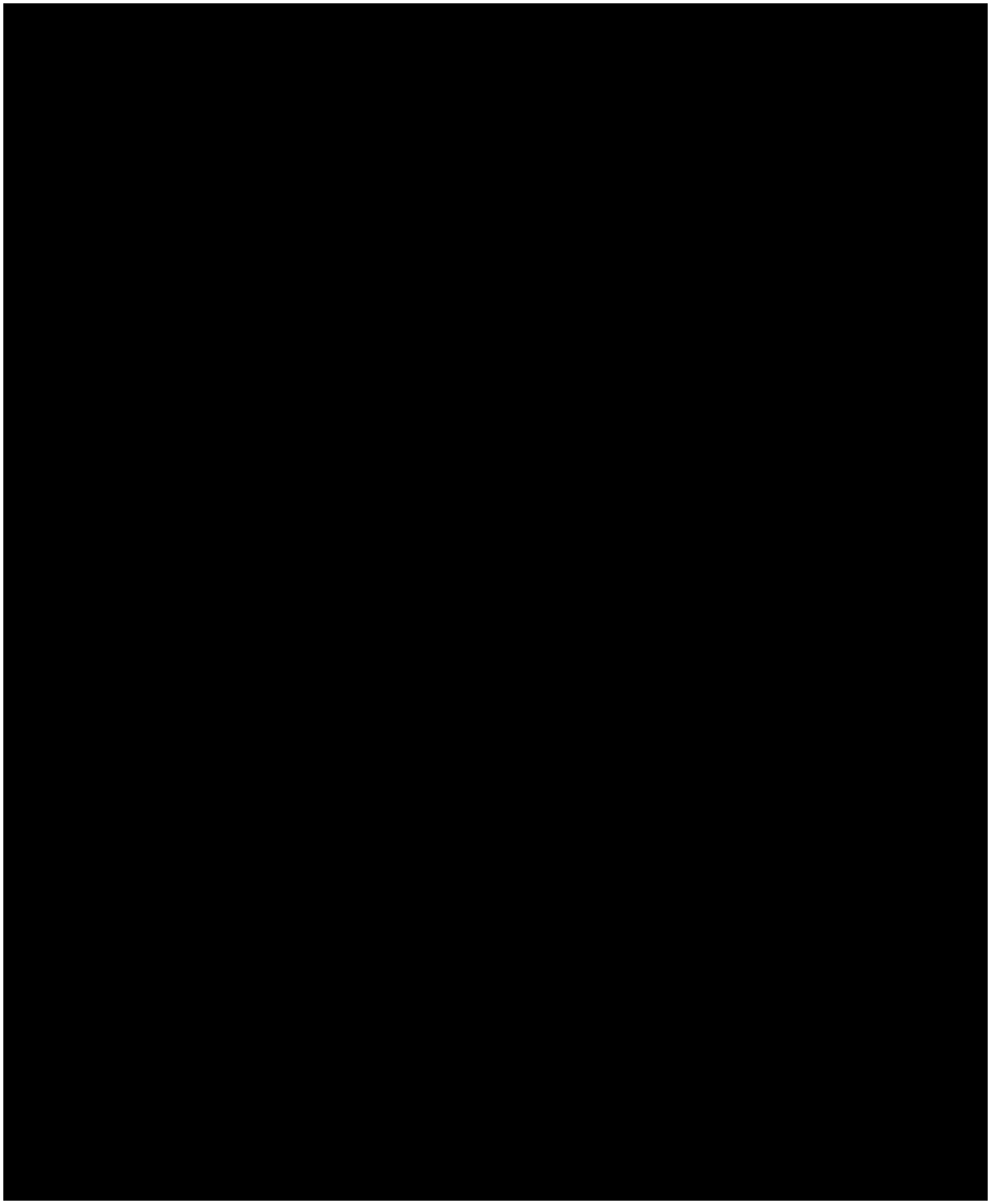
Light Colour	Settings
Days after Seeding	1 - 14
White (5700 K)	0
Blue (450 nm)	1000
Red (660 nm)	270
Far Red (730 nm)	0

Appendix F Unit Conversion of Light Intensity



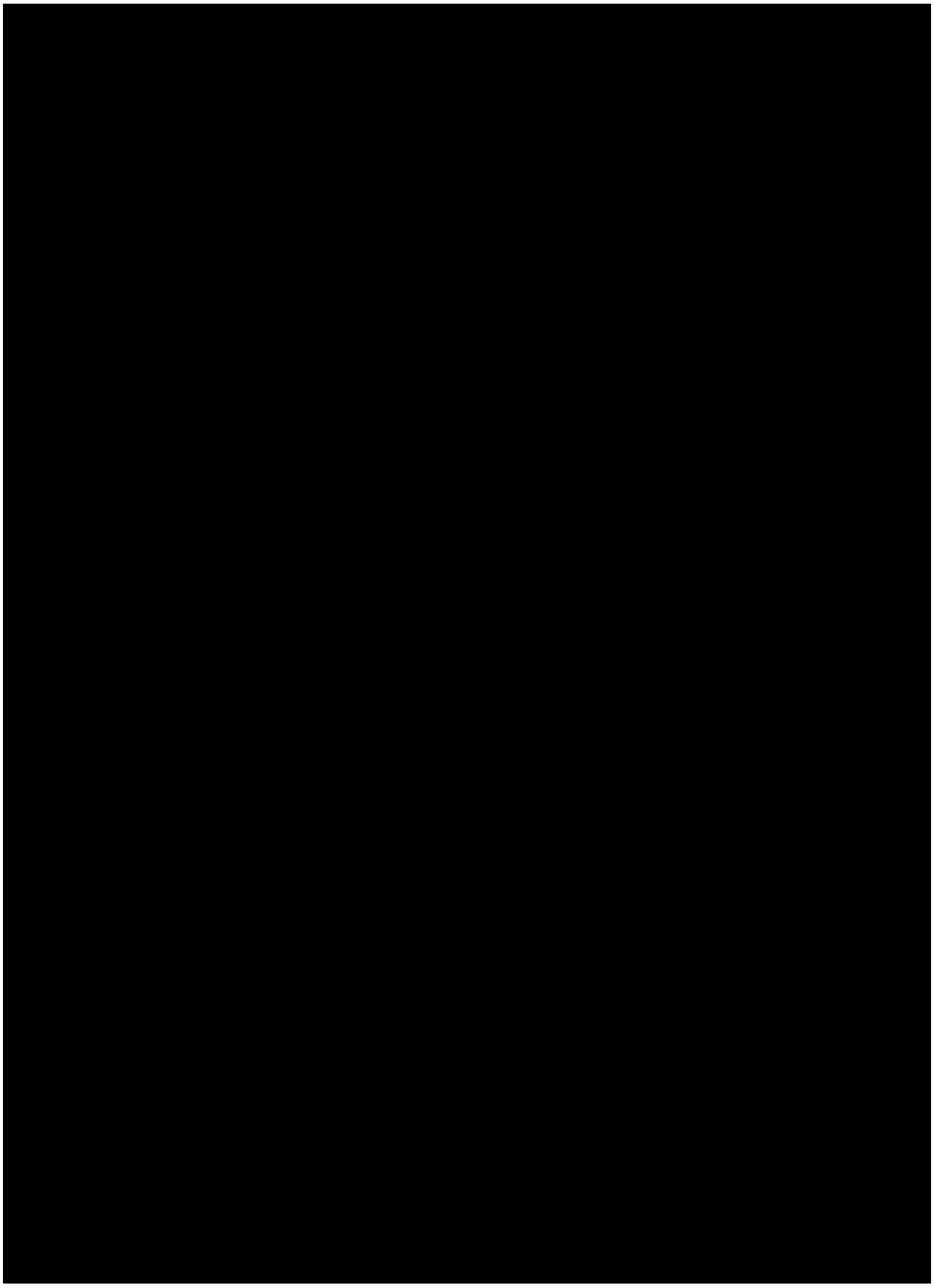
Appendix G Ratios of Coloured Light within White Light

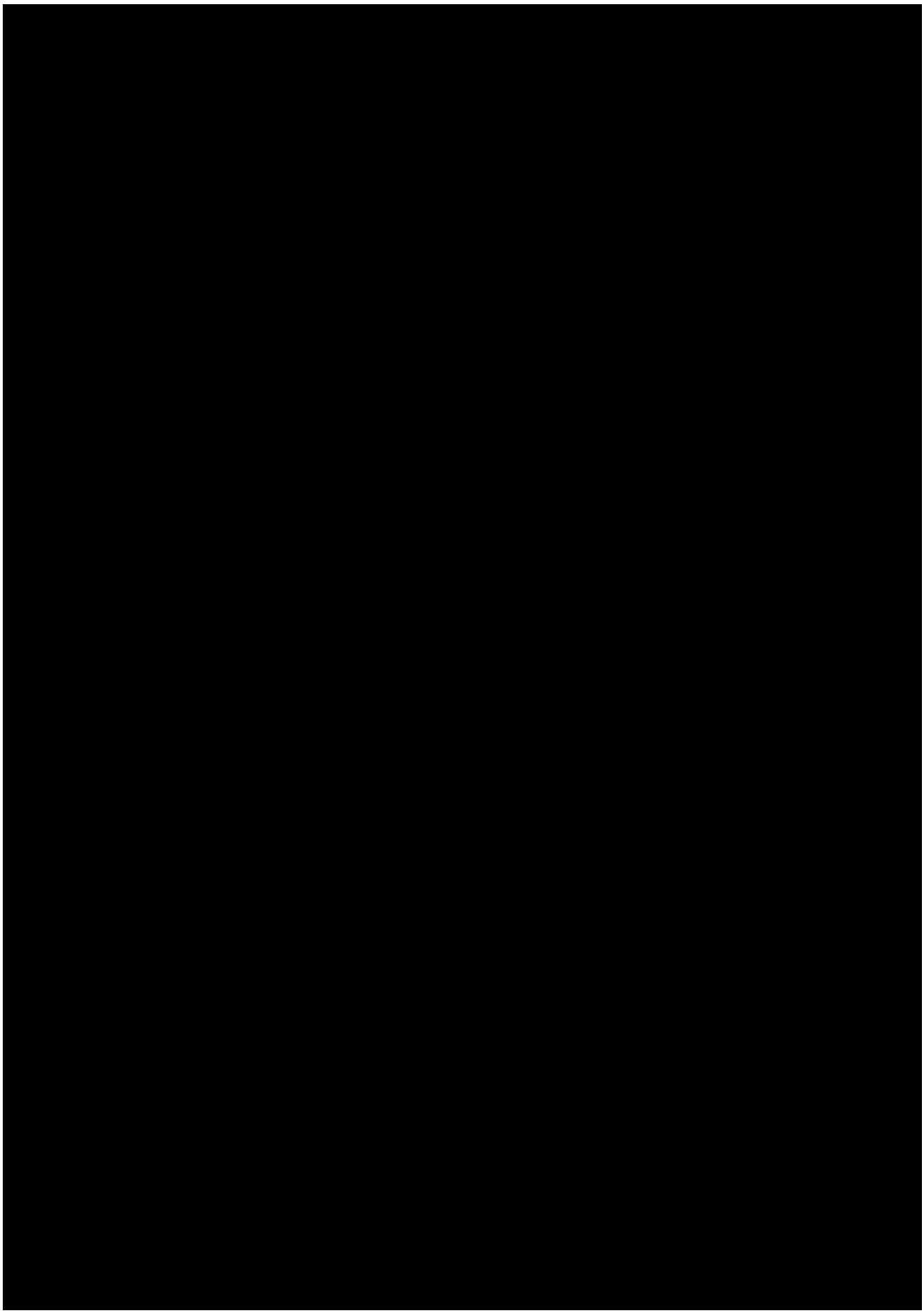


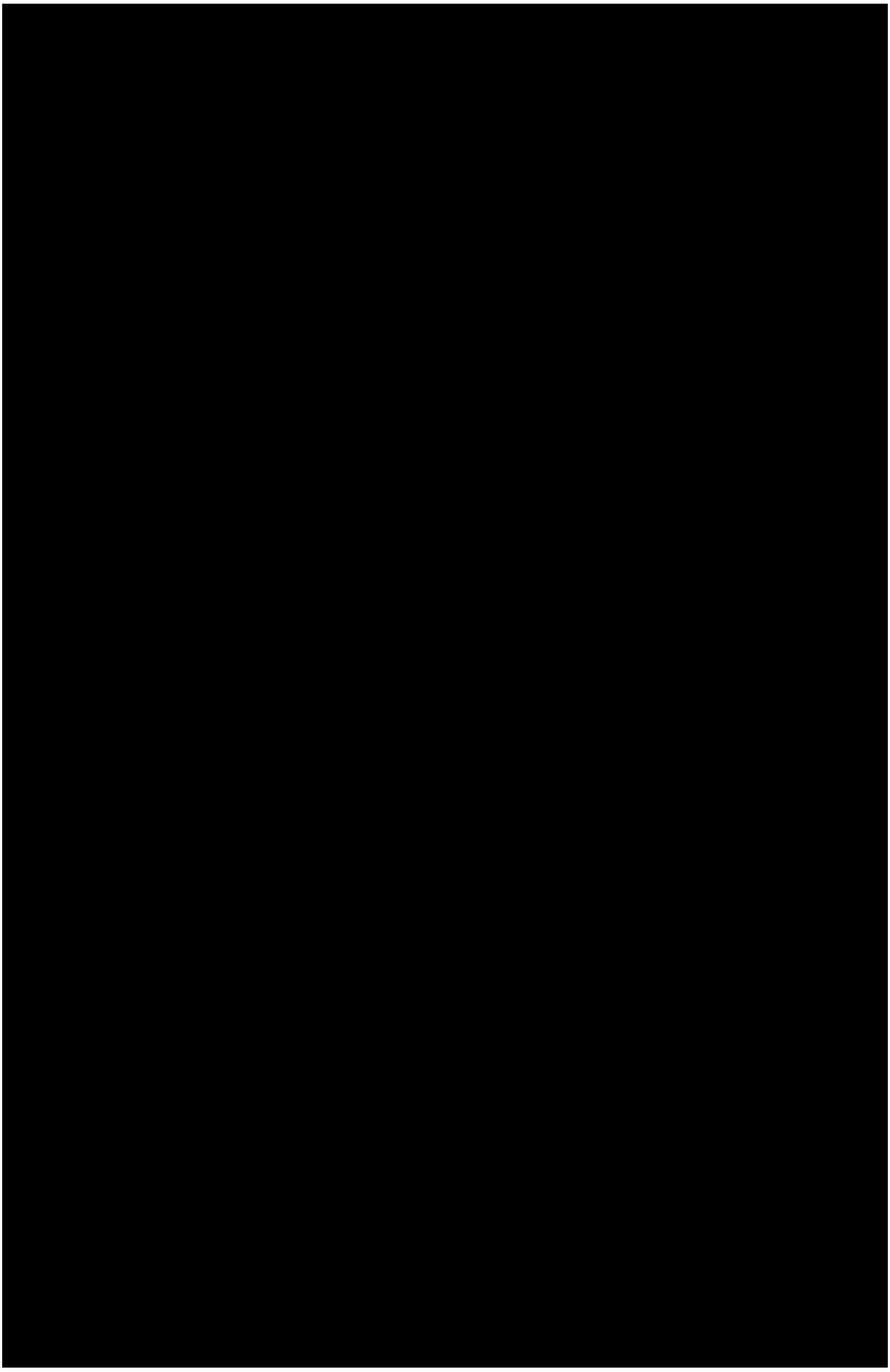


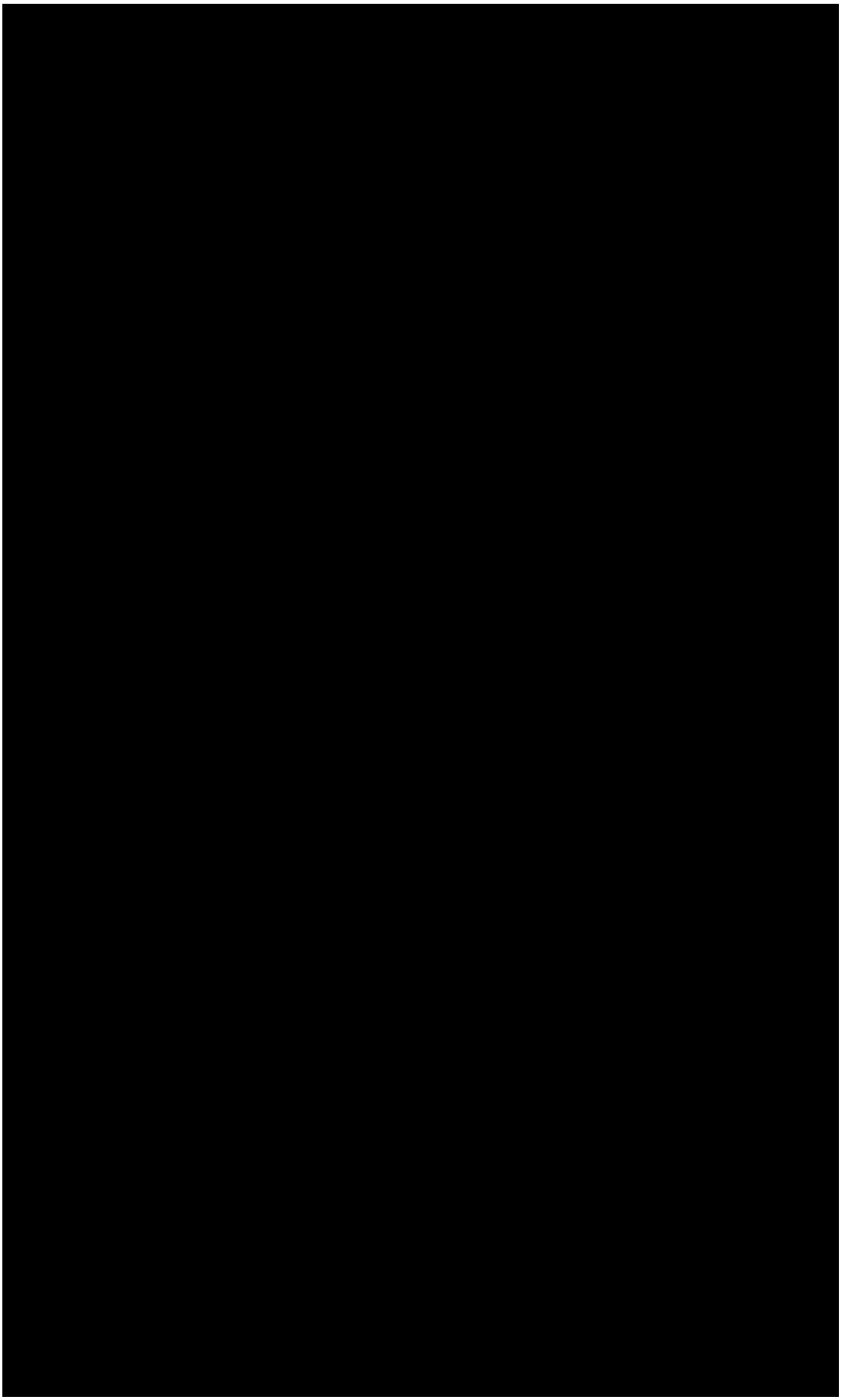
Appendix H Calculation of Light Settings for Experiment 2

```
# Script for calculating LED-settings from target ratios
```

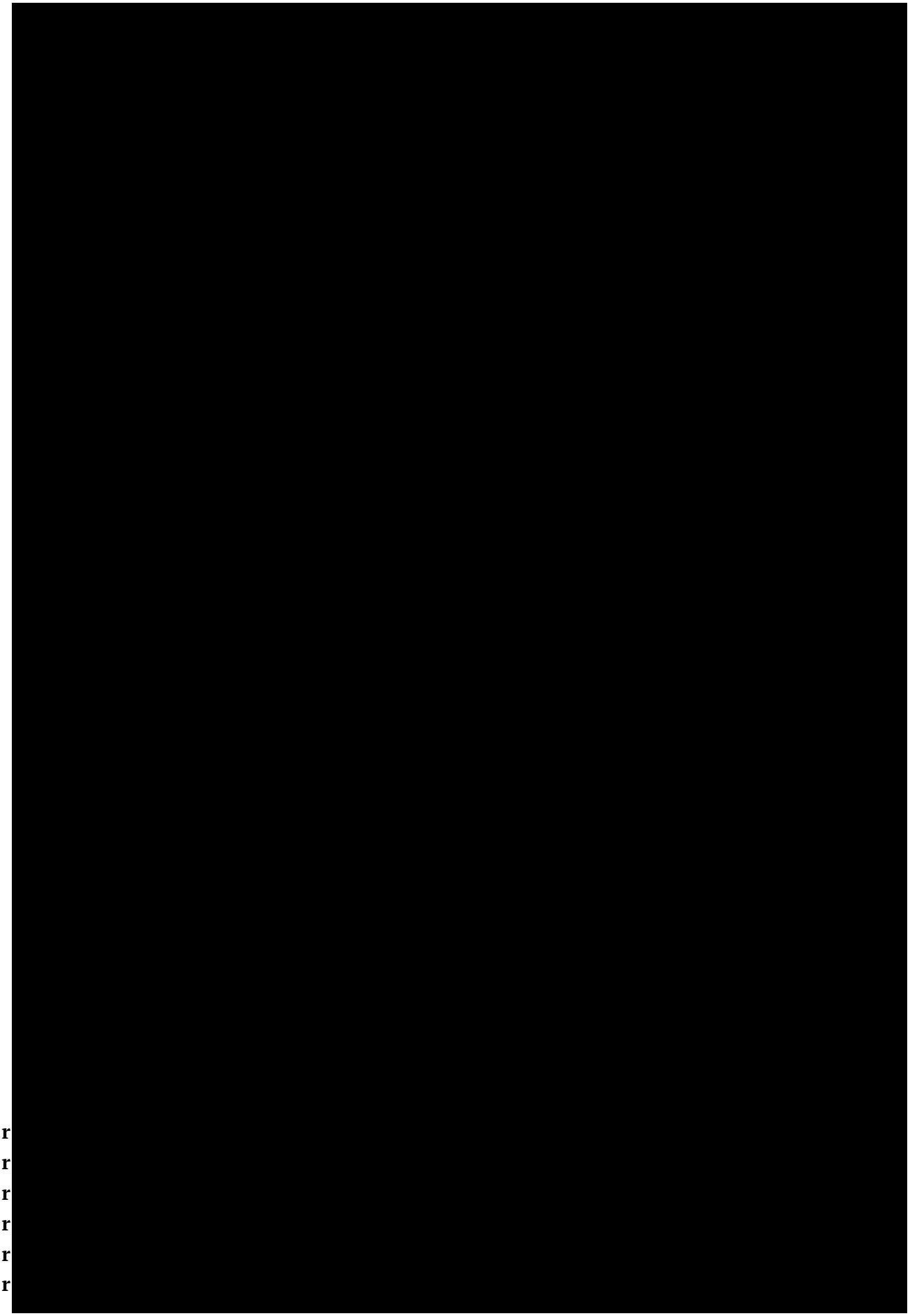








Appendix



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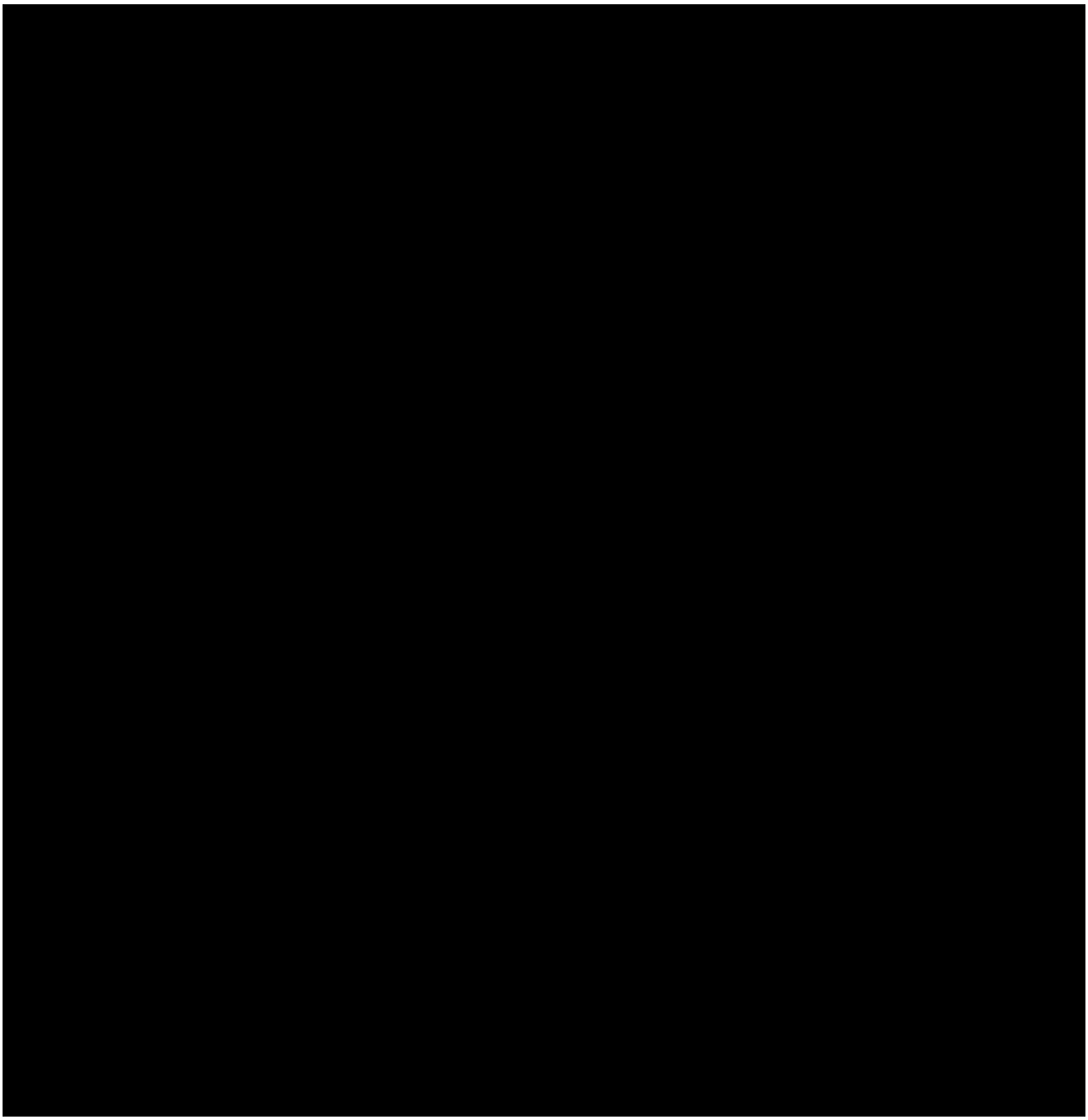
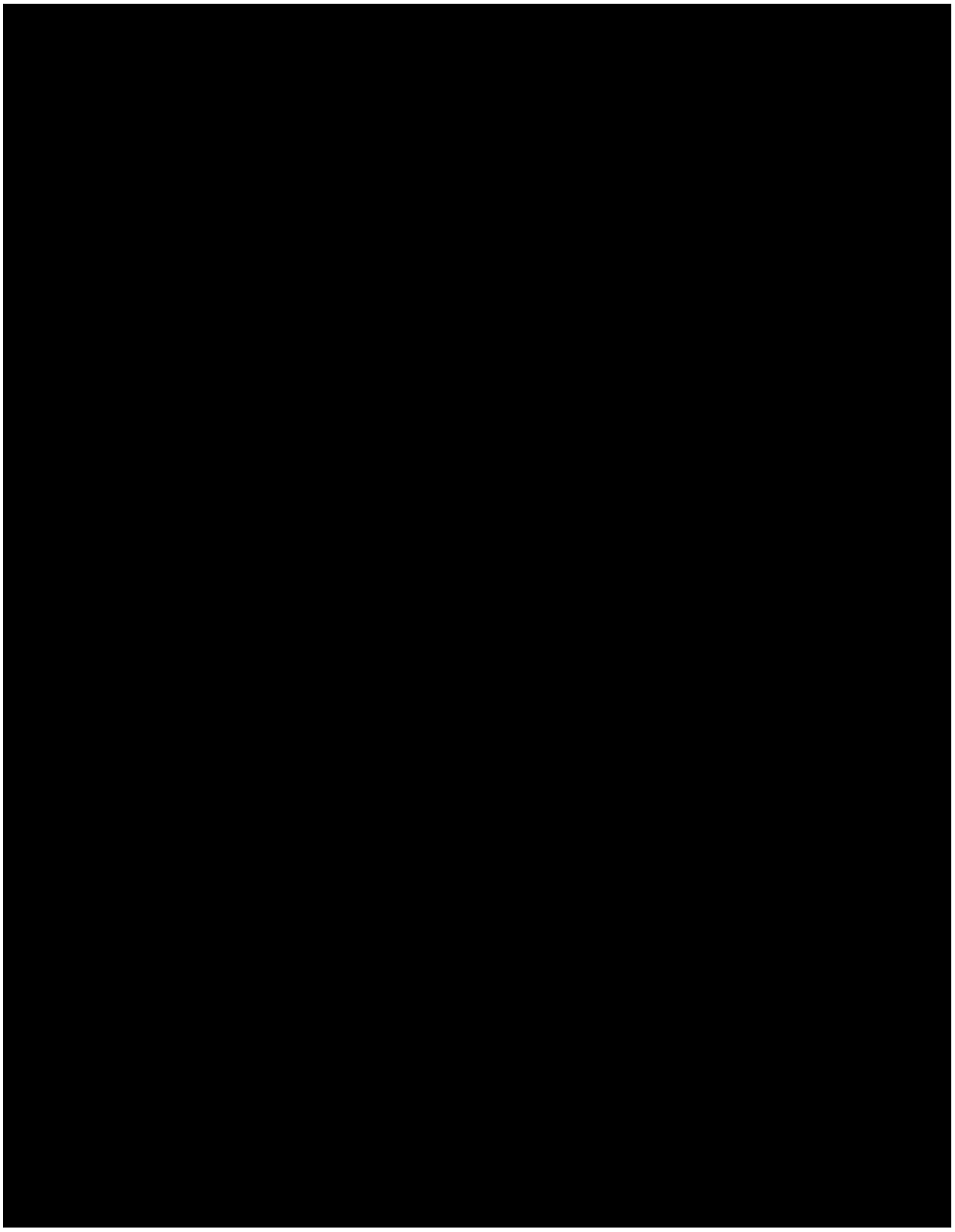


Appendix I Calculation of Light Ratios from LED-Settings

```
# Calculation of Colour Concentrations from LED-settings

import numpy as np
```



Appendix J Set-Up of Plant Trays in EDEN LUNA

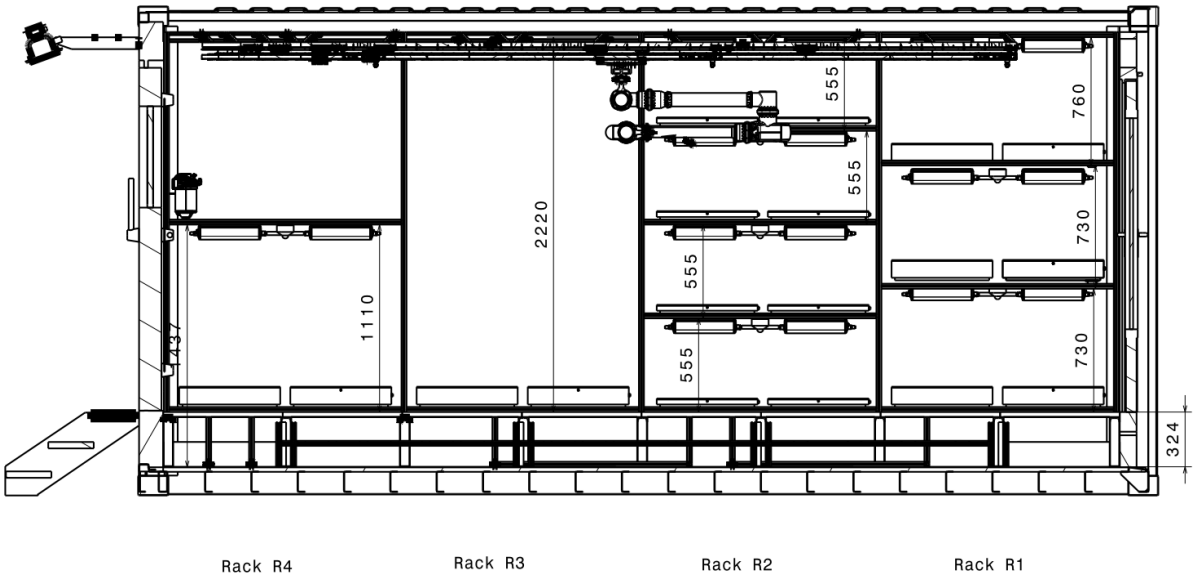


Figure J.1: Set Up of Plant Trays in EDEN LUNA

Appendix K Template for Light Recipes

Crop: _____ Date: _____

Crop: _____

Life Cycle	**Germination Stage**	**Seedling Stage**	**Vegetative Stage**	**Reproductive Stage**
Days				

Time of Harvest [d]: _____ Stage of Harvest: _____

Part of Plant which is harvested: _____

Light Recipe:

	Germination Stage	**Seedling Stage**	**Vegetative Stage**	**Reproductive Stage**
Photoperiod $[\frac{h}{d}]$				
Light Intensity $[\frac{\mu mol}{m^2 s}]$				
Light Composition [%]				
UV:				
Blue:				
Green:				
Orange:				
Red:				
Far Red:				

Crop: _____ Date: _____

Additional Information: