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Thema: Optimizing Lunar Crop Systems: Selection and Cultivation Models for Leafy Greens and Microgreens

Bachelorarbeit

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List of Abbreviations

AMS	Air Management System
BBCH	Biologische Bundesanstalt für Land- und Forstwirtschaft, Bundessortenamt und CHemische Industrie – Federal Biological Research Centre for Agriculture and Forestry
BLSS	Bioregenerative Life Support System
Ca	Calcium
CEA	Controlled Environment Agriculture
CO_2	Carbon dioxide
DLR	Deutsches Zentrum für Luft- und Raumfahrt – German Aerospace Center
EDEN ISS	Evolution & Design of Environmentally-closed Nutrition-Sources (DLR project)
FM	Fresh mass
ISS	International Space Station
K	Potassium
LAM-GTD	Lunar Agriculture Model – Ground Test Demonstrator (DLR project)
LEO	Low Earth Orbit
LiOH	Lithium hydroxide
Mg	Magnesium
NASA	National Aeronautics and Space Administration
NDS	Nutrient Delivery System
O_2	Oxygen
RH	Relative humidity

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1 Introduction

This chapter introduces the topic of this thesis, with a focus on familiarising the reader with spaceflight and space agriculture research and challenges. It also presents the aim and outline of the thesis.

Although representations of the human spaceflight mission of Apollo 11 persist in popular consciousness and are found in numerous posters and books, contemporary spaceflight is limited to low Earth orbit (LEO). Instead of exploring the moon, as was previously the case, human spaceflight has shifted its focus to missions to the International Space Station (ISS), where a variety of experiments are conducted to facilitate the understanding of space, including the effects of microgravity on humans and plants. However, this focus on the low Earth orbit is only the temporal plan, and projects are under development that aim to explore more distant destinations, such as the Moon and Mars, through human spaceflight. These projects face several environmental challenges, including high vacuum, electromagnetic radiation, particle radiation, and magnetism, the effects of which on humans and plants are not fully understood. Despite these uncertainties, it is known that plants play a fundamental role in sustaining human life and well-being in long-duration missions and have multiple benefits, even for short-term missions. Given that plants are the most significant source of food on Earth, they are also critical for sustaining the crew during spaceflight by providing essential nutrients through fresh food supply. Beyond their nutritional contribution, plants play a key role in sustaining life by producing oxygen and recycling water (Galston, 1992; Perchonok et al., 2012; Stankovic, 2018; Watkins et al., 2022).

An approach for transporting plants to space involves their processing to food on Earth, followed by shipment to space. This approach, however, is not only costly but also occupies valuable space, making it impractical for long-term missions. Despite advancements in commercial launch systems, such as SpaceX’s Falcon 9, which leads to a substantial reduction in the cost of space launches, the expense of each launch remains high, with a cost of $62 million for a delivery of 22,800 kilograms to LEO, at a cost of $2,720 per kilogram (Jones, 2018). Missions to more distant destinations, such as geosynchronous transfer orbits, are even more costly — not to mention the additional expenses associated with orbital insertion or, in the case of lunar missions, surface operations (Apgar, 2015). To optimise space and cost efficiency while reducing logistical challenges, the development of a system that enables plant cultivation and growth in space can be seen as a compelling alternative (Cooper et al., 2011).

Additionally, the effects of plants and fresh food on human health and well-being should also be taken into account. Astronauts aboard the ISS are required to consume fresh food at least every 21 days, as the long-term consumption of pre-packaged food is not deemed healthy. The on-site production of fresh food on the ISS or other spacecraft would solve challenges and potentially replace the need for pre-packaged meals (Douglas et al., 2016; Sirmons et al., 2020). The objective of cultivating plants for food production in space is twofold: first, to establish a self-sustaining, regenerative growth system, thereby simplifying the logistics of long-term space missions (Stankovic, 2018), and second, to advance the physical and psychological well-being of the crew by providing fresh food (Haeuplik-Meusburger et al., 2014; Hoff et al., 1982).

In light of the current challenges concerning the necessity of fresh food for the physical and mental health of long-term astronauts, the objective of this thesis is more evident. The aim is to provide an overview of the current research status of crop cultivation in space, integrating diverse insights and structuring them in a manner that allows for an initial estimation of the potential output. This thesis is based on the ongoing research of the Deutsches Zentrum für Luft- und Raumfahrt (DLR – German Aerospace Center) Lunar Agriculture Model – Ground Test Demonstrator (LAM-GTD) project, which serves as a case study, aiming to support and enable more precise research in the future.

Part of this thesis presents a comprehensive investigation into the optimal methods for growing plants in space, including the development of a cultivation model suitable for the LAM-GTD environment. This includes an investigation of a possible crop selection, with particular emphasis on the plant requirements (the necessary input parameters for the system) and the astronauts' needs (the output parameters planned to be achieved by the system).

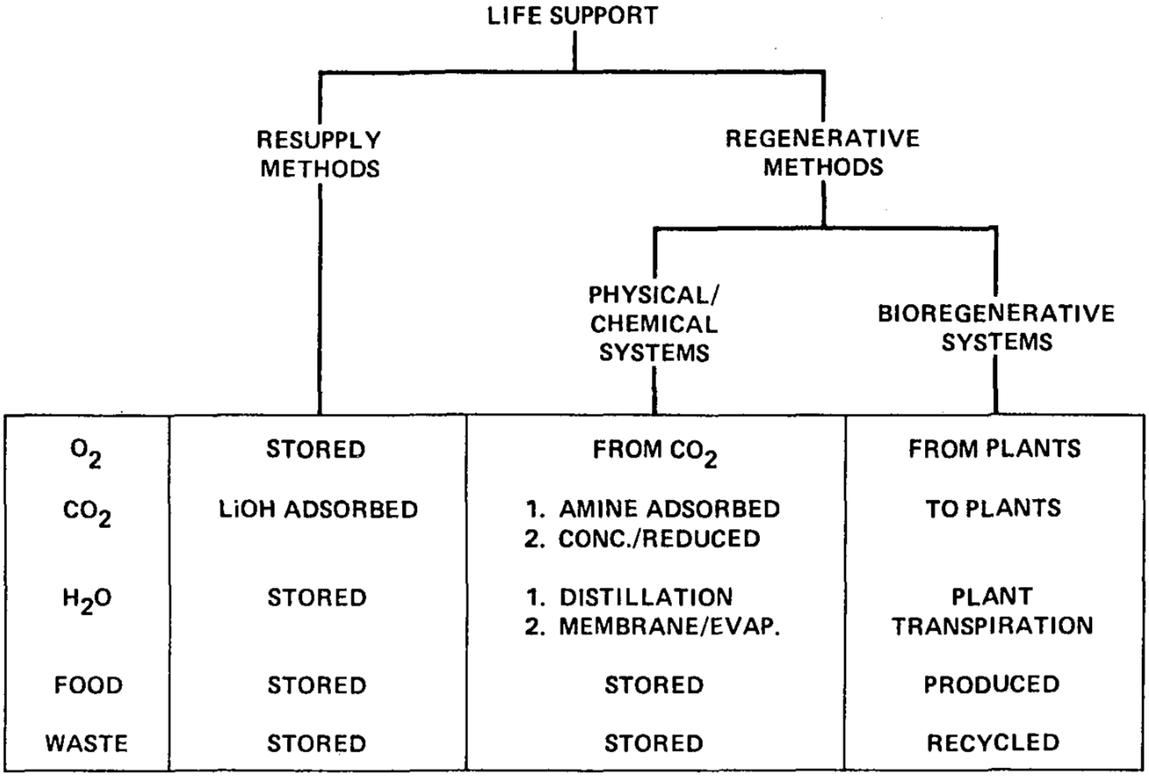
Figure 1 Growth of radish, mizuna and lettuce plants in the eXposed Root On-Orbit Test System (XROOTS®) payload integrated with Veggie hardware aboard the International Space Station (ISS) (Wetzel et al., 2023)

2 Scientific Background

This chapter introduces the different types of life support systems and the possibilities they create, focusing particularly on biological systems including plants. It also offers a comprehensive overview of the LAM-GTD project design.

2.1 Bio-regenerative Life Support Systems for Space Applications

Life support systems are critical for sustaining human life in space. They vary in their capacity to replicate Earth's conditions and satisfy fundamental human needs, such as oxygen, water, and food. The simplest life support strategy is a resupply from Earth. However, this method is both costly and impractical for long-term missions. In this scenario, O_2, water, food, and waste are stored, and CO_2 is adsorbed by lithium hydroxide (LiOH). Implementing regenerative methods during long-duration space missions results in cost savings and weight reductions. The simplest form of regenerative method is the physical/chemical system. When implemented, these systems require the storage of only food and waste, with the potential to derive O_2 from CO_2. Additionally, these methods can adsorb and reduce CO_2 and purify water through distillation or evaporation (MacElroy and Bredt, 1984).



	RESUPPLY METHODS	PHYSICAL/ CHEMICAL SYSTEMS	BIOREGENERATIVE SYSTEMS
O_2	STORED	FROM CO_2	FROM PLANTS
CO_2	LiOH ADSORBED	1. AMINE ADSORBED 2. CONC./REDUCED	TO PLANTS
H_2O	STORED	1. DISTILLATION 2. MEMBRANE/EVAP.	PLANT TRANSPIRATION
FOOD	STORED	STORED	PRODUCED
WASTE	STORED	STORED	RECYCLED

Figure 2 Overview of the various life support systems and their classification, including storage requirements and recycling options for different substances (MacElroy and Bredt, 1984)

Bioregenerative Life Support Systems (BLSS) represent significant advancements in this field. These systems are defined as closed-loop systems that provide the necessary environmental conditions for the growth of plants in extraterrestrial habitats. BLSS possess the capacity to revitalize air, produce food, and recycle waste materials, thereby eliminating the need to store them. Complete regeneration of air is enabled by integrating biological and physical techniques (MacElroy and Bredt, 1984; Quantius et al., 2014). The DLR Project LAM-GTD focuses on developing such a BLSS system with the objective of reducing the need for continuous resupply from the Earth. Although chemical and physical systems demonstrate notable efficacy, the cultivation of higher plants, as exemplified by BLSS, offers additional benefits. This is due to their capacity to synthesise essential nutrients suitable for human consumption (Tibbitts and Alford, 1979). Different subsystems are required to ensure the climatic conditions necessary for both plants and humans to thrive. While quantitative material exchanges are quite complex and dependent on the exact mission scenario, qualitative material exchange is illustrated in Figure 3. This figure shows the different subsystems as well as the qualitative material flows between the systems (Quantius et al., 2014).

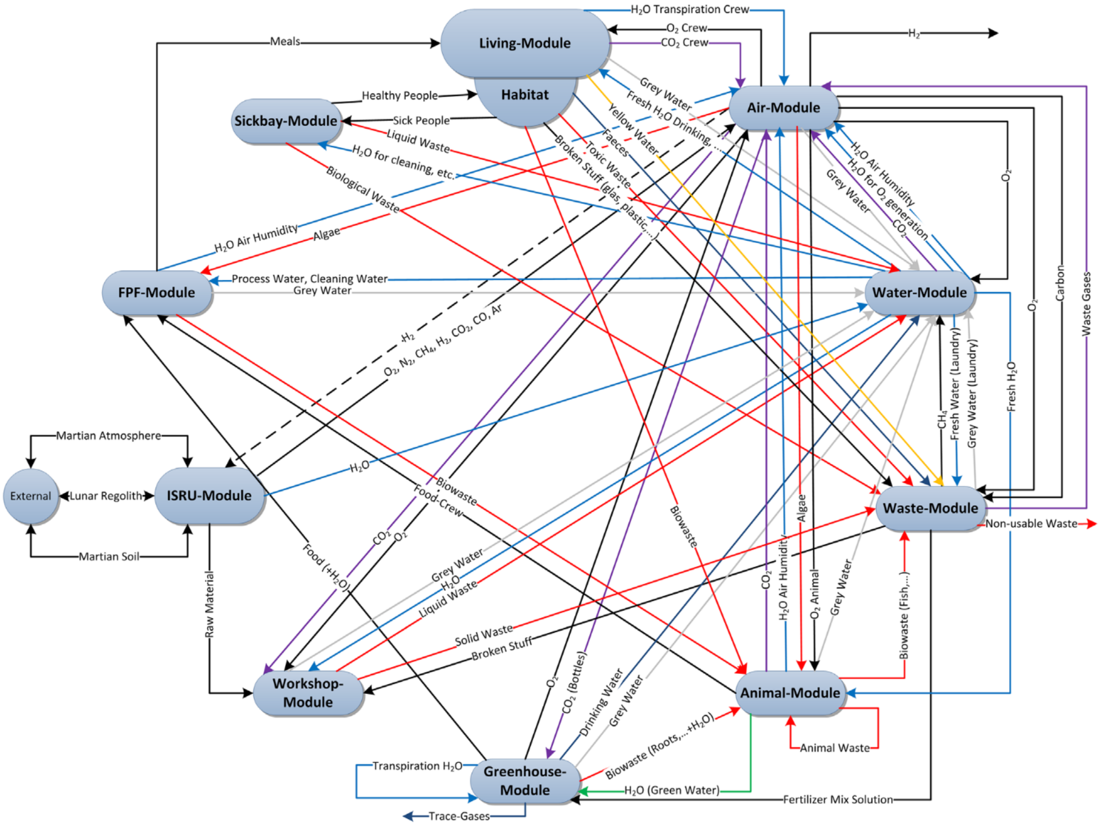


Figure 3 Overview of the different modules of a bioregenerative life support system and their quantitative material exchange (Quantius et al., 2014)

The cultivation model (bottom of Figure 3) uses a greenhouse model in which an air module introduces CO_2 (purple arrow) to enhance plant growth. These plants subsequently convert CO_2 to O_2 (black arrow) during photosynthesis. The animal or waste module converts the biowaste (red arrow) into usable 'green water' (green arrow) and fertilizer mix solution (black arrow) for plants in the greenhouse module. 'Grey water', used water from the plants, can be refreshed in the water module and reused elsewhere. Transpiration water can be captured with a condensate and reused by plants (blue arrow). However, trace gases (dark blue arrows) are not reusable.

The LAM-GTD project involves not only the examination of plants but also the creation of an agricultural module. To achieve a chemical/biological life support system that incorporates plants, it is necessary to develop and design different systems to work together using system engineering methodologies.

2.2 Life Support in the Context of the LAM-GTD Project by DLR

As this thesis is situated within the context of the LAM-GTD project, the following overview will be provided: an outline of the project, its capabilities, and the requirements it imposes on plants.

The LAM-GTD builds upon the findings of the EDEN ISS mission project in Antarctica. The objective of the project is the development of a ground-based, semi-closed-loop BLSS. It is designed to be a high-fidelity analogue to the flight model and aims to replicate the lunar environment, except for the Moon's reduced gravitation. However, the GTD is capable of simulating both climate and air pressure conditions on Earth. It is designed to achieve a high level of autonomy, enabled by robotic support. The goal for it is to function as a testbed, facilitating research on plant development and behaviour within a LAM on the Moon. The GTD is a collaborative effort involving the DLR, the Canadian Space Agency, and various subcontractors. Their research includes the optimisation of biomass output, selection of crops and cultivars, testing and developing of the Controlled Environment Agriculture (CEA) technologies, and developing a holistic growth recipe. The ultimate objective of this research endeavour is to test the capability of the LAM to provide a minimum of 10 % of the crew's daily caloric requirements (Maiwald, 2025).

As illustrated in Figure 4, there are several technical subsystems necessary to ensure plant growth. The three primary systems are the Nutrient Delivery System (NDS), the Air Management System (AMS), and the Illumination Control System. The NDS supplies the plants with a nutrient solution. In the design of LAM-GTD, the NDS consists of two separate recirculating irrigation loops, one for each side of the module, with each loop comprising a nutrient tank. In these tanks, the solution is mixed from a concentrated nutrient solution, water, as well as an acid and a base to regulate the pH and electrical conductivity of the final solution. The AMS is responsible for regulating the temperature using a heater and a heat recovery system, while also controlling the air composition, including the O_2 and CO_2 concentrations, and the relative humidity. The system's humidity control begins with germicidal lamps sterilising the incoming air and condensed water. Subsequently, air filters remove any undesirable gas molecules from the air, and a dehumidifier then extracts water from the air, thereby reducing the overall humidity. The extracted water can be purified and subsequently added to the nutrient solution within the NDS. The AMS is also responsible for the ventilation and regulation of cabin pressure. Sensors are installed in the module to detect temperature, relative humidity, CO_2 and O_2 levels, particulate matter, volatile organic compounds, ethylene, volume flow, and air velocity (Maiwald et al., 2024).

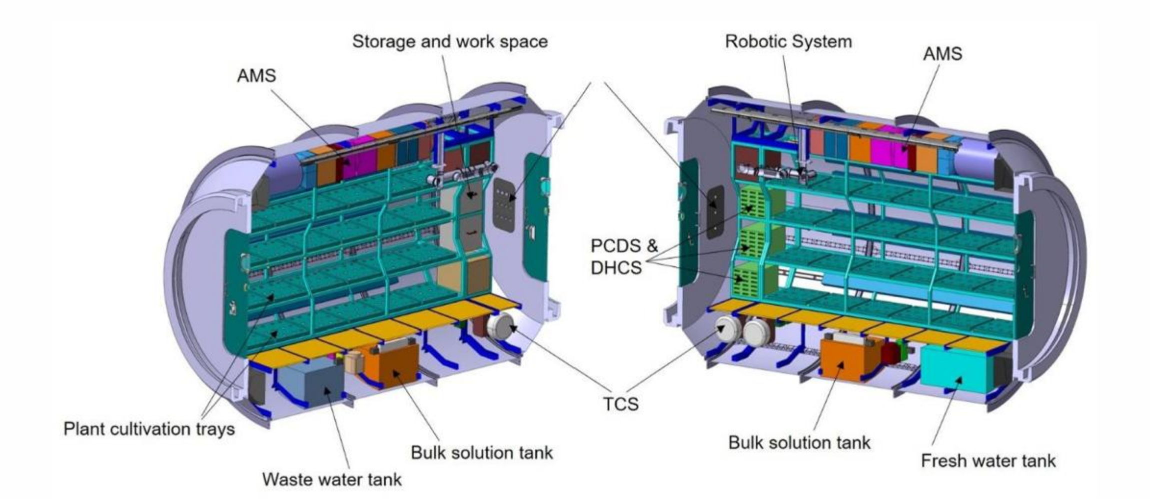


Figure 4 Current Design of the LAM-GTD, showing the cross section with the trays racks and trays for plant cultivation on each side, as well as several subsystems, including the Air Management System (AMS), Thermal Control system (TCS), Power Conditioning and Distribution System (PCDS) and Data Handling and Control System (DHCS) (Maiwald et al., 2024)

Inside the module there are 48 trays, each 70 cm in both length and width, resulting in a total growth area of 23.52 m². The trays are compatible with a variety of lids, each offering distinct capacities for plant cultivation, tailored to the specific needs of the crops to grow. The precise final height of the plants is yet to be determined; however, estimations are that they will reach approximately 30 cm in height. The exact biomass requirements depend on the mission duration. Mission scenarios involve different requirements for the crop choice and differentiate between nutritional challenges a mission may face, depending on the mission's duration. The short-term mission will not provide for food storage or options for the preparation of food, so the focus will be on pick-and-eat crops. It is planned that the LAM would prepare the crop production autonomously, 28 days before the crew's arrival, ensuring that the food is ready or nearly ready upon their arrival. The crew mission time is then planned for an additional 14 days. The long-term mission scenario involves a more extensive range of potential crops, given the extended timeframe and the necessity of ensuring a balanced diet, as the return to Earth-based nutrition is distant.

The selection of crops for this project must be capable of growing in the CEA environment in relatively small areas with as similar environmental requirements as possible. Crops should be selected with the aim of meeting the nutritional requirements of the crew to the greatest extent possible within the available cultivation area. With the overarching framework of the project in mind, the various factors can be examined more precisely, thereby facilitating a well-informed crop selection process.

2.3 Focus on Leafy Greens and Microgreens

The research thus far on short-term missions focuses on diverse pick-and-eat crops, of which leafy greens constitute a considerable proportion. Leafy greens include lettuce (*Lactuca sativa*), kale (*Brassica oleracea/Brassica napus*), Swiss chard (*Beta vulgaris*), mizuna (*Brassica rapa*) and purslane (*Portulaca oleracea*), amongst other varieties. For long-term missions, the list can be extended to include more diverse crops.

Despite the extensive range of crops that are available, this study will focus on the selection of leafy greens and microgreens. They are characterised by their good nutritional profile, relative ease of cultivation, homogeneous environmental conditions and short growth cycle. This, combined with their compact growing space and ability to grow in hydroponics, makes them ideal candidates for cultivation in space. These plants include amongst others lettuce, kale and radish (*Raphanus sativus)*, as well as microgreens of even more diverse plants and plant families. They are a good source of vitamins, minerals and antioxidants such as A, C and K, as well as iron, calcium and fibre. This makes them beneficial to the diet, especially as these compounds are often less stable in packaged foods such as those used in space. Beyond their nutritional value, the inclusion of leafy greens and microgreens in the crew's diet can positively impact their mental well-being due to their diverse flavours and colours (Dueck et al., 2016; Ewert et al., 2022; Fritsche et al., 2024; Massa et al., 2015).

Microgreens are edible seedlings from various plant families, including Brassicaceae, Asteraceae and Amaranthaceae. Despite their small size, their nutrient concentration is exceptionally high, often higher than that of the mature plants. While the biomass output is low, they can provide the crew with a high nutrient content per unit of biomass. Furthermore, since they are harvested as seedlings, the time until harvest is only a couple of weeks, depending on the type of microgreen. This flexibility in cultivation allows for rapid response to anticipated shortfalls in yield. However, microgreens have limitations in CO_2 fixation, O_2 regeneration, and water recycling compared to other crops (Di Gioia et al., 2015; Ebert, 2022; Ewert et al., 2022; Kyriacou et al., 2017; Pinto et al., 2015). Also, while microgreens have numerous benefits, their low yield — especially relative to seed weight — is a concern. As space transport is expensive, one factor to consider is the amount of biomass that can be produced from one seed — more precisely, from a given seed weight. It is necessary to evaluate the economic viability of harvesting plants at such a young growth stage, as is typically done with microgreens.

The key characteristics that make these crops suitable for space farming are as follows:

- High nutrient density (especially in microgreens)
- Fast growth cycles
- Low/similar resource demand
- Compact growth
- Psychological benefits

Especially for long-term space missions, plant cultivation becomes an unavoidable necessity to provide adequate human nutrition. Leafy greens and microgreens offer a promising solution as they meet many of the growth requirements. Their nutritional profile secures the dietary needs of the crew, their adaptability to controlled environments ensures a reliable food source, and their psychological benefits contribute to the well-being of astronauts.

3 Crop Selection and Growth Factors

In crop cultivation models, crop selection is a primary and essential focus point. This section of the report focuses on aspects of human nutrition, such as the output of edible fresh weight, nutrient density and composition. The second aspect of the section is the crop's needs, so that the selected crops that are fit for human consumption can be assured of being able to grow in similar environments.

3.1 Nutritional Aspects

3.1.1 Nutritional Requirements for Humans in Spaceflight

The objective of this section is to provide an overview of key nutritional considerations and a guide to which crops are suitable. The selected crops must provide the astronauts with a nutritious diet that is beneficial for their physiological and psychological health (Hoff et al., 1982). The most fundamental consideration is that the edible biomass produced by the plants must be safe for consumption. Considering the present state of spaceflight storage and food preparation methods — or, more precisely, the absence thereof — the optimal crops are those that are ready to eat. Additionally, the energy density of a crop must be considered. The energy content refers to the calories derived from foods. This is a relevant consideration given the limited availability of livestock and packaged food options in spaceflight. Beyond caloric intake, crops must also provide a well-balanced composition of essential nutrients, including protein, fats, carbohydrates, vitamins, and minerals. While these factors are important, the present focus is on vitamins and minerals, since they often are not stable when stored. Other factors, such as the calories, can be more effectively obtained from prepackaged food. Consequently, the initial missions, designated as short-term, will most likely prioritise the balanced diet aspect rather than the actual amount of food, although this should not be overlooked. Maintaining this nutritional balance is crucial for sustaining astronaut health and performance also during long-duration missions (Dueck et al., 2016; Hoff et al., 1982). Cooper et al. (2011) investigate the dietary needs of humans during spaceflight missions. A minimised table with important vitamins and minerals is shown below (see Table 1, (Cooper et al., 2011)).

Potassium (K) is significant due to its prevalence of deficiency in space food (Massa et al., 2015). Potassium aids the control of heart, muscle and nervous system activity, and a lack of it can lead to fatigue and muscle weakness. Processed foods tend to be low in potassium due to the cooking process, but raw, steamed or stir-fried vegetables are good sources of potassium (Campbell, 2001). Magnesium (Mg) and calcium (Ca) are also considered essential nutrients, although the precise calcium requirement remains uncertain. Magnesium is involved in cellular metabolism, including protein production and energy control in the Krebs cycle. Symptoms of deficiency include poor appetite, irritability, weakness and muscle tremor. Insufficient magnesium in the body can lead to calcification of arteries, increasing the risk of cardiovascular disease. Factors such as insufficient stomach acid can further reduce magnesium absorption, leading to even less absorption. Foods high in magnesium include green vegetables and soybeans. Calcium works closely with magnesium in the body. Most of it is found in bones and teeth, where it strengthens the skeletal structure and reduces the risk of osteoporosis. Furthermore, calcium regulates the heartbeat, nerve transmission, and muscle contraction. Calcium deficiency can be worsened by excessive intake of synthetic vitamin D. Also, calcium absorption decreases with age. Calcium can be obtained from dairy products and various vegetables (Campbell, 2001). Vitamin K similarly faces the challenge of deficiency, also due to its limited storage viability. It is important for blood clotting. Sources of vitamin K include vegetables containing vitamin K1 (phylloquinone), as well as animal products containing vitamin K2 (Maqbool et al., 2018). The study conducted by Fritsche et al. (2024) also placed emphasis on vitamins C (specifically ascorbic acid) and B1 (thiamine). Vitamin B1 is part of the vitamin B complex, which consists of multiple B vitamins. It plays a key role in energy metabolism. Deficiency can lead to damage in the nervous system, heart and brain. Good sources include microgreens as well as various types of vegetables and legumes (Fritsche et al., 2024; Maqbool et al., 2018). Vitamin C acts as an antioxidant and helps with iron uptake. Deficiency can cause scurvy and a range of other diseases, as well as allergies. It can be obtained from various fruits and vegetables (Maqbool et al., 2018). However, the ascorbic acid content is dependent upon agronomic factors, and therefore it is important to consider environmental conditions (Kathi et al., 2022). The nutrients referenced in these two studies have thus been selected to be shown in the following table:

Table 1 Average dietary requirements of humans during spaceflight for selected important nutrients (Modified after Cooper et al., 2011)

Nutrients	Daily dietary intake
Vitamin K	Women: 90 µg, men: 120 µg
Vitamin C	90 mg
Vitamin B1	Women: 1.1 mg, men: 1.2 mg
Calcium	1200 – 2000 mg
Magnesium	Women: 320 mg, men: 420 mg
Potassium	4.7 g

From a horticultural perspective, it is advantageous to select crops that yield a higher harvest index, meaning they produce a greater amount of edible biomass, since that results in a higher food yield with less waste (Hoff et al., 1982; Wheeler et al., 2003). The proportion of edible biomass produced in relation to the total crop is important in optimising the utilisation of available nutrients. Reducing the proportion of inedible biomass leads to enhanced efficiency in the use of these resources, since greater edibility corresponds with less solid waste (Wheeler, 2003). While numerous studies have been conducted on various crops, further research is necessary in the CEA environment to evaluate the crop's performance under these conditions (Hoff et al., 1982).

3.1.2 Nutritional Content of Microgreens

Microgreens are a valuable addition to any diet due to their diverse colours and flavours, high nutrient content, short production cycle and small plant size. In comparison to their mature stages, microgreens generally contain higher levels of phytonutrients and lower levels of nitrate, which can be harmful (Pinto et al., 2015). They are particularly rich in vitamins, minerals and antioxidants, and are ready to eat, making them an ideal fresh food supplement (Falcinelli and Galieni, 2023; Fritsche et al., 2024; Kyriacou et al., 2017; Xiao et al., 2012). From the range of different microgreens that are available, it is necessary to select those that are the most suitable in terms of space conditions and have a high nutritional content. Given the wide range of factors to be considered, the present study will focus on crops that have been tested in space or mentioned in other publications as being suitable. The objective is to determine which of these have a good nutritional profile.

Bafumo et al. (2024) conducted a study on the morphological and phytochemical characteristics of Brassica microgreens, tailored to Brassica microgreens. The outcome ranking shows that radish microgreens perform best, followed by cauliflower, broccoli, cabbage and mustard (Bafumo et al., 2024). Similarly, in their study, Izzo et al. (2023) document a list that assesses growth, phytochemical and elemental composition. Radish is placed at the top of the ranking, followed by various types of cabbage (*Brassica oleracea)*, another type of radish and coriander (also known as cilantro; *Coriandrum sativum*). Radish exhibits the highest fresh biomass yield and dry matter, as well as the highest amount of total ascorbic acid. In contrast, coriander ranks lowest in these categories, as well as in hypocotyl length. However, it ranks highest in dry matter (Izzo et al., 2023). A more extensive study by Di Gioia et al. (2023) lists the yield and nutrient content of 17 common microgreens is examined. Radish and Borage (*Borago officinalis*) have the highest fresh yield, while Amaranth and beet are ranked highest in potassium. Cabbage and Amaranth have among the highest calcium values, and Amaranth contains the highest amount of magnesium. Some crops that achieve the best rankings in the content of certain nutrients are added to the Table 2 (Di Gioia et al., 2023). Xiao et al. (2012) provide in their study contents of the mean total ascorbic acid, where cabbage and amaranth (*Amaranthus spp*.) microgreens have the highest values of vitamin C. Also radish and basil (*Ocimum basilicum*) rank quite high (Xiao et al., 2012). Vitamin C content is also measured by Balik et al. (2015) yet investigating different microgreens. In their study pea (*Pisum sativum*) microgreens rank high in the contents of vitamin C and kalium. While in magnesium, broccoli (*Brassica oleracea*) and in calcium sunflower (*Helianthus annuus*) microgreens rank the highest. In general pea, bean, broccoli and beet (*Beta vulgaris*) microgreens contain a high nutrient value (Balik et al., 2025). According to De la Fuente et al. (2019), kale exhibits the highest vitamin C content among the evaluated crops. Both mustard and kale rank highest in potassium, with kale also showing the greatest calcium content and mustard (here, *Brassica juncea*) leading in magnesium levels (De la Fuente et al., 2019). Complementing these findings, Rani et al. (2024) identify sunflower, mung bean (*Vigna radiata*), beet, and radish as the top performers regarding nutrient content. Mung beans also rank a generally high nutritional value (Priti et al., 2021). Additionally, buckwheat (*Fagopyrum esculentum*) has a particularly high calcium content (Rani et al., 2024). Regarding yield, while there are — even considerable — differences between the species, the biomass of microgreens is especially dependent on the day of harvest. A variation of as little as a couple of days can have a substantial impact on yield. In a similar manner, the density at which seeds are sown significantly impacts the resulting yield (Signore et al., 2024). For a more specific overview of the data and sources, see Appendix A.

Table 2 Overview of important nutrients and microgreens tested high in these nutrients, with corresponding sources

Nutrient	Crop	Source
Vitamin C	Radish	Izzo et al., 2023; Xiao et al., 2012
	Cabbage	Di Gioia et al., 2023
	Amaranth	Di Gioia et al., 2023 ; Yadav et al., 2019
	Kale	De la Fuente et al., 2019
	Bean	Balik et al., 2025
	Pea	Balik et al., 2025
Vitamin K	Mustard	De la Fuente et al., 2019
	Kale	De la Fuente et al., 2019
Vitamin B1	Different microgreens	Fritsche et al., 2024
K	Bean	Balik et al., 2025
	Pea	Balik et al., 2025
	Amaranth	Di Gioia et al., 2023
	Beet	Di Gioia et al., 2023
Mg	Broccoli	Balik et al., 2025
	Sunflower	Balik et al., 2025
	Mustard	De la Fuente et al., 2019
	Amaranth	Di Gioia et al., 2023
Ca	Amaranth	Di Gioia et al., 2023
	Scallion	Di Gioia et al., 2023
	Red Cabbage	Di Gioia et al., 2023
	Basil	Di Gioia et al., 2023
	Kale	De la Fuente et al., 2019

In summary, microgreens are distinguished by their high nutrient density, short growth cycles, and high levels of vitamins and minerals, especially vitamin C, potassium, calcium, and magnesium. Radish, amaranth, beet, cabbage, sunflower, mung bean and basil are among the most promising candidates based on yield and nutritional profiles.

3.1.3 Nutritional Content of Leafy Greens

Leafy greens are even more wide-ranging than microgreens. The US National Aeronautics and Space Administration (NASA) has previously conducted a considerable amount of testing on leafy greens in space and on the ground for spaceflight. Different studies point out notable characteristics of leafy greens including their high calcium, potassium and magnesium content. In general, this aspect qualifies the leafy greens to meet the requirements for nutritional aspects (Maqbool et al., 2018; Wheeler et al., 2003; Xiao et al., 2012). Furthermore, the USDA website is a valuable source of information on nutrition, providing detailed data on the nutritional content of numerous foods.

Firstly, the plants that are suitable for spaceflight according to various research papers need to be identified. The initial selection of vegetables as done by Massa et al. (2015) includes two types of spinach (*Spinacia oleracea*) and lettuce, in addition to a single variety of beet, Swiss chard, Chinese cabbage (*Brassica rapa*) and mizuna. The ranking reveals that Chinese Cabbage is the most abundant source of these nutrients. It demonstrates the fastest growth rate and has the highest concentrations of calcium and the lowest concentrations of iron, which is also desirable. While this makes this crop seem like a well-suited plant, Chinese cabbage, or at least this variety of it, did not grow well on the ISS and the cultivation there resulted in leaf chlorosis, necrosis and uneven growth. This appears to be due to the high CO_2 concentration, as the Chinese cabbage is unable to tolerate elevated levels (Burgner et al., 2020). Swiss chard, meanwhile, displays a comparatively slower growth rate, yet still scores medium to high in terms of overall nutrient content. It is a significant source of potassium, magnesium, and also has the highest ranking in terms of O_2 production and CO_2 adsorption (Ewert et al., 2022). Mizuna, in third position, has a similar nutrient profile, but lower concentrations of potassium and magnesium. As per the findings documented by (Ewert et al., 2022), mizuna is positioned at the lower end of the spectrum in terms of nutrient content when compared to the other greens under consideration. Additionally, the lettuce ‘Outredgeous’ exhibits accelerated growth, demonstrating the highest concentrations of potassium (Ewert et al., 2022; Massa et al., 2015).

Fritsche et al. (2024) display a more detailed overview, listing different leafy greens according to their nutrients. Table 3 provides a summary of different key nutrients and the crops that rank high in these categories. For a more specific overview of the data and sources, see Appendix B. Additionally, the Crop

Readiness Level (CRL) is indicated, which corresponds to the phase that the crops passed during testing. The phases range from 1 to 9, where a CRL of 9 corresponds to 'good growth in space and consumption by crew with acceptability' (Fritsche et al., 2024). While several leafy greens attain a CRL of 9, none of the microgreens have yet done so. This is a significant finding, particularly considering the potential for microgreens to be a viable source of vitamins, such as B1. It is important to note, however, that the testing process is still ongoing, and further testing and adaptation to their environmental needs might be necessary for microgreens, as well as other crops that have yet to achieve a CLR of 9 in space cultivation (Fritsche et al., 2024).

Table 3 Overview of the key nutrients, tested crops, and their Crop Readiness Level (CRL), where CRL ranges from 1 (lowest) to 9 (highest) (Modified after Fritsche et al., 2024)

Nutrient	Crop	CRL
Vitamin C	Kale, 'Red Russian'	9
	Bok choy, 'Extra Dwarf'	9
	Mustard, 'Wasabi'	9
Vitamin K	Kale, 'Red Russian'	9
	Mustard, 'Wasabi'	9
	Mustard, 'Amara'	9
Vitamin B1	Different microgreens	None has reached 9 yet
K	Kale, 'Red Russian'	9
	Bok choy, 'Extra Dwarf'	9
	Red Romaine Lettuce	9
Mg	Bok choy, 'Extra Dwarf'	9
	Kale, 'Red Russian'	9

To conclude, the crops should be safe for consumption, ready to eat and high in energy content with a balanced nutrient composition. It is also important to consider the content of potassium, magnesium, calcium as well as Vitamin contents, especially of the vitamins B, C and K. A single plant is unable to provide all the essential nutrients; therefore, it is necessary for a selection of different crops to be combined to satisfy human nutritional needs.

3.2 Horticultural Aspects

3.2.1 Overview of Plant Development Phases

The optimal requirements for plant growth are often variable during the different stages of plant development. Hopper et al. (1997) identify two main stages of plant development: vegetative and reproductive. Research indicates that different climatic conditions are preferable at different stages (Hopper et al., 1997). However, it is recognised that certain development procedures require specific plant growth. In 1995, the German Biologische Bundesanstalt für Land- und Forstwirtschaft, Bundessortenamt und CHemische Industrie (BBCH – Federal Biological Research Centre for Agriculture and Forestry) working group developed a general scheme to categorise the different growth stages observed in various plant species. The principal growth stages, designated 0 to 9, are universally applicable to all plant species, apart from those plants that bypass specific stages, for example, in the absence of side shoot formation. The secondary growth stages, ranging from 0 to 9, denote the advancement of the plant phase, such as the number of leaves already developed or the percentage of growth that has been completed. Regarding leafy vegetable crops, the following growth stages are to be considered: 00 'Seed treatment before planting' until 49 'Typical size, form and firmness of heads reached' for leafy vegetables that form heads, and 'Typical leaf mass reached' for leafy vegetables that do not form heads. After reaching this stage, the plants can be harvested if seed production is not desired (Feller et al., 2001). Using such a scale enables a clearer understanding of plant development and helps optimise environmental conditions for each stage. In the case of leafy greens, this implies the establishment of specific conditions during the germination phase, which extends until the development of the first true leaf, and the vegetative growth phase, which persists until harvest. In the case of microgreens, there is even less differentiation between growth phases, since they are harvested at an even earlier stage of development.

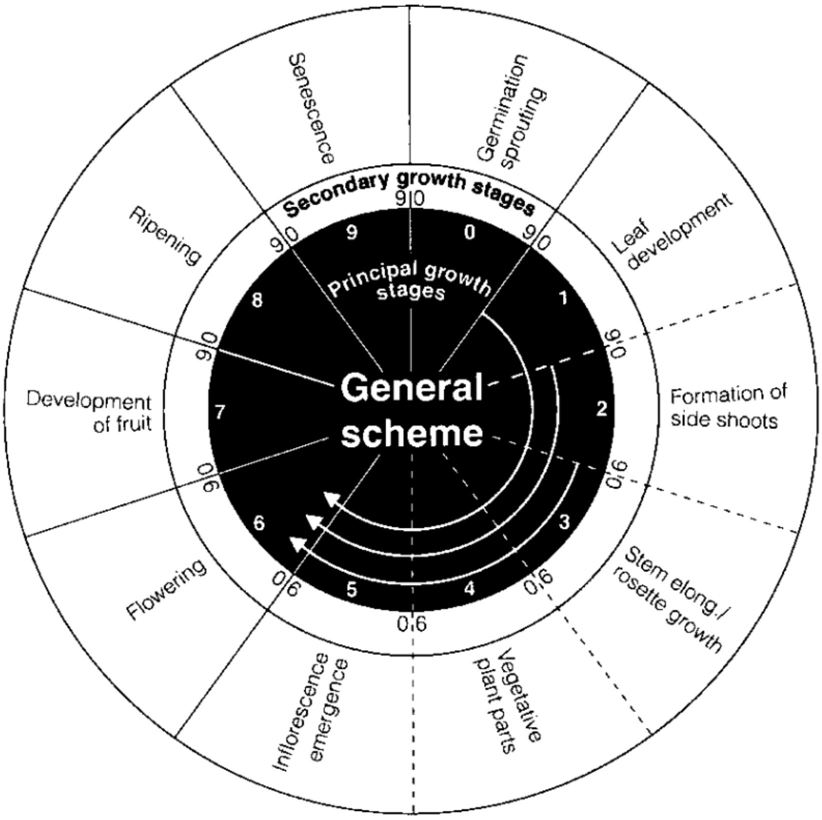


Figure 5 General scheme of principal and secondary growth stages in plant development (Feller, 2001)

In the case of the LAM-GTD, it is planned that the plants will be evaluated according to this growth scheme. While existing literature typically contains no information regarding the time a plant needs from planting to reach a certain BBCH growth stage, doing so would help better plan the time required for the development of the plant until transfer from the nursery to a tray and until harvest. This also allows for a better estimation of yield.

3.2.2 Factors Influencing Plant Growth and Development

The following is a list of the factors in CEA that need to be regulated. These factors are then brought into relation with leafy greens and microgreens in the next sections. A variety of factors can impact plant growth and development, including light conditions, temperature, relative humidity (RH) and CO_2 levels. These conditions can vary depending on the specific plant or cultivar (Hopper et al., 1997). Light has a significant effect on plant growth, depending on its intensity, duration and quality. An increased amount of light enhances photosynthetic rates and affects various physiological processes, including leaf movement, photomorphogenesis, stomatal opening and flowering. The identification of optimal light conditions for diverse plant species across their life cycles has been a persistent objective in horticultural research (Morison and Morecroft, 2006; Teixeira, 2020). In their study on lettuce, Ahmed et al. (2020) conclude that light affects plant growth, nutritional quality, as well as photosynthesis and transpiration. The study proposes light intensity between 200 and 250 µmol m^{-2} s^{-1}, as well as a photoperiod between 16 and 18 hours per day. In contrast, Massa et al. (2015) conclude that a light intensity of 400 µmol m^{-2} s^{-1} is suitable for lettuce and other leafy greens. For a comprehensive overview of the Ahmad et al. (2020) study, refer to Figure 6.

In addition to light, temperature affects plant growth and development, influencing phenology (the timing of biological events), photosynthesis, and respiration. Elevated temperatures increase the growth rate and development of plants and may result in earlier flowering and bud burst. However, the optimal temperature for each individual plant is unique (Hatfield and Prueger, 2015; Morison and Morecroft, 2006). Temperature affects stomatal conductance, photosynthetic rate, and transpiration rate. Research indicates that higher RH can promote enhanced growth in a variety of plants. For instance, a study on lettuce growth revealed that increasing the RH from 50 to 85 % resulted in increased leaf number, size, and yield (Tibbitts and Bottenberg, 1976). The consensus on the optimal RH for most plants appears to be about 60 to 70 % (Hopper et al., 1997), with Ahmed et al. (2020) suggesting that for lettuce, the optimal RH is between 70 and 80 %. These effects on stomatal conductance, photosynthetic rate and transpiration rate are comparable to the effects of temperature on plants. Not to forget that the RH itself is affected by the air temperature. Furthermore, air velocity also has an impact on air resistance, although this topic will not be covered in detail here (Ahmed et al., 2020; Chia and Lim, 2022). Ahmed et al. (2020) evaluate the effects of CO_2 concentration and conclude that an optimal concentration falls between 1000 and 1500 µmol mol^{-1}. In contrast, Morrow and Wheeler (1997) determine that the optimal concentration ranges up to 2000 µmol mol^{-1} (Ahmed et al., 2020; Morrow and Wheeler, 1997).

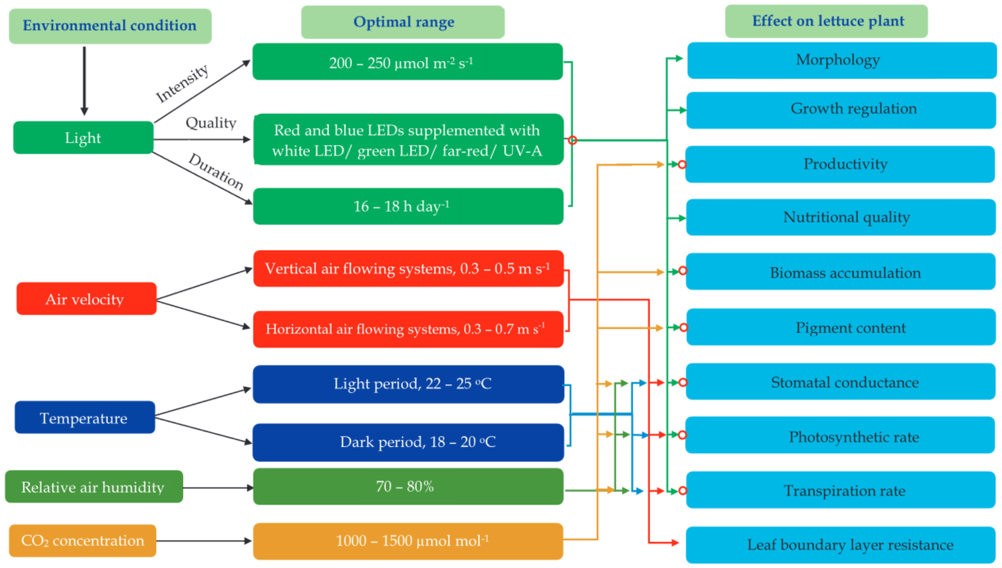


Figure 6 Overview of environmental factors influencing plant growth, showing optimal values for lettuce in the controlled environment agriculture (CEA) setting. Coloured arrows indicate the impact of each condition on plant growth, with red circles (O) indicating a stronger interaction between condition and effect. (Ahmed et al., 2020)

In addition to these factors, space environments differ significantly from terrestrial cultivation systems. Key environmental differences include hypogravity, the absence of Earth's geomagnetic field, and decreased total atmospheric pressure. Regarding gravity, research on plant growth has thus far been conducted exclusively under microgravity conditions, such as aboard the International Space Station (ISS), rather than under hypogravity as found on the Moon. Nonetheless, plants can be successfully cultivated in microgravity without displaying notable morphological changes (Musgrave et al., 2000; Salisbury et al., 2003; Tibbitts and Henninger, 1997; Wolff et al., 2013). However, challenges may arise during the reproductive phase. Although reproduction is not directly dependent on gravity, it is reduced in space, potentially leading to lower resource-use efficiency during long-term missions (De Micco et al., 2014; Kordyum, 2014). Hypobaric conditions do not show significant effects on plant development (Tibbitts and Henninger, 1997). Furthermore, atmospheric pressure levels can be regulated within the LAM system. Unlike Earth, the Moon does not possess a global magnetic field. However, localised magnetic anomalies exist and vary in strength (Mitchell et al., 2008; Purucker, 2008). Experimental studies investigating altered magnetic field conditions suggest potential effects on plant cellular structures, particularly in root tissues, under weak magnetic fields in the range of 0.5 to 2 nT

(Belyavskaya, 2001; Galland and Pazur, 2005). Radiation levels in space are significantly higher than on Earth due to the lack of a magnetic field and atmosphere (Wolff et al., 2014). Shielding is essential in any case to protect astronauts, which would also benefit plant systems. Several studies indicate that exposure to magnetic fields weaker than Earth's geomagnetic field affects plant growth and development (Galland and Pazur, 2005; Karoliussen et al., 2013), as well as plant metabolism (Belyavskaya, 2001; Wolff et al., 2014). Nevertheless, further research is required to fully understand these effects and how they relate to different plant species.

As with other projects, certain factors are selected for the LAM-GTD to identify suitable crops. These factors focus on plant requirements to ensure compatibility and optimal growth within the same room. Since cultivating in a single room with uniform conditions is challenging, the selected crops should have similar needs. Suitable crops are those with high resistance to stress, low maintenance requirements, and high yield and nutritional value.

For the present study, focusing on a shorter-term mission scenario — specifically one that does not involve a lunar base — within the LAM-GTD project, the following factors should be optimised for best results: a shorter time to harvest, minimised height and root depth, and maximised harvest index and yield. These factors, influenced by both crop choice and growth parameters (light, temperature, and air requirements), must be optimised (Maiwald, 2025). The LAM-GTD crop selection process is based on the following factors:

- Days to harvest
- Plant height (minimised)
- Root depth (minimised)
- Harvest index (maximised)
- Planting density/yield
- Photoperiod (adapted to selected crops)
- Temperature (adapted to selected crops)
- Humidity (adapted to selected crops)

In summary, the successful cultivation of crops in CEA is dependent upon the regulation of key growth factors such as light, temperature, humidity, and CO_2 concentration. These parameters must be adapted to the specific needs of the crop cultivated to ensure optimal growth, yield, and quality. Furthermore, additional research on the lunar-specific parameters is necessary. For the LAM-GTD project, the focal point of the crop selection process is the selection of crops that exhibit short growth cycles, compact size, and high productivity under uniform environmental conditions. The key to efficient and sustainable food production in closed systems is to align controlled conditions with crop requirements.

3.2.3 Horticultural Requirements for Microgreens

To effectively adapt the environment to the cultivated crops, it is essential to first identify their specific environmental requirements. Aligning these requirements as closely as possible enhances compatibility and promotes optimal growth, particularly in multi-species cultivation systems.

Dhaka et al. (2023) aim at determining optimal germination conditions for various microgreens, with a particular focus on the influence of temperature due to its critical role in seed germination. The results indicate that microgreens from the Brassicaceae family exhibit the highest germination rates at lower temperatures from 24 to 26 °C, whereas species from the Fabaceae and Poaceae families prefer higher temperatures around 28 °C. These findings are particularly valuable when sowing multiple species together, suggesting that separating Brassicaceae from other microgreens during the germination phase could maximise germination rates across species (Dhaka et al., 2023).

Table 4 Overview of different microgreens with their optimal germination temperature and corresponding germination rate (Modified after Dhaka et al., 2023)

Crop	Scientific name	Optimal germination temperature [°C]	Germination rate [%]
Mustard	*Brassica juncea*	24	90
Red cabbage	*Brassica oleracea*	24	75
Red radish	*Raphanus raphanistrum*	26	75
Mungbean	*Vigna radiata*	28	95
Lentil	*Lens culinaris*	28	90
Pearlmillet	*Cenchrus americanus*	28	85

Further evidence of species-specific environmental preferences is provided by production data from Johnny's Selected Seeds (2017), Sharma (2023), and Mishra (2022), which outline detailed cultivation parameters for various microgreens. Radish microgreens mature the fastest, reaching harvest size in just eight days, followed by sunflower, pea, and mustard microgreens. In contrast, coriander microgreens can take up to 20 days to reach harvest maturity. Yield data from Johnny's (2017) indicates that broccoli has the highest overall biomass yield, followed by kale and kohlrabi (*Brassica oleracea*). However, when normalised for seed input, basil demonstrates the highest efficiency with a yield of 33 g g^{-1} (grams of biomass per gram of seed), followed by kohlrabi with 32.2 g g^{-1} and kale with 30.3 g g^{-1}. Light requirements also varied: cabbage, radish, and amaranth thrive under low light conditions of 6 h d^{-1}, while kohlrabi and sunflower require extended photoperiods of up to 16 h d^{-1}. Temperature preferences among microgreens were similarly diverse. Brassicaceae species such as cabbage and radish generally perform better under lower temperatures but can also tolerate elevated temperatures. In contrast, warm-climate species like buckwheat, amaranth, and sunflower perform best under higher temperature conditions. Interestingly, while mung bean microgreens are typically considered warm-climate crops, Sharma (2023) finds them to perform well under cooler conditions, though Dhaka et al. (2023) reports higher optimal germination temperatures for this species. Humidity preferences also varied widely. Buckwheat grows well at relatively low humidity of around 40 %, whereas amaranth and sunflower require higher levels, around 80 %, to achieve optimal performance (Dhaka et al., 2023; Johnny's Selected Seeds, 2017; Mishra et al., 2022; Sharma et al., 2023). For a more specific overview of the data and sources, see Appendix A.

In contrast to these species-specific findings, Izzo et al. (2023) apply a uniform environmental protocol across all tested microgreens. During germination, the temperature is set to 24 °C. Post-emergence, environmental conditions are modified to simulate a natural diurnal cycle with 24 °C during the day and 18 °C at night. A 12-hour photoperiod is implemented, with relative humidity controlled at 65 % and a light intensity of 300 µmol m^{-2} s^{-1} (Izzo et al., 2023).

Table 5 Requirements for microgreen growth during germination and vegetative growth phases (Modified after Izzo et al., 2023)

	Unit	Germination	After microgreens emerged
Photoperiod	h	-	12
Light intensity at canopy level	µmol m^{-2} s^{-1}	-	300 ± 15
Wavelength	nm	-	400 – 700
Temperature	°C	24	24/18 ± 2
Relative Humidity	%	100	65 ± 5

These environmental factors must be considered in CEA systems to provide crops with the right growth parameters in terms of temperature, humidity, light exposure, germination duration, and harvest timelines. When multiple crops are grown together, a compromise must be made, yet integrating this information into controlled horticultural systems enhances crop productivity.

3.2.4 Horticultural Requirements for Leafy Greens

Leafy greens represent a major category of widely cultivated crops. They are valued not only for their high nutritional content, but also for their relatively short growth cycles. Leafy greens include a range of species, each of which requires distinct horticultural characteristics that influence their suitability.

Massa et al. (2015) evaluate leafy greens within CEA systems, identifying species with optimal performance under such conditions. Their work, in combination with environmental growth parameter models developed by Ewert et al. (2022), supports the systematic selection of crops for both terrestrial CEA and extraterrestrial agricultural systems (Ewert et al., 2022; Massa et al., 2015). Moreover, the provision of grower data, as the information supplied by Johnny's Selected Seeds, offers practical cultivation guidelines that contribute to the refinement of environmental control strategies.

The time required for germination can vary considerably among leafy greens. For instance, lettuce seeds germinates in as little as two days, whereas corn salad (*Valerianella locusta*) may take between 10 and 14 days (Johnny's Selected Seeds, 2025a; Maynard and Hochmuth, 2007). Furthermore, harvest timelines differ between species. The baby leaf stage of mustard 'Amara' can be harvested within 21 days, while red cabbage may take up to 73 days to mature (Johnny's Selected Seeds, 2025b, 2025c). Furthermore, the regrowth capacity of certain leafy greens offers additional benefits for space agriculture. Meinen (2018) observes that species demonstrating the capacity for regrowth subsequent to initial harvesting can enhance overall yield efficiency (Meinen et al., 2018).

Throughout the history of human spaceflight, several crops have been identified as potential candidates for space-based cultivation. As early as the Soviet Salyut programme, leafy greens were considered for experimental cultivation in microgravity conditions, owing to their short growth cycles and low resource requirements (Zabel et al., 2016). The compact morphology of these species, their rapid maturation, and their low energy input requirements still make them prime candidates for use in bioregenerative life support systems in space exploration missions. A variety of crops have already been cultivated in space, including lettuce, kale, bok choy, pea, mizuna and wasabi. A number of these crops successfully passed the NASA testing on the Crop Readiness Level for space cultivation (Fritsche et al., 2024; Zabel et al., 2016). Crops at CRL 3 have thrive under ISS-like conditions including elevated CO_2 levels of around 3000 µmol mol^{-1}, low relative humidity of roughly 40 % RH, constant temperatures between 20 and 23 °C, and artificial lighting (Fritsche et al., 2024). This finding confirms their fundamental compatibility with space-based controlled environments. In relation to temperature preference, the majority of leafy greens are categorised as cool-season crops, with optimal growth temperatures generally ranging from 16 to 18 °C (Maynard and Hochmuth, 2007). Exceptions to this rule include warm-season crops such as amaranth and purslane. however, corn salad exhibits optimal germination at temperatures between 10 and 15 °C (Johnny's Selected Seeds, 2025a), while some species, including cabbage, kale and Swiss chard, grow optimally at temperatures ranging from 23 to 25 °C (Ewert et al., 2022). Furthermore, humidity is also known to have a significant impact on the cultivation of leafy green crops. While all CRL 2 crops demonstrate to thrive under conditions of low humidity, studies suggest that relative humidity levels from 60 to 70 % lead to enhanced growth performance (Chia and Lim, 2022; Langhans et al., 1996). Regarding the effects of CO_2 on plant growth, certain crops, including lettuce, spinach, Swiss chard, and mizuna, demonstrate enhanced growth at elevated concentrations of CO_2 up to 1000 µmol mol^{-1}. Among the evaluated crops, Chinese cabbage 'Tokyo Bekana' ranks highest nutritionally but shows poor growth on the ISS, likely due to sensitivity to high CO_2 (Burgner et al., 2020). Ewert et al. (2022) furthermore demonstrate that several leafy greens exhibit good development under a 16-hour light period. Light intensity is another critical factor. A photosynthetic photon flux density of approximately 400 µmol m^{-2} s^{-1} is suitable for many species under controlled conditions (Ewert et al., 2022).

Table 6 Requirements for leafy green growth (Modified after Ewert et al., 2022)

	Unit	**Lettuce**	**Spinach**	**Swiss Chard**	**Mizuna**
Growth period	[d]	28	30	28	23
Plant height	[m]	0.25[1)]	0.25[1)]	0.18[2)]	0.16[2)]
Growth area per plant[2)]	[cm^2]	~ 350	~ 350	~ 550	~700
Photoperiod[1)]	[h]	16	16	16	16[2)]
Lightintensity[2)]	[µmol m^{-2} s^{-1}]	~400	~400	~400	~400
Air temperature day[1)]	[°C]	23	23	23[2)]	23[2)]
Air temperature night[2)]	[°C]	18	18	18	18
Humidity[2)]	[%]	70	70	70	70
CO_2[2)]	[µmol mol^{-1}]	1000	1000	1000	1000

[1)] (Wheeler et al., 2003)

[2)] (Massa et al., 2015)

Further research is required to evaluate how plants adapt to reduced atmospheric pressure and gravity on the Moon and Mars. As the study by Stutte et al. (2022) demonstrates, the cultivation of lettuce plants under hypobaric conditions results in a decline in both yield and biomass production (Stutte et al., 2022). The minimum gravity level required for optimal plant function remains to be determined. Although available data are limited, some evidence suggests a threshold around 0.3 *g* or lower, relative to Earth's nominal gravity of 1 *g* (Kiss, 2014). Given that lunar gravity is below that threshold — approximately 0.17 *g* — further research is required to identify the lowest possible gravity that still supports healthy plant growth.

In summary, leafy greens remain a central focus in the study of sustainable and controlled agriculture, not only for their terrestrial applications but also for their role in the future of long-duration space missions. The data provide a foundation for the evaluation of the suitability of these crops in terms of environmental requirements, and operational efficiency.

3.3 Methodology of the Crop Selection

Space missions require sustainable food systems that can provide astronauts with a reliable source of fresh, nutritious, and psychologically satisfying foods. To address this, the present methodology focused on evaluating the suitability of specific crops — namely leafy greens and microgreens — for space-based cultivation within the context of the LAM-GTD project. The aim was to identify crops that not only meet nutritional requirements but are also capable of growing efficiently in controlled spaceflight environments.

The selection criteria for crops were derived from previous studies on the topic of crop selection processes and crop requirements. A division was made between nutritional and horticultural factors. This was done to ensure that the crew receives an adequate supply of essential nutrients, while also allowing for the successful cultivation of crops in space. The nutritional value of the selected crops was a central factor in the methodology. Emphasis was placed on crops that are rich in essential minerals such as calcium, potassium, and magnesium, as well as vitamins B1, C, and K, which are vital for maintaining both the physiological and psychological health of astronauts during missions (Hoff et al., 1982). Leafy greens and microgreens were assessed due to their high nutrient density and promising results in previous studies. Nutritional content data were sourced primarily from studies such as Massa et al. (2015), Ewert et al. (2022), and Fritsche et al. (2024). Also, the USDA FoodData Central database was used to obtain specific vitamin and mineral quantities. Appendices A and B contain an overview of these data (USDA, 2025).

Alongside nutritional value, crops were evaluated based on their horticultural performance in controlled environments. Priority was given to those with documented success in NASA trials. Factors considered included growth rate, biomass production, harvest index, and overall adaptability to CEA conditions. A key part of this evaluation was the CRL system, which rates crops from early testing stages to full suitability for space cultivation and consumption (Fritsche et al., 2024). Environmental adaptability was another major criterion, especially regarding temperature ranges. As light conditions can be tailored more easily than temperature, it played a less decisive role. Plants with overlapping environmental needs were favoured to ensure they grow well in the same room together. Although evaluating crops according to the BBCH growth stage scale could help better estimate time to transplant and harvest, microgreens undergo really only one phase and leafy greens are harvested before they leave the vegetative phase, so the applications of these insights are limited. The growth stage classification can still be important for later stages of the LAM-GTD project but is not applied in depth here due to the current exploratory nature of crop selection. In general, ISS validation and CRL scores were a helpful guide in narrowing the list of possible crops.

As demonstrated by Massa et al. (2015), microgreens grew best at higher temperatures, typically between 23 and 25 °C (Massa et al., 2015). Conversely, leafy greens have been observed to flourish at temperatures of approximately 18 °C or lower. Crops were selected for their capability to grow effectively within an environment at a compromise temperature range of 18 to 20 °C, facilitating the cultivation of both crop types. While this range may not be optimal for either group, it is believed to support the growth of both microgreens and cool-season leafy greens. Varieties of leafy greens and microgreens that require significantly higher or lower temperatures were excluded from the final crop selection to ensure compatibility with this intermediate temperature. While certain species offer high nutritional value, their preference for significantly warmer or more humid climates limits their suitability for cultivation and therefore they were excluded. Instead, emphasis was placed on microgreens like cabbage, and beet, which not only provide relevant nutritional benefits but also exhibit environmental compatibility with the leafy greens under the defined controlled conditions. Buckwheat and sunflower microgreens had to be excluded as well as the leafy greens amaranth and purslane due to their classification as warm-season crops, for which growth under the specified conditions cannot be guaranteed. In a similar manner, corn salad demonstrated a preference for even lower temperatures and was, for this reason, also excluded from the study.

Based on the above criteria, a group of leafy greens and microgreens was selected for further consideration. Crops were chosen for their potential to contribute to a balanced diet, safety for consumption, and ease of growth in space-like conditions. Among leafy greens, Chinese cabbage, Swiss chard, lettuce, and mizuna were selected based on prior test results and nutrient content. For microgreens, radish, red and white cabbage, daikon radish, savoy cabbage, and coriander were identified as strong candidates. These selections serve as a preliminary framework for future testing in the LAM-GTD project, where environmental conditions can be more closely simulated and refined.

3.4 Results of the Crop Selection

3.4.1 Microgreen Selection

The selection of microgreens was based primarily on their nutrient density, especially in vitamins — particularly B1, C, and K — and their contents of potassium, magnesium, and calcium. Table 7 provides an overview of selected microgreens, highlighting those high in specific nutrients. Despite their high nutrient content, none of the microgreens achieved a CRL of 9, indicating that their cultivation in space environments has not yet reached the same level as that of some leafy greens. Nevertheless, they remain promising due to their compact growth, short cultivation cycle and high vitamin concentrations. The Brassicaceae family is most frequent, with cultivars high in yield and nutrients such as broccoli, kale, kohlrabi, and mustard. These crops demonstrate high biomass output, making them particularly suitable for volume-efficient growth systems. Other species, such as mung beans and basil, also have a high nutrient density. Several species stand out for their high vitamin and mineral levels, including amaranth, beet, cabbage and pea. These offer valuable levels of essential vitamins and minerals.

Table 7 Selected microgreens with their botanical names, plant family, Crop Readiness Level (CRL) ranging from 1 (lowest) to 9 (highest), key nutrients and additional notes

Common Name	Botanical Name	CRL	Family	Key Nutrients	Horticultural Notes
Amaranth	*Amaranthus spp.*	-	Amaranthaceae	K, Mg, Ca	
Basil	*Ocimum basilicum*	3	Lamiaceae	Vitamin K	
Beet, 'Bulls Blood'	*Beta vulgaris*	3	Amaranthaceae	K, Ca	
Borage	*Borago officinalis*	3	Boraginaceae		
Broccoli	*Brassica oleracea*	3	Brassicaceae		High yield
Cabbage, red	*Brassica oleracea*	3	Brassicaceae	Vitamin C, Ca	
Coriander	*Coriandrum sativum*	5	Apiaceae	Vitamin K	
Kale, 'Red Russian'	*Brassica oleracea*	6	Brassicaceae		High yield
Kohlrabi, white	*Brassica oleracea*	5	Brassicaceae		High yield
Mung beans	*Vigna radiata*	5	Fabaceae	Mg	
Mustard, 'Wasabi'	*Brassica juneca*	6	Brassicaceae		High yield
Pea, 'Dwarf Grey Sugar'	*Pisum sativum*	5	Fabaceae	Mg, K	
Radish, 'Daikon'	*Raphanus sativus*	5	Brassicaceae		

To summarise, while none of the microgreens under review currently meet the highest CRL standards, their nutritional value, rapid growth and efficient use of space make them promising candidates for inclusion in future sustainable agricultural systems.

3.4.2 Leafy Green Selection

An evaluation of leafy greens was carried out based on their nutritional value and performance in space-based cultivation systems, referencing the experiments conducted by NASA. Table 8 provides an overview of the key species, their CRL, family classifications, nutritional highlights, environmental performance, and spaceflight validation where applicable. All selected crops are cool-season species. Several species, including lettuce cultivars and different Brassicaceae as 'Red Russian' kale, mizuna, bok choy and 'Wasabi' mustard, achieve CRL 9. This CRL rating indicates the successful cultivation and consumption of the crop in space and suitability for early deployment in the LAM-GTD project. The selected crops also display advantageous characteristics, including high content of vitamin C, vitamin K, calcium, magnesium and vitamin B1. For instance, 'Red Russian' kale and 'Toscano' kale offer significant levels of vitamin B1, vitamin C, and calcium. Swiss chard, though having a comparatively lower CRL of 3, contains elevated levels of vitamin K and magnesium.

Table 8 Selected leafy greens with their botanical names, plant family, Crop Readiness Level (CRL) ranging from 1 (lowest) to 9 (highest), key nutrients and additional notes

Common Name	Botanical Name	CRL	Family	Key Nutrients	Environmental Notes
Beet greens	Beta vulgaris	2	Amaranthaceae		
Cabbage, red	*Brassica oleracea*	-	Brassicaceae	K	
Kale, 'Red Russian'	*Brassica napus*	9	Brassicaceae	Vitamin B1, Vitamin C, Ca	ISS validated, excellent germination and growth
Kale, 'Toscano'	*Brassica oleracea*	5	Brassicaceae		
Lettuce, 'Dragoon'	*Lactuca sativa*	9	Asteraceae		ISS-validated, low germination after long storage
Lettuce, 'Outredgeous'	*Lactuca sativa*	9	Asteraceae		
Lettuce, 'Walsman's Green'	*Lactuca sativa*	9	Asteraceae		
Mizuna	*Brassica rapa var. japonica*	9	Brassicaceae	Average	ISS validated
Mustard, 'Amara'	*Brassica carinata*	9	Brassicaceae	Average	ISS validated, excellent germination and growth
Mustard, 'Wasabi'	*Brassica juncea var. japonica*	9	Brassicaceae		
Bok choy, 'Extra Dwarf'	*Brassica rapa var. chinensis*	9	Brassicaceae		ISS validated, excellent germination and growth
Sorrel	*Rumex spp.*	3	Polygonaceae	Vitamin C	
Swiss Chard, 'Bright Lights'	*Beta vulgaris*	3	Amaranthaceae	Vitamin K, Mg	Sanitisation method affected germination
Watercress	*Nasturtium officinale*	-	Capparaceae		

4 Creation of Crop Selection Sets

4.1 Methodology for Creating Crop Selection Sets

The objective of this study is to identify and evaluate three potential crop sets based on nutritional density, biomass production, and suitability for controlled environments. Given the broad spectrum of species available, it is impractical to evaluate every potential option in depth. Consequently, the selection process concentrated on crops that demonstrated significant performance in previous research, with particular emphasis on family diversity, crop readiness, and biomass yield.

The decision to divide the crop selection into three distinct sets was driven by the need to balance multiple evaluation criteria while preserving analytical clarity. Each set was designed to target a specific criterion. Set 1 prioritised genetic diversity, Set 2 emphasised readiness for space-based or controlled environment agriculture, and Set 3 focused on biomass optimisation.

Set 1 — Diverse Families (10 Leafy Greens and 5 Microgreens)

This data set was methodically designed to include a broad range of plant families, thereby ensuring both genetic and pathogen diversity. The selection of different families was chosen as an effective strategy for minimise pathogen spread, as each family responds differently to pests and diseases. It was determined to include 10 leafy greens and 5 microgreens, representing a range of plant families that was identified in the literature, particularly from NASA testing. Since the focus was on the crop diversity, the CRL was considered only, if multiple crops within the same family were evaluated. The set comprises following elements:

- Three types of Brassicaceae (kale, bok choy) and Asteraceae.
- Two species each from the Amaranthaceae and Fabaceae families.
- One species each from the Polygonaceae, Capparaceae, Lamiaceae, Boraginaceae and Apiaceae families.

The objective of this set is to minimise the risk of plant specific pathogen contamination by selecting crops from diverse families, while maximising the variety of nutrients, textures, and flavours provided. Including both leafy greens and microgreens enables comparison of biomass production across different plant types.

Set 2 — High CRL Focus (CRL Prioritised, 10 Leafy Greens and 5 Microgreens)

In the second set, the focus shifted towards crops with the highest Crop Readiness Level (CRL), reflecting their proven performance in space environments. The set also was determined to include 10 leafy greens and 5 microgreens that demonstrated strong results in previous evaluations. Crops with a CRL of 9 were preferred, as this indicates a high cultivation readiness in space-based systems. Key characteristics of this set include:

- All the leafy greens in this set have a CRL of 9, signifying their suitability for space or controlled environment cultivation.
- The microgreens chosen obtained a CRL of 5.
- The Brassicaceae family dominated this set, as it constituted a significant portion of the high-performing crops. The Asteraceae family also contributed notably.

Among the microgreens, a select number with relatively high CRL scores were included, despite not reaching the CRL of 9, to provide a more complete comparison of species within this category.

Set 3 — Leafy Greens Only

The third data set was compiled exclusively of leafy greens, excluding microgreens due to their low biomass production, compared to seed weight. This set was developed to assess the potential for obtaining higher biomass yields and nutrient content from leafy greens alone. The selection was carried out combining crops from Sets 1 and 2, with a particular focus on those exhibiting high biomass potential and nutrient density. The objective of this set was to evaluate differences in nutrient content and biomass output when microgreens were excluded from the selection. This set allowed for a comparison of the performance of leafy greens under conditions prioritising space efficiency and biomass yield over short growth cycles and compact growth forms.

The data sets under consideration were created based on a combination of prior research findings, nutrient composition tables, and CRL ratings from space agriculture studies. The primary factors that guided the inclusion of species in each set were nutrient density, biomass production and adaptability to controlled environments.

4.2 Results from Creating Crop Selection Sets

Set 1 — Diverse Families (10 Leafy Greens and 5 Microgreens)

The crops in Set 1 demonstrate a broad range of genetic diversity, comprising 15 leafy greens and microgreens from 10 plant families. The three Brassicaceae leafy greens, ‘Toscano’ and ‘Red Russian’ kale and ‘Extra Dwarf’ bok choy, all attained a CRL of 9. They also provide high levels of vitamins C and K, as well as potassium and magnesium, thereby contributing to the nutrient density and cultivation readiness of the overall set. Asteraceae species such as ‘Outredgeous’ and ‘Waldmann’s Green’ lettuces also perform well, achieving a CRL of 9. Other entries, such as beet greens and Swiss chard from the Amaranthaceae family, contribute to nutrient diversity, although having lower CRL ratings. Adding microgreens to this set enhances phytonutrient and species variety. However, microgreens have yet to achieve a high CRL rating. Overall, Set 1 includes leafy greens and microgreens from a variety of different plant families, adding to the diversity of the crops.

Table 9 Selected leafy greens and microgreens for Set 1, focusing on diverse families. Crop Readiness Level (CRL) ranging from 1 (lowest) to 9 (highest), is provided for plants included in NASA testing. Additionally, key nutrients are listed, in which each crop scored highly compared to the other crops.

Common Name	Botanical Name	Type	CRL	Family	Key Nutrients
Beet greens	*Beta vulgaris*	Leafy Green	2	Amaranthaceae	Vitamin B1, Vitamin K K, Mg
Kale, ‘Red Russian’	*Brassica napus*	Leafy Green	9	Brassicaceae	Vitamin C Vitamin K Ca
Kale, ‘Toscano’	*Brassica oleracea*	Leafy Green	9	Brassicaceae	
Lettuce, ‘Dragoon’	*Lactuca sativa*	Leafy Green	9	Asteraceae	
Lettuce, ‘Outredgeous’	*Lactuca sativa*	Leafy Green	9	Asteraceae	
Lettuce ‘Waldmann’s Green’	*Lactuca sativa*	Leafy Green	9	Asteraceae	
Bok choy, ‘Extra Dwarf’	*Brassica rapa var. chinensis*	Leafy Green	9	Brassicaceae	Vitamin C Vitamin K Mg
Sorrel	*Rumex acetosa*	Leafy Green	3	Polygonaceae	Vitamin B1, Vitamin C Mg
Swiss Chard, ‘Bright Lights’	*Beta vulgaris*	Leafy Green	3	Amaranthaceae	Vitamin K, Mg
Watercress	*Nasturtium officinale*	Leafy Green	-	Capparaceae	Vitamin B1
Basil	*Ocimum basilicum*	Microgreen	3	Lamiaceae	
Borage	*Borago officinalis*	Microgreen	3	Boraginaceae	
Coriander	*Coriandrum sativum*	Microgreen	5	Apiaceae	
Mung beans	*Vigna radiata*	Microgreen	5	Fabaceae	Mg
Pea, ‘Dwarf Grey Sugar’	*Pisum sativum*	Microgreen	5	Fabaceae	Mg

Set 2 — High CRL Focus (CRL Prioritised, 10 Leafy Greens and 5 Microgreens)

Set 2 prioritises crops with a high CRL and includes 10 leafy greens, all of which are rated at CRL 9. The Brassicaceae crops, such as ‘Red Russian’ and ‘Toscano’ kale, ‘Wasabi’ mustard, and ‘Extra Dwarf’ bok choy, demonstrate reliable growth under validation on the ISS. Additionally, they exhibit high levels of vitamins C and K, as well as calcium. The set also includes lettuces from the Asteraceae family, such as ‘Dragoon’ and ‘Outredgeous’. Microgreens in this set, including coriander, mung beans, and peas, contribute additional phytonutrient diversity and introduce new plant families such as Apiaceae and Fabaceae. However, their relatively low CRL of 5 highlights the need for further optimisation in controlled environments. Overall, Set 2 presents a target group of high-reliability crops with balanced diversity through the inclusion of microgreens.

Table 10 Selected leafy greens and microgreens for Set 2, focusing on a high Crop Readiness Level (CRL) ranging from 1 (lowest) to 9 (highest), for plants included in NASA testing. Additionally, key nutrients are listed, in which each crop scored highly compared to the other crops.

Common Name	Botanical Name	Type	CRL	Family	Key Nutrients
Kale, ‘Red Russian’	*Brassica napus*	Leafy Green	9	Brassicaceae	Vitamin C Vitamin K Ca
Kale, ‘Toscano’	*Brassica oleracea*	Leafy Green	9	Brassicaceae	
Lettuce, ‘Dragoon’	*Lactuca sativa*	Leafy Green	9	Asteraceae	
Lettuce, ‘Outredgeous’	*Lactuca sativa*	Leafy Green	9	Asteraceae	
Lettuce ‘Waldmann’s Green’	*Lactuca sativa*	Leafy Green	9	Asteraceae	
Mizuna	*Brassica rapa var. japonica*	Leafy Green	9	Brassicaceae	
Mustard, ‘Amara’	*Brassica carinata*	Leafy Green	9	Brassicaceae	
Mustard, ‘Wasabi’	*Brassica rapa var. japonica*	Leafy Green	9	Brassicaceae	
Bok choy, ‘Extra Dwarf’	*Brassica rapa var. chinensis*	Leafy Green	9	Brassicaceae	
Radish, ‘Cherry Belle’	*Raphanus sativus*	Leafy Green	9	Brassicaceae	
Coriander	*Coriandrum sativum*	Microgreen	5	Apiaceae	
Cress, ‘Cressida’	*Lepidium sativum*	Microgreen	5	Brassicaceae	
Kohlrabi, White	*Brassica oleracea*	Microgreen	5	Brassicaceae	
Mung beans	*Vigna radiata*	Microgreen	5	Fabaceae	Mg
Pea, ‘Dwarf Grey Sugar’	*Pisum sativum*	Microgreen	5	Fabaceae	Mg

Set 3 — Leafy Greens Only

Set 3 comprises a diverse selection of leafy greens, combining high-CRL crops values alongside species with lower CRL values to enhance nutritional diversity. High-performing varieties include Brassicaceae such as ‘Red Russian’ and ‘Toscano’ kale, ‘Amara’ mustard and ‘Extra Dwarf’ bok choy, all of which are rated CRL 9 and noted for their high levels of vitamins C and K and calcium. These are complemented by Asteraceae lettuces such as ‘Dragoon’ and ‘Outredgeous’, which are also rated CRL 9. Lower-CRL entries such as beet greens, Swiss chard, sorrel and watercress contribute additional nutrients such as vitamin B1 and magnesium, though their reduced cultivation readiness suggests potential challenges in controlled environments. Overall, Set 3 provides a balance of high-reliability crops with additional nutrient-dense leafy greens broadening species range and enhancing phytonutrient diversity.

Table 11 Selected leafy greens for Set 3, focusing on Leafy greens only. Crop Readiness Level (CRL) ranging from 1 (lowest) to 9 (highest), is provided for plants included in NASA testing. Additionally, key nutrients are listed, in which each crop scored highly compared to the other crops.

Common Name	Botanical Name	Type	CRL	Family	Key Nutrients
Beet greens	*Beta vulgaris*	Leafy Green	2	Amaranthaceae	Vitamin B1, Vitamin K K, Mg
Cabbage, red	*Brassica oleracea*	Leafy Green		Brassicaceae	K
Kale, ‘Red Russian’	*Brassica napus*	Leafy Green	9	Brassicaceae	Vitamin C Vitamin K Ca
Kale, ‘Toscano’	*Brassica oleracea*	Leafy Green	9	Brassicaceae	
Lettuce, ‘Dragoon’	*Lactuca sativa*	Leafy Green	9	Asteraceae	
Lettuce, ‘Outredgeous’	*Lactuca sativa*	Leafy Green	9	Asteraceae	
Lettuce ‘Waldmann’s Green’	*Lactuca sativa*	Leafy Green	9	Asteraceae	
Mizuna	*Brassica rapa var. japonica*	Leafy Green	9	Brassicaceae	
Mustard ‘Amara’	*Brassica carinata*	Leafy Green	9	Brassicaceae	
Mustard, ‘Wasabi’	*Brassica rapa var. japonica*	Leafy Green	9	Brassicaceae	
Bok choy, ‘Extra Dwarf’	*Brassica rapa var. chinensis*	Leafy Green	9	Brassicaceae	Vitamin C Vitamin K Mg
Radish, ‘Cherry Belle’	*Raphanus sativus*	Leafy Green	9	Brassicaceae	
Sorrel	*Rumex acetosa*	Leafy Green	3	Polygonaceae	Vitamin B1, Vitamin C Mg
Swiss Chard, ‘Bright Lights’	*Beta vulgaris*	Leafy Green	3	Amaranthaceae	Vitamin K, Mg
Watercress	*Nasturtium officinale*	Leafy Green	-	Capparaceae	Vitamin B1

5 Static Yield Calculation

5.1 Methodology for Static Yield Calculation

The static yield calculation presented in this chapter was based on the crop selection and set creation processes described in previous chapters. Data for each species were compiled from various scientific publications, commercial seed catalogues and validated horticultural databases.

Data, including yield and nutritional information, were collected from the literature. Where yield data were missing, values from similar crops or estimates based on closely related species were used. Key parameters were then identified from these data to enable the calculation of static yields. Where possible, the following data points were gathered:

- **Planting density:** Where available, the recommended planting density was included. In cases where data were based on trays of different dimensions, plant density was recalculated accordingly, fitting the 70 × 70 cm trays. For species with data gaps, estimates were made based on morphological growth habits and comparisons with similar species.

- **Individual plant biomass:** Information on the average fresh biomass per plant at harvest was compiled. Where necessary, literature values were averaged.

- **Total biomass per tray:** The calculation was made by multiplying the individual plant biomass with the number of plants per tray.

- **Growth cycle duration:** Defined as the time between sowing and harvest, reflecting the growth periods of different species. This allowed the yield data to be normalised over time. For leafy greens, the germination period was subtracted to exclude the time spent in the nursery and only count the days spent cultivating in trays.

- **Static yield calculation:** The yield per tray and day was calculated by dividing the total yield per tray by the duration of the growth cycle. This approach enabled direct comparisons to be made between the static productivity of different species, independent of dynamic variables specific to the cultivation system.

Nutritional parameters were integrated alongside yield data to enable subsequent yield-quality assessments. For each species, the following nutrients were documented per 100 g of fresh mass (FM), primarily based on data from USDA FoodData Central for leafy greens, as well as a variety of other sources for microgreens (Balik et al., 2025; Dhaka et al., 2023; Di Gioia et al., 2015; Rizvi et al., 2023; Xiao et al., 2012; Yadav et al., 2019):

- Energy content
- Macronutrients: protein, carbohydrate, total lipid
- Micronutrients: vitamin B1 (thiamine), vitamin C (total ascorbic acid), vitamin K (phylloquinone), potassium, magnesium, and calcium.

Due to incomplete data for certain parameters, the missing nutritional values per 100 g FM were estimated by taking the average of the available values for the other plants in the same selection set. This approach was chosen to ensure that the averaged values more accurately reflect the characteristics of the current set of plants. These values were then scaled to the total yield per crop across all trays.

Given the nature of the static yield approach, the methodology involved several assumptions. These included considering single harvest scenarios and assuming that plant growth and productivity in the LAM-GTD are comparable to data in the literature, even though the exact plant variety or environmental conditions were not necessarily specified in the literature and will not precisely match those in the LAM-GTD. Additionally, the nutritional data used were standardised averages that vary within individual plants and were influenced by environmental conditions.

Based on this information and the crop sets defined in the previous chapter, the yield for each selection was calculated. However, first, it had to be determined how the 48 cultivation trays should be distributed among the selected crops. In flight missions, this distribution can be adjusted dynamically according to crew needs; for the purposes of this static analysis, however, the trays were distributed as deemed most appropriate. Crops that showed lower yield or nutritional value were assigned to fewer trays. Total average yields and nutrient yields were then calculated and compared for each set.

5.2 Results of Static Yield Calculation

This chapter presents the results of the static yield calculation, which is based on the methodology outlined in the previous section. These calculations were carried out using the leafy greens and microgreens selected during the crop selection process, which were organised into distinct crop sets. This results section provides an overview of the calculated static yields, with nutritional values presented alongside the yield data to enable an initial evaluation of the crops' potential to contribute to dietary requirements.

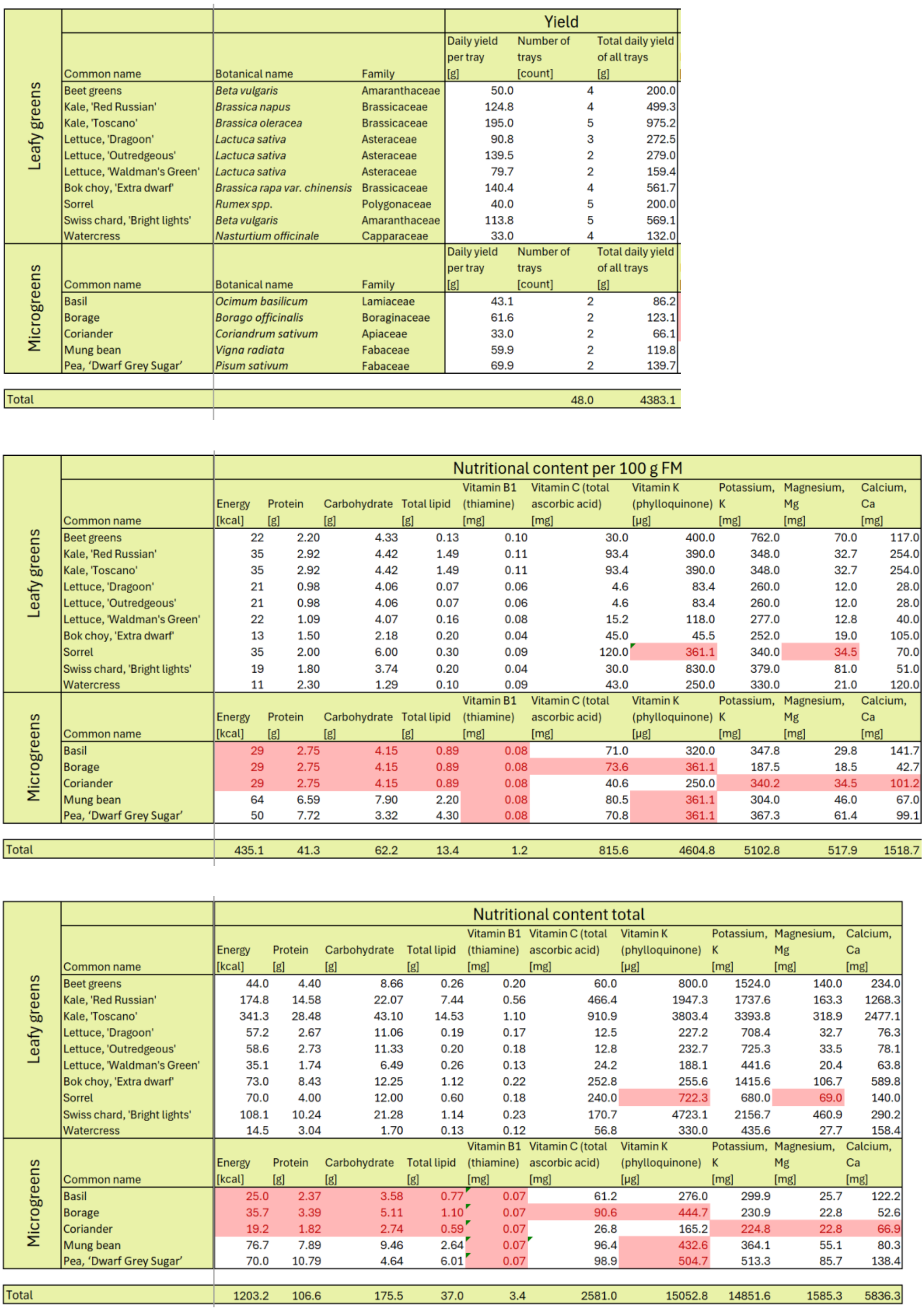
Set 1 — Diverse Families (10 Leafy Greens and 5 Microgreens)

The static yield calculation for Set 1 results in a total daily yield of 4383.1 g of FM across the 48 trays. Among the leafy greens, kale ‘Toscano’ has the highest daily yield per tray at 195 g, followed by lettuce ‘Outredgeous’ and bok choy ‘Extra Dwarf’, both at around 140 g. By contrast, microgreens produce lower yields per tray, with pea ‘Dwarf Grey Sugar’ achieving the highest daily yield of 69.9 g per tray.

The combined nutritional yield of Set 1, calculated from the static yield and nutrient values per 100 g FM, result in a theoretical overall daily energy production of 1203.2 kcal, with 106.6 g of protein and 175.5 g of carbohydrates. Among the leafy greens, kale varieties ‘Red Russian’ and ‘Toscano’ are among the most significant contributors of energy, protein, and key micronutrients, while sorrel shows considerable amounts of vitamin C. Despite their relatively low contribution to the overall yield, microgreens provide notably high nutrient concentrations, often scoring higher than the leafy greens per 100 g FM.

Across Set 1, the total contributions of key nutrients are:

- Energy: 1203.2 kcal
- Protein: 106.6 g
- Carbohydrates: 175.5 g
- Total lipid: 37 g
- Vitamin B1: 3.4 mg
- Vitamin C: 2 581.0 mg — 2.58 g
- Vitamin K: 15 052.8 µg — 15.05 mg
- Potassium: 14 851.6 mg — 14.85 g
- Magnesium: 1585.3 mg — 1.59 g
- Calcium: 5836.3 mg — 5.84 g



				Yield		
	Common name	Botanical name	Family	Daily yield per tray [g]	Number of trays [count]	Total daily yield of all trays [g]
Leafy greens	Beet greens	*Beta vulgaris*	Amaranthaceae	50.0	4	200.0
	Kale, 'Red Russian'	*Brassica napus*	Brassicaceae	124.8	4	499.3
	Kale, 'Toscano'	*Brassica oleracea*	Brassicaceae	195.0	5	975.2
	Lettuce, 'Dragoon'	*Lactuca sativa*	Asteraceae	90.8	3	272.5
	Lettuce, 'Outredgeous'	*Lactuca sativa*	Asteraceae	139.5	2	279.0
	Lettuce, 'Waldman's Green'	*Lactuca sativa*	Asteraceae	79.7	2	159.4
	Bok choy, 'Extra dwarf'	*Brassica rapa var. chinensis*	Brassicaceae	140.4	4	561.7
	Sorrel	*Rumex spp.*	Polygonaceae	40.0	5	200.0
	Swiss chard, 'Bright lights'	*Beta vulgaris*	Amaranthaceae	113.8	5	569.1
	Watercress	*Nasturtium officinale*	Capparaceae	33.0	4	132.0
Microgreens	Common name	Botanical name	Family	Daily yield per tray [g]	Number of trays [count]	Total daily yield of all trays [g]
	Basil	*Ocimum basilicum*	Lamiaceae	43.1	2	86.2
	Borage	*Borago officinalis*	Boraginaceae	61.6	2	123.1
	Coriander	*Coriandrum sativum*	Apiaceae	33.0	2	66.1
	Mung bean	*Vigna radiata*	Fabaceae	59.9	2	119.8
	Pea, 'Dwarf Grey Sugar'	*Pisum sativum*	Fabaceae	69.9	2	139.7
Total					48.0	4383.1

		Nutritional content per 100 g FM									
	Common name	Energy [kcal]	Protein [g]	Carbohydrate [g]	Total lipid [g]	Vitamin B1 (thiamine) [mg]	Vitamin C (total ascorbic acid) [mg]	Vitamin K (phylloquinone) [µg]	Potassium, K [mg]	Magnesium, Mg [mg]	Calcium, Ca [mg]
Leafy greens	Beet greens	22	2.20	4.33	0.13	0.10	30.0	400.0	762.0	70.0	117.0
	Kale, 'Red Russian'	35	2.92	4.42	1.49	0.11	93.4	390.0	348.0	32.7	254.0
	Kale, 'Toscano'	35	2.92	4.42	1.49	0.11	93.4	390.0	348.0	32.7	254.0
	Lettuce, 'Dragoon'	21	0.98	4.06	0.07	0.06	4.6	83.4	260.0	12.0	28.0
	Lettuce, 'Outredgeous'	21	0.98	4.06	0.07	0.06	4.6	83.4	260.0	12.0	28.0
	Lettuce, 'Waldman's Green'	22	1.09	4.07	0.16	0.08	15.2	118.0	277.0	12.8	40.0
	Bok choy, 'Extra dwarf'	13	1.50	2.18	0.20	0.04	45.0	45.5	252.0	19.0	105.0
	Sorrel	35	2.00	6.00	0.30	0.09	120.0	361.1	340.0	34.5	70.0
	Swiss chard, 'Bright lights'	19	1.80	3.74	0.20	0.04	30.0	830.0	379.0	81.0	51.0
	Watercress	11	2.30	1.29	0.10	0.09	43.0	250.0	330.0	21.0	120.0
Microgreens	Common name	Energy [kcal]	Protein [g]	Carbohydrate [g]	Total lipid [g]	Vitamin B1 (thiamine) [mg]	Vitamin C (total ascorbic acid) [mg]	Vitamin K (phylloquinone) [µg]	Potassium, K [mg]	Magnesium, Mg [mg]	Calcium, Ca [mg]
	Basil	29	2.75	4.15	0.89	0.08	71.0	320.0	347.8	29.8	141.7
	Borage	29	2.75	4.15	0.89	0.08	73.6	361.1	187.5	18.5	42.7
	Coriander	29	2.75	4.15	0.89	0.08	40.6	250.0	340.2	34.5	101.2
	Mung bean	64	6.59	7.90	2.20	0.08	80.5	361.1	304.0	46.0	67.0
	Pea, 'Dwarf Grey Sugar'	50	7.72	3.32	4.30	0.08	70.8	361.1	367.3	61.4	99.1
Total		435.1	41.3	62.2	13.4	1.2	815.6	4604.8	5102.8	517.9	1518.7

		Nutritional content total									
	Common name	Energy [kcal]	Protein [g]	Carbohydrate [g]	Total lipid [g]	Vitamin B1 (thiamine) [mg]	Vitamin C (total ascorbic acid) [mg]	Vitamin K (phylloquinone) [µg]	Potassium, K [mg]	Magnesium, Mg [mg]	Calcium, Ca [mg]
Leafy greens	Beet greens	44.0	4.40	8.66	0.26	0.20	60.0	800.0	1524.0	140.0	234.0
	Kale, 'Red Russian'	174.8	14.58	22.07	7.44	0.56	466.4	1947.3	1737.6	163.3	1268.3
	Kale, 'Toscano'	341.3	28.48	43.10	14.53	1.10	910.9	3803.4	3393.8	318.9	2477.1
	Lettuce, 'Dragoon'	57.2	2.67	11.06	0.19	0.17	12.5	227.2	708.4	32.7	76.3
	Lettuce, 'Outredgeous'	58.6	2.73	11.33	0.20	0.18	12.8	232.7	725.3	33.5	78.1
	Lettuce, 'Waldman's Green'	35.1	1.74	6.49	0.26	0.13	24.2	188.1	441.6	20.4	63.8
	Bok choy, 'Extra dwarf'	73.0	8.43	12.25	1.12	0.22	252.8	255.6	1415.6	106.7	589.8
	Sorrel	70.0	4.00	12.00	0.60	0.18	240.0	722.3	680.0	69.0	140.0
	Swiss chard, 'Bright lights'	108.1	10.24	21.28	1.14	0.23	170.7	4723.1	2156.7	460.9	290.2
	Watercress	14.5	3.04	1.70	0.13	0.12	56.8	330.0	435.6	27.7	158.4
Microgreens	Common name	Energy [kcal]	Protein [g]	Carbohydrate [g]	Total lipid [g]	Vitamin B1 (thiamine) [mg]	Vitamin C (total ascorbic acid) [mg]	Vitamin K (phylloquinone) [µg]	Potassium, K [mg]	Magnesium, Mg [mg]	Calcium, Ca [mg]
	Basil	25.0	2.37	3.58	0.77	0.07	61.2	276.0	299.9	25.7	122.2
	Borage	35.7	3.39	5.11	1.10	0.07	90.6	444.7	230.9	22.8	52.6
	Coriander	19.2	1.82	2.74	0.59	0.07	26.8	165.2	224.8	22.8	66.9
	Mung bean	76.7	7.89	9.46	2.64	0.07	96.4	432.6	364.1	55.1	80.3
	Pea, 'Dwarf Grey Sugar'	70.0	10.79	4.64	6.01	0.07	98.9	504.7	513.3	85.7	138.4
Total		1203.2	106.6	175.5	37.0	3.4	2581.0	15052.8	14851.6	1585.3	5836.3

Figure 7 Daily yield and nutritional output of Set 1 crops extracted from Excel. Static yield and nutritional content per 100 g fresh mass, with corresponding total daily nutritional contributions from leafy greens and microgreens grown across 48 trays. Nutritional values were calculated based on the crop-specific total yield and known nutrient content per 100 g fresh mass. For parameters where data were unavailable (highlighted in red), values were estimated using the average per 100 g fresh mass of the other crops within the same set.

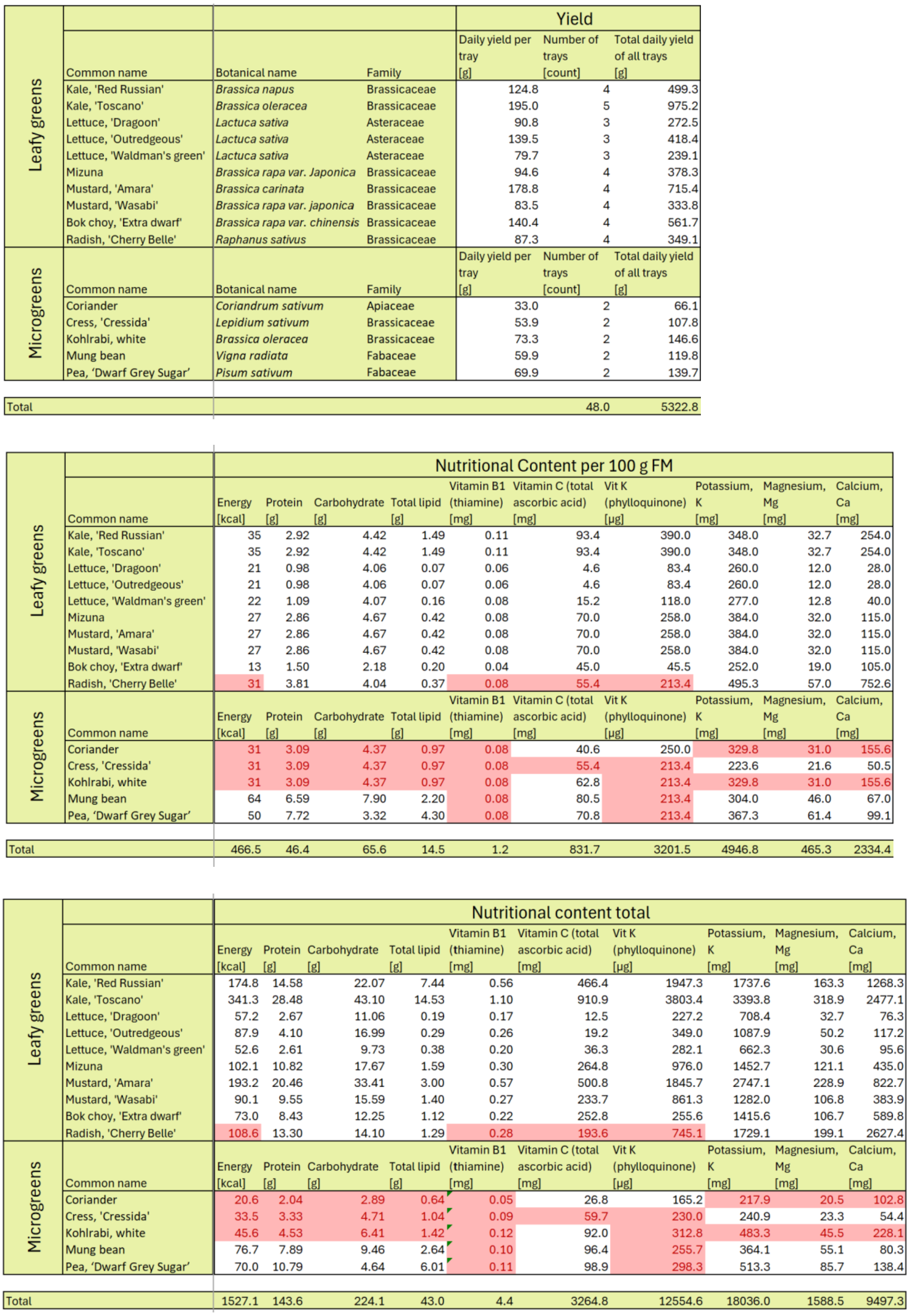
Set 2 — High CRL Focus (CRL Prioritised, 10 Leafy Greens and 5 Microgreens)

The total FM yield for Set 2 is 5322.8 g per day across 48 trays. In this set, as in Set 1, microgreens are allocated to 10 trays overall, while the remaining 38 trays are assigned to leafy greens. Kale 'Toscano' again in the best-performing leafy green, with a daily yield of 195.0 g per tray, followed closely by mustard 'Amara' at 178.8 g. Here too, microgreens yield less daily biomass per tray, with white kohlrabi microgreens leading among them at 73.3 g. Other microgreens, including pea 'Dwarf Grey Sugar' and mung bean, contribute to the daily yield with values of 69.9 g and 59.9 g per tray, respectively.

Nutritionally, Set 2 produces an estimated 1527.1 kcal per day, delivering 143.6 g of protein and 224.1 g of carbohydrates. Once again, kale varieties contribute substantially to protein and micronutrient content. Radish is a noteworthy species within the leafy greens group for mineral contribution, with the highest values of potassium, magnesium and calcium per 100 g FM — namely 495.3 mg, 57 mg, and 752.6 mg respectively. Only pea 'Dwarf Grey Sugar' microgreens show higher levels of magnesium per 100 g, with 61.4 mg. Microgreens such as pea and mung bean also rank highest in energy, protein, carbohydrate and total lipid content compared to the leafy greens. Mung bean microgreens have the highest energy content per 100 g FM at 64 kcal and the highest carbohydrate content of 7.9 g. Pea microgreens exhibit the highest values per 100 g FM for Protein at 7.7 g and total lipid at 4.3 g.

Across Set 2, the total contributions of key nutrients are:

- Energy: 1527.1 kcal
- Protein: 143.6 g
- Carbohydrates: 224.1 g
- Total lipid: 43 g
- Vitamin B1: 4.4 mg
- Vitamin C: 3264.8 mg — 3.27 g
- Vitamin K: 12 554.6 µg — 12.56 mg
- Potassium: 18 036 mg — 18.04 g
- Magnesium: 1588.5 mg — 1.59 g
- Calcium: 9497.3 mg — 9.45 g



				Yield		
	Common name	Botanical name	Family	Daily yield per tray [g]	Number of trays [count]	Total daily yield of all trays [g]
Leafy greens	Kale, 'Red Russian'	*Brassica napus*	Brassicaceae	124.8	4	499.3
	Kale, 'Toscano'	*Brassica oleracea*	Brassicaceae	195.0	5	975.2
	Lettuce, 'Dragoon'	*Lactuca sativa*	Asteraceae	90.8	3	272.5
	Lettuce, 'Outredgeous'	*Lactuca sativa*	Asteraceae	139.5	3	418.4
	Lettuce, 'Waldman's green'	*Lactuca sativa*	Asteraceae	79.7	3	239.1
	Mizuna	*Brassica rapa var. Japonica*	Brassicaceae	94.6	4	378.3
	Mustard, 'Amara'	*Brassica carinata*	Brassicaceae	178.8	4	715.4
	Mustard, 'Wasabi'	*Brassica rapa var. japonica*	Brassicaceae	83.5	4	333.8
	Bok choy, 'Extra dwarf'	*Brassica rapa var. chinensis*	Brassicaceae	140.4	4	561.7
	Radish, 'Cherry Belle'	*Raphanus sativus*	Brassicaceae	87.3	4	349.1
Microgreens	Common name	Botanical name	Family	Daily yield per tray [g]	Number of trays [count]	Total daily yield of all trays [g]
	Coriander	*Coriandrum sativum*	Apiaceae	33.0	2	66.1
	Cress, 'Cressida'	*Lepidium sativum*	Brassicaceae	53.9	2	107.8
	Kohlrabi, white	*Brassica oleracea*	Brassicaceae	73.3	2	146.6
	Mung bean	*Vigna radiata*	Fabaceae	59.9	2	119.8
	Pea, 'Dwarf Grey Sugar'	*Pisum sativum*	Fabaceae	69.9	2	139.7
Total					48.0	5322.8

		Nutritional Content per 100 g FM									
	Common name	Energy [kcal]	Protein [g]	Carbohydrate [g]	Total lipid [g]	Vitamin B1 (thiamine) [mg]	Vitamin C (total ascorbic acid) [mg]	Vit K (phylloquinone) [µg]	Potassium, K [mg]	Magnesium, Mg [mg]	Calcium, Ca [mg]
Leafy greens	Kale, 'Red Russian'	35	2.92	4.42	1.49	0.11	93.4	390.0	348.0	32.7	254.0
	Kale, 'Toscano'	35	2.92	4.42	1.49	0.11	93.4	390.0	348.0	32.7	254.0
	Lettuce, 'Dragoon'	21	0.98	4.06	0.07	0.06	4.6	83.4	260.0	12.0	28.0
	Lettuce, 'Outredgeous'	21	0.98	4.06	0.07	0.06	4.6	83.4	260.0	12.0	28.0
	Lettuce, 'Waldman's green'	22	1.09	4.07	0.16	0.08	15.2	118.0	277.0	12.8	40.0
	Mizuna	27	2.86	4.67	0.42	0.08	70.0	258.0	384.0	32.0	115.0
	Mustard, 'Amara'	27	2.86	4.67	0.42	0.08	70.0	258.0	384.0	32.0	115.0
	Mustard, 'Wasabi'	27	2.86	4.67	0.42	0.08	70.0	258.0	384.0	32.0	115.0
	Bok choy, 'Extra dwarf'	13	1.50	2.18	0.20	0.04	45.0	45.5	252.0	19.0	105.0
	Radish, 'Cherry Belle'	31	3.81	4.04	0.37	0.08	55.4	213.4	495.3	57.0	752.6
Microgreens	Common name	Energy [kcal]	Protein [g]	Carbohydrate [g]	Total lipid [g]	Vitamin B1 (thiamine) [mg]	Vitamin C (total ascorbic acid) [mg]	Vit K (phylloquinone) [µg]	Potassium, K [mg]	Magnesium, Mg [mg]	Calcium, Ca [mg]
	Coriander	31	3.09	4.37	0.97	0.08	40.6	250.0	329.8	31.0	155.6
	Cress, 'Cressida'	31	3.09	4.37	0.97	0.08	55.4	213.4	223.6	21.6	50.5
	Kohlrabi, white	31	3.09	4.37	0.97	0.08	62.8	213.4	329.8	31.0	155.6
	Mung bean	64	6.59	7.90	2.20	0.08	80.5	213.4	304.0	46.0	67.0
	Pea, 'Dwarf Grey Sugar'	50	7.72	3.32	4.30	0.08	70.8	213.4	367.3	61.4	99.1
Total		466.5	46.4	65.6	14.5	1.2	831.7	3201.5	4946.8	465.3	2334.4

		Nutritional content total									
	Common name	Energy [kcal]	Protein [g]	Carbohydrate [g]	Total lipid [g]	Vitamin B1 (thiamine) [mg]	Vitamin C (total ascorbic acid) [mg]	Vit K (phylloquinone) [µg]	Potassium, K [mg]	Magnesium, Mg [mg]	Calcium, Ca [mg]
Leafy greens	Kale, 'Red Russian'	174.8	14.58	22.07	7.44	0.56	466.4	1947.3	1737.6	163.3	1268.3
	Kale, 'Toscano'	341.3	28.48	43.10	14.53	1.10	910.9	3803.4	3393.8	318.9	2477.1
	Lettuce, 'Dragoon'	57.2	2.67	11.06	0.19	0.17	12.5	227.2	708.4	32.7	76.3
	Lettuce, 'Outredgeous'	87.9	4.10	16.99	0.29	0.26	19.2	349.0	1087.9	50.2	117.2
	Lettuce, 'Waldman's green'	52.6	2.61	9.73	0.38	0.20	36.3	282.1	662.3	30.6	95.6
	Mizuna	102.1	10.82	17.67	1.59	0.30	264.8	976.0	1452.7	121.1	435.0
	Mustard, 'Amara'	193.2	20.46	33.41	3.00	0.57	500.8	1845.7	2747.1	228.9	822.7
	Mustard, 'Wasabi'	90.1	9.55	15.59	1.40	0.27	233.7	861.3	1282.0	106.8	383.9
	Bok choy, 'Extra dwarf'	73.0	8.43	12.25	1.12	0.22	252.8	255.6	1415.6	106.7	589.8
	Radish, 'Cherry Belle'	108.6	13.30	14.10	1.29	0.28	193.6	745.1	1729.1	199.1	2627.4
Microgreens	Common name	Energy [kcal]	Protein [g]	Carbohydrate [g]	Total lipid [g]	Vitamin B1 (thiamine) [mg]	Vitamin C (total ascorbic acid) [mg]	Vit K (phylloquinone) [µg]	Potassium, K [mg]	Magnesium, Mg [mg]	Calcium, Ca [mg]
	Coriander	20.6	2.04	2.89	0.64	0.05	26.8	165.2	217.9	20.5	102.8
	Cress, 'Cressida'	33.5	3.33	4.71	1.04	0.09	59.7	230.0	240.9	23.3	54.4
	Kohlrabi, white	45.6	4.53	6.41	1.42	0.12	92.0	312.8	483.3	45.5	228.1
	Mung bean	76.7	7.89	9.46	2.64	0.10	96.4	255.7	364.1	55.1	80.3
	Pea, 'Dwarf Grey Sugar'	70.0	10.79	4.64	6.01	0.11	98.9	298.3	513.3	85.7	138.4
Total		1527.1	143.6	224.1	43.0	4.4	3264.8	12554.6	18036.0	1588.5	9497.3

Figure 8 Daily yield and nutritional output of Set 2 crops extracted from Excel. Static yield and nutritional content per 100 g fresh mass, with corresponding total daily nutritional contributions from leafy greens and microgreens grown across 48 trays. Nutritional values were calculated based on the crop-specific total yield and known nutrient content per 100 g fresh mass. For parameters where data were unavailable (highlighted in red), values were estimated using the average per 100 g fresh mass of the other crops within the same set.

Set 3 — Leafy Greens Only

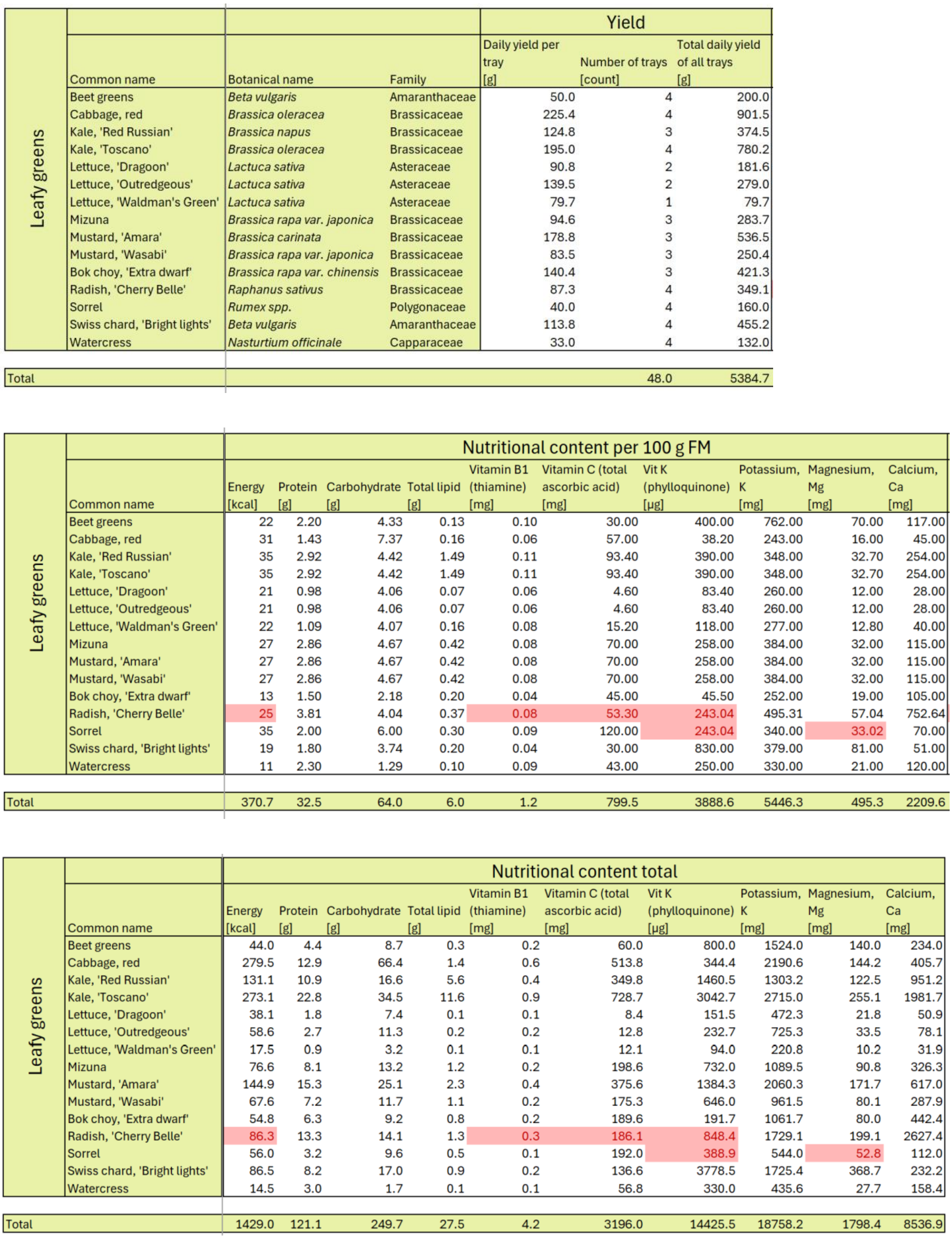
Set 3 is calculated to have a total FM yield of 5384.7 g per day across 48 trays. Red cabbage has the highest daily yield, at 225.4 g per tray. The kale cultivar ‘Toscano’ also produces a notable daily yield of 195.0 g per tray, closely followed by the mustard cultivar ‘Amara’.

The nutritional output based on the total estimated yield, is 1429 kcal per day, along with 121.1 g of protein and 249.7 g of carbohydrates. As in the other sets, members of the Brassicaceae family contribute significantly to nearly all measured nutrient categories. Kale varieties provide high levels of protein and calcium, while radish ‘Cherry Belle’ offers the highest levels of potassium and calcium per 100 g FM. Additionally, the Amaranthaceae family — represented by beet greens and Swiss chard — adds to the mineral profile, especially with respect to magnesium. Per 100 g FM, beet greens contain 70 mg of magnesium, and Swiss chard contains 81 mg. The Swiss chard cultivar ‘Bright Lights’ also shows particularly high levels of vitamin K, with 830 µg per 100 g FM.

Interestingly, the overall yield and nutrient output can be significantly increased by adjusting the number of trays per crop — for example, by removing lettuce entirely and replacing it with additional trays of kale, beet, and cabbage. Adjusted values for this configuration are provided in Figure 10.

Across Set 3, the total contributions of key nutrients are:

- Energy: 1429 kcal
- Protein: 121.1 g
- Carbohydrates: 149.7 g
- Total lipid: 27.5 g
- Vitamin B1: 4.2 mg
- Vitamin C: 3196 mg — 3.2 g
- Vitamin K: 14 425.5 µg — 14.43 mg
- Potassium: 18 758.2 mg — 18.76 g
- Magnesium: 1798.4 mg — 1.8 g
- Calcium: 8536.9 mg — 8.54 g

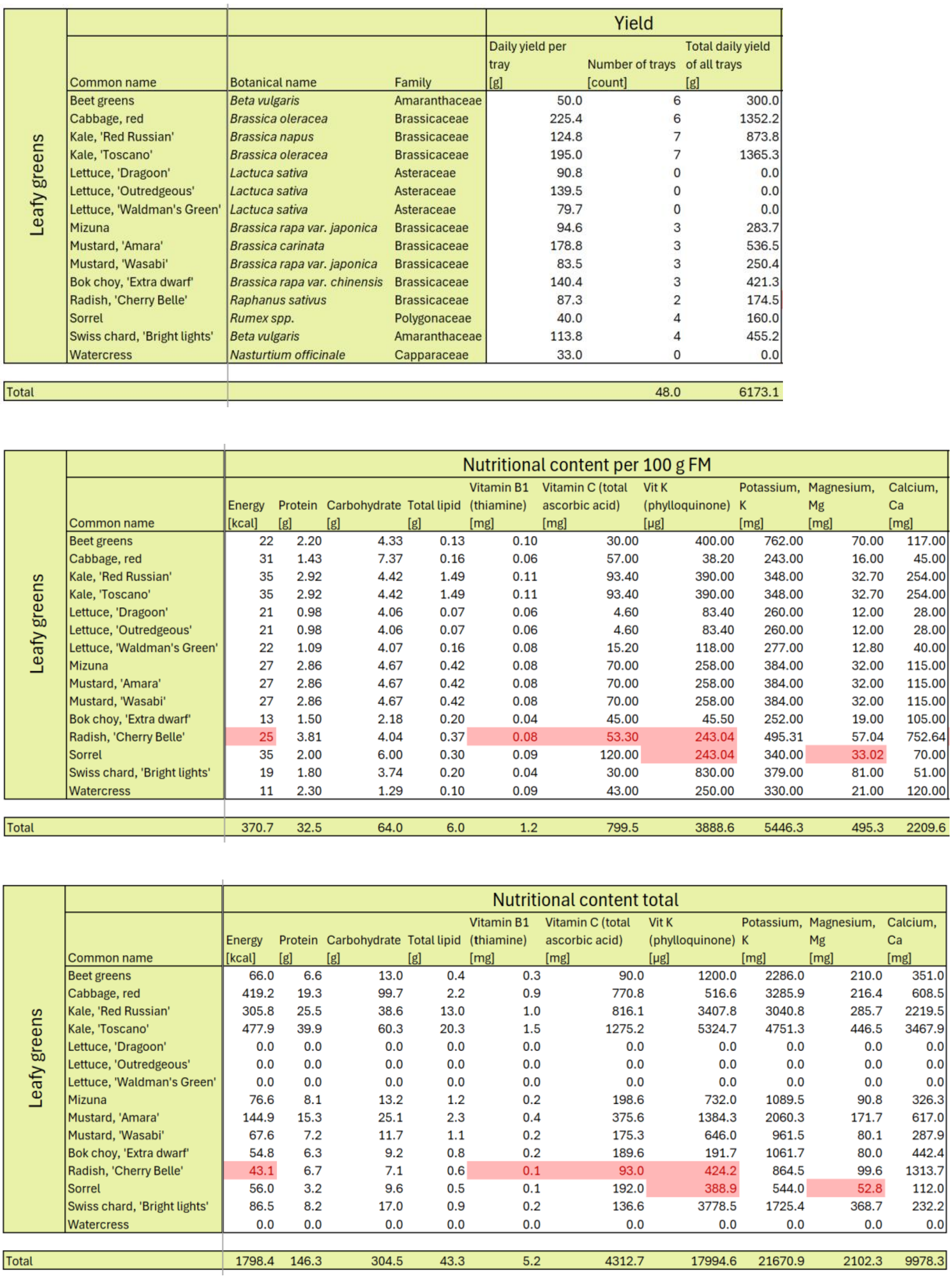


				Yield		
	Common name	Botanical name	Family	Daily yield per tray [g]	Number of trays [count]	Total daily yield of all trays [g]
Leafy greens	Beet greens	*Beta vulgaris*	Amaranthaceae	50.0	4	200.0
	Cabbage, red	*Brassica oleracea*	Brassicaceae	225.4	4	901.5
	Kale, 'Red Russian'	*Brassica napus*	Brassicaceae	124.8	3	374.5
	Kale, 'Toscano'	*Brassica oleracea*	Brassicaceae	195.0	4	780.2
	Lettuce, 'Dragoon'	*Lactuca sativa*	Asteraceae	90.8	2	181.6
	Lettuce, 'Outredgeous'	*Lactuca sativa*	Asteraceae	139.5	2	279.0
	Lettuce, 'Waldman's Green'	*Lactuca sativa*	Asteraceae	79.7	1	79.7
	Mizuna	*Brassica rapa var. japonica*	Brassicaceae	94.6	3	283.7
	Mustard, 'Amara'	*Brassica carinata*	Brassicaceae	178.8	3	536.5
	Mustard, 'Wasabi'	*Brassica rapa var. japonica*	Brassicaceae	83.5	3	250.4
	Bok choy, 'Extra dwarf'	*Brassica rapa var. chinensis*	Brassicaceae	140.4	3	421.3
	Radish, 'Cherry Belle'	*Raphanus sativus*	Brassicaceae	87.3	4	349.1
	Sorrel	*Rumex spp.*	Polygonaceae	40.0	4	160.0
	Swiss chard, 'Bright lights'	*Beta vulgaris*	Amaranthaceae	113.8	4	455.2
	Watercress	*Nasturtium officinale*	Capparaceae	33.0	4	132.0
Total					48.0	5384.7

		Nutritional content per 100 g FM									
	Common name	Energy [kcal]	Protein [g]	Carbohydrate [g]	Total lipid [g]	Vitamin B1 (thiamine) [mg]	Vitamin C (total ascorbic acid) [mg]	Vit K (phylloquinone) [µg]	Potassium, K [mg]	Magnesium, Mg [mg]	Calcium, Ca [mg]
Leafy greens	Beet greens	22	2.20	4.33	0.13	0.10	30.00	400.00	762.00	70.00	117.00
	Cabbage, red	31	1.43	7.37	0.16	0.06	57.00	38.20	243.00	16.00	45.00
	Kale, 'Red Russian'	35	2.92	4.42	1.49	0.11	93.40	390.00	348.00	32.70	254.00
	Kale, 'Toscano'	35	2.92	4.42	1.49	0.11	93.40	390.00	348.00	32.70	254.00
	Lettuce, 'Dragoon'	21	0.98	4.06	0.07	0.06	4.60	83.40	260.00	12.00	28.00
	Lettuce, 'Outredgeous'	21	0.98	4.06	0.07	0.06	4.60	83.40	260.00	12.00	28.00
	Lettuce, 'Waldman's Green'	22	1.09	4.07	0.16	0.08	15.20	118.00	277.00	12.80	40.00
	Mizuna	27	2.86	4.67	0.42	0.08	70.00	258.00	384.00	32.00	115.00
	Mustard, 'Amara'	27	2.86	4.67	0.42	0.08	70.00	258.00	384.00	32.00	115.00
	Mustard, 'Wasabi'	27	2.86	4.67	0.42	0.08	70.00	258.00	384.00	32.00	115.00
	Bok choy, 'Extra dwarf'	13	1.50	2.18	0.20	0.04	45.00	45.50	252.00	19.00	105.00
	Radish, 'Cherry Belle'	25	3.81	4.04	0.37	0.08	53.30	243.04	495.31	57.04	752.64
	Sorrel	35	2.00	6.00	0.30	0.09	120.00	243.04	340.00	33.02	70.00
	Swiss chard, 'Bright lights'	19	1.80	3.74	0.20	0.04	30.00	830.00	379.00	81.00	51.00
	Watercress	11	2.30	1.29	0.10	0.09	43.00	250.00	330.00	21.00	120.00
Total		370.7	32.5	64.0	6.0	1.2	799.5	3888.6	5446.3	495.3	2209.6

		Nutritional content total									
	Common name	Energy [kcal]	Protein [g]	Carbohydrate [g]	Total lipid [g]	Vitamin B1 (thiamine) [mg]	Vitamin C (total ascorbic acid) [mg]	Vit K (phylloquinone) [µg]	Potassium, K [mg]	Magnesium, Mg [mg]	Calcium, Ca [mg]
Leafy greens	Beet greens	44.0	4.4	8.7	0.3	0.2	60.0	800.0	1524.0	140.0	234.0
	Cabbage, red	279.5	12.9	66.4	1.4	0.6	513.8	344.4	2190.6	144.2	405.7
	Kale, 'Red Russian'	131.1	10.9	16.6	5.6	0.4	349.8	1460.5	1303.2	122.5	951.2
	Kale, 'Toscano'	273.1	22.8	34.5	11.6	0.9	728.7	3042.7	2715.0	255.1	1981.7
	Lettuce, 'Dragoon'	38.1	1.8	7.4	0.1	0.1	8.4	151.5	472.3	21.8	50.9
	Lettuce, 'Outredgeous'	58.6	2.7	11.3	0.2	0.2	12.8	232.7	725.3	33.5	78.1
	Lettuce, 'Waldman's Green'	17.5	0.9	3.2	0.1	0.1	12.1	94.0	220.8	10.2	31.9
	Mizuna	76.6	8.1	13.2	1.2	0.2	198.6	732.0	1089.5	90.8	326.3
	Mustard, 'Amara'	144.9	15.3	25.1	2.3	0.4	375.6	1384.3	2060.3	171.7	617.0
	Mustard, 'Wasabi'	67.6	7.2	11.7	1.1	0.2	175.3	646.0	961.5	80.1	287.9
	Bok choy, 'Extra dwarf'	54.8	6.3	9.2	0.8	0.2	189.6	191.7	1061.7	80.0	442.4
	Radish, 'Cherry Belle'	86.3	13.3	14.1	1.3	0.3	186.1	848.4	1729.1	199.1	2627.4
	Sorrel	56.0	3.2	9.6	0.5	0.1	192.0	388.9	544.0	52.8	112.0
	Swiss chard, 'Bright lights'	86.5	8.2	17.0	0.9	0.2	136.6	3778.5	1725.4	368.7	232.2
	Watercress	14.5	3.0	1.7	0.1	0.1	56.8	330.0	435.6	27.7	158.4
Total		1429.0	121.1	249.7	27.5	4.2	3196.0	14425.5	18758.2	1798.4	8536.9

Figure 9 Daily yield and nutritional output of Set 3 crops extracted from Excel. Static yield and nutritional content per 100 g fresh mass, with corresponding total daily nutritional contributions from leafy greens and microgreens grown across 48 trays. Nutritional values were calculated based on the crop-specific total yield and known nutrient content per 100 g fresh mass. For parameters where data were unavailable (highlighted in red), values were estimated using the average per 100 g fresh mass of the other crops within the same set.



				Yield		
	Common name	Botanical name	Family	Daily yield per tray [g]	Number of trays [count]	Total daily yield of all trays [g]
Leafy greens	Beet greens	*Beta vulgaris*	Amaranthaceae	50.0	6	300.0
	Cabbage, red	*Brassica oleracea*	Brassicaceae	225.4	6	1352.2
	Kale, 'Red Russian'	*Brassica napus*	Brassicaceae	124.8	7	873.8
	Kale, 'Toscano'	*Brassica oleracea*	Brassicaceae	195.0	7	1365.3
	Lettuce, 'Dragoon'	*Lactuca sativa*	Asteraceae	90.8	0	0.0
	Lettuce, 'Outredgeous'	*Lactuca sativa*	Asteraceae	139.5	0	0.0
	Lettuce, 'Waldman's Green'	*Lactuca sativa*	Asteraceae	79.7	0	0.0
	Mizuna	*Brassica rapa var. japonica*	Brassicaceae	94.6	3	283.7
	Mustard, 'Amara'	*Brassica carinata*	Brassicaceae	178.8	3	536.5
	Mustard, 'Wasabi'	*Brassica rapa var. japonica*	Brassicaceae	83.5	3	250.4
	Bok choy, 'Extra dwarf'	*Brassica rapa var. chinensis*	Brassicaceae	140.4	3	421.3
	Radish, 'Cherry Belle'	*Raphanus sativus*	Brassicaceae	87.3	2	174.5
	Sorrel	*Rumex spp.*	Polygonaceae	40.0	4	160.0
	Swiss chard, 'Bright lights'	*Beta vulgaris*	Amaranthaceae	113.8	4	455.2
	Watercress	*Nasturtium officinale*	Capparaceae	33.0	0	0.0
Total					48.0	6173.1

		Nutritional content per 100 g FM									
	Common name	Energy [kcal]	Protein [g]	Carbohydrate [g]	Total lipid [g]	Vitamin B1 (thiamine) [mg]	Vitamin C (total ascorbic acid) [mg]	Vit K (phylloquinone) [μg]	Potassium, K [mg]	Magnesium, Mg [mg]	Calcium, Ca [mg]
Leafy greens	Beet greens	22	2.20	4.33	0.13	0.10	30.00	400.00	762.00	70.00	117.00
	Cabbage, red	31	1.43	7.37	0.16	0.06	57.00	38.20	243.00	16.00	45.00
	Kale, 'Red Russian'	35	2.92	4.42	1.49	0.11	93.40	390.00	348.00	32.70	254.00
	Kale, 'Toscano'	35	2.92	4.42	1.49	0.11	93.40	390.00	348.00	32.70	254.00
	Lettuce, 'Dragoon'	21	0.98	4.06	0.07	0.06	4.60	83.40	260.00	12.00	28.00
	Lettuce, 'Outredgeous'	21	0.98	4.06	0.07	0.06	4.60	83.40	260.00	12.00	28.00
	Lettuce, 'Waldman's Green'	22	1.09	4.07	0.16	0.08	15.20	118.00	277.00	12.80	40.00
	Mizuna	27	2.86	4.67	0.42	0.08	70.00	258.00	384.00	32.00	115.00
	Mustard, 'Amara'	27	2.86	4.67	0.42	0.08	70.00	258.00	384.00	32.00	115.00
	Mustard, 'Wasabi'	27	2.86	4.67	0.42	0.08	70.00	258.00	384.00	32.00	115.00
	Bok choy, 'Extra dwarf'	13	1.50	2.18	0.20	0.04	45.00	45.50	252.00	19.00	105.00
	Radish, 'Cherry Belle'	25	3.81	4.04	0.37	0.08	53.30	243.04	495.31	57.04	752.64
	Sorrel	35	2.00	6.00	0.30	0.09	120.00	243.04	340.00	33.02	70.00
	Swiss chard, 'Bright lights'	19	1.80	3.74	0.20	0.04	30.00	830.00	379.00	81.00	51.00
	Watercress	11	2.30	1.29	0.10	0.09	43.00	250.00	330.00	21.00	120.00
Total		370.7	32.5	64.0	6.0	1.2	799.5	3888.6	5446.3	495.3	2209.6

		Nutritional content total									
	Common name	Energy [kcal]	Protein [g]	Carbohydrate [g]	Total lipid [g]	Vitamin B1 (thiamine) [mg]	Vitamin C (total ascorbic acid) [mg]	Vit K (phylloquinone) [μg]	Potassium, K [mg]	Magnesium, Mg [mg]	Calcium, Ca [mg]
Leafy greens	Beet greens	66.0	6.6	13.0	0.4	0.3	90.0	1200.0	2286.0	210.0	351.0
	Cabbage, red	419.2	19.3	99.7	2.2	0.9	770.8	516.6	3285.9	216.4	608.5
	Kale, 'Red Russian'	305.8	25.5	38.6	13.0	1.0	816.1	3407.8	3040.8	285.7	2219.5
	Kale, 'Toscano'	477.9	39.9	60.3	20.3	1.5	1275.2	5324.7	4751.3	446.5	3467.9
	Lettuce, 'Dragoon'	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Lettuce, 'Outredgeous'	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Lettuce, 'Waldman's Green'	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mizuna	76.6	8.1	13.2	1.2	0.2	198.6	732.0	1089.5	90.8	326.3
	Mustard, 'Amara'	144.9	15.3	25.1	2.3	0.4	375.6	1384.3	2060.3	171.7	617.0
	Mustard, 'Wasabi'	67.6	7.2	11.7	1.1	0.2	175.3	646.0	961.5	80.1	287.9
	Bok choy, 'Extra dwarf'	54.8	6.3	9.2	0.8	0.2	189.6	191.7	1061.7	80.0	442.4
	Radish, 'Cherry Belle'	43.1	6.7	7.1	0.6	0.1	93.0	424.2	864.5	99.6	1313.7
	Sorrel	56.0	3.2	9.6	0.5	0.1	192.0	388.9	544.0	52.8	112.0
	Swiss chard, 'Bright lights'	86.5	8.2	17.0	0.9	0.2	136.6	3778.5	1725.4	368.7	232.2
	Watercress	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total		1798.4	146.3	304.5	43.3	5.2	4312.7	17994.6	21670.9	2102.3	9978.3

Figure 10 Daily yield and nutritional output of Set 3 altered extracted from Excel. Static yield and nutritional content per 100 g fresh mass, with corresponding total daily nutritional contributions from leafy greens and microgreens grown across 48 trays. Nutritional values were calculated based on the crop-specific total yield and known nutrient content per 100 g fresh mass. For parameters where data were unavailable (highlighted in red), values were estimated using the average per 100 g fresh mass of the other crops within the same set.

6 Discussion

The findings from the crop selection and static yield calculations reveal key insights into optimising plant-based food systems in controlled environments, particularly for space missions or closed-loop terrestrial applications. This discussion evaluates the three defined crop sets — Set 1 (Diverse Families), Set 2 (High CRL Focus), and Set 3 (Leafy Greens Only) — focusing on their nutritional output, biomass yield, and suitability for cultivation under operational constraints. For highlighted data overview, refer to Appendix C.

Set 1, which emphasises plant family diversity, ranks the lowest in overall yield and most other performance categories. The inclusion of microgreens is beneficial in terms of micronutrient density, particularly vitamins B1 and K. However, they contribute little to FM because of their low biomass per tray. Even though the nutrient density in some microgreens surpasses that of fully grown plants, the low yield results in a reduced overall nutrient output. The high vitamin values in the set are attributed to beet greens and kale, which are rich in vitamin B1, and Swiss chard, which is notably rich in vitamin K. Although this set performs moderately well in terms of lipid content, it ranks the lowest among the three in all other aspects. While the diversity of textures and flavours helps reduce menu fatigue on long-duration missions, lower productivity and efficiency present clear limitations. These results suggest that including many low-yield microgreens compromises overall system efficiency. Furthermore, the lettuce varieties contributed only minimal micronutrient content. Strategies to enhance the performance of diverse crop sets like Set 1 could include selectively retaining high nutrient, higher-yield species and increasing the number of trays per productive crop.

Set 2 emerges as the most balanced and operationally viable option. It delivers the highest values for energy, protein, total lipid, vitamin C, and calcium, making it the best-performing across most nutritional categories. This set highlights the robustness of CRL-based selection, as crops with established performance in space or controlled environments offer predictability. The dominance of Brassicaceae in this set, supplemented by microgreens and select lettuces, underscores their importance in space agriculture. Brassicaceae are essential for any viable space-based cultivation system due to their relatively high yield and nutrient density. However, the potential downsides of over-reliance on a narrow genetic base — including increased pathogen susceptibility and dietary monotony — must be explored. Nevertheless, these data suggest that Set 2 represents the most flight-ready configuration. The inclusion of crops with high CRL ratings reduces the number of unknowns in cultivation performance. Because some values in this analysis are based on averaged data, further validation in the LAM-GTD or other controlled settings would help confirm its suitability.

Set 3 produces the highest total biomass largely because it excluded microgreens, which inherently have lower yields. It also ranks highest in carbohydrate, potassium, and magnesium content, likely because of crops such as beet greens, radish, and Swiss chard. In addition, selecting only leafy greens reduces the number of seeds that must be transported. These attributes make Set 3 attractive for missions. The simplicity of its composition also reduces logistical complexity.

Interestingly, adjustments in tray allocation — for example, replacing lower-yielding crops like lettuce with additional trays of kale, beet, or cabbage — can significantly enhance the overall performance. When this strategy is applied, this set can outperform the other sets across every category as the suggest. However, such a method may contribute to diet monotony and reduce long-term acceptability.

Table 12 Total yield and nutrient content per yield for three crop sets, each covering an area of 48 trays (70 cm × 70 cm each). Set 1 includes 10 leafy greens and 5 microgreens, focusing on different plant families. Set 2 comprises 10 leafy greens and 5 microgreens, prioritising crops with successful growth in space testing. Set 3 contains only leafy greens. The Set 3 altered consists of 11 high-performing leafy greens.

Set	1	2	3	3 Altered
Total yield of all trays per day [g]	4383.15	5322.83	5384.73	6173.06
Energy [kcal]	1203.22	1527.14	1428.99	1798.36
Protein [g]	106.56	143.57	121.06	146.30
Carbohydrate [g]	175.47	224.09	249.70	304.48
Total lipid [g]	36.97	42.99	27.51	43.29
Vitamin B1 (thiamine) [mg]	4.43	4.40	4.18	5.18
Vitamin C (total ascorbic acid) [mg]	2580.97	3264.82	3196.04	4312.74
Vit K (phylloquinone) [µg]	15 052.81	12 554.63	14 425.48	17 994.61
Potassium, K [mg]	14 851.62	18 036.05	18 758.17	21 670.86
Magnesium, Mg [mg]	1585.29	1588.47	1798.35	2102.33
Calcium, Ca [mg]	5836.26	9497.31	8536.94	9978.32

For some nutrients, the challenge may be not in maximisation, but rather in balancing intake and avoiding excesses in some areas and deficiencies in others.

The cultivation time and final yield of leafy greens can vary significantly depending on the variety, harvest stage, environmental conditions, and growth management strategies. Therefore, values obtained from existing literature should be treated as indicative estimates rather than absolute figures. Plant development can accelerate or decelerate in response to variations in temperature, humidity, light exposure, and nutrient availability. Consequently, any biomass or productivity figures referenced are approximations, intended to support comparative assessments rather than serve as definitive outcomes. Balancing yield efficiency and psychological sustainability remains a complex challenge. Not only crop choice and distribution but also growth parameters and harvest type strongly influence the outcomes.

The static yield approach enables standardised comparisons but oversimplifies the dynamic nature of plant growth. Environmental factors, such as light spectrum, temperature, and nutrient delivery can significantly impact yield and nutritional values. Estimating missing nutritional values through averaging introduces uncertainty — particularly for lesser-researched crops. Additionally, extrapolating from literature-based biomass data must be performed cautiously and checked in later testing. Therefore, more comprehensive studies are needed to address the limitations of this analysis. Key areas for further research include:

- Incorporating multi-harvest productivity simulations for a more accurate assessment.
- Investigating the nutritional composition of all the selected crops and the effects of altered environmental factors — especially space-specific factors — on plant growth and nutrient composition.
- Pathogen resistance and microbiome analysis, especially for monoculture-dominant sets such as Set 2, where pathogen spread could be more rapid.
- Assessing how plant-based systems contribute to oxygen production, humidity regulation, and CO_2 recycling in closed habitats.

It is also important to distinguish between cultivation conditions on the ISS and those on the lunar surface. The ISS operates under microgravity, whereas the Moon has approximately one-sixth of Earth's gravity. Existing research has largely focused on microgravity conditions and not in hypogravity, presenting a knowledge gap for lunar missions. Similar gaps exist in understanding the effects of magnetic field exposure — or more precisely, the effects of their absence.

The high nutrient density found especially in microgreens, along with their short growth periods, makes them attractive. However, the resulting requirement to transport larger amounts of seeds might be a critical limiting factor. Furthermore, it is worth investigating how well microgreens and leafy greens grow when cultivated together. Leafy greens and microgreens share desirable features such as high nutrient density, compact growth, relatively low resource demand, and psychological benefits. However, these traits may be optimised only under tailored environmental conditions. Research must investigate the requirements for a separate nursery with warmer temperatures and specific climate parameters for young leafy greens, and possibly even microgreens.

In conclusion, each crop set presents unique strengths and limitations for controlled environment agriculture in space missions. While Set 1 offers diversity but low yield, Set 2 provides a balanced, reliable selection with proven space performance, and Set 3 maximises biomass and simplicity. Optimising plant-based systems will likely require a flexible approach that adapts crop choices according to mission needs, resource constraints, and crew health, balancing nutritional output, psychological benefits, and operational efficiency. Further research on multi-harvest dynamics, environmental effects, and pathogen risks is essential to refine these strategies for future missions.

7 Summary

Human spaceflight increasingly focuses on long-duration missions, including lunar and Martian exploration. These missions present significant challenges, particularly in sustaining astronaut health and well-being. The cultivation of fresh food in space plays a vital role in not only providing essential nutrients, but also recycling water, producing oxygen, and improving psychological well-being. The high costs and spatial limitations of transporting processed food further underscore the necessity for regenerative plant growth systems. Therefore, the viability of crop cultivation in controlled, extraterrestrial environments must be evaluated. The central research objective is to evaluate the suitability of specific crop species for space-based cultivation, using the German Aerospace Center's Lunar Agricultural Model – Ground Test Demonstrator (LAM-GTD) as a case study. The methodological approach involves crop selection process based on nutritional content, horticultural performance, environmental adaptability, and Crop Readiness Level (CRL). Nutritional data focuses particularly on the vitamins B1, C, and K, as well as to the minerals calcium, potassium and magnesium. Horticultural evaluation centres on growth rate, environmental compatibility, and prior success in NASA trials.

Among promising microgreens are cabbage, kale, and radish, as well as leafy greens such as mizuna, bok choy, and kale cultivars. Although microgreens generally achieve lower CRL scores, their rapid growth, compact form, and nutrient content support their potential inclusion in future systems. Leafy greens, particularly Brassicaceae and Asteraceae species, show high CRL ratings and demonstrate suitability for space cultivation. Three crop sets were developed for comparative evaluation: Set 1 (Diverse Families), Set 2 (High CRL Focus), and Set 3 (Leafy Greens Only). Set 1, with the emphasis on botanical diversity and including microgreens, scores lowest in overall biomass and many nutritional categories despite its benefit of micronutrient density from crops like beet greens and kale. The low biomass yield of microgreens limits their contribution to total nutrient availability, suggesting that inclusion of too many low-yield species may reduce system efficiency. Set 2 demonstrates the most balanced and operationally viable option, delivering the highest values in energy, protein, lipids, vitamin C, and calcium. This highlights the robustness of CRL-based crop selection, as crops with proven space cultivation performance, particularly Brassicaceae, provide both high yield and nutrient density. However, potential risks such as pathogen growth and dietary monotony require more research. Set 3 produces the highest total biomass, carbohydrate output and mineral contents by excluding microgreens and focusing solely on leafy greens. This simplicity reduces logistical complexity and seed transport mass, and strategic tray allocation can further enhance its performance, although potential impacts on diet variety should be considered. A modified version of Set 3, excluding crops yielding low in mass or nutrient content, can raise the overall nutritional output by far, making it the best performing set across all categories.

8 Abstract

Controlled environment agriculture is a key component in enabling long-duration human space missions, including potential lunar and Martian habitats. To support regenerative life support systems, the viability of crop cultivation under extraterrestrial conditions is examined using the German Aerospace Center's Lunar Agricultural Model – Ground Test Demonstrator (LAM-GTD) as a case study.

Crop species were selected and evaluated based on nutritional profile, horticultural performance, environmental adaptability, and Crop Readiness Level (CRL). Nutrient values for vitamins B1, C, K and minerals (calcium, potassium, magnesium) were compiled from literature. Yield was calculated using a static model based on tray size (70 × 70 cm), number of trays (48), and average growth cycles. All reported yield and nutritional values represent totals based on daily biomass production across all trays. Three crop sets were constructed and compared. Key results include:

Set 1 (Diverse Families — 15 crops including 5 microgreens from multiple families):

- Lowest biomass at 4383 g
- Moderate concentrations of vitamin B1 and vitamin K
- Low energy and protein content

Set 2 (High CRL Focus — 15 crops including 5 microgreens with high CRL):

- High nutritional values for energy of 1527 kcal, protein at 144 g, total lipid of 43 g, and calcium amounting to 9497 mg
- Strong operational performance and high reliability

Set 3 (Leafy Greens Only — 15 crops, no microgreens):

- High total biomass yield per day with 5385 g
- Elevated carbohydrate and mineral content
- Reduced logistical complexity

Set 3 Modified (optimised to 11 high-performing leafy greens):

- Highest values across all categories, including 6173 g total biomass per day, 1798 kcal, and 4313 mg vitamin C

The results enable standardised comparison between crop types and support early-stage decisions for plant-based systems in space applications.

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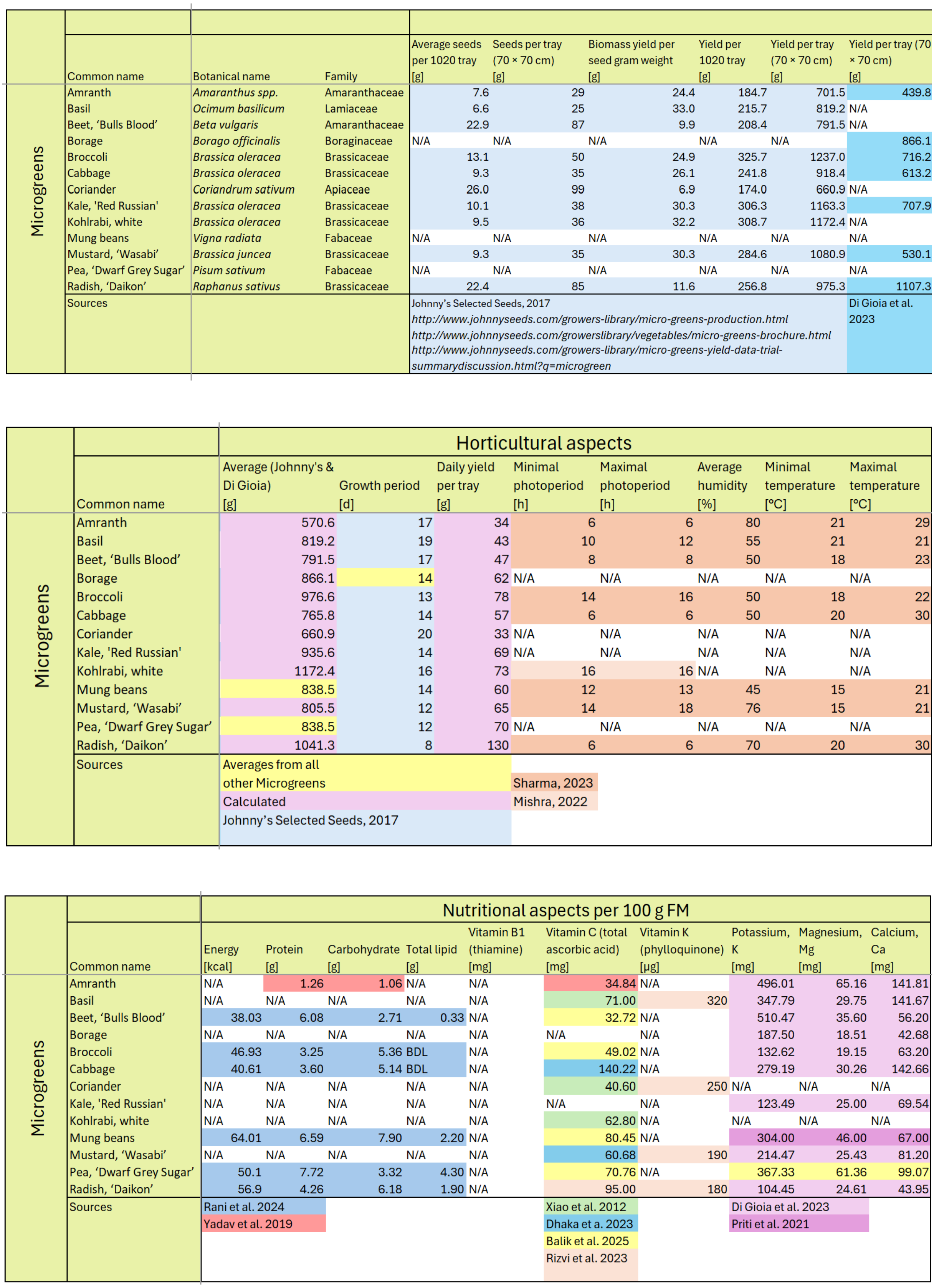
Appendices

Appendix A: Sources for Data on Microgreens



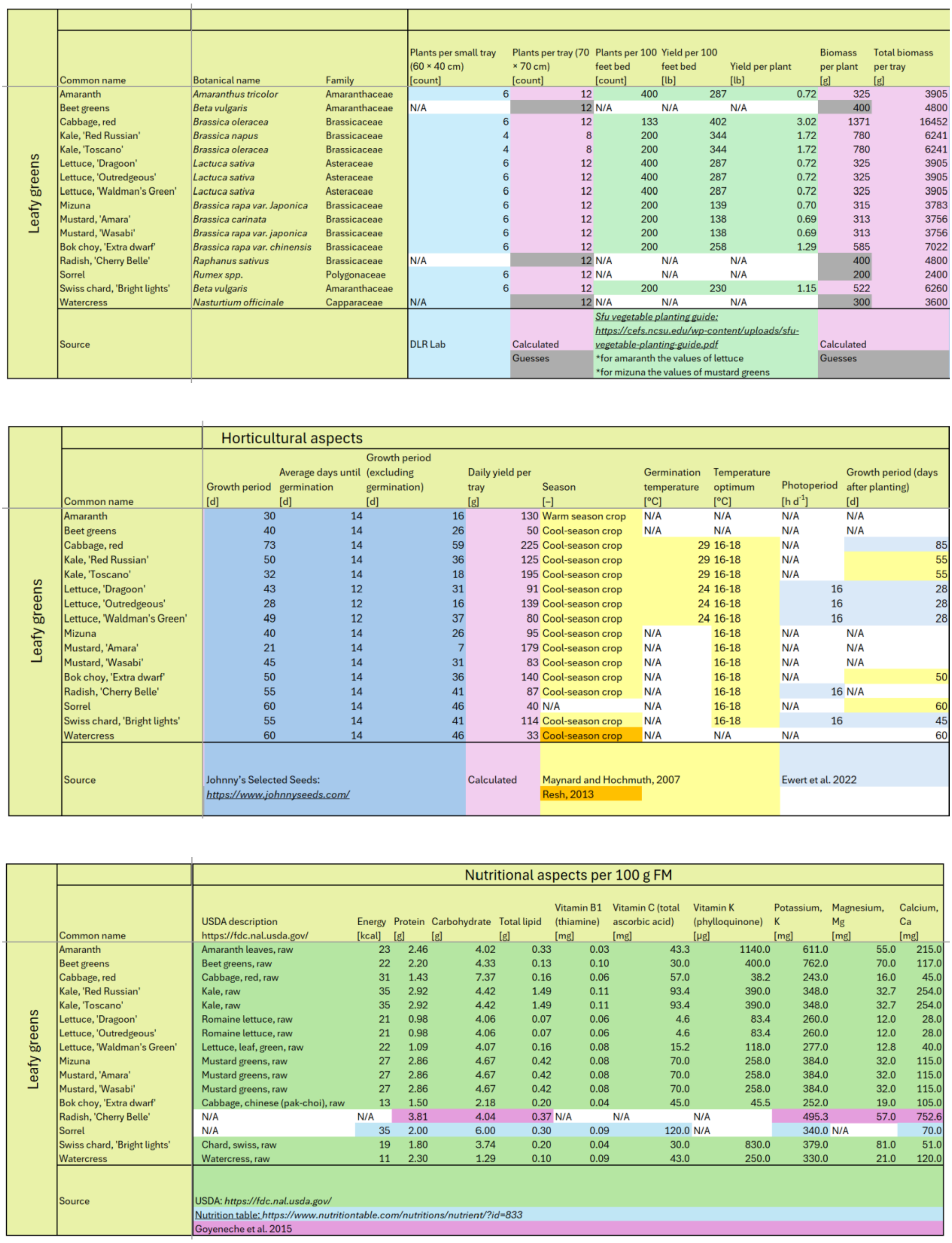
	Common name	Botanical name	Family	Average seeds per 1020 tray [g]	Seeds per tray (70 × 70 cm) [g]	Biomass yield per seed gram weight [g]	Yield per 1020 tray [g]	Yield per tray (70 × 70 cm) [g]	Yield per tray (70 × 70 cm) [g]
Microgreens	Amranth	*Amaranthus spp.*	Amaranthaceae	7.6	29	24.4	184.7	701.5	439.8
	Basil	*Ocimum basilicum*	Lamiaceae	6.6	25	33.0	215.7	819.2	N/A
	Beet, 'Bulls Blood'	*Beta vulgaris*	Amaranthaceae	22.9	87	9.9	208.4	791.5	N/A
	Borage	*Borago officinalis*	Boraginaceae	N/A	N/A	N/A	N/A	N/A	866.1
	Broccoli	*Brassica oleracea*	Brassicaceae	13.1	50	24.9	325.7	1237.0	716.2
	Cabbage	*Brassica oleracea*	Brassicaceae	9.3	35	26.1	241.8	918.4	613.2
	Coriander	*Coriandrum sativum*	Apiaceae	26.0	99	6.9	174.0	660.9	N/A
	Kale, 'Red Russian'	*Brassica oleracea*	Brassicaceae	10.1	38	30.3	306.3	1163.3	707.9
	Kohlrabi, white	*Brassica oleracea*	Brassicaceae	9.5	36	32.2	308.7	1172.4	N/A
	Mung beans	*Vigna radiata*	Fabaceae	N/A	N/A	N/A	N/A	N/A	N/A
	Mustard, 'Wasabi'	*Brassica juncea*	Brassicaceae	9.3	35	30.3	284.6	1080.9	530.1
	Pea, 'Dwarf Grey Sugar'	*Pisum sativum*	Fabaceae	N/A	N/A	N/A	N/A	N/A	N/A
	Radish, 'Daikon'	*Raphanus sativus*	Brassicaceae	22.4	85	11.6	256.8	975.3	1107.3
	Sources			Johnny's Selected Seeds, 2017 *http://www.johnnyseeds.com/growers-library/micro-greens-production.html* *http://www.johnnyseeds.com/growerslibrary/vegetables/micro-greens-brochure.html* *http://www.johnnyseeds.com/growers-library/micro-greens-yield-data-trial-summarydiscussion.html?q=microgreen*					Di Gioia et al. 2023

		Horticultural aspects							
	Common name	Average (Johnny's & Di Gioia) [g]	Growth period [d]	Daily yield per tray [g]	Minimal photoperiod [h]	Maximal photoperiod [h]	Average humidity [%]	Minimal temperature [°C]	Maximal temperature [°C]
Microgreens	Amranth	570.6	17	34	6	6	80	21	29
	Basil	819.2	19	43	10	12	55	21	21
	Beet, 'Bulls Blood'	791.5	17	47	8	8	50	18	23
	Borage	866.1	14	62	N/A	N/A	N/A	N/A	N/A
	Broccoli	976.6	13	78	14	16	50	18	22
	Cabbage	765.8	14	57	6	6	50	20	30
	Coriander	660.9	20	33	N/A	N/A	N/A	N/A	N/A
	Kale, 'Red Russian'	935.6	14	69	N/A	N/A	N/A	N/A	N/A
	Kohlrabi, white	1172.4	16	73	16	16	N/A	N/A	N/A
	Mung beans	838.5	14	60	12	13	45	15	21
	Mustard, 'Wasabi'	805.5	12	65	14	18	76	15	21
	Pea, 'Dwarf Grey Sugar'	838.5	12	70	N/A	N/A	N/A	N/A	N/A
	Radish, 'Daikon'	1041.3	8	130	6	6	70	20	30
	Sources	Averages from all other Microgreens Calculated Johnny's Selected Seeds, 2017			Sharma, 2023 Mishra, 2022				

		Nutritional aspects per 100 g FM									
	Common name	Energy [kcal]	Protein [g]	Carbohydrate [g]	Total lipid [g]	Vitamin B1 (thiamine) [mg]	Vitamin C (total ascorbic acid) [mg]	Vitamin K (phylloquinone) [µg]	Potassium, K [mg]	Magnesium, Mg [mg]	Calcium, Ca [mg]
Microgreens	Amranth	N/A	1.26	1.06	N/A	N/A	34.84	N/A	496.01	65.16	141.81
	Basil	N/A	N/A	N/A	N/A	N/A	71.00	320	347.79	29.75	141.67
	Beet, 'Bulls Blood'	38.03	6.08	2.71	0.33	N/A	32.72	N/A	510.47	35.60	56.20
	Borage	N/A	N/A	N/A	N/A	N/A	N/A	N/A	187.50	18.51	42.68
	Broccoli	46.93	3.25	5.36	BDL	N/A	49.02	N/A	132.62	19.15	63.20
	Cabbage	40.61	3.60	5.14	BDL	N/A	140.22	N/A	279.19	30.26	142.66
	Coriander	N/A	N/A	N/A	N/A	N/A	40.60	250	N/A	N/A	N/A
	Kale, 'Red Russian'	N/A	N/A	N/A	N/A	N/A	N/A	N/A	123.49	25.00	69.54
	Kohlrabi, white	N/A	N/A	N/A	N/A	N/A	62.80	N/A	N/A	N/A	N/A
	Mung beans	64.01	6.59	7.90	2.20	N/A	80.45	N/A	304.00	46.00	67.00
	Mustard, 'Wasabi'	N/A	N/A	N/A	N/A	N/A	60.68	190	214.47	25.43	81.20
	Pea, 'Dwarf Grey Sugar'	50.1	7.72	3.32	4.30	N/A	70.76	N/A	367.33	61.36	99.07
	Radish, 'Daikon'	56.9	4.26	6.18	1.90	N/A	95.00	180	104.45	24.61	43.95
	Sources	Rani et al. 2024 Yadav et al. 2019					Xiao et al. 2012 Dhaka et a. 2023 Balik et al. 2025 Rizvi et al. 2023		Di Gioia et al. 2023 Priti et al. 2021		

Figure A 1 Data table extracted from Excel with the different sources on data for microgreens

Appendix B: Sources for Data on Leafy Greens



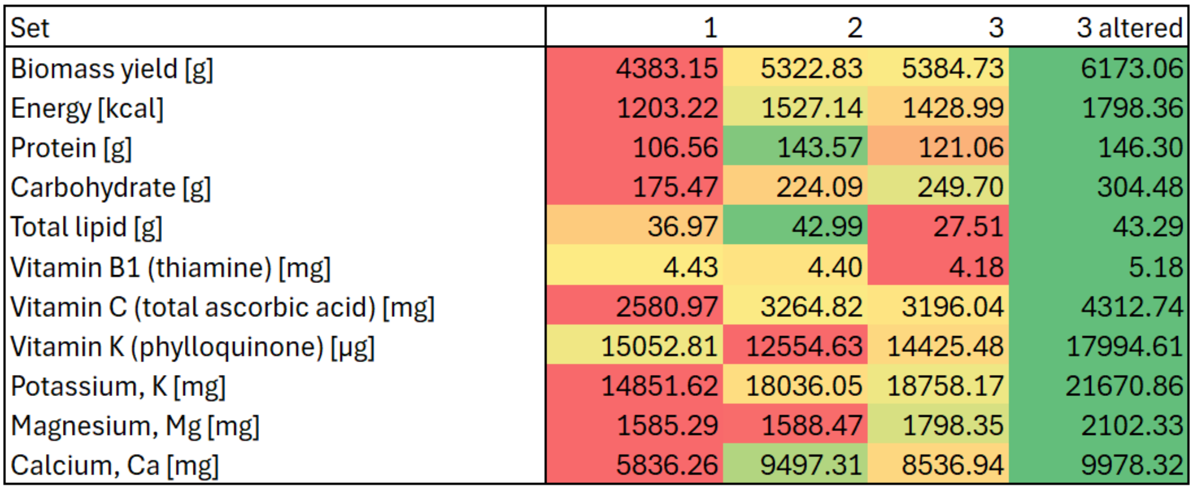
	Common name	Botanical name	Family	Plants per small tray (60 × 40 cm) [count]	Plants per tray (70 × 70 cm) [count]	Plants per 100 feet bed [count]	Yield per 100 feet bed [lb]	Yield per plant [lb]	Biomass per plant [g]	Total biomass per tray [g]
Leafy greens	Amaranth	*Amaranthus tricolor*	Amaranthaceae	6	12	400	287	0.72	325	3905
	Beet greens	*Beta vulgaris*	Amaranthaceae	N/A	12	N/A	N/A	N/A	400	4800
	Cabbage, red	*Brassica oleracea*	Brassicaceae	6	12	133	402	3.02	1371	16452
	Kale, 'Red Russian'	*Brassica napus*	Brassicaceae	4	8	200	344	1.72	780	6241
	Kale, 'Toscano'	*Brassica oleracea*	Brassicaceae	4	8	200	344	1.72	780	6241
	Lettuce, 'Dragoon'	*Lactuca sativa*	Asteraceae	6	12	400	287	0.72	325	3905
	Lettuce, 'Outredgeous'	*Lactuca sativa*	Asteraceae	6	12	400	287	0.72	325	3905
	Lettuce, 'Waldman's Green'	*Lactuca sativa*	Asteraceae	6	12	400	287	0.72	325	3905
	Mizuna	*Brassica rapa var. Japonica*	Brassicaceae	6	12	200	139	0.70	315	3783
	Mustard, 'Amara'	*Brassica carinata*	Brassicaceae	6	12	200	138	0.69	313	3756
	Mustard, 'Wasabi'	*Brassica rapa var. japonica*	Brassicaceae	6	12	200	138	0.69	313	3756
	Bok choy, 'Extra dwarf'	*Brassica rapa var. chinensis*	Brassicaceae	6	12	200	258	1.29	585	7022
	Radish, 'Cherry Belle'	*Raphanus sativus*	Brassicaceae	N/A	12	N/A	N/A	N/A	400	4800
	Sorrel	*Rumex spp.*	Polygonaceae	6	12	N/A	N/A	N/A	200	2400
	Swiss chard, 'Bright lights'	*Beta vulgaris*	Amaranthaceae	6	12	200	230	1.15	522	6260
	Watercress	*Nasturtium officinale*	Capparaceae	N/A	12	N/A	N/A	N/A	300	3600
	Source			DLR Lab	Calculated Guesses	*Sfu vegetable planting guide: https://cefs.ncsu.edu/wp-content/uploads/sfu-vegetable-planting-guide.pdf* *for amaranth the values of lettuce *for mizuna the values of mustard greens			Calculated Guesses	

		Horticultural aspects								
	Common name	Growth period [d]	Average days until germination [d]	Growth period (excluding germination) [d]	Daily yield per tray [g]	Season [–]	Germination temperature [°C]	Temperature optimum [°C]	Photoperiod [h d^{-1}]	Growth period (days after planting) [d]
Leafy greens	Amaranth	30	14	16	130	Warm season crop	N/A	N/A	N/A	N/A
	Beet greens	40	14	26	50	Cool-season crop	N/A	N/A	N/A	N/A
	Cabbage, red	73	14	59	225	Cool-season crop	29	16-18	N/A	85
	Kale, 'Red Russian'	50	14	36	125	Cool-season crop	29	16-18	N/A	55
	Kale, 'Toscano'	32	14	18	195	Cool-season crop	29	16-18	N/A	55
	Lettuce, 'Dragoon'	43	12	31	91	Cool-season crop	24	16-18	16	28
	Lettuce, 'Outredgeous'	28	12	16	139	Cool-season crop	24	16-18	16	28
	Lettuce, 'Waldman's Green'	49	12	37	80	Cool-season crop	24	16-18	16	28
	Mizuna	40	14	26	95	Cool-season crop	N/A	16-18	N/A	N/A
	Mustard, 'Amara'	21	14	7	179	Cool-season crop	N/A	16-18	N/A	N/A
	Mustard, 'Wasabi'	45	14	31	83	Cool-season crop	N/A	16-18	N/A	N/A
	Bok choy, 'Extra dwarf'	50	14	36	140	Cool-season crop	N/A	16-18	N/A	50
	Radish, 'Cherry Belle'	55	14	41	87	Cool-season crop	N/A	16-18	16	N/A
	Sorrel	60	14	46	40	N/A	N/A	16-18	N/A	60
	Swiss chard, 'Bright lights'	55	14	41	114	Cool-season crop	N/A	16-18	16	45
	Watercress	60	14	46	33	Cool-season crop	N/A	N/A	N/A	60
	Source	Johnny's Selected Seeds: *https://www.johnnyseeds.com/*			Calculated	Maynard and Hochmuth, 2007 Resh, 2013			Ewert et al. 2022	

		Nutritional aspects per 100 g FM										
	Common name	USDA description https://fdc.nal.usda.gov/	Energy [kcal]	Protein [g]	Carbohydrate [g]	Total lipid [g]	Vitamin B1 (thiamine) [mg]	Vitamin C (total ascorbic acid) [mg]	Vitamin K (phylloquinone) [µg]	Potassium, K [mg]	Magnesium, Mg [mg]	Calcium, Ca [mg]
Leafy greens	Amaranth	Amaranth leaves, raw	23	2.46	4.02	0.33	0.03	43.3	1140.0	611.0	55.0	215.0
	Beet greens	Beet greens, raw	22	2.20	4.33	0.13	0.10	30.0	400.0	762.0	70.0	117.0
	Cabbage, red	Cabbage, red, raw	31	1.43	7.37	0.16	0.06	57.0	38.2	243.0	16.0	45.0
	Kale, 'Red Russian'	Kale, raw	35	2.92	4.42	1.49	0.11	93.4	390.0	348.0	32.7	254.0
	Kale, 'Toscano'	Kale, raw	35	2.92	4.42	1.49	0.11	93.4	390.0	348.0	32.7	254.0
	Lettuce, 'Dragoon'	Romaine lettuce, raw	21	0.98	4.06	0.07	0.06	4.6	83.4	260.0	12.0	28.0
	Lettuce, 'Outredgeous'	Romaine lettuce, raw	21	0.98	4.06	0.07	0.06	4.6	83.4	260.0	12.0	28.0
	Lettuce, 'Waldman's Green'	Lettuce, leaf, green, raw	22	1.09	4.07	0.16	0.08	15.2	118.0	277.0	12.8	40.0
	Mizuna	Mustard greens, raw	27	2.86	4.67	0.42	0.08	70.0	258.0	384.0	32.0	115.0
	Mustard, 'Amara'	Mustard greens, raw	27	2.86	4.67	0.42	0.08	70.0	258.0	384.0	32.0	115.0
	Mustard, 'Wasabi'	Mustard greens, raw	27	2.86	4.67	0.42	0.08	70.0	258.0	384.0	32.0	115.0
	Bok choy, 'Extra dwarf'	Cabbage, chinese (pak-choi), raw	13	1.50	2.18	0.20	0.04	45.0	45.5	252.0	19.0	105.0
	Radish, 'Cherry Belle'	N/A	N/A	3.81	4.04	0.37	N/A	N/A	N/A	495.3	57.0	752.6
	Sorrel	N/A	35	2.00	6.00	0.30	0.09	120.0	N/A	340.0	N/A	70.0
	Swiss chard, 'Bright lights'	Chard, swiss, raw	19	1.80	3.74	0.20	0.04	30.0	830.0	379.0	81.0	51.0
	Watercress	Watercress, raw	11	2.30	1.29	0.10	0.09	43.0	250.0	330.0	21.0	120.0
	Source	USDA: *https://fdc.nal.usda.gov/* Nutrition table: *https://www.nutritiontable.com/nutritions/nutrient/?id=833* Goyeneche et al. 2015										

Figure B 1 Data table extracted from Excel with the different sources on data for leafy greens

Appendix C: Highlighted Overview of the Set Results



Set	1	2	3	3 altered
Biomass yield [g]	4383.15	5322.83	5384.73	6173.06
Energy [kcal]	1203.22	1527.14	1428.99	1798.36
Protein [g]	106.56	143.57	121.06	146.30
Carbohydrate [g]	175.47	224.09	249.70	304.48
Total lipid [g]	36.97	42.99	27.51	43.29
Vitamin B1 (thiamine) [mg]	4.43	4.40	4.18	5.18
Vitamin C (total ascorbic acid) [mg]	2580.97	3264.82	3196.04	4312.74
Vitamin K (phylloquinone) [µg]	15052.81	12554.63	14425.48	17994.61
Potassium, K [mg]	14851.62	18036.05	18758.17	21670.86
Magnesium, Mg [mg]	1585.29	1588.47	1798.35	2102.33
Calcium, Ca [mg]	5836.26	9497.31	8536.94	9978.32

Figure C 1 Total daily yield and nutritional values of the different sets, extracted from Excel. The values highlighted in red are the lowest and green the highest.

Declaration of Authenticity

Ich erkläre hiermit an Eides statt, dass ich die vorliegende Arbeit selbstständig und ohne unzulässige fremde Hilfe angefertigt habe; die aus fremden Quellen direkt oder indirekt übernommenen Gedanken sind als solche kenntlich gemacht. Die Arbeit wurde bisher in gleicher oder ähnlicher Form keiner anderen Prüfungsbehörde vorgelegt und auch noch nicht veröffentlicht.

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