A smart-sensing AI-driven platform for scalable, low-cost hydroponic units

D1.1 Report on nutrient and production parameters and light requirements for microgreen production in hydroponic units

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RESPONSIBLE AUTHOR	Reed Cowden (UCPH) & Bhim Bahadur Ghaley (UCPH)

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COORDINATOR	Panagiotis Zervas
COORDINATOR EMAIL	panagiotis@scio.systems
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RESPONSIBLE AUTHOR EMAIL	Cowden@plen.ku.dk
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CONTRIBUTORS	Teodor Rusu (USAMV)
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PARTICIPANTS		CONTACT PERSON
SCiO P.C. (SCiO, Greece) **Coordinator**		Panagiotis Zervas Email: panagiotis@scio.systems
Department of Plant and Environmental Sciences, University of Copenhagen (UCPH, Denmark)		Bhim Bahadur Ghaley Email: bbg@plen.ku.dk
Holisun SRL (Holisun, Romania)		Oliviu Matei Email: oliviu.matei@holisun.com
nr21 DESIGN GmbH (nr21 DESIGN, Germany)		Niklas Galler Email: niklas.galler@nr21.com
Institute of Nanoscience and Nanotechnology, National Centre for Scientific Research "Demokritos" (NCSR-D, Greece)		Eleni Makarona Email: e.makarona@inn.demokritos.gr
Department of Technical and Soil Sciences, University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca (USAMV, Romania)		Teodor Rusu Email: trusu@usamvcluj.ro

ACRONYMS LIST

FW	Fresh Weight
DW	Dry Weight
AA	Ascorbic Acid (Vit C)
Ht	Height
PP	Photoperiod
GP	Growing Period
LED	Light Emitting Diode
H	Hour
NS	Nutrient Solution
PPFD	Photosynthetic Photon Flux Density
Pure blue	100% blue light 445 nm
Pure Fr	100% far red light 730 nm
Maj Blue	Majority blue
Maj Reda	Majority red 638 nm
Maj Redb	Majority red 660 nm
Maj R/R	Majority red 638 nm and red 660 nm
B/R	Blue and red in equal proportion
Maj B/R Fr	Majority blue and red with far red
Maj R/R Fr	Majority red 638 nm and red 660 nm
Maj HPS	Majority HPS with blue, orange, red 660 nm, far red, or UV

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EXECUTIVE SUMMARY

Microgreens are young plants between sprouts and baby greens with a growing period of about 7 to 16 days, depending on the variety. They are gaining increasing attention because of their short growing cycle and their beneficial attributes such as high nutritional content, valuable secondary metabolite production, and gastronomic applications. However, although growing microgreens is not a novel practice, best methods have not clearly been established. Therefore, this report, which is a deliverable within the GOhydro research project, has undertaken a literature review from 69 different studies in order to collect, harmonize, and synthesize information about existing production practices and current research trends. We have presented the results in three main sections: the first section is on substrate selection and fertilization regimes; the second section reviews the key production parameters (e.g EC, pH, temperature, relative humidity, photoperiod, daily light integral etc.) under which different studies were carried out; and the third section details light quantity and quality, which can influence productivity, nutrient density, colour, taste, and beneficial plant compounds. The results of our literature review, which contains data on 30 different varieties of microgreens, have shown that there is much variety-specific response variation to environmental parameters, fertilization, and different lighting conditions. One key result from our literature review is that an increase in cumulative light integral (DLI * growing period) corresponds to an increase in dry matter production up to 300 mol/m^2 (R^2=0.83), past which gains are minimal or even negative. Another key result is that there are important tradeoffs between secondary metabolite production and growth, which are inversely associated for fertilization, but are positively associated with light. Finally, although there is no single optimal light ratio, there are suggested light regimes that incorporate 5-15% blue light, 85-95% red light, with supplementary far red, UV, or even green/amber light, depending on the desired outputs and species responsivity. This report has synthesized and harmonized the data from all 69 papers, which have been collected and presented in two key tables (Table 8.1 and 8.2 in appendix) that includes information on the species and author, experimental methodology, and key results. This allows for anyone interested in microgreen production to have access to the historical and current practices derived from the published scientific literature.

1 INTRODUCTION

Microgreens are young plants at the phenological stage between sprouts and baby greens that are gaining increasing awareness because of their many beneficial properties. Some of these benefits are the unique colors, textures, and flavor profiles they offer, while they also contain higher concentrations of valuable macro- and micronutrients and antioxidants than more mature plants (Treadwell et al., 2020; Xiao et al., 2012). Microgreens have another advantage in that they have a short grow cycle from sowing to harvest of about 7 to 16 days. This allows for high production turnover, while also mitigating against the risk of pests and disease due to the short grow cycle. This is in comparison to other plant production methodologies that require a much longer growing period from germination to harvest, which increases risk. The risk associated with long-term growing periods is only increasing in severity and likelihood, given the recent climate trends of increased incidence and severity of drought and extreme weather events (Masson-Delmotte et al., 2021). Therefore, microgreens offer a means to buffer against the risk of crop failures by providing nutrient-dense plants for human consumption on a short production timescale. Furthermore, producing microgreens can be incredibly water efficient, as hydroponic systems have been shown to use 12.5 times less water compared to conventional agriculture (20 L/kg/y and 250 L/kg/y, respectively) (Barbosa et al., 2015). Targeted fertilization regimes can also reduce the inputs necessary to produce comparable nutrient-dense food, while also avoiding issues of environmental pollution associated with conventional fertilization methods (Good & Beatty, 2011).

Despite the link between environmental parameterization (i.e. growth chambers) and high-quality microgreens, the degree of capital or technological insight necessary for production exists on a continuum. That is, the degree of technological sophistication varies for microgreen production, with some low-tech systems that simply use water and fluorescent light achieving success, and with others using tailored growth chambers with specific LED spectrums and light intensities, targeted fertilization regimes, and complete climate control achieving successful production as well. This paper discusses in detail the evidence from the literature on some of the ideal ranges of environmental conditions and focus points for future trends as they appear in the research. This discussion is centered on the augmentation or diminution of certain parameters necessary to achieve a balance of inputs and outputs, and costs and yields. The objective of the GOhydro Deliverable 1.1 is to present a synthesized corpus of literature in a refined fashion to make the information available to anyone interested in starting or learning about the production of microgreens. This will provide a detailed but understandable text that can be used in the production process (for personal, research, or commercial applications) to inform the grower about basic standards up through advanced environmental parameterization. This deliverable describes the fundamentals concerning nutrient fertilization regimes, substrate selection, microgreen species selection, specific environmental parameters, and tailored light conditions based on production goals.

2 MICROGREENS PRODUCTION BACKGROUND

Almost every plant cultivated for human consumption at a mature stage can be produced at an earlier stage as a microgreen. Accordingly, there are currently around 80-100 commonly cultivated species of microgreens (Ying, Kong, & Zheng, 2020c). However, there exists a large variety of microgreens suitability to the specific conditions associated with indoors hydroponic production. For instance, some species are cultivated more often than others, with the most commonly cultivated species being from the Brassica family, which includes broccoli, cabbage, arugula, kale, and mustard, to name a few (Björkman et al., 2011). In general, microgreens production ideally takes place indoors in a climate controlled environment. This allows for some key advantages: firstly, it allows year-round production, as there is no dependence on natural photoperiod or light; secondly, the disease/competition burden associated with high humidity and high density planting would be immense if exposed to open field conditions; thirdly, it allows targeted delivery of resources viz. water and nutrients with no possibility of competition from unwanted weed species. This resource delivery can be achieved by any of the six most common hydroponic systems that are used today:

1. **Wicking**, which is when a substance 'wicks' or moves water via diffusion from the solution to the growing substrate
2. **Drip** systems, which are most appropriate for large-scale industrial processes, flush the Nutrient Solution (NS) at regular or nearly continuous intervals through narrow channels where the shallow depth allows for oxygen uptake by the roots
3. **Nutrient film technique**, which uses a delivery system via pumps to the substrate and requires oxygen input
4. **Ebb and flow**, which uses an external reservoir that is pumped and drained through the growing medium at regular timed intervals to deliver nutrients to the plants; the ebb and flow allows for oxygen incorporation when pumps are not running, as roots are exposed to the air
5. **Deep water culture**, which uses a reservoir of nutrient solution (NS) which constantly immerses the roots in NS, which therefore requires oxygen
6. **Aeroponics**, which involves suspended plant roots that are misted via a spraying pump to encourage root growth while also allowing for oxygen incorporation

All of these hydroponics systems can supply the same inputs for plant production: i.e. nutrient solution, water, oxygen, growing medium, with the additional inputs of light source and atmospheric parameters (air temperature, relative humidity (RH), and CO_2 levels, e.g.). The most commonly used hydroponic systems for microgreens are drip, ebb and flow, and nutrient film technique because microgreens have smaller roots than mature plants and grow at a much higher density, thereby making these hydroponic systems optimal.

These hydroponic systems all provide essential components that are necessary for microgreens production; for instance, the microgreens have to be grown in an appropriate medium that has enough porosity, strength, durability, and will not leech harmful materials for safe and effective growth. Some examples of appropriate substrates are coconut coir, polyethylene terephthalate, peat moss, or even gauze, to name a few. The substrate will anchor the seeds and later the microgreens while allowing enough air to penetrate. This will keep the root systems oxygenated and will help avoid anaerobic conditions or microbial contamination, the latter of which can also easily occur if substrate and microgreens container are not replaced or cleaned in between growth cycles. The lack of other competition, the moist environment, and the frequent presence of nutrients offers opportunity for deleterious microorganism growth. Usually a 1:9 or 1:10 solution of bleach to water is recommended for use between production cycles to adequately ensure that no pathogenic organisms establish in the hydroponic system.

Besides having the hydroponic system and grow medium, the next important component for microgreens production is the nutrient solution (NS), which should contain concentrations of macro- and micro-nutrients that loosely follow Hoagland's solution of nitrogen, phosphorous, potassium, calcium, sulfur, magnesium, chlorine, salt, manganese, zinc, copper, molybdenum, and iron, the concentrations of which can be seen in Table 4.2. The nitrogen source is important to consider as well; ideally, the NS should contain a ratio of ammonium (NH_4) and nitrate (NO_3), which is discussed in section 4 (e.g. Figures 4.1 and 4.2). Normally the NS is delivered via mechanical pump, although it can also be done by hand; the type and quality of pump scales with the degree of production. The NS should also be kept around 21 °C with a pH of 6.0. The amount of NS depends on production goals and growing period.

Beyond the hydroponic system, the microgreens should have other environmental parameters controlled, such as air temperature, relative humidity, growing period (days), photoperiod (day length), and CO_2 if possible. These are controlled to ensure optimal physiological conditions, health, and successful production of microgreens. Microgreens production can be achieved on a continuum of technological and capital input; a shelf or series of shelves in an ambient office, a grow tent with circulating fan, an industrial warehouse with fixed parameters, and a climate-controlled research growth chamber, are all possible methods of keeping the environmental parameters in check. The ideal ranges of these parameters are discussed in section 4 (e.g. Table 4.4).

The seeds of microgreens should also be sown at the appropriate density: sowing too dense leads to disease and lack of growth, while too little can be inefficient with seedlings also lacking cohesion to one another. The specific seeding densities are usually labeled on most commercial packaging. However, values can also be referenced from Tables 8.1 and 8.2 in the appendix; many of these papers have presented their seeding densities.

The final important category is light. This is currently the focus of most recent research, as the connection between different spectra (quality) and amount (quantity) of light and production outputs is being established. For instance, the physiological machinery of the plants can be manipulated by specific spectra of light to produce more or less compounds and achieve greater rates of growth. This further optimization of microgreens production is discussed in section 4.3. Microgreens can be grown via a variety of light inputs, from greenhouses that use natural light, to fluorescent, HPS, or LED lights. LEDs are likely the best choice, especially for the future, given their decreasing price and increasing efficiency and targeted spectra production capabilities. In general, a hydroponic system, a NS, substrate, microgreens seeds sown at the appropriate density, tailored environmental conditions, and a light source are all needed to successfully produce microgreens. However, the degree of sophistication is flexible, as low-tech and high-tech producers achieve success. This literature review helps demonstrate some of the advantages and outputs of more sophisticated approaches, as seen in the research, to show how microgreens can be manipulated for improved productivity. Despite this, there is much room for experimentation and development of production practices on a continuum of technological and parameter control options based on user needs.

3 MATERIALS AND METHODS

The initial steps for the creation of this deliverable began with a literature review. We used the Royal Danish Library's online catalogue (*kb.dk*) to search through three main categories of microgreens research. The first search keywords were for general microgreens information, including book chapters on the history of their production, basic methodological concerns, and issues such as preservation of microgreens after harvest. The second main category was for nutrient fertilization regimes, including biofortification and dosage studies; in this category we also searched for the influence and selection of substrate materials. The third and primary category was on the influence of light on production outcomes, as this is most in line with recent research and is of increasing importance considering the improvement in cost and output of LED lights.

The main approach taken to find as many relevant papers as possible was to decide on the search terms (microgreens, sprouts, LED, light, nutrient solution, etc.), then use them in various combinations to find relevant papers. We also searched for exact phrases such as "Microgreens and LED light impact growth" or species-specific searches such as "Brassica and light" to narrow the results to a specific range when we were doing the light-focused literature review. We also used truncated terms and 'wildcard' words as well. Once we had a dataset of about 40 papers, we then began to search the internal citations and references to find relevant papers that might not immediately come up during our database search.

Once we had the core database of papers, we began the process of synthesizing the data. We used Microsoft Excel to organize our literature review, as seen in Figures 8.1 and 8.2 in the appendix. We organized the literature review by three main categories: paper details, production inputs, and production outputs. We therefore detailed the author, title, experimental design, microgreens species, yield parameters, results, treatment, sub-treatment, sub-sub-treatment; tabulated a variety of input parameters such as light, fertilization, photoperiod etc.; and incorporated all the values of measured variables such as fresh weight, carotenoids, phenols, ascorbic acid, etc. Units and values were organized row by row for later analyses. We collected the readily available data in tables and used WebPlotDigitizer software (automeris.io) to collect the data presented in figures, including the standard errors. The automeris software has been shown to be an effective, accurate, and reliable tool for mining data from figures (Drevon et al., 2017; Rohatgi, 2020). This allowed for complete mining of the papers for an inclusive future synthesis of research results.

Once the literature review was completed, we had collected detailed information on 69 usable papers across the three main categories. Table 3.1 demonstrates all the common names of the varieties covered by this literature review. For our main category, light, we had 42 unique papers. For fertilization regimes/substrate use and production methodologies, we had 27 papers. To prepare the data for analysis after organization and collection, as seen in the appendix Figures 8.1 and 8.2, we standardized the units of the data for comparison. For Chlorophyll, Fresh Weight, Dry Weight, Glucosinolates, and DPPH, two units were chosen because of a lack of comparability. For example, Chlorophyll values for five papers were presented with the units of an Index, while for the other papers, the values could be standardized in mg/g FW. Besides simple metric conversions (e.g. mg/100 g to mg/kg), and the separation of output variables into discrete categories (as in the Chlorophyll example), the only other main conversion was to transform units that were in dry weight to fresh weight. For this transformation, we used work by (Xiao et al., 2012), which collected dry weight percentages, as well as work from other relevant studies in our literature review, to transform dry weight values into fresh weight estimations. This was done in a species-specific context: i.e. (Xiao et al., 2012) showed a dry weight value of 5.3% for Mizuna, and this was used as the basis for a conversion ratio to transform dry weight values into fresh weight for Mizuna. We transformed the results in order to make the trends seen in the literature comparable, and as there is no single best-case regime or prescription that can be offered, we believe that it is of value to see the research results presented in common units that are comparable to other studies. This allows for the comparison across and within studies, seeing how different methodologies translate to different production outcomes. Once the data was homogenized and organized, we used Sigmaplot (v. 14) to create figures that demonstrated the patterns of microgreen production as they varied based on different inputs.

Table 3.1 List of all the microgreens species/varieties (n=30) that were reported from the GOhydro literature review.

Family	Genus	Species	Common Name
Amaranthaceae	*Amaranthaceae*	*amaranthus*	Amaranth
Amaranthaceae	*Amaranthaceae*	*amaranthus*	Leafy Amaranth
Amaranthaceae	*Amaranthaceae*	*amaranthus*	Red Amaranth
Amaranthaceae	*Beta*	*vulgaris*	Beet
Asteraceae	*Lactuca*	*sativa*	Angel
Asteraceae	*Lactuca*	*sativa*	Mantecosa
Asteraceae	*Lactuca*	*sativa*	Romana
Boraginaceae	*Borago*	*officinalis*	Borage
Brassica	*Eruca*	*vesicaria*	Arugula
Brassica	*Brassica*	*oleracea*	Broccoli
Brassica	*Brassica*	*oleracea*	Cabbage
Brassica	*Lepidium*	*sativum*	Cress
Brassica	*Brassica*	*oleracea*	Kale
Brassica	*Brassica*	*oleracea*	Kohlrabi
Brassica	*Brassica*	*rapa*	Mizuna
Brassica	*Brassica*	*juncea*	Mustard
Brassica	*Brassica*	*juncea*	Mustard Barbarosa
Brassica	*Brassica*	*juncea*	Mustard Garnet
Brassica	*Brassica*	*juncea*	Mustard Scarlet
Brassica	*Raphanus*	*raphanistrum*	Radish
Brassica	*Brassica*	*oleracea*	Red Cabbage
Brassica	*Brassica*	*rapa*	Red Pak Choi
Brassica	*Brassica*	*oleracea*	Red Russian Kale
Brassica	*Brassica*	*rapa*	Tatsoi
Fabaceae	*Pisum*	*sativum*	Pea
Lamiaceae	*Salvia*	*hispanica*	Chia
Ocimum	*Ocimum*	*basilicum*	Green Basil
Ocimum	*Ocimum*	*basilicum*	Red Basil
Petroselinum	*Petroselinum*	*crispum*	Parsely
Portulacaceae	*Portulaca*	*portulaca*	Purslane

4 RESULTS

The literature review undertaken by the GOhydro project yielded interesting results and trends concerning the influence of environmental parameters on outcomes such as yield and secondary metabolite production for microgreens. The first research category discussed here concerns substrate and fertilization regimes for microgreen production. A complete list of results on the substrate, fertilization, and miscellaneous papers can be found in Table 8.2 in the appendix. This table can be used to investigate in greater detail the existing practices on substrate selection, fertilization regimes, including important procedures such as biofortification using selenium or calcium chloride to improve nutrient density and integrity of microgreens, and a variety of other miscellaneous subjects such as shelf life, pathogen control, and marketability.

4.1 SUBSTRATE AND FERTILIZATION SELECTION

For substrate selection, the literature review showed that it is important to select an appropriate medium, such as those listed in Table 4.1, but there are no significant influences of substrate on yield outcomes (Wieth et al., 2019). For instance, work by Wieth et al. (2019) showed that four different substrates (CSC® vermiculite, Beifiur® S10, Carolina Soil® seedling, and Carolina Soil® organic) did not significantly influence fresh weight (FW), dry weight (DW), or height (Ht) of microgreens. Therefore, Table 4.1 shows a list of the common general substrates used in microgreens production that can be selected by the interested grower for successful microgreen production. In practice, there can exist various combinations of the listed substrates. Furthermore, almost any porous medium with room for penetration of air, root attachment, lack of contaminants, and delivery of nutrients is suitable for microgreens production.

Table 4.1 List of substrates used in the literature.

Substrate Type	Example Reference
30% compost, 30% peat, 30% coir, 10% perlite	Gerovac et al. 2016
Sphagnum peat moss	Samuoliene et al. 2017
Coconut fiber (coir)	Kong et al. 2020
Polyethylene terephthalate fiber	Craver et al. 2017
Gauze	Zhang et al. 2019
Peat moss and Rockwool	Kamal et al. 2020
General purpose soil	Lobiuc et al. 2017

Overall, the literature review revealed that it is important to consider the amount and type of fertilizer for microgreen production, especially as the literature suggests that there is no single best practice. However, there are established ranges for mature-plant hydroponics, which is the standard applied for microgreens. Many of the papers included in the literature review used and cited Hoagland's nutrient solution (NS), the contents of which are listed in Table 4.2. This NS is derived from research by Hoagland and Snyder in 1933 and updated in 1950 by Hoagland and Arnon. These elemental concentrations are essential for growing plants hydroponically;

interestingly, microgreens pose a unique issue because they go through about 5-7 days of their lifecycle by obtaining nutrients from their seed, which reduces the need for intense fertilization. This is one of the reasons that low-tech microgreens farms can also be effective for producing adequate yields, as the plant begins its growth with a source of essential nutrients from the seed. However, to enhance production of desirable secondary metabolites or improve growth and quality conditions, a more complete NS is required. Therefore, Table 4.2 is a useful resource for showing current NS recipes on the market, while also planning potential interventions by the grower to complement product deficiencies. Furthermore, Table 4.2 also lists the recommended molecules from which these essential nutrients are derived. It is worth noting, as mentioned above, that microgreens pose a unique issue because of their short growth cycle; therefore, the Hoagland's solution, which is designed for mature hydroponic plants, might not be as directly relevant for microgreens. This is discussed as a future direction for research in the literature, and different authors mention that best practices are still being developed (e.g. Wieth et al. 2019). For instance, research has pointed out that there are a variety of electrical conductivities (EC), which is the concentration of nutrients in solution, used by various authors. For example, EC values of 1.12, 0.3, 1.3, 1.8 mS/cm have all been reported with adequate production outcomes (Bulgari et al., 2017; M. C. Kyriacou et al., 2019; Renna et al., 2018). Furthermore, work by (Di Gioia et al., 2017) used nutrient concentrations of 105.1, 117.4, 15.5, 92.5, 26.0, and 34.6 mg/L of N, K,P, Ca, Mg, and S, respectively, while (Wieth et al., 2019) used 0, 50 and 100% NS concentrations of 214.2, 250.6, 43.7, 136.0, 26.5, and 35.0 mg/L of N, K, P, Ca, Mg, and S, respectively. Therefore, the optimal NS has not been statistically proven, although existing effective ranges do exist and are reported in the literature and in this deliverable (e.g. Table 4.2).

Table 4.2 Hydroponic fertilization regimes derived from (Hoagland & Snyder, 1933) and (Hoagland & Arnon, 1950). Values for general elements are presented in parts per million (ppm), while molecular nutrient source is presented in concentration.

Nutrient	Elemental Acronym	Parts per million (ppm)	Molecular Nutrient Source	Concentration
Nitrogen	N	210 ppm	$NH_4H_2PO_4$	115 g/L
Phosphorous	P	31 ppm	*See nitrogen*	
Potassium	K	235 ppm	KNO_3	202 g/L
Calcium	Ca	160 ppm	$Ca(NO_3)_2$	472 g/L
Sulfur	S	64 ppm	$MgSO_4$	493 g/L
Magnesium	Mg	48.6 ppm	*See sulfur*	
Chlorine	Cl	0.65 ppm	$MnCl_2$	1.81 g/L
Salt	Na	1.2 ppm	NaCl	
Boron	B	0.5 ppm	H_3BO_3	2.86 g/L
Manganese	Mn	0.5 ppm	*See chlorine*	
Zinc	Zn	0.05 ppm	$ZnSO_4$	0.22 g/L
Copper	Cu	0.02 ppm	$CuSO_4$	0.08 g/L
Molybdenum	Mo	0.011 ppm	H_2MoO_4	0.02 g/L
Iron	Fe	5 ppm	$C_{12}H_{12}Fe_2O_{18}$	5 g/L

Research such as (Wieth et al., 2019) went beyond substrate selection; they also looked at the relationship between nutrient concentration and production outcomes to correlate between the two. Table 4.3 demonstrates the inverse relationship that is reflected in other research (e.g. (Alrifai et al., 2019, 2021)) concerning carotenoid production as it relates to physiological stress: as the NS concentration increases, the carotenoid concentration decreases. Therefore, if production of these valuable secondary metabolites is the primary goal, excessive fertilization should be avoided. The relationship between NS concentration and chlorophyll content was similar to that of carotenoids, with increasing NS resulting in little or negative change in chlorophyll content. However, Figure 4.1 shows that there is a positive correlation between nutrient content and fresh weight, dry weight, and height. It is worth noting that for all three parameters, the increase was greater from 0% to 50% NS than from 50% to 100% NS. Therefore, these results demonstrate that tradeoffs must be made for NS, as some secondary metabolite production is associated with physiological stress, including light stress, which is discussed in later sections.

Table 4.3 Adapted from data presented in Wieth et al. 2019 for the carotenoid and chlorophyll content of purple cabbage microgreens grown in four different substrates at 0, 50 and 100% NS concentrations (214.2, 250.6, 43.7, 136.0, 26.5, and 35.0 mg/L of N, K, P, Ca, Mg, and S, respectively).

Substrate	Carotenoids (micro grams SFMY)			Chlorophyll (micro grams SFMY)		
	0% NS	50% NS	100% NS	0% NS	50% NS	100% NS
CSC® vermiculite	10.24	5.05	7.50	372.53	456.08	435.82
Beifiur® S10	9.64	8.51	7.58	439.37	413.04	399.37
Carolina Soil® seedling	9.70	7.34	6.05	363.42	394.30	275.32
Carolina Soil® organic	9.38	4.78	5.40	429.75	257.09	346.20

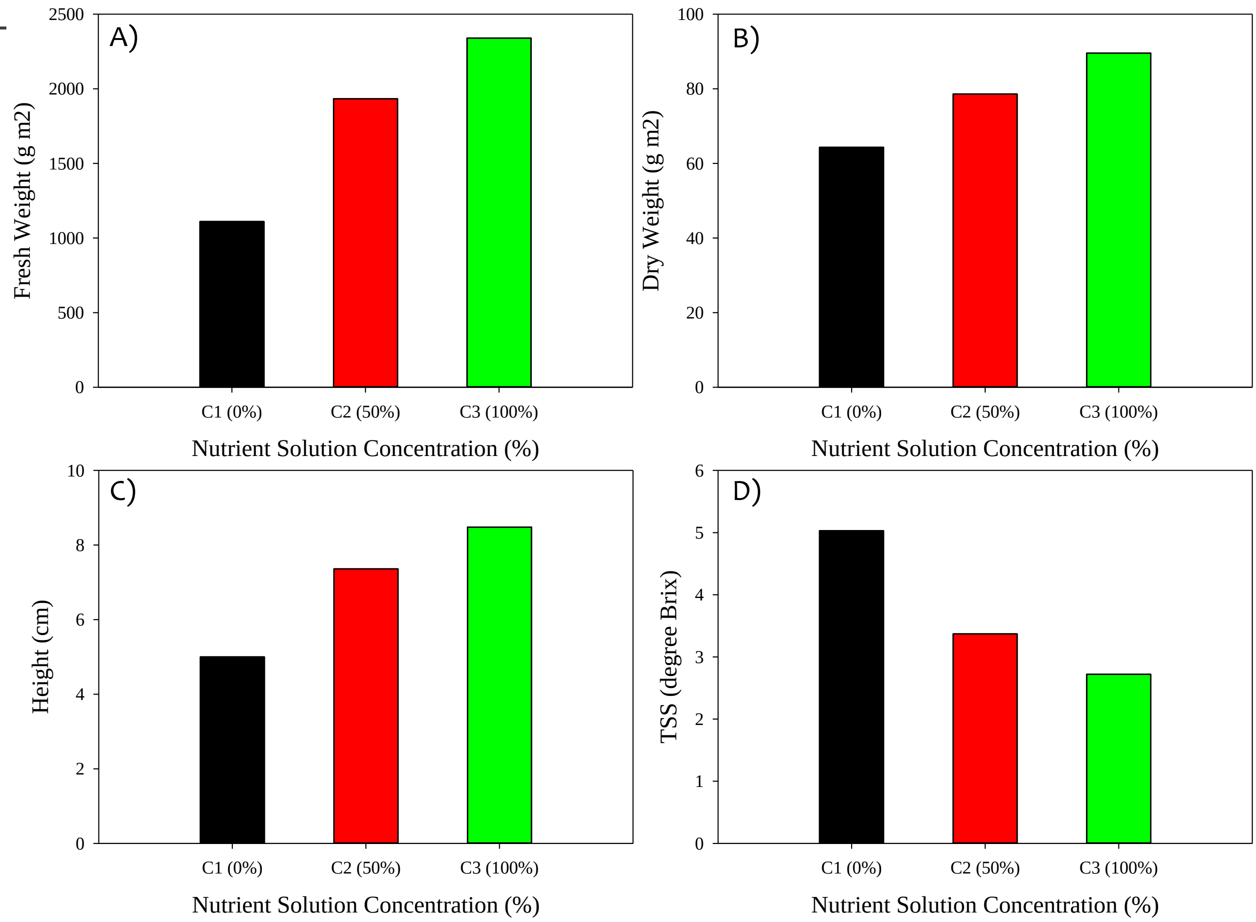
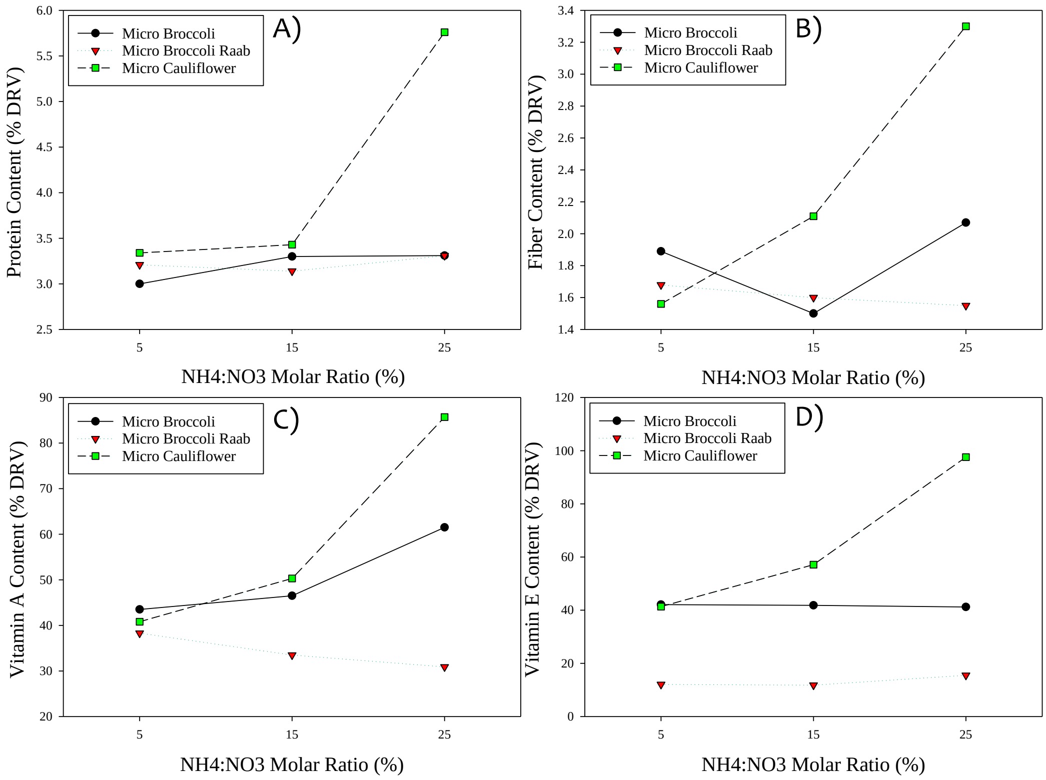


Figure 4.1 Different microgreens production outputs for A) fresh weight, B) dry weight, C) height, and D) total soluble solids, derived from data presented in (Wieth et al., 2019). The y-axis presents the outputs, while the x-axis categories are Hoagland's Nutrient Solution at different concentrations (0%, 50%, and 100%).

Another important research theme is illustrated by (Palmitessa et al., 2020), who investigated the link between three different Hoagland's NS and production outcomes. Their point of interest was on the responses of three different microgreens varieties to changes in the molar ratio of NH4 (ammonium) to NO3 (nitrate) in NS. Nitrate is a non-toxic molecule that nevertheless is part of molecular reaction processes that can result in nitrite, nitric oxide, or other N-compounds that are undesirable. Therefore, recent research has been investigating whether increasing the proportion of ammonium compared to nitrate, therefore buffering against these undesirable reaction chains, can retain or improve production outcomes. Palmitessa et al. (2020) demonstrated an essential research trend in this regard that is also seen in light papers: there is substantial species variation in response to environmental conditions. For instance, Figure 4.2 shows that cauliflower microgreens responded much more strongly to higher ratios of NH4:NO3, while broccoli was less responsive. However, even subspecies of broccoli showed differences in these responses, indicating the necessity of designing species and variety-specific environmental recipes for ideal growth conditions. Overall, Figure 4.2 shows that increasing the molar ratio of NH4:NO3 can increase the protein content, fiber content, Vitamin A content, and Vitamin E content of microgreens grown in hydroponic systems. These desirable production outcomes increase the value of microgreens and are therefore worth considering when selecting a NS that has a higher NH4:NO3 molar ratio. For further details, see Table 8.2 in the appendix for substrate selection, fertilization regimes, and other miscellaneous papers on biofortification, general practices, and shelf life



retention.

Figure 4.2 Different microgreen outputs for A) protein content, B) fiber content, C) vitamin A, and D) vitamin E, on the y-axis with the NH4:NO3 molar ratio (as a %) on the x-axis. Different categories are for the three varieties of microgreens (broccoli, broccoli raab, and micro cauliflower). Data derived from (Palmitessa et al., 2020).

4.2 OVERVIEW OF MICROGREEN PRODUCTION ENVIRONMENTS UNDER STUDY

Table 4.4 shows the different environmental parameters for microgreen production derived from our literature review. The parameters listed are pH, electrical conductivity (EC), air temperature for day and night, relative humidity (RH), daily light integral (DLI), photoperiod, growth period and cumulative light integral (CLI). Table 4.4 data shows the average values, +/- the standard deviation, with (n) number of samples for the most important environmental parameters. This is a useful presentation of the ranges of key production parameters that researchers have used in their own studies for the successful production of different microgreens in varied environments, which can help aid decision-making for interested microgreen producers. This table demonstrates that there is much species-specific variation, which is a common trend revealed by the literature review: there is no single optimal prescription for environmental production methods; each species or variety can operate at different ranges. For instance, the average pH value in the studies, with a sample size of 440 data points, was 6.0 with a low pH of 5.5 in pea, kohlrabi, borage and broccoli and a high pH of 7.1 in arugula and 7.2 in cabbage (Table 4.4). The other microgreens like amaranth, angel, basil etc. were produced with intermediate pH range (pH 5.8 to 6). For electrical conductivity, the average was 1.15 ds/m, with the highest value at 2.2 for the three varieties of lettuce (angel, mantecosa, romana), and the lowest for amaranth, cress, and purslane at 0.20. For daytime temperature, the average value was 21.4 °C, the highest value was 25 °C for radish, and the lowest was 20.0 °C for the varieties of lettuce, borage, and pea. For nighttime temperature, the average value was 16.9 °C, the highest value was 18 °C for purslane and cress, and the lowest was 16.0 °C for pea, beet, borage. The average RH was 66.8%, the highest value was 80% for the three varieties of lettuce, radish, and red cabbage, and the lowest was 55% for basil, beet, borage, parsley, and pea. The average DLI was 12.33 mol/m^2/day with a high value 20.2 for borage, and a low value of 1.2 for chia. For photoperiod, the average was 17 hours, with a high value of 24 for chia, and a low value of 12 for cress and purslane. The average growing period (days) was 11.8, with a high of 21 for purslane, and a low value of 6.5 for beet. For CLI (mol/m^2), the average was 152.9, with a high value of 276.9 for parsley, and a low value of 86.4 for chia.

When deciding on which environmental parameters to design and monitor, Table 4.4 can be used to find the specific species, or different varieties within the same species, and get an idea of the average values that reflect real production parameters. However, the values shown in Table 4.4 are not reflective of optimal conditions, or the final recommendation for each of the listed species; this table is primarily a demonstration of the range of environmental parameters that have been used in different studies. Furthermore, it is necessary to consider these production parameters under different growth environments. For instance, the quantity of light (DLI or CLI) is not the only indicator of production yields; there is also quality of light (light spectrum) that determines production outputs. There is also a very important trend in the research that dictates that stress, such as that cued by UV or Fr light incidence, which can result in lower yields, can increase the production of secondary metabolites such as anthocyanins and carotenoids, which have valuable health benefits for humans, such as free radical scavenging. Selection of environmental parameters is therefore a balance between the inputs and outputs measured against the desired production goals. This will be discussed more in detail in later sections.

Table 4.4 Average values for each microgreens species or variety for pH, electrical conductivity (EC), temperature (T) at day and night, relative humidity (RH), daily light integral (DLI), photoperiod (PP), growing period (GP), and cumulative light integral (CLI). Values are presented as means, +/- the standard deviation, with (n) number of samples.

Row Labels	pH	EC (ds/m)	T (Day) °C	T (Night) °C	RH (%)	DLI (mol m^{-2} day^{-1})	PP (hours)	GP (days)	CLI (mol m^{-2})
Amaranth	6.0 ± 0.2 (29)	0.2 ± 0.0 (3)	24.3 ± 1.5 (29)	17.2 ± 1.1 (5)	79.3 ± 7.8 (29)	11.95 ± 4.55 (29)	15.0 ± 2.8 (29)	11.0 ± 2.8 (29)	132.9 ± 62.1 (29)
Angel	5.8 ± 0.0 (3)	2.2 ± 0.0 (3)	20.0 ± 0.0 (3)		80.0 ± 0.0 (3)	7.6 ± 1.3 (3)	16.0 ± 0.0 (3)	15.0 ± 0.0 (3)	114.6 ± 19.6 (3)
Arugula	7.1 ± 0.3 (24)	1.6 ± 0.5 (24)	21.6 ± 1.1 (55)	17.2 ± 0.6 (27)	71.6 ± 9.6 (55)	13.3 ± 6.9 (55)	19.2 ± 3.9 (52)	10.6 ± 1.9 (55)	140.3 ± 77.9 (55)
Basil	5.9 ± 0.2 (34)		20.9 ± 0.2 (34)	16.9 ± 0.2 (34)	55.0 ± 0.0 (34)	11.7 ± 4.1 (42)	15.2 ± 1.6 (42)	14.7 ± 2.1 (42)	175.1 ± 79.3 (42)
Beet	5.7 ± 0.3 (12)	1.2 ± 0.6 (10)	20.8 ± 0.39 (12)	16.0 ± 1.0 (12)	55.0 ± 0.0 (12)	7.6 ± 7.5 (38)	21.5 ± 3.8 (38)	6.5 ± 3.8 (38)	74.1 ± 95.9 (38)
Borage	5.5 ± 0.0 (2)		20.0 ± 0.0 (2)	16.0 ± 0.0 (2)	55.0 ± 0.0 (2)	20.2 ± 0.0 (2)	16.0 ± 0.0 (2)	11.0 ± 0.0 (2)	221.8 ± 0.0 (2)
Brassica					70.0 ± 0.0 (4)	8.6 ± 0.0 (4)	16.0 ± 0.0 (4)	8.5 ± 0.0 (4)	73.4 ± 0.0 (4)
Broccoli	5.5 ± 0.0 (10)	0.6 ± 0.0 (4)	22.6 ± 1.8 (25)	16.8 ± 0.4 (10)	56.4 ± 2.3 (14)	9.3 ± 8.1 (53)	19.9 ± 4.5 (53)	7.0 ± 3.5 (53)	89.0 ± 108.7 (53)
Cabbage	7.2 ± 0.3 (12)	1.4 ± 0.6 (12)	22.0 ± 1.0 (40)	17.0 ± 0.0 (12)	70.2 ± 10.7 (40)	12.8 ± 7.2 (40)	20.2 ± 3.9 (40)	10.3 ± 2.2 (40)	132.4 ± 78.6 (40)
Chia			22.0 ± 0 (3)			1.23 ± 1.23 (3)	24.0 ± 0.0 (3)	7.0 ± 0 (3)	8.6 ± 8.6 (3)
Cress	6.30 ± 0 (3)	0.2 ± 0.0 (3)	22.0 ± 0 (3)	18.0 ± 0.0 (3)	70.0 ± 0 (3)	13.0 ± 0.0 (3)	12.0 ± 0.0 (3)	20.0 ± 0 (3)	259.2 ± 0.0 (3)
Kale	6.9 ± 0.6 (20)	1.5 ± 0.5 (18)	21.8 ± 1.0 (48)	16.9 ± 0.3 (20)	70.8 ± 10.8 (48)	9.9 ± 7.8 (74)	21.1 ± 3.8 (74)	7.8 ± 3.2 (74)	94.6 ± 90.0 (74)
Kohlrabi	5.5 ± 0.0 (18)	0.6 ± 0.0 (9)	21.0 ± 0 (36)	16.9 ± 0.4 (36)	61.0 ± 8.1 (36)	15.0 ± 5.6 (36)	16.0 ± 0.0 (36)	12.0 ± 2.03 (36)	174.5 ± 59.0 (36)
Mantecosa	5.8 ± 0.0 (3)	2.2 ± 0.0 (3)	20.0 ± 0 (3)		80.0 ± 0 (3)	7.6 ± 1.3 (3)	16.0 ± 0.0 (3)	15.0 ± 0.0 (3)	114.6 ± 19.6 (3)
Mizuna	5.7 ± 0.4 (11)	0.4 ± 0.2 (7)	21.1 ± 0.3 (29)	17.1 ± 0.3 (29)	59.7 ± 4.21 (29)	15.0 ± 4.0 (45)	15.7 ± 1.0 (45)	13.8 ± 1.9 (45)	205.3 ± 59.6 (45)
Mustard	6.1 ± 0.6 (111)	1.3 ± 0.6 (37)	21.5 ± 1.2 (146)	17.0 ± 0.4 (109)	63.1 ± 10.2 (137)	13.7 ± 5.5 (193)	16.8 ± 2.5 (192)	10.5 ± 3.4 (195)	145.8 ± 81.6 (195)
Parsley	5.7 ± 0.3 (14)	1.8 ± 0.0 (5)	20.9 ± 0.4 (14)	16.9 ± 0.4 (14)	55.0 ± 0.0 (14)	17.8 ± 1.0 (14)	16.0 ± 0.0 (14)	15.7 ± 3.5 (14)	276.9 ± 53.4 (14)
Pea	5.5 ± 0.0 (2)		20.0 ± 0.0 (2)	16.0 ± 0.0 (2)	55.0 ± 0.0 (2)	20.2 ± 0.0 (2)	16.0 ± 0.0 (2)	11.0 ± 0.0 (2)	221.8 ± 0.0 (2)
Purslane	6.3 ± 0.0 (3)	0.2 ± 0.0 (3)	22.0 ± 0.0 (3)	18.0 ± 0.0 (3)	70.0 ± 0.0 (3)	13.0 ± 0.0 (3)	12.0 ± 0.0 (3)	21.0 ± 0.0 (3)	272.2 ± 0.0 (3)
Radish			25.0 ± 0.0 (8)		80.0 ± 0.0 (8)	12.4 ± 7.01 (24)	18.7 ± 3.9 (24)	11.3 ± 5.3 (24)	176.3 ± 119.8 (24)
Red Cabbage	6.9 ± 0.0 (6)	1.9 ± 0.0 (6)	21.0 ± 0.0 (6)	17.0 ± 0.0 (6)	80.0 ± 0.0 (6)	17.3 ± 0 (6)	16.0 ± 0.0 (6)	10.0 ± 0.0 (6)	172.8 ± 0.0 (6)
Red pak choi	5.7 ± 0.2 (67)	0.6 ± 0.0 (28)	21.0 ± 0.0 (42)	17.0 ± 0.0 (42)	58.0 ± 8.2 (42)	14.5 ± 4.7 (75)	16.0 ± 0.0 (75)	9.6 ± 2.61 (75)	144.9 ± 71.0 (75)
Romana	5.8 ± 0.0 (3)	2.2 ± 0.0 (3)	20.0 ± 0.0 (3)		80.0 ± 0.0 (3)	7.6 ± 1.3 (3)	16.0 ± 0.0 (3)	15.0 ± 0.0 (3)	114.6 ± 19.6 (3)

Tatsoi	5.7 ± 0.3 (53)	0.60 ± 0.0 (12)	20.9 ± 0.3 (28)	16.9 ± 0.3 (28)	59.5 ± 9.6 (28)	14.8 ± 5.2 (53)	16.0 ± 0.0 (53)	8.6 ± 1.6 (53)	132.6 ± 64.8 (53)
Total Average	6.0 ± 0.2 (440)	1.2 ± 0.2 (190)	21.4 ± 0.4 (574)	16.9 ± 0.3 (394)	66.7 ± 3.6 (555)	12.3 ± 3.5 (803)	17.0 ± 1.3 (799)	11.8 ± 1.7 (805)	152.9 ± 48.7 (805)

4.3 LIGHT QUANTITY AND QUALITY EFFECTS ON MICROGREEN YIELDS

The GOhydro literature review has shown that it is critical to evaluate not just the quantity of light (DLI or CLI) when investigating the impact of environmental parameters on production outputs, but also the quality (light spectrum) as well. However, we show here that there are linear relationships between quantity of light and simple outputs such as fresh weight or dry weight: as quantity of light increases, so too does biomass production (Figure 4.3). For instance, Figure 4.3 shows that there is a positive correlation (R^2=0.83) between microgreen dry matter production and the cumulative light integral (CLI, mol/m^2) provided during the growing period of microgreens. Most studies quantify the amount of light input via the daily light integral (DLI, µmol/m^2/day) metric; however, we incorporated time as a factor by multiplying the growing period (number of days) by the DLI to calculate the cumulative light integral (CLI, mol/m^2). In this way, studies that had a high DLI but short growing period can be compared with studies that had low DLI and long growing period. Furthermore, Figure 4.3 shows that, with increasing CLI, there was an overall increase in dry matter production up to a CLI of 300, irrespective of the light spectrum combinations, past which productivity gains disappear and even decrease on average. This maximum production CLI value (300 mol/m^2) can be achieved by microgreen growers via a high light intensity for a small number of days (i.e. 35 DLI over 8.5 days), or in contrast, opt for a longer growth period with less light intensity (i.e. 20 DLI over 15 days). Figure 4.3 also shows that many of the studies in our literature review had a mean CLI amounting to 180 mol/m^2, which corresponds to a mean DLI of 17.28 (300 µmol/m^2/day for 16 hours over 24 hour cycle) for approximately 10 days. Therefore, many studies did not maximize the production potential of their respective microgreens species. This could be because of tradeoffs concerning energy use and output, as well as tradeoffs between light levels and secondary metabolite production.

Despite the consistent regression line trend across different spectra, the effects of increasing CLI on dry matter production is particularly evident with red/blue combinations, as the lowest dry weight values were associated with different spectra such as pure blue or pure far red. However, it is worth noting that the initial increase in dry matter, as CLI increases from about 25 to 60 mol/m^2, is much steeper than larger CLI values. This increased sensitivity could either be the result of the non-ideal spectra or the low CLI. It is therefore recommended that CLI values be between 60 and 350 mol/m^2, while the spectra should likely include both red and blue proportions (e.g. see (Ying, Kong, & Zheng, 2020c), which recommends 5-15% blue, and 85-95% red). Based on the linear regression, it is also worth pointing out that the inclusion of Fr light, in combination with an equal proportion of red 638 nm and red 660 nm (red inverted triangles in Figure 4.3), resulted in dry weight values that were consistently above the average of the plotted regression. Therefore, Figure 4.3 demonstrates the ranges that are likely good candidates for successful biomass accumulation for microgreens, considering both quantity and quality of light.

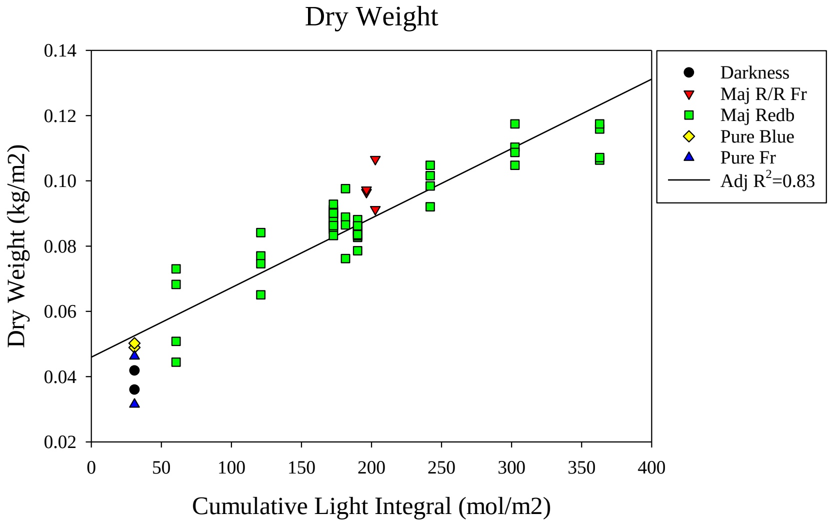


Figure 4.3 Correlation of mean dry weight (kg/m²) and cumulative light integral (mol/m²) (total n=66; arugula n=21; cabbage n=12; kale n=12; mustard n=21). The different symbols and colors are categories of light: Darkness, Maj R/R Fr (majority red 638 nm and red 660 nm), Maj Redb (majority red 660 nm), pure blue (100% blue light 445 nm), and pure Fr (100% far red light 730 nm).

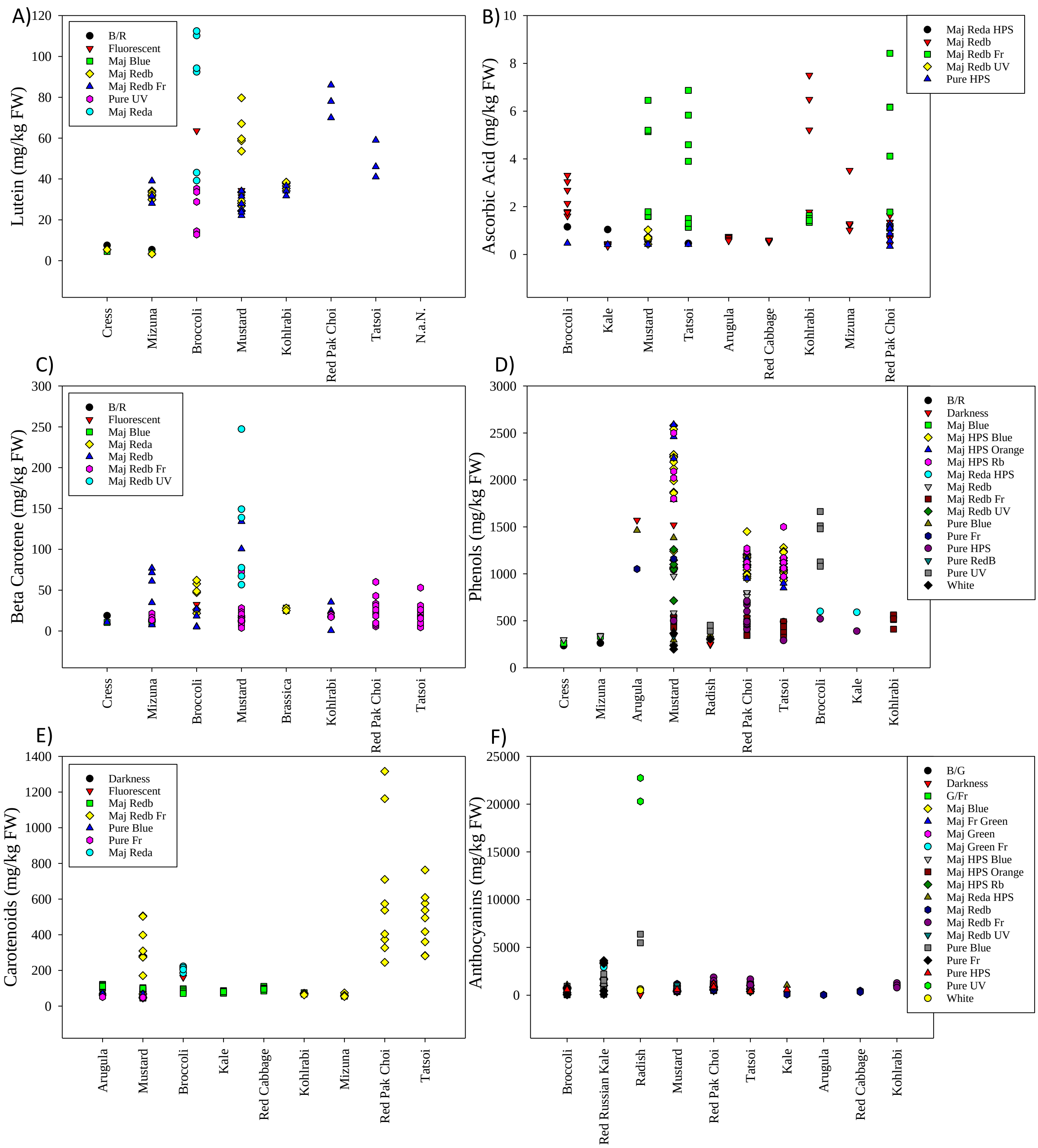
In general, recent research has shown that LED lights with a specific ratio of about 5% to 15% blue light (450 nm peak) and 85% to 95% red light (630-660 nm peak), with a PPFD (photon flux density) of approximately 300 to 400 μmol/m²/s, and a photoperiod of 16 hours, translates to generalized high quality and quantity microgreen production (Jones-Baumgardt et al., 2019; Ying et al., 2020a; Ying, Kong, & Zheng, 2020c). Similar research has also shown that, in general, more blue light is associated with more leaf area and mass, higher levels of minerals and nutrients, including carotenoids, chlorophyll a and b, and anthocyanins (Gerovac et al., 2016; Kamal et al., 2020; Samuolienė et al., 2017a); increasing light intensity is associated with more carotenoids (Craver et al., 2015); phenols can be produced in greater amounts with more Fr light compared to standard light recipes (Lobiuc et al., 2017); and that increasing light intensity is associated with less height and more biomass, which is important for auto-harvesting operations that require a certain height of microgreens (Samuolienė et al., 2019). These trends represent just a few of the relationships that are presented in Table 8.1 in the appendix.

Beyond the proportion of red and blue light, recent research has demonstrated how including light spectra beyond the visible range (400-700 nm) such as UVA (390 nm), UVB (375 nm), or Far Red (750 nm) has positive impacts on production. In general, adding these light spectra to the production system affects the physiology of plants by inducing shade-avoidance responses, as plants receiving higher proportions of FR or UV light are cued for incidental light. This prompts the production of desirable outputs, such as height and biomass, in an attempt to avoid incidental light. For instance, (Lee et al., 2016) have shown how increasing levels of Fr, from 12 to 149 μmol increased lettuce fresh weight and dry weight. Furthermore, (Park & Runkle, 2017) showed that FR (16-64 μmol) increased the leaf area and dry weight of geranium and snapdragon plants. For microgreens, 7% FR light has been shown to increase height and fresh weight in mustard microgreens (Gerovac et al., 2016). However, it is important to note that the gains in FW and height could result from blue light being replaced with more red light, thereby putting the light ratio into the optimal suggested by (Ying, Kong, & Zheng, 2020c). Furthermore, experiments dealing with green light have demonstrated that, via cryptochrome inhibition (Meng et al., 2019) and the ability of green light to better penetrate plants (Jindong Sun et al., 1998), FW can be increased as well. For instance, with only 10% of green light (B10G10R80 compared to B20R80), the FW of red lettuce was about 61% higher than the control (Son & Oh, 2015). Another study on mustard microgreens showed that comparing B8G18R74 to B13R87 resulted in an increase in hypocotyl length and shoot FW for the light recipe that included green light (Gerovac et al., 2016). This demonstrates the capacity of targeted LEDs to outperform other light sources, as they can be programmed for exact light recipe generation, thereby improving production.

Beyond FW, DW, and Ht, it is also important to consider secondary metabolites. Figure 4.4 shows that there is substantial species-specific variation for the concentrations of various secondary metabolites, such as ascorbic acid (vitamin c), lutein (a carotenoid), beta carotene, phenols (specific molecules with a hydroxyl group bonded to an aromatic hydrocarbon), total carotenoids (pigment molecules), and anthocyanins (another type of pigment molecules). These secondary metabolites are important compounds that are measured by researchers because of their alleged health benefits for human consumption. Some of these benefits are free radical scavenging, anti-inflammatory properties, immune regulation, anti-microbial properties, or assistance in cardiovascular health, among many other posited advantages. Therefore, Figure 4.4 demonstrates the species-specific production of these compounds, as well as categorizing them by light spectrum for further pattern identification. For lutein, broccoli had some of the highest overall values (110 mg/kg FW), but red pak choi had the highest average values (80 mg/kg FW), while cress had the lowest at around 5 mg/kg FW; the best light spectra was majority red 638 nm. For ascorbic acid, kohlrabi had the highest values (4.5 mg/kg FW), while red cabbage and arugula had the lowest values at 3 mg/kg FW; the best light spectra was majority red 660 nm with different proportions of far red 730 nm. For beta carotene, mustard had the highest values at around 100 mg/kg FW, while cress had the lowest at 10 mg/kg FW; the best light spectra was majority red 660 nm with varying proportions of UV light. Mustard also had the highest values for phenols, at around 1500 mg/kg FW, while mizuna and cress had the lowest value at around 250 mg/kg FW; the best light spectra was HPS with either orange, blue, or red 660 nm. Red pak choi and tatsoi had the highest carotenoid content (around 600 mg/kg FW), while kale, red cabbage, kohlrabi, and mizuna had the overall lowest values (around 80 mg/kg FW); the best light was majority red 660 nm with varying proportions of far red light. Red Russian kale and radish had the highest anthocyanin content (around 1900 mg/kg FW and 12000 mg/kg, respectively), with arugula having the smallest amount (around 25 mg/kg FW); the best light was pure blue. Overall, Figure 4.4 demonstrates the different ranges of production values for both species and light spectra when growing microgreens. Figure 8.3 in the appendix complements this by presenting the concentration of micro- and macro-nutrients for different microgreens, organized by light spectrum categories. These figures are a useful reference tool for designing specific production regimes while maximizing valuable secondary metabolite production.

For a more in-depth presentation of the literature review results, see Table 8.1 in the appendix, which has synthesized the 42 papers on light recipes for microgreen production. This table is a core reference tool for this deliverable, as it synthesizes the primary literature by highlighting the species used for production, the experimental methodology used, and the key results of light on downstream outputs. In this table, key results were bolded for clarity. This allows the table to be used by interested growers, who can reference specific species or varieties of microgreens to get the most accurate and tailored relevant results for their use.

Figure 4.4 Selected secondary metabolite concentrations (in mg/kg of fresh weight) of microgreens as derived from



the literature. A) Lutein; B) Ascorbic Acid; C) Beta Carotene; D) Phenols; E) Carotenoids; F) Anthocyanins. Legend shows categories of light quality (spectrum ratio). Categories are: Fluorescent; B/R (blue and red in equal proportion); Maj R/R (majority red 638 nm and red 660 nm); Maj B/R Fr (majority blue and red with far red); Maj HPS (majority HPS with blue, orange, red 660 nm, far red, or UV); Maj Reda (majority red 638 nm); Maj Blue (majority blue); Maj Redb (majority red 660 nm with far red or UV); pure blue (100% blue light 445 nm); and pure Fr (100% far red light 730 nm).

5 DISCUSSION

This report presented results on microgreens production parameters for substrate selection, fertilization recipes, and light regimes to provide a reference tool for interested producers. For substrate selection, no research has indicated statistically significant influences on the production outputs of microgreens. However, there are important influences of fertilization; in general, fertilization improves microgreens production outputs, but there is a difference in response sensitivity according to fertilization concentrations. For instance, greater responsivity was seen in microgreens production from 0 to 50% NS concentration than from 50 to 100% concentration (Wieth et al., 2019). However, gains were still made in FW, DW, and height, indicating that full NS strength can be beneficial if total production, and not efficiency, is the primary concern. Furthermore, the literature review revealed that there are important tradeoffs that must be considered when designing production environments. For instance, the tradeoff between secondary metabolite (such as carotenoids or chlorophyll) and biomass production: as physiological stress increases, such as via nutrient stress, secondary metabolite production can increase, but FW or DW will likely decrease. Research has also shown that it is important to consider the molar ratio of NH4:NO3; it has been shown that higher proportions of NH4, which also has beneficial production benefits by avoiding undesirable molecular production, also improves protein, fiber, vitamin A, and vitamin E content. However, as is consistent with other results from this literature review, there is much variety-specific variation, indicating the need for continued experimentation and refinement of environmental parameters for production environments.

Results on the average values of environmental parameters also demonstrated the necessity of considering variety-specific variation when designing growth chambers. Although there are useful averages seen across species and varieties, which can be used by interested microgreen growers for a first-look approach, much variation exists for the environmental ranges used by the authors for specific varieties. It is important to mention that these synthesized results are not proof of optimality, but are rather presentations of the ranges of values that have been used in real experiments by researchers. Future work would also improve existing knowledge by comparing researcher production values to those grown commercially: having a comparison for FW, DW, Leaf Area, and secondary metabolites would be an essential validation of researcher work, or indicator of needed refinement. Future research should also compare low-tech and high-tech inputs to determine what the gains are in FW, DW, flavor, nutrient, and secondary metabolite production per unit input, as current research focuses on increased technological specificity, while some commercial farmers still rely on very simple setups. The large number (n=42) of light papers, considering the niche of microgreens production literature, used in this part of the literature review should provide a useful reference of the existing breadth of research. Furthermore, 40 out of 42 light papers were published within the last 5 years, therefore indicating the novelty of the research undertaken, the lack of concrete established optimality, and the likely direction of further research. This therefore means that there is also much room for investigating and establishing optimal standards for major microgreens species, including variety-specific fertilization, light regimes, and environmental parameterization.

Although the noted examples of the influence of light on microgreen production demonstrates some generalized physiological interactions, there is no single optimal light or environmental recipe, as much variation exists based on the intensity and quality of the light, the phenological stage, and the particular variety being grown (Ying et al., 2020a). However, some important results indicate that there are some generalizations such as the suggested light proportion of 5-15% blue, and 95-85% red light (Ying, Kong, & Zheng, 2020c); when light intensity increases, so too does biomass accumulation (Brazaityte et al., 2015; Gerovac et al., 2016; Jones-Baumgardt et al., 2019); the inclusion of Fr or UV light induces shade-response in low doses that can promote height and biomass accumulation (Kong et al., 2020; Kong & Zheng, 2020), and physiological stress and concomitant secondary metabolite production in high doses (Brazaitytė et al., 2019; Moreira-Rodríguez et al., 2017); higher concentrations of secondary metabolites and chlorophylls a and b are associated with higher blue percentages compared to lower ones (Samuolienė et al., 2017b); and spectra such as green, orange/amber, or yellow light can be usefully applied to the light recipes for increased biomass or secondary metabolite production (Alrifai et al., 2021; Brazaitytė et al., 2018; Samuolienė et al., 2019).

Furthermore, although greenhouse production with natural light, or complemented with fluorescent, LED, or HPS light has and continues to be used as a successful microgreen production process, an increasing number of farms are moving production indoors into climate controlled environments with exclusive use of LEDs. This is mainly due to the increasing advantages and cost-reduction in LED technology, which allows for year-round high quality production and the manipulation of physiological and morphological pathways that are responsive to specific spectra and intensities of light (Davis & Burns, 2016; Morrow, 2008). The increased efficiency of LEDs and their capacity to emit targeted light spectra has likely made it the future standard for both experimentation and for commercial production, given its much lower energy use. Table 8.1 in the appendix on collected papers has examples where LEDs are compared with HPS (Vaštakaitė-Kairienė et al., 2020) and fluorescent (Kopsell et al., 2014). For instance, (Ying, Kong, & Zheng, 2020c) showed that blue/red LEDs, compared to fluorescents at a PPFD of 70 to 250 μmol/m^2/s increased the FW of broccoli in multiple studies (Gangadhar et al., 2012; Johkan et al., 2010; Kopsell et al., 2014; Lin et al., 2013; Shin et al., 2008). Although HPS lights can still competitively contribute to the production of secondary metabolite or biomass production, as seen in Figure 4.4, the energy and environmental costs of using HPS lights with disposable bulbs and a short lifespan make this less competitive when compared to LEDs. It is also important to note that it is possible, because of the nature of microgreen lifecycle, to produce them with low-input environments (e.g. low or no fertilization and with only fluorescent lights). However, quality, desirable secondary metabolite concentration, and elemental concentration have been shown to vary with light source. The harnessing of existing genetic and physiological pathways, which can be manipulated via environmental stimuli, makes microgreen production a novel and interesting production process that has a wide variety of outputs for any single given species, depending on the desired outputs and the corresponding inputs used.

6 CONCLUSIONS

This deliverable has produced a synthesis of key research themes derived from the existing literature on microgreens production. Substrate, fertilization, and light regimes were the three primary categories described here. Overall, the literature review contained results from 69 studies (42 on light and 27 on substrate, fertilization, and miscellaneous areas) that described 30 different varieties of microgreens. It should be noted, however, that there are at least 80-100 suitable microgreens species that can be produced. The production of microgreens is still developing best practices and refining optimal conditions for producing desired outputs. The research themes and main results presented throughout are therefore indicative of existing practices used by researchers, but this does not reflect either optimal conditions or even necessarily those that are used commercially. Furthermore, one of the main research results of this literature review showed that there is much variety-specific variation and there is no single optimal production environment for all species or varieties of microgreens. When planning the production of any given variety of microgreen, the results presented in this deliverable on the environmental, fertilization and light regimes can be taken as a useful reference tool to begin the design process. Although this should offer similar results as those seen in the studies, as the authors used the referenced production environments, there is much room for variability and interactive effects to influence production outputs. Therefore, the synthesized results presented here should primarily be considered as a reference guide that can inform initial parameterization, as production will always require some experimentation.

With that said, there are some clear generalized patterns that can be elucidated upon: for instance, more light, up to a CLI of 300 mol/m^2, translates to greater biomass production; light recipes should include approximately 90% red, and 10% blue, (+/- 5%) light; non-visible spectra (UV and Fr) have valuable contributions to secondary metabolite and growth production; fertilization should follow Hoagland's updated hydroponic recipe; and growth chambers should be parameterized according to Table 4.2. This literature review has therefore presented results from many different studies from across the world on microgreens production research. This report can be used as a reference toolkit for designing hydroponic microgreens production systems using low-tech systems, with a primary focus on creating conditions that incorporate the most important parameters of air temperature, photoperiod, and perhaps relative humidity, all of which can be controlled relatively easily with a grow tent and a low-tech hydroponic system. Microgreens have the advantage of being relatively easy to grow and they are relatively resilient to environmental conditions because of the buffer provided by their seed nutrition. Because commercial practices exist on a wide spectrum of technological input, observing only a few environmental parameters likely will have positive impacts on any given production system. Therefore, all of the parameters do not need to be fixed exactly as in research settings; they are intended to indicate the existing ranges of research values that have been presented in order to provide interested producers with useful references. This can be used in the beginning of the process when designing the production process, but it can also be used later on to diagnose problems by comparing the user's values and those that are presented in the research.

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8 APPENDIX

Author	Title	Experimental Design/Sample size	Microgreens Species	Hydroponics Type	Yield Parameters	Results	Treatment	Sub-treatment	Sub-Sub-Treatment
Kamal et al. 2020	Evaluation of growth and nutritional value of Brassica microgreens grown under	Microgreens were grown under four different LEDs ratios (%); red:blue 80:20 and 20:80	21 varieties of Brassica (5 species)		Growth and nutritional content; hypocotyl length (HL), leaf area (LA); fresh	Results indicated that supplemental lighting with green LEDs (R70:G10:B20) enhanced vegetative growth and morphology, while blue LEDs (R20:B80)	z		
							Brassica	R80B20	
							Brassica	R20B80	
							Brassica	R70G10B20	
							Brassica	R20G10B70	
Samuoliene et al. 2017	Blue light dosage affects carotenoids and tocopherols in microgreens	selected LEDs: 638 + 660 + 731 + 0% 445 nm; 638 + 660 + 731 + 8%	Mustard, beet, parsley		Concentrations of a-carotene, b-carotene, lutein, neoxanthin,	From 1.2 to 4.3 times higher concentrations of chlorophylls a and b, carotenoids, a- and b-carotenes, lutein, violaxanthin and zeaxanthin was found under	z		
							Mustard	B 0%	
							Mustard	B 8%	
							Mustard	B 16%	
							Mustard	B 25%	
							Mustard	B 33%	
							Beet	B 0%	
							Beet	B 8%	
							Beet	B 16%	
							Beet	B 25%	
							Beet	B 33%	
							Parsley	B 0%	
							Parsley	B 8%	
							Parsley	B 16%	
							Parsley	B 25%	
							Parsley	B 33%	
Craver et al. 2017	Light Intensity and Light Quality from Sole-source Light-emitting Diodes Impact	A daily light integral (DLI) of 6, 12, or 18 mol.m(-2).d(-1) was achieved from SS LED arrays	Kohlrabi (Brassica oleracea var.	Hydroponic tray systems placed on	Specifically, phytochemical measurements included 1) total anthocyanins, 2) total	Regardless of light quality, total carotenoids were significantly lower under increasing light intensities for mizuna and mustard microgreens. In addition,	z		intensity

Figure 8.1 Image of literature review layout as seen in excel which details the author, title, experimental methodology, microgreens species, hydroponics type used, yield parameters, results, treatment, sub-treatment, and sub-sub-treatment.

Substrate	pH	EC (ds/m + nutrient content	Water Temperature	Spectrum	Quantity (Q) (umol/m2		Photoperiod (PP)	Daily light integral (Q x PP) (mo		Growth Period	White	Red	Red 638	Red 660	Royal Blue	Cyan	Blue	Green	Yellow	Orange	Far Red	UV	UVA	UVB	HPS
Peat moss and rockwool				LEDs	150		16	8.64																	
				R80B20	150		16	8.64		8.5			6.912	half??			1.728								
				R20B80	150		16	8.64		8.5			1.728	half??			6.912								
				R70G10B20	150		16	8.64		8.5			6.048	half??			1.728	0.864							
				R20G10B70	150		16	8.64		8.5			1.728	half??			0.864	6.048							
Peat (Profi 1, JSC	6	1.0 and 2.5		445-731	300		16	17.28																	
Peat	6	1.0 and 2.5		445-731	300		16	17.28		10			7.4139	9.695			0				0.1426				
Peat	6	1.0 and 2.5		445-731	300		16	17.28		10			5.9881	9.695			1.4257				0.1426				
Peat	6	1.0 and 2.5		445-731	300		16	17.28		10			4.5624	9.695			2.8515				0.1426				
Peat	6	1.0 and 2.5		445-731	300		16	17.28		10			3.1366	9.695			4.2772				0.1426				
Peat	6	1.0 and 2.5		445-731	300		16	17.28		10			1.7109	9.695			5.703				0.1426				
Peat	6	1.0 and 2.5		445-731	300		16	17.28		14			7.4139	9.695			0				0.1426				
Peat	6	1.0 and 2.5		445-731	300		16	17.28		14			5.9881	9.695			1.4257				0.1426				
Peat	6	1.0 and 2.5		445-731	300		16	17.28		14			4.5624	9.695			2.8515				0.1426				
Peat	6	1.0 and 2.5		445-731	303		16	17.4528		14			3.1366	9.695			4.2772				0.1426				
Peat	6	1.0 and 2.5		445-731	303		16	17.4528		14			1.7109	9.695			5.703				0.1426				
Peat	6	1.0 and 2.5		445-731	303		16	17.4528		13			7.4139	9.695			0				0.1426				
Peat	6	1.0 and 2.5		445-731	303		16	17.4528		13			5.9881	9.695			1.4257				0.1426				
Peat	6	1.0 and 2.5		445-731	303		16	17.4528		13			4.5624	9.695			2.8515				0.1426				
Peat	6	1.0 and 2.5		445-731	303		16	17.4528		13			3.1366	9.695			4.2772				0.1426				
Peat	6	1.0 and 2.5		445-731	303		16	17.4528		13			1.7109	9.695			5.703				0.1426				

Figure 8.2 Image of literature review layout directly form excel which details the environmental parameters from substrate to different light spectra.

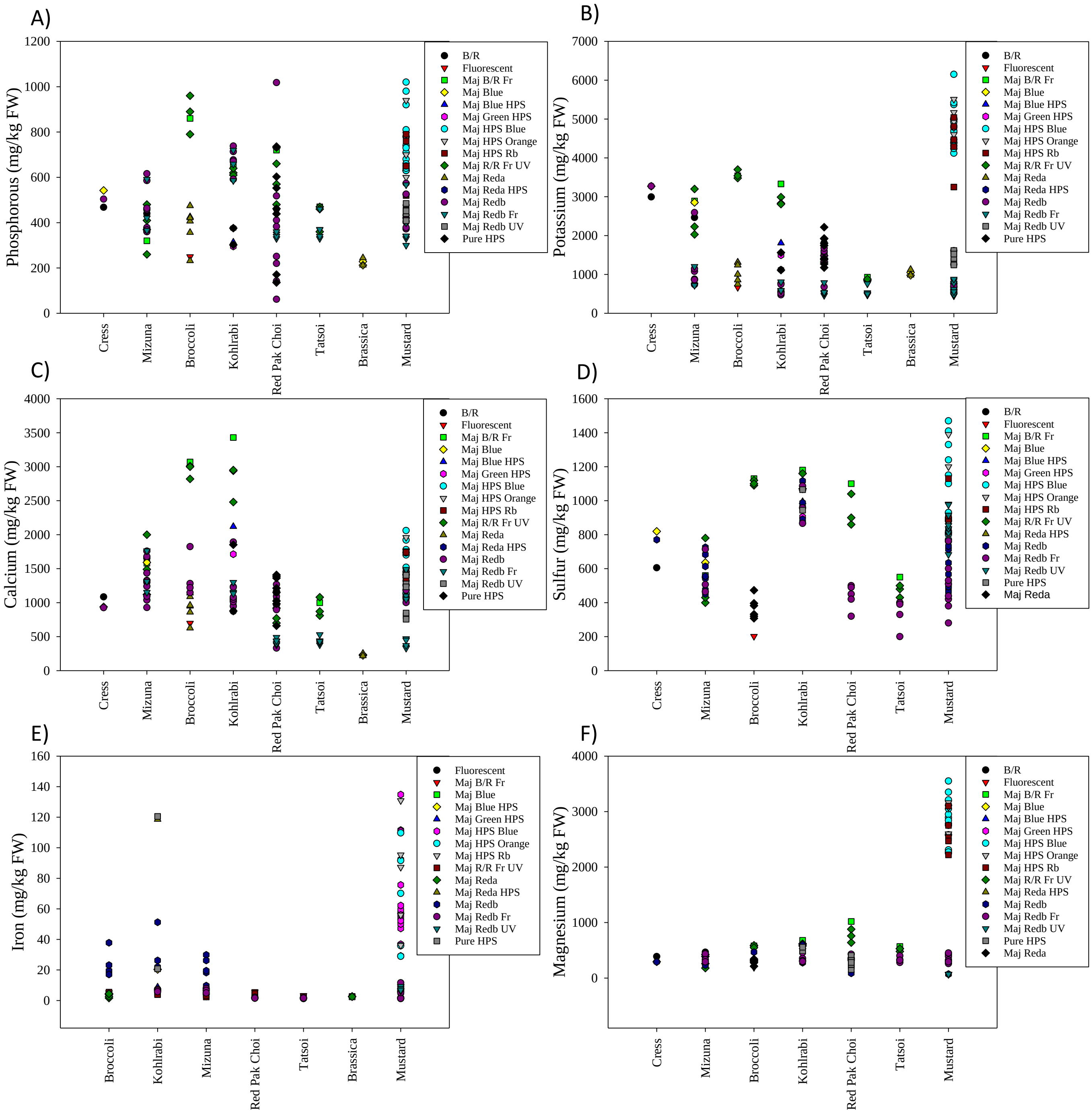

Figure 8.3 Macro- and micro-nutrient concentrations (in mg/kg of fresh weight) of microgreens as derived from the literature. A) phosphorous; B) Potassium; C) Calcium; D) Sulfur; E) Iron; F) Magnesium. Different shapes and colors correspond to categories of light quality (spectrum ratio) as defined by the original data as seen in each figure's legend. The categories are: Fluorescent; B/R (blue and red in equal proportion); Maj R/R (majority red 638 nm and red 660 nm); Maj B/R Fr (majority blue and red with far red); Maj HPS (majority HPS with blue, orange, red 660 nm, far red, or UV); Maj Reda (majority red 638 nm); Maj Blue (majority blue); Maj Redb (majority red 660 nm with far red or UV); pure blue (100% blue light 445 nm); and pure Fr (100% far red light 730 nm).

Table 8.1 Collected light papers (n=42) for microgreens production experiments

Common Name and Reference	Treatment details	Treatment outcome on yield quantity and growth parameters
Brassica: 21 varieties (Kamal et al., 2020)	Microgreens were grown under four different LEDs ratios (%); red:blue 80:20 and 20:80, or red:green:blue 70:10:20 and 20:10:70	Supplemental lighting with green LEDs (R70:G10:B20) enhanced vegetative growth and morphology, while blue LEDs (R20:B80) increased the mineral and vitamin contents. They found that the best lighting to promote the microgreen growth was the green LEDs combination (R70:G10: B20)
Mustard, beet, parsley (Samuolienė et al., 2017b)	Selected LEDs: Red 638 nm and Red 660 nm + Far Red 731 nm + 0, 8, 16, 25, and 33% Blue (445 nm)	From 1.2 to 4.3 times higher concentrations of chlorophylls a and b, carotenoids, a- and b-carotenes, lutein, violaxanthin and zeaxanthin was found under blue 33% treatment in comparison to lower blue light dosages.
Kohlrabi, Mustard, Mizuna (Craver et al., 2015)	A daily light integral (DLI) of 6, 12, or 18 mol/m²/d from LEDs with light ratios of red:blue 87:13, red:far-red:blue 84:7:9, or red:green:blue 74:18:8 with a total photon flux of 105, 210, or 315 μmol/m²/s for 16 hours	Total carotenoids were significantly lower under increasing light intensities for mizuna and mustard microgreens. For kohlrabi, with increasing light intensities, the total concentration of anthocyanins was greater compared with those grown under lower light intensities. In addition, for kohlrabi, the light ratios of R87:B13 or R84:FR7:B9 produced significantly higher anthocyanin compared with the light ratio of R74:G18:B-8 under a light intensity of 315 μmol/m²/s. Light quality also influenced the total phenolic concentration of kohlrabi, with significantly greater levels for the light ratio of R84:FR7:B9 compared to R74:G18:B8 under a light intensity of 105.
Green and red Basil (Lobiuc et al., 2017)	The 4 light treatments were 100% white (White) and various red (R) to blue (B) ratios, as follows: 2R:1B, 1R:1B and 1R:2B. After seeding, the boxes were kept in the dark for 3 days and afterwards light was supplied at a rate of 120 μmol/m²/s for 12 h each day.	Growth of microgreens was enhanced with predominantly blue illumination with larger cotyledon area and higher fresh mass. The same treatment elevated chlorophyll a and anthocyanin pigments contents. Stimulation of phenolic synthesis and free radical scavenging activity were improved by predominantly red light in the green cultivar (up to 1.87 fold) and by predominantly blue light in the red cultivar (up to 1.73 fold). Rosmarinic and gallic acid synthesis was higher (up to 15- and 4-fold, respectively, compared to white treatment) in predominantly blue illumination.
Purple kohlrabi, mizuna, and mustard (Gerovac et al., 2016)	A daily light integral (DLI) of 6, 12, or 18 mol/m²/d with light ratios of red:green:blue 74:18:8, red:blue 87:13, or red:far-red:blue 84:7:9 with a PPFD of 105, 210, or 315 for 16 hours.	Regardless of LQ, as the LI increased from 105 to 315 μmol/m²/s, hypocotyl length (HL) decreased and percent dry weight (DW) increased for kohlrabi, mizuna, and mustard microgreens. With increasing LI, leaf area (LA) of kohlrabi generally decreased and relative chlorophyll content (RCC) increased. In addition, nutrient content increased under low LIs regardless of LQ.
Kohlrabi, broccoli, and mizuna (Samuolienė et al., 2019)	LED light at red 638 and 665 nm, and far-red at 731 nm, or supplemented with LED green light at 520 nm, yellow at 595 nm, or orange at 622 nm.	Under supplemental yellow light at 595 nm, the content of soluble carbohydrates increased significantly in mizuna and broccoli. Under all supplemental light components, β-carotene accumulated in mizuna, and ascorbic acid accumulated significantly in kohlrabi. Under supplemental orange light at 622 nm, Fe, Mg, and Ca contents increased significantly in all microgreens. The accumulation of Fe was highly dependent on promoters and inhibitors of Fe absorption, as demonstrated by the very strong positive correlations between Fe and Ca and between Fe and Mg in kohlrabi and broccoli, and the strong negative correlations between Fe and β-carotene and between Fe and soluble carbohydrates in kohlrabi.
Mustard, red pak choi, tatsoi (Brazaityte et al., 2015)	447, 638, 665, and 731 nm LEDs were used. (1) evaluation of LED irradiance levels of 545, 440, 330, 220, and 110 PPFD and (2) evaluation of adding 520-, 595-, and 622-nm LEDs.	Concentrations of carotenoids in red pak choi and tatsoi were higher under illumination of 330–440 PPFD and at 110–220 PPFD in mustard. All supplemental wavelengths increased total carotenoid content in mustard but decreased it in red pak choi. Carotenoid content increased in tatsoi under supplemental yellow light. Generally, Brassicaceae microgreens accumulated more total carotenoids at irradiance levels of 330–440 PPFD compared to normal PPFD irradiance. In addition, the lowest irradiance levels (110 PPFD) resulted in decreased carotenoid contents in red pak choi and tatsoi; total carotenoid content in mustard, however, increased 1.6 times.
Kale, cabbage, arugula, mustard (Jones-Baumgardt et al., 2019)	The effects of SS light intensity (LI) on growth, yield, and quality. LEDs at 6 PPFD treatments of 100, 200, 300,	As LI increased from 100 to 600 PPFD, fresh weight (FW) increased by 0.59 kg·mL2 (36%), 0.70 kg·mL2 (56%), 0.71 kg·mL2 (76%), and 0.67 kg·mL2 (82%) for kale, cabbage, arugula, and mustard, respectively. Similarly, dry weight (DW) increased by 47 g·mL2

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	400, 500, and 600 μmol/m²/s with a ratio of 15 blue: 85 red and a 16-h PP.	(65%), 45 g·mL2 (69%), 64 g·mL2 (122%), and 65 g·mL2 (145%) for kale, cabbage, arugula, and mustard, respectively, as LI increased from 100 to 600 μmol/m²/s.
Basil and parsley (G. Samuoliene et al., 2016)	B-455, R-638, R-665, FR731 (control); B-455, R*(638), R-665, FR731; B-455, R-638, R*(665), FR731; R-638. PPFD was set from 231 during growth, up to 300 PPFD during 3-day treatment changing R638 or R665 PPFD level; in (II) greenhouse (November): HPS and HPS + 638	**In general, under supplemental or increased red 638 nm light, amounts of tested antioxidants were greater in basil, whereas sole 665 nm or sole 638 nm is more favourable for parsley**. Increased or supplemental red light significantly increased contents of phenolics, beta-tocopherol, ascorbic acid and DPPH but suppressed accumulation of lutein and beta-carotene in basil, whereas an increase of beta-carotene and DPPH was observed in parsley.
Cabbage, kale, arugula and mustard (Ying et al., 2020a)	Red Blue LED light ratios with 5%, 10%, 15%, 20%, 25% and 30% blue light	To reach a balance of yield and appearance quality, 15% blue light was recommended for indoor production of cabbage microgreens, while 5% blue light for the other three species, under similar environmental conditions.
Arugula, kale, 'Mizuna' mustard, and red cabbage (Al., 2021)	LED ratios of blue light (5% to 30%) and red light (70% to 95%)	20% blue light supplied from LED arrays is ideal for achieving optimal levels of both reduced and total ascorbate in all microgreens except red cabbage, and that 30% blue light promotes the greatest accumulation of total anthocyanin in indoor-grown Brassicaceae microgreens, with the exception of mustard.
Kohlrabi, mustard (Red Lion), red pak choi, and tatsoi (Giedre Samuoliene et al., 2013)	455, 638, 665 and 731 nm LEDs at PPFDs of 545, 440, 330, 220 and 110 μmol m-2s-1 respectively were used	Insufficient levels of photosynthetically active photon flux (110 μmol m-2 s-1) suppressed normal growth and diminished the nutritional value of the Brassica microgreens studied. In general, the most suitable conditions for growth and nutritional quality of the microgreens was 330–440 μmol m-2 s-1 irradiation, which resulted in a larger leaf surface area, lower content of nitrates and higher total anthocyanins, total phenols and 2,2 diphenyl–1–picrylhydrazyl (DPPH) free-radical scavenging capacity. High light levels (545 μmol m-2 s-1), which was expected to induce mild photostress, had no significant positive impact for most of investigated parameters.
Broccoli (Gao et al., 2021)	PPFDs of 30, 50, 70 and 90 with red: green: blue = 1:1:1 LEDs	**The broccoli microgreens grown under 50 PPFD had the highest fresh weight, dry weight, and moisture content, while the phytochemical contents were the lowest.** With increasing light intensity, the chlorophyll content increased, whereas the carotenoid content decreased. The contents of soluble protein, soluble sugar, free amino acid, flavonoid, vitamin C, and glucosinolates were higher under 70 PPFD. Overall, 50 PPFD was the optimal light intensity for enhancement of growth of broccoli microgreens, while 70 PPFD was more feasible for improving the phytochemicals
Broccoli (Kopsell et al., 2014)	Light treatments of: 1) fluorescent/incandescent light; 2) 5% blue (442 to 452 nm)/95% red (622 to 632 nm); 3) 5% blue/85% red/10% green (525 to 535 nm); 4) 20% blue/80% red; and 5) 20% blue/70% red/10% green	Microgreens under fluorescent/incandescent had significantly lower fresh mass than plants under the 5% blue/95% red, 5% blue/85% red/10% green, and the 20% blue/80% red LED light treatments. The highest concentrations of shoot tissue chlorophyll, b-carotene, lutein, total carotenoids, calcium (Ca), magnesium (Mg), phosphorus (P), sulfur (S), boron (B), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), zinc (Zn), were found in microgreens grown under the 20% blue/80% red light treatment. **In general, the fluorescent/incandescent light treatment resulted in significantly lower concentrations of most metabolites measured in the sprouting broccoli tissue.**
Broccoli (Moreira-Rodríguez et al., 2017)	Seven-day-old broccoli sprouts were exposed to UVA (9.47 W/m²) or UVB (7.16 W/m²) radiation for 120 min alone or in combination with a MJ solution	UVA + MJ and UVB + MJ treatments increased the total glucosinolate content by ~154% and ~148%, respectively. MJ induced the biosynthesis of indole glucosinolates, especially neoglucobrassicin (~538%), showing a synergistic effect with UVA stress. UVB increased the content of aliphatic and indole glucosinolates, such as glucoraphanin (~78%) and 4-methoxy-glucobrassicin (~177%). UVA increased several phenolics such as gallic acid (~57%) and a kaempferol glucoside (~25.4%). UVA increased lutein (~23%), chlorophyll b (~31%), neoxanthin (~34%), and chlorophyll a (~67%).
Broccoli, kohlrabi, mizuna, RPC, tatsoi (Brazaityte, Viršile, et al., 2020)	Blue 447-, red 638- and 665-, and far-red 731 nm light-emitting diodes (LEDs), and the UV-A wavelengths of 366-, 390- or 402 nm were added for experiments.	**The overall results showed that UV-A negatively affected the accumulation of mineral elements in all plants, except mizuna, when the 366 nm had the impact of increased contents of nutrients.** The supplemental UV-A radiation significantly decreased the assimilation of nitrates in kohlrabi, mizuna, red pak choi (RPC), but increased in broccoli and tatsoi microgreens.

2 mizunas; Pak choi ; 2 radishes, and 3 mustards (Alrifai et al., 2021)	Various ratios of combined red, blue, and amber light-emitting diodes (rbaLEDs) were investigated for their effect on the expression of carotenoid biosynthetic genes and carotenoid accumulation in eight Brassica microgreens	Total and individual carotenoids were increased 20–44 and 10–55%, respectively, under dose-dependent increasing amber–blue light and decreasing red in most microgreens. Lipophilic 2,2-diphenyl-1- picrylhydrazyl and ferric reducing antioxidant power antioxidant activities were significantly increased under higher amber and blue light fractions, while oxygen radical absorbance capacity was generally decreased. This study demonstrated for the first time that amber LED was involved in the regulatory mechanism of carotenoid biosynthesis, thus a potential novel approach to production of antioxidant-rich microgreens.
Red Lion Mustard (Brazaitytė et al., 2019)	UV-A LEDs at different wavelengths (366, 390, and 402 nm) and durations (10 and 16 h) on the growth and phytochemical contents of mustard microgreens, when used as supplemental light to the main LED lighting system (with peak wavelengths of 447, 638, 665, and 731 nm).	Supplemental UV-A radiation did not affect biomass accumulation; however, the longest UV-A wavelength (402 nm) increased the leaf area of mustard microgreens, regardless of the duration of irradiance. The concentration of the total phenolic content and α-tocopherol mostly increased under 402-nm UV-A. The contents of lutein/zeaxanthin and β-carotene increased in response to the shortest UV-A wavelength (366 nm) at 10-h irradiance as well as longer UV-A wavelength (390 nm) at 16 h irradiance. The most positive effect on the accumulation of mineral elements, except iron, was observed under longer UV-A wavelengths at 16-h irradiance.
Arugula, cabbage, mustard, kale (Kong, Kamath, et al., 2019)	1) R, monochromatic red (665 nm) and 2) B, monochromatic blue (440 nm) using continuous (24-hour light/0-hour dark) or periodic (16-hour light/8-hour dark) LED lighting with PPFD of 100	After 7 to 8 days of lighting treatment, regardless of photoperiod, B promoted elongation growth compared with R, as demonstrated by a greater stem extension rate, hypocotyl length, or petiole length, except for mustard. The promotion effects on elongation were greater under 24- vs. 16-hour lighting in many cases.
Arugula, cabbage, mustard, kale (Kong, Schiestel, et al., 2019)	(1) R, "pure" red (660 nm); (2) B, "pure" blue (450 nm); (3) BU, "unpure" blue created by mixing B with a low level of UVA (≈7.5%); and (4) BF, "unpure" blue created by mixing B with a low level of far-red (≈ 10%). (24- hour) light-emitting diode lighting with either 100 or 50 PPFD	B vs. R promoted elongation growth as demonstrated by a greater stem extension rate, hypocotyl length, or petiole length. The promotion effects on elongation were stronger under lower vs. higher light. BU vs. B inhibited elongation growth for some species at 100 PPFD in most cases, but BU vs. R did not, except for mustard at 50 PPFD. BF vs. If considering all plant traits together using principle component analysis, BU and BF effects were similar to B, but different from R.
Arugula, cabbage, mustard, kale (Kong & Zheng, 2020)	(1) R, narrow-band red (660 nm); (2) B, narrow-band blue (455 nm); (3) BU, broad-band blue created by mixing B with a low level (≈ 0.7 PPFD) of UVB (310 nm); and (4) BG, B with (≈ 6 %) of green light (530 nm). 24 -h with 100 PPFD.	B, compared to R, had promoted elongation growth (i.e., longer hypocotyls or petioles, faster stem extension), and induced some other typical shade-avoidance responses (e.g., smaller cotyledons, lighter plant color, or greater biomass allocation to stem). If considering all the plant traits together, BU and BG effect was similar to B, but different from R. Therefore, narrow-band blue vs. red light can promote elongation growth as a shadeavoidance response at both plant and cell levels, and adding low-level UVB or green light can only slightly change the shade-avoidance response, despite varying sensitivity among species.
Arugula, cabbage, mustard, kale (Kong et al., 2020)	Treatments: (1) R, pure red; (2) B, pure blue; (3) BRF0, (4) BRF2, (5) BRF4, and (6) BRF6: unpure blue by mixing B with (6%) R, and further adding 0, 2, 4, and 6 PPFD of far-red light.	Generally, the elongation growth (including stem extension rate, hypocotyl length, or petiole length) under blue lights increased with the decreasing PPS values, showing the highest and lowest sensitivity for arugula and mustard, respectively. However, the elongation promoted by blue lights gradually became saturated once the phytochrome was deactivated. Biomass allocation and plant color, varied with increasing shade-avoidance responses to blue lights with decreasing PPS values relative to R. The response sensitivity was highest in elongation growth for arugula and cabbage, and highest in plant color for kale and mustard.
Amaranth (Meas et al., 2020)	1) Red, blue, R&B (70R:30B) and white with 130 PPFD. 2) various light intensities: 130, 180, 230, 280 PPFD with (70R:30B). 3) different photoperiods: 8, 12, 16, 20 h under 70R:30B & 280 PPFD.	The results indicated that red plus blue (70R:30B) spectrum, 280 µmol PPFD and 16 h photoperiod enhanced the fresh yield, chlorophyll a, b, total carotenoids, anthocyanin, and vitamin C contents and total antioxidant capacity for both red amaranth and leafy vegetable amaranth microgreens.
Brassica (Park et al., 2020)	White, blue, or red LED with a flux rate of 90 PPFD and a long-day photoperiod (16 h)	The highest total desulfoglucosinolate content was observed in response to white LED light treatment, followed by treatment with red LED light, and then blue LED light. The highest total phenolic contents were recorded after one week of white and blue LED light treatment, whereas blue LED irradiation increased the production of most of the phenolic compounds identified. The production of phenolics decreased gradually with increasing duration of LED light treatment, whereas anthocyanin accumulation showed a progressive increase during the treatment. These findings indicate that white LED light is appropriate for glucosinolate accumulation, whereas blue LED light is effective in increasing the production of phenolic compounds

Radish (Zhang et al., 2019)	Hydrogen-rich water (HRW) in combination with different light spectra, such as white, blue, ultraviolet-A (UV-A), as well as darkness.	The results showed that HRW significantly reversed UV-A-induced hypocotyl growth inhibition compared to the white light control. The total phenolic content of microgreens grown under blue light + HRW and UV-A + HRW treatment were 1.12 and 1.17 times, respectively, higher than that of blue light and UV-A treatment alone.
Cabbage, kale, arugula and mustard (Ying, Kong, & Zheng, 2020c)	1) FL: fluorescent; 2) BR: 15% blue and 85% red LED; 3) BRFRL: 15% B, 85% R, and 15.5 PPFD far red (FR); 4) BRFRH: 15% B, 85% R, and 155 PPFD FR LED; 5) BGL R: 9% B, 6% G, and 85% R; and 6) BGHR: 5% B, 10% G, and 85% R. PPFD was set at 330 at 17-h PP	At harvest, BR vs. FL increased plant height for all except arugula, and enlarged cotyledon area for kale and arugula. Adding high-intensity FR light to blue and red light (i.e., BRFRH) further increased plant height for all species, and cotyledon area for mustard, but it did not affect the fresh or dry biomass. However, BGLR, BGHR, and BRFRL, compared with BR, did not affect plant height, cotyledon area, or fresh or dry biomass. These results suggest that the combination of 15% blue and 85% red LED light can potentially replace FL as the sole light source for indoor production of the tested microgreen species.
Arugula and Mustard (Ying, Kong, & Zheng, 2020b)	16-h PP with 20% B and 80% red (R), and a total PPFD of 300. During 8-h night, plants were exposed to: 1) dark (D); 2) 4 hours of B at 40 followed by 4 hours of D (40B-D); 3) 4 hours of D followed by 4 hours of B at 40 (D-40B); 4) 8 hours of B at 20 (20B); 5) 8 hours of B + FR, each at 20 (20B20FR); and 6) 8 hours of FR at 20	Nighttime B treatments (40B-D, D-40B, and 20B), compared with D, increased plant height by 34% and 18% for mustard and arugula, respectively, with no difference among the three B treatments. The combination of B and FR (20B20FR), compared with B alone, further increased plant height by 6% and 15% for mustard and arugula, respectively, and showed a similar promotion effect as 20FR. There was no difference in biomass among all treatments. **Overall, nighttime B alone, or its combination with FR, promoted microgreen elongation without compromising yield and quality.**
Mustard, arugula (Ying, Kong, & Zheng, 2020d)	Low-intensity (14 PPFD) B or FR was applied to microgreens overnight, and no supplemental lighting (D) was used as a control.	After 2 weeks, B compared to D promoted stem elongation by 16% and 10%, respectively, and increased crop yield by 32% and 29%, in mustard and arugula. B compared to D also increased the LA in mustard and leaf mass per area in arugula and enhanced cotyledon color in both species despite having no effects on total chlorophyll, carotenoid, and phenolic contents. However, FR did not increase stem length or fresh weight compared with D, reduced plant height compared with B in both species, and reduced LA in arugula. **FR, compared with D and B, reduced the stem diameter and phytochemical contents of both species.**
Red russian kale, broccoli, beet (Carvalho & Folta, 2016)	Far-red, blue, and green light at different fluences (0, 1, 50, 100 PPFD)	The results show that while anthocyanins are induced with far-red light, green light cannot reverse, and may enhance, their accumulation under low-fluence-rate conditions, but the trend reverses in some seedlings under high-fluence rate conditions. On the other hand, blue-light-induced anthocyanin accumulation may be inhibited by the addition of green wavebands, and the effect is fluence-rate dependent and varies in sensitivity and amplitude, depending on the genotype.
Kohlrabi, beet (Brazaitytė et al., 2018)	HPS lighting was supplemented with LED light at 445 and 530 nm during the whole growing period; II, at the pre-harvest stage of 3 d, HPS lamps were supplemented by a solid-state illuminator containing 638 nm LEDs.	Both microgreens grown under supplemental 445 nm irradiation accumulated higher contents of all macroelements and nitrates in comparison with those grown under solely HPS illumination. Supplemental 530 nm irradiation resulted in increased content of nitrates and almost all mineral elements investigated in beet, but decreased content in kohlrabi. Short-term pre-harvest treatment with 638 nm LEDs to supplement HPS illumination and natural light produced increased content of mineral elements and reduced nitrate concentration in beet, but had almost no effect on kohlrabi.
Red pak choi (Brazaityte, Vaštakaite, et al., 2020)	Each lamp was designed using red (662 nm) and blue LEDs (451 nm). Reference microgreens were grown under HPS lamps. The PPFD of LEDs and HPS lamps was 150, 200, 250 and 300. For the LED lamps, red to blue light ratio was 91:9	LED lamps resulted in decrease of elongation of red pak choi microgreens under all PPFD in greenhouse, but opposite results were obtained under indoor conditions. LED lamps illumination decreased nitrate content under both growing conditions. PPFD had no effect on fresh weight, however higher PPFD of LED lamps increased it indoors. It was determined that all irradiance levels of LED lamps no effect on ascorbic acid, total phenols, DDPH; however, an increase in total anthocyanins and a decrease in macro elements were determined indoors. **The opposite effect was observed in greenhouse grown plants.**
Mustard (Red Lion), red pak choi, and tatsoi (Brazaityte, Vaštakaite, et al., 2020)	Standard 445-, 640-, 660-, and 735-nm LEDs was used with blue component of 0, 8, 16, 25 and 33% changing the PPFD level of red (640 nm) light.	An increase of various mineral elements content was mostly caused by higher percentage of blue light. However, the changes on contents of mineral elements depended on microgreens species and percentage of blue light. The highest content of macro- and microelements was determined at 25% of blue light in mustard and at 33% – in red pak choi and tatsoi. The absence (0%) of blue light led to lower content of macroelements in red pak choi and tatsoi.
Mustard (Red Lion), red pak choi, and tatsoi (Brazaityte et al., 2016)	Red 638, 665, blue 455 and far red 731 PPFD of 200. 3 days before harvest PPFD was raised to 300. The red was illuminated with only 638 or 665 at 300.	638 and 665 nm light, applied before harvest, caused stem elongation, increased fresh weight and decreased leaf area, but varied between species. Red improved the nutritional quality. **Comparison of different red-wavelength effects showed that more antioxidants, ascorbic acid and β-carotene, were accumulated in microgreens exposed to 638 nm, than exposed to 665 nm light.**

Mizuna, amaranth, cress, and purslane (Marios C. Kyriacou et al., 2019)	Light treatments examined in the present experiment were: red (90% R, 10% G, 0% B), blue (0% R, 10% G, 90% B), and red blue (45% R, 10% G, 45% B)	Growth parameters dependent on primary metabolism were most favored by blue-red light's efficiency in activating the photosynthetic apparatus. Although mineral composition was mostly genotype-dependent, monochromatic red and blue lights tended to increase K and Na and decrease Ca and Mg concentrations. Lutein, β-carotene, and lipophilic antioxidant capacity were generally increased by bluered light. The general response across species was a decrease in polyphenolic and total polyphenols under blue-red light.
Mustard (Red Lion) (Vaštakaitė-Kairienė et al., 2020)	HPS supplemented with 20 PPFD of monochromatic 455, 470, 505, 590, or 627 nm LED (total PPFD 200). For pulsed light treatments, the frequencies at 2, 32, 256, and 1024 Hz with a duty cycle of 50% of monochromatic LED was used.	The highest content of potassium under the treatment of blue 455 nm and yellow 590 nm at 2 Hz frequency was determined. All the supplemented monochromatic wavelengths affected the higher content of calcium at 32 and 256 Hz frequencies. The similar tendencies for accumulation of phosphorus and sulfur were determined. The pulsed LED light had negative effect for accumulation of magnesium. **Supplemental to HPS lamps royal blue 455 nm, cyan 505 nm and yellow 590 nm LED light at 32 and 256 Hz frequencies had the most distinguished effects on accumulation of mineral elements in mustard microgreens.**
Mustard (Kopsell et al., 2012)	14 h photoperiod under 275 PPFD. Upon emergence of the first true leaf, light treatments of: (1) 275 and (2) 463 PPFD.	Significant decreases in chlorophyll a concentrations under the 463 PPFD light treatment indicated high light stress had occurred. There were significant decreases in carotene in the 463 PPFD light treatment; however, lutein concentrations were unchanged. Increases in ZEA occurred under the 463 PPFD light treatment.
Broccoli (Kopsell & Sams, 2013)	1) red and blue LED light (350 μmol/m²/s); or 2) blue LED light (41 μmol/m²/s) treatments for 5 days before harvest.	**Short duration blue increased shoot tissue b-carotene, violaxanthin, total xanthophyll cycle pigments, glucoraphanin, epiprogoitrin, aliphatic glucosinolates, essential micronutrients of copper (Cu), iron (Fe), boron (B), manganese (Mn), molybdenum (Mo), sodium (Na), zinc (Zn), and the essential macronutrients of calcium (Ca), phosphorus (P), potassium (K), magnesium (Mg), and sulfur (S).**
Amaranth, basil, mustard, spinach, broccoli, borage, beet, kale, parsley, pea (G. Samuoliene et al., 2012)	HPS lamps were supplemented by 638 nm LEDs, whereas reference plants continued staying under lighting conditions identical to those of growth. PPFD was 170 and net PPFD in combination with HPS lamps was 300	Natural antioxidant compounds were in order: pea>broccoli>borage>mustard=amaranth> basil=kale>beet=parsley>tatsoi. Total phenols increased with supplemental red in all microgreens from 9.1% in mustard to 40.8% in tatsoi, except of amaranth, where it decreased by 14.8%. Ascorbic acid content increased in amaranth (79.5%), pea (65.2%), kale (60.6%), broccoli (59.1%) and mustard (25.0%), but decreased in basil (53.9%) and borage (46.9%), and had no significant effect in tatsoi, beet and parsley. Total anthocyanins significantly increased in broccoli (45.1%), kale (44.0%), amaranth (38.0%), tatsoi (34.5%), parsley (27.0%) and pea (14.6%), with significant decrease in borage (51.8%), mustard (45.1%) and beet (43.3%).
Red pak choi, mustard, and tatsoi (Vaštakaite et al., 2017)	HPS lamps supplemented with monochromatic (455, 470, 505, 590, and 627 nm) LEDs with PPFD of 200. For pulsed light treatments, the frequencies at 2, 32, 256, and 1024 Hz with a duty cycle of 50% monochromatic LEDs.	The summarized data suggested that pulsed light affected accumulation of secondary metabolites both positive and negative in microgreens. The most positive effects of 2, 256, and 1024 Hz for total phenolic compounds in mustard under all wavelength LEDs were achieved. The LED frequencies at 2 and 32 Hz were the most suitable for accumulation of anthocyanins in red pak choi and tatsoi. The highest antiradical activity under the treatments of 32, 256, and 1024 Hz in mustard and under the 2 Hz frequency in red pak choi and tatsoi was determined
Basil (Vaštakaitė et al., 2018)	HPS was supplemented with 20 PPFD of monochromatic LEDs with peaks 455 nm, blue 470 nm, cyan 505 nm, yellow 590 nm, or red 627 nm, and total PPFD was 200. 2, 32, 256, and 1024 Hz (duty cycle of 50%) of monochromatic LED.	The results showed that the effects of supplemental pulsed light on total phenolic compounds, total anthocyanins, DPPH free-radical scavenging activity and ascorbic acid depended on the wavelength of monochromatic LEDs and frequency. Supplemental lighting of blue 470 nm or red 627 nm at 1024 Hz was the most effective for accumulation of total phenolic compounds as well as total anthocyanins. The highest antiradical activity in basil microgreens treated under all supplemental LEDs, was determined, except red 627 nm at 256 Hz. Accumulation of ascorbic acid was promoted by pulsed light at all frequencies.
Lettuce (Ferrón-Carrillo et al., 2021)	3 LED: (i) artificial white light (T0); (ii) continuous light emitting diodes with longer blue-wavelength (T1), and (iii) continuous light-emitting diodes with longer red-wavelength (T2).	Accumulation of nitrates at initial stages in plant tissues was clearly lower than at final stages of crop development, ranging from 50.2 to 73.4 mg 100 g1 fresh weight for T2. Nitrate amounts at microgreen stage were lower than in baby leaf stage, and this content was inversely correlated with carotenoid content, which in tissues was higher at microgreens stage influenced by LED.
Chia (Mlinarić et al., 2020)	LED irradiance for 24 and 48 h on dark-grown chia microgreens	Analysis of the results showed that illumination significantly increased the content of all measured bioactive compounds as well as antioxidative capacity, especially 48 h after exposure to light. Illumination has a positive effect on the antioxidant potential of chia microgreens

Table 8.2 Collected papers (n=27) on substrate, fertilization regimes, and miscellaneous papers		
Common Name and Reference	**Treatment details**	**Treatment outcome on yield quantity and growth paramaters**
Purple cabbage (Wieth et al., 2019)	Completely randomized design and three replications with a 4×3 factorial arrangement consisted of 4 commercial substrates and 3 nutrient concentrations in the nutritive solution (0%, 50%, and 100%).	Different substrates had no effect on the FW, DW, and height; the increasing addition of nutrients to the nutritive solution increased the values of these variables. The TSS and total carotenoid contents decreased as the nutrient concentration in the nutritive solution was increased.
Basil, Swiss chard, and rocket (Bulgari et al., 2017)	5 L of half-strength Hoagland's nutrient solution (macroelements expressed in mM: N 7.5, P 0.5, K 3.0, Ca 2.5, Mg 1.0; microelements expressed in µM: Fe 25.0, B 23.1, Mn 4.6, Zn 0.39, Cu 0.16, Mo 0.06).	There were high concentrations of minerals, but their uptake was limited due to low yield. Nitrates content was lower compared with baby leaf or adult vegetables of **the same species, as well as the concentration of chlorophylls, carotenoids, phenols, and sugars.**
Wheat (Islam et al., 2020)	Different concentrations of Se (0 [control], 0.125, 0.25, 0.50, and 1.00 mg/L from sodium selenite)	Se biofortification increased the germination rate and decreased microgreen length and yield. Chlorophyll and carotenoid levels increased in the Se-biofortified microgreen extract. Bioactive compounds such as phenolics, flavonoids, vitamin C, and anthocyanin significantly increased in 0.25–0.50 mg/L of Se-biofortified microgreen extracts. Antioxidant (ABTS, DPPH, NSA and SOD-like) activity also increased at moderate levels (0.25–0.50 mg/L) of Se biofortification
Coriander, green basil and purple basil, and tatsoi (Pannico et al., 2020)	Sodium selenate applications at three concentrations (0, 8, and 16 µM Se)	In coriander and tatsoi microgreens, the application of 16 µM Se increased the total phenols content by 21% and 95%, respectively; moreover, it improved the yield by 44% and 18%, respectively. In green and purple basil microgreens, the 8 µM Se application enhanced the lutein concentration by 7% and 19%, respectively. The same application rate also increased the overall macroelements content by 35% and total polyphenols concentration by 32% but only in the green cultivar. All microgreen genotypes exhibited an increase in the Se content in response to the biofortification treatments, thereby satisfying the recommended daily allowance for Se (RDA-Se) from 20% to 133%. The optimal Se dose that guarantees the effectiveness of Se biofortification and improves the content of bioactive compounds was 16 µM in coriander and tatsoi, and 8 µM in basil.
Broccoli, cauliflower, Turnip (Palmitessa et al., 2020)	Fertigated with three modified strength Hoagland nutrient solutions (1/2, 1/4, and 1/8 strength) or with three modified half-strength Hoagland nutrient solutions with three different NH4:NO(3)molar ratios (5:95, 15:85, and 25:75)	**Micro cauliflower showed the highest yield, as well as a higher content of mineral elements and alpha-tocopherol (10.4 mg 100 g(-1)fresh weight (FW)) than other genotypes. The use of nutrient solution at half strength gave both a high yield (0.23 g cm(-2)) and a desirable seedling height. By changing the NH4:NO(3)molar ratio in the nutrient solution,** no differences were found on yield and growing parameters. The lowest nitrate content (on average 6.8 g 100 g(-1)dry weight) was found in micro broccoli and micro broccoli raab by using a nutrient solution with NH4:NO(3)molar ratios of 25:75 and 5:95, respectively. Micro cauliflower fertigated with a NH4:NO(3)molar ratio of 25:75 showed the highest dry matter (9.8 g 100 g(-1)FW) and protein content (4.2 g 100 g(-1)FW).
Chicory, lettuce (Renna et al., 2018)	Different potassium (K) levels (0, 29.1, 58.4, and 117 mg L-1) in order to produce microgreens with a low potassium content	Independent of the genotype, the K content in the microgreens was successfully reduced using a nutrient solution (NS), without K or with 29.1 mg K L-1, which supplied between 103 and 129 mg of K 100 g(-1) FW (about 7.7-8.6% of the K daily intake that was recommended for the patients that were affected by chronic kidney disease)
Broccoli (Weber, 2017)	Microgreens produced using compost-based and hydroponic growing methods	Compost-grown microgreens had higher P, K, Mg, Mn, Zn, Fe, Ca, Na, and Cu concentrations than the vegetable. The average Compost microgreen: vegetable nutrient ratio was 1.73. Extrapolation from experimental data presented here indicates that broccoli microgreens would require 158-236 times less water than it does to grow a nutritionally equivalent amount of mature vegetable in the fields of California's Central Valley in 93-95% less time and without the need for fertilizer, pesticides, or energy-demanding transport from farm to table
Kale, mustard (Wang & Kniel, 2016)	Samples were collected from a newly contaminated system (recirculated water inoculated with 3 log PFU/ml	The behaviors of the virus in kale and mustard microgreens were similar. MNV was detected in edible tissues and roots after 2 h postinoculation, and the levels were generally stable during the first 12 h. Cross-contamination occurred easily; MNV remained

	MNV on day 8) and from a previously contaminated system	infectious in previously contaminated hydroponic systems for up to 12 days (2.26 to 1.00 PFU/ml), and MNV was detected in both edible tissues and roots.
Daikon radish (Xiao, Bauchan, et al., 2015)	Radish microgreens were produced from seeds inoculated with Escherichia coli O157:H7 by using peat moss based soil-substitute and hydroponic production systems	E. coli O157:H7 was shown to survive and proliferate significantly during microgreen growth in both production systems, with a higher level in the hydroponic production system. Contaminated seeds led to systematic contamination of whole plants, including both edible and inedible parts, and seed coats remained the focal point of E. coli O157:H7 survival and growth throughout the period of microgreen production.
Ten culinary microgreens belonging to eight botanical families (Ghoora et al., 2020)	Microgreens were analysed for protein, dietary fibre profile, ICP-OES based elemental profile and ascorbic acid. Alpha-tocopherol and beta-carotene were analysed using HPLC-DAD	The microgreens were moderate to good sources of protein, dietary fibre and essential elements. They were excellent sources of ascorbic acid, Vitamin E and beta-carotene (pro-vitamin A), meeting 28-116 %, 28-332 %, and 24-72 % of reference daily intake of the respective vitamins. Based on NQS 11.2, radish microgreens were found to be the most nutrient dense, followed by French basil and roselle microgreens. Least nutrient-dense microgreens were fenugreek and onion. The NQS 11.2 showed that all microgreens are 2-3.5 times more nutrient dense than spinach mature leaves cultivated under similar conditions
Mustard, opal basil, bull's blood beet, red amaranth, peppercress, and China rose radish (Xiao, Lester, et al., 2015)	(1) assess sensory quality and consumer acceptance of selected microgreens; (2) correlate chemical compositions with sensory attributes of those microgreens; and (3) evaluate the nutritional values of these microgreens	Results showed that bull's blood beet had the highest rating on acceptability of flavor and overall eating quality while peppercress the lowest. Regarding the phytonutrient concentrations, the highest concentrations of total ascorbic acid, phylloquinone, carotenoids, tocopherols, and total phenolics were found in China rose radish, opal basil, red amaranth, China rose radish, and opal basil, respectively.
Broccoli (Chen et al., 2020)	A total of 150 participants completed an acceptability study of broccoli microgreens and answered questions regarding perceived pricing, perceived benefits, and their willingness-to-buy.	Overall, participants rated microgreens from the local farm as more favorable, regardless of growing method. The commercial microgreen sample from the local grocery had the lowest scores on all sensory attributes. The results also indicated that both sensory evaluation and consumers' perceived benefits present important roles in consumers' reference and consumption of microgreens. Pricing, however, did not show significant and direct effect on consumers' purchase intention.
Broccoli (Kou et al., 2014)	Broccoli microgreens were sprayed daily with calcium chloride at concentrations of 1, 10 and 20 mM, or water (control) for 10 days. The fresh-cut microgreens were packaged in sealed polyethylene film bags. Package headspace atmospheric conditions, overall visual quality and tissue membrane integrity were evaluated on days 0, 7, 14, and 21, during 5◦C storage.	Ten mM $CaCl_2$significantly promoted broccoli hypocotyl length. However, 1and 20 mM $CaCl_2$treatments did not show obvious growth promoting effect. More-over, 20 mM treatment resulted in yellow cotyledons. These results suggest that the dosage of calcium is important for the growth stimulation, and too much calcium application may have the adverse effect on growth. Microgreens treated with calcium chloride had significantly lower bacterial counts than those sprayed with water at the end of storage. In addition, the calcium content in calcium-treated microgreens has been significantly increased
Basil (Puccinelli et al., 2019)	Totally randomized design with four replicates, each consisting of a tank with one plant. nutrient solution, containing 0 (control), 4 or 8mg Se L−1 as sodium selenate	Seeds from plants treated with Se showed a significantly higher germination index than seeds from control plants, but no differences were detected among Se treatments. The antioxidant capacity of Se-fortified microgreens was higher compared to the control.
Wild Rocket, brussel sprouts, cabbage (El-Nakhel et al., 2021)	Grown in 204 cm^2 plastic trays filled with 600 mL peat moss mix each and fertigated daily with a quarter-strength customized Hoagland nutrient solution or simply irrigated daily with distilled water	Brussels sprouts and cabbage yield was only reduced by 10%, while nitrate was reduced by 99% in the absence of nutrient supplementation. Rocket yield was prominently reduced by 47%, with a corresponding nitrate reduction of 118%. Brussels sprouts secondary metabolites were not improved by the absence of nutrient supplementation, whereas cabbage microgreens demonstrated a 30% increase in total ascorbic acid and a 12% increase in total anthocyanins. As for rocket, the absence of nutrient supplementation elicited an extensive increase in secondary metabolites, such as lutein (110%), B-carotene (30%), total ascorbic acid (58%) and total anthocyanins (20%), but caused a decrease in total phenolic acids.
Mustard, broccoli (Di Gioia et al., 2017)	Recycled textile-fiber (TF; polyester, cotton and polyurethane traces) and jute-kenaf-fiber (JKF;85%jute,15%kenaf-fibers) mats	All substrates had suitable physicochemical properties for the production of microgreens. On average, microgreens fresh yield was 1502 gm−2 in peat, TF and JKF, and was 13.1% lower with STG. Peat-grown microgreen shoots had a higher concentration of

	were characterized and compared with peat and Sure to Grow®	K+ and SO42−and a two-fold higher NO3 − concentration [1959 versus 940mgkg−1 fresh weight (FW)] than those grown on STG, TF and JKF. At harvest, substrates did not influence microgreens aerobic bacterial populations (log 6.48 CFU g−1 FW)
Broccoli (Jianghao Sun et al., 2015)	Preharvest calcium application	Chemical composition comparison shows that glucosinolates, a very important group of phytochemicals, are the major compounds enhanced by preharvest treatment with 10 mM calcium chloride (CaCl2). Glucosinolates were increased significantly in the CaCl2 treated microgreens using metabolomic approaches.
Broccoli (Lu et al., 2018)	Preharvest calcium application and UV-B	Total aliphatic GLS levels increased significantly after 10mM CaCl2 treatment, while postharvest UV-B radiation further boosted GLS levels in microgreens. Furthermore, preharvest calcium spray showed improved overall visual quality and longer storage life. Hence, CaCl2 application is the major factor to increase GLS levels and postharvest quality. Broccoli microgreens are a better source of GLS intake than florets, and preharvest CaCl2 and postharvest UV have positive influence on maintaining the health-beneficial compounds and extending the shelf life of broccoli microgreens
Cabbage, lettuce (Weber, 2016)	Nutrient contents of lettuce and cabbage microgreens grown hydroponically (HP) and on vermicompost (C) were assessed and compared to each other as well as to the nutrient contents of store-bought cabbage and lettuce (mature vegetables)	**Of the 10 nutrients examined (P, K, S, Ca, Mg, Mn, Cu, Zn, Fe, Na), C cabbage microgreens had significantly larger quantities of** all nutrients than HP cabbage microgreens with the exception of P; C lettuce microgreens had significantly larger quantities of all nutrients than HP lettuce microgreens except for P, Mg and Cu. Compared to the mature vegetable, C or HP cabbage microgreens had significantly larger quantities of all nutrients examined
Radish (Goble, 2018)	A solution range of 0 to 160 mM Ca was applied to determine upper limits of Ca fertilization.	**Solutions above 20 mM Ca showed toxic effects to germination and growth, while 5 and 10 mM Ca resulted in** the greatest percent of shoots that grew to a desired size for harvest (%H), as well as greater average hypocotyl length per plant (HL) and cotyledon surface area per plant (CSA). In general, Ca content of plant tissues increased with Ca solution concentration; however, the level of increase was dependent on the media and whether treatments were applied at the time of planting or delayed until after germination
Sunflower and Daikon Radish (Supapvanich et al., 2020)	The baby vegetables were dipped in water (control), 0.05 or 0.1 µM cyanocobalamin for 5 min and then stored at 4 ± 1 °C for 9 d	We found that cyanocobalamin immersion, especially at 0.1 µM, could induce antioxidant capacity and certain biologically active compounds such as total phenols and flavonoids concentrations of all baby vegetables when compared to control samples. Vitamin B12, is a new potential natural agent improving health beneficiary bioactive compounds in ready to eat baby vegetables during cold storage.
Sunflower, Brocolli (Baczek-Kwinta et al., 2020)	Seeds treated with 0, 10, 20 and 30 µg mL−1 ZnSO4 responded in a differentiated way to Zn.	Pea seed germination and sprout growth was diminished by 30 µg mL−1 ZnSO4, but for sunflower sprouts this Zn level resulted in the highest fresh mass and largest hypocotyls. Zn content in sprouts greatly increased in a dose-dependent manner, mostly in broccoli (up to 25 times) and peas (up to 4 times), **and to a lesser extent (up to 120%) for sunflowers. Free radical scavenging activity was usually decreased.**
Cauliflower, broccoli and broccoli raab (Renna et al., 2020)	Nutrient solutions with three different NH4:NO3 molar ratios (5:95, 15:85, and 25:75).	Using NH4:NO3 25:75 molar ratio, the average score was 27% higher than other molar ratios. In all cases, the microgreens in the present study showed a higher NQS 11.1 than their mature counterpart: the score of micro cauliflower was about six-fold higher than mature cauliflower
Black Kale (Tavan et al., 2021)	Optimal irrigation level using a sensor that could facilitate the development of a more efficient, low-cost automated irrigation system.	Crop water stress index (CWSI) increased at 7.5% EVC in both sensor-based and gravimetric treatments, and infrared index (Ig) and fresh yield decreased. The irrigation level of 17.5% EVC was found to be optimal. It resulted in a WUE of 88 g/L, an improvement of 30% over the gravimetric method at the same irrigation level. Furthermore, fresh yield increased by 11.5%.
Broccoli, green curly kale, red mustard, and radish (Beatriz de la Fuente et al., 2019)	Evaluation of the Bioaccessibility of Antioxidant Bioactive Compounds and Minerals of Four Genotypes of Brassicaceae Microgreens	All microgreens provided relevant amounts of vitamin C (31–56 mg/100 g fresh weight) and total carotenoids (162–224 mg B-carotene/100 g dry weight). Both total soluble polyphenols and total isothiocyanates were the greatest contributors to the total antioxidant capacity after digestion (43–70% and 31–63% bioaccessibility, respectively) while macroelements showed an important bioaccessibility (34–90%). In general, radish and mustard presented the highest bioaccessibility of bioactive compounds and minerals