Chapter 7
Microgreens: A Novel Food for Nutritional Security

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Abstract Microgreens are 7–21-day-old seedlings of certain crop species which are harvested at first true leave stage manually or mechanically cutting the seedlings 5–10 mm above the growing media surface. Microgreens are considered as high-value functional foods as these are the storehouse of various antioxidants and certain minerals like K, Ca, Fe, and Zn. Microgreens have gained a lot of attention and popularity over last few years as a novel food, mainly due to their unique flavor, color, texture, and nutritional profiles. Recent studies have revealed that microgreens are richer than mature greens in some vitamins, sugars, and antioxidants, including carotenoids. The consumption of microgreens also appears to be associated with multiple health benefits like reduced risk of cardiovascular disease, possibly due to prevention of hypercholesterolemia, and also provides protection against inflammatory processes, oxidative stress, and chronic diseases. Until now, microgreens have gained market mostly in the western countries; however, in other parts of the world, this is gaining foothold, especially in the urban and peri-urban settings. Rapid growth cycle, limited space requirement, rich flavor, diverse color, and highly economic produce make microgreens a dietary alternative that may contribute to the nutritional security of a large population. Success of microgreens technology will largely depend on the collective and collaborative efforts from the industry and researchers in the food chemistry, biochemistry, genetics, and human nutrition

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R. S. V., S. Praveen (eds.), *Conceptualizing Plant-Based Nutrition*,
https://doi.org/10.1007/978-981-19-4590-8_7

working to enhance the production of secondary metabolites. In this chapter, we have comprehensively covered various functional and nutritional aspects of a number of microgreens which are popularly being grown and consumed across the globe.

Keywords Biofortification · Functional foods · Lighting · Microgreens · Novel foods

7.1 Introduction

In an era of fast-paced lifestyle, humans require easily available, and healthy food options at affordable prices (Cohen and Garrett 2010). In this context, microgreens are nutrient-rich food crops which can be produced from a number of crops like vegetables, herbs, grains, or even some wild species. The term "microgreens" signify the very small ("micro") and delicate seedlings (mostly of "green" color) of certain crop species which are consumed either raw or partially cooked. Microgreens are also called "vegetable confetti" which are generally 7–21-day-old tender immature greens of 5–10 cm height (Fig. 7.1) having three major parts, viz. stem, cotyledonary leaf, and a pair of true leaves (Xiao et al. 2012; Sun et al. 2013). The global market of microgreens can be segmented mainly into four broad categories, viz. (1) green types like Brassicaceae (cabbage, broccoli, etc.), Asteraceae (lettuce, chicory, etc.), Amaranthaceae (amaranth, spinach, etc.), Cucurbitaceae (cucumber, melons, etc.), Lamiaceae (basil, mint, etc.), and others (lentils, mung bean, leeks, etc.); (2) farm

Fig. 7.1 Microgreens of (**a**) mungbean, (**b**) mustard, (**c**) red cabbage, and (**d**) lettuce

types (outdoor farming, greenhouse farming, vertical farming); (3) end uses (food and beverages, cosmetics, etc.); and (4) geographical region-based (North America, Latin America, Europe, Asia Pacific, Middle East, and Africa) (Globe Newswire Europe 2018; Samuolienė et al. 2013a).

The United States of America (U.S.A.) is a major producer of microgreens in the global market which is followed by Canada and Mexico. In terms of geography, North America is leading the microgreens market with a share of nearly 50% in terms of dollar sales in 2019. The large-scale microgreens farming and consumption (mostly in the restaurants) in the U.S.A. are supporting the microgreens market in this region (https://www.datamintelligence.com). During the 5-year period of 2020–2025, the global microgreens market is anticipated to grow at a CAGR (compound annual growth rate) of 7.5–8.0% (www.researchandmarkets.com), while in U.S.A. it is projected to register a CAGR of 10.1% (www.reportlinker.com). Overall, the market of indoor farming, including the hydroponic system kits for microgreens, was assessed to have a worth of nearly 25.40 billion US dollars in the year 2017 and is expected to reach the value of 40.25 billion US dollars (Globe Newswire Europe 2018).

Microgreens, as a culinary delight, were first reported in late 1980s by the chefs of some restaurants in San Francisco, California (USA), especially in imparting color and flavor to the cuisines. It has then gained attention during last decade as an innovative cooking constituent (Treadwell et al. 2010). The popularity of microgreens is also due to their uniquely varied colors, delicate structures, textures, and flavors, which are required for the garnishing of salads, sandwiches, soups, etc. (www.agresearchmag.ars.usda.gov). In addition, microgreens are loaded with an array of phytonutrient constituents possessing potential bioactive functions (Sun et al. 2013; Mishra et al. 2022; Xiao et al. 2012).

Microgreens are sometimes misconstrued as sprouts and baby greens or baby leaf. However, sprouts, microgreens, and baby leaf are of different food categories which are of special interest due to their unique sensorial and nutritional properties. According to definition of European Union (2013), "sprouts" are the "product obtained from the germination of seeds and their development in water or another medium, harvested before the development of true leaves and which is intended to be eaten whole, including the seed" (EU/208/2013), while "baby leaf" is the "young leaves and petioles of any crops (including Brassica) harvested up to 8 true leaf stage" (EU 752/2014). However, till now there is no "legal definition" for "microgreens," and it is still a marketing or a commercial term (Treadwell et al. 2010). The fine differences between these terminologies are presented in the Table 7.1.

Microgreens differ from sprouts as the former requires light, a growing medium (both soil or soilless), more growth period, and shoots are the edible portion. Nevertheless, compared to baby greens, microgreens need less growth period, do not necessitate any agrochemicals, and may be marketed without cutting of the seedlings (with growing media), which extends their shelf life window (www.botanicalinterests.com). However, all the three are preferably consumed as raw (Di Gioia et al. 2017a). When microgreens are grown in some solid medium (soil,

Table 7.1 Key characteristics of sprouts, microgreens, and baby leaf or baby greens

Features	Sprouts	Microgreens	Baby leaf/baby greens
Growth period (day)	4–10	7–21	20–40
Edible portion	Sprout	Shoots (cotyledons and first pair of true leaves, but no roots)	True leaves (no roots)
Growth system	Soilless (only water)	Mainly soilless (require some growing medium)	Soil or soilless (as growing medium)
Light requirement	No	Yes	Yes
Nutrient requirement	No	Yes (if growing medium is devoid of nutrients)	Yes
Agrochemicals requirements	No	No	Yes
Plant harvest stage	After germination but before full cotyledonary leaves stage	Generally, between full cotyledonary leaf and first true leaves stage	Between first to eighth true leaves stage
Harvesting (cutting)	No	Yes	Yes

Adapted from Di Gioia et al. (2015, 2017a)

peat, vermiculite, etc.), they pose very little risk of microbial contamination compared to that of sprouts (Di Gioia et al. 2017a).

Microgreens can be comfortably grown either at home or at commercial scale under controlled environmental conditions (greenhouses) or even under open conditions, irrespective of the season (Ebert et al. 2015, 2017) in a variety of growing medium (soil, soilless), depending on the scale of production. The growing media is very crucial for the proper germination and growth of microgreens. The desired physical properties of the solid growing media include nearly 85% porosity, water holding capacity between 55 and 70% of the total volume, and aeration to the extent of 20–30% of total volume for the roots (Abad et al. 2001). The growing media can be organic (peat, coir, etc.) or inorganic (like perlite and vermiculite). The most commonly used growing substrates for the microgreens production are vermiculite, peat, sand, and perlite either individually or in combination depending on the species grown (Di Gioia et al. 2015). Desired chemical properties of the media include a pH range of 5.5–6.5 and electrical conductivity below 500 μS/cm and should be free of any heavy metal and microbial contamination such as *Salmonella* and *E. coli* (Di Gioia et al. 2015, 2017a). Microgreens are generally grown in the plastic trays, of various sizes having depth of 3–5 cm, which is required for placing the ample growing medium to support the microgreens till it reaches the harvesting stage. Based on the type of microgreens grown, the base of the tray can be with or without holes, more often with holes for facilitation of the drainage (Di Gioia et al. 2015).

The trays should be placed on a leveled surface on the benches (movable or static) (Di Gioia et al. 2017a).

Special attention is required while harvesting the microgreens to avoid the sticking of any growing media particles and seed integuments which in certain species tend to remain attached (Di Gioia et al. 2015). Immediately after the harvest, microgreens are washed and cooled (1–5 °C) (Kyriacou et al. 2016) or alternatively marketed in trays or growing plants are packed with the growing media (Di Gioia et al. 2017a). Thus, postharvest handling is very crucial for extending the shelf life of the microgreens which otherwise are highly perishable. A method of shelf life extension of microgreens, to at least 10 days, has been patented by Sasuga (2014). The most important parameters for the storage of microgreens are temperature (18–24 °C) and relative humidity (40–60%) (Hodges and Toivonen 2008) as these factors significantly affect the tissue electrolytic leakage and influence microbial contamination (Kou et al. 2013).

Phytonutrient content is reportedly varying with the changing growth stage of the plants, and a decrease has been observed from the seedling (sprout/microgreen) to the fully grown stage. Seed germination enhances the nutritive value of the plants by activation of the enzymes which reduces or even eliminates the antinutritional factors, especially in the legumes (Bau et al. 1997; Mubarak 2005). During germination, there is breakdown of fibrous components which are bound to vitamins, minerals, and amino acids, and thus, the availability of these desired phytochemicals including micronutrients like Fe and Zn increases. In addition, germination also eliminates the flatulence-causing agents (Bird 2014).

Considering a few days of photosynthesis, microgreens are reported to contain much higher contents of various antioxidants, vitamins, and minerals than the sprouts. In general, microgreens contain nearly 4–6 times more nutrients than that of their mature leaves. Microgreens contain relatively high phytonutrients (ascorbic acid, β-carotene, α-tocopherol, and phylloquinone) and minerals (Ca, Mg, Fe, Mn, Zn, Se, and Mo) and less nitrate contents than their mature counterparts (Pinto et al. 2015; Xiao et al. 2012). In this context, microgreens are one of the novel food products which could also be considered as functional and nutraceutical foods for the health-conscious consumers (Kyriacou et al. 2016). Microgreens offer a great potential to become a food of choice to achieve nutritional security of a broad range of settlements due to their ease in the cultivation under varied environmental conditions.

7.2 Crop Species Suitable for Microgreens Cultivation

The crop species used for the production of microgreens are generally of intense color and flavor and rich in various phytochemicals such as antioxidants and vitamins. In addition, the selected crop species are of such type which can be consumed raw as seedlings. A range of crops can be used for the production of microgreens which include beet, broccoli, flax, kale, peas, and radish. The most

Table 7.2 List of commonly grown microgreens belonging to nine crop families

S. no.	Family/species	Species
1.	Amaranthaceae	Amaranth, beet, chard, quinoa, spinach
2.	Amaryllidaceae	Chive, garlic, leeks, onion
3.	Apiaceae	Carrot, celery, dill, fennel
4.	Asteraceae	Chicory, endive, lettuce, radicchio
5.	Brassicaceae	Arugula, broccoli, cabbage, cauliflower, Chinese cabbage, kale, mustard, radish, radish, savoy cabbage, tatsoi, watercress
6.	Cucurbitaceae	Cucumber, melon, squash
7.	Fabaceae	Alfalfa, beans, chickpea, clover, fenugreek, fava bean, lentil, mung bean, pea
8.	Lamiaceae	Mint, basil, rosemary, sage, oregano
9.	Poaceae	Barley, corn, rice, oat, pearl millet, wheatgrass
10.	Aromatic species	Basil, chives, cilantro, cumin
11.	Wild edible plants	Amaranth, *Beta vulgaris,* borage, common dandelion, *Diplotaxis erucoides,* goatsbeard, *Portulaca oleracea*, prickly golden fleece, pigweed, salicornia, sea fennel, wild chicory, wild fennel, wild radish, white mustard

Source: https://grocycle.com/types-of-microgreens/; Turner et al. (2020) and Di Gioia et al. (2015)

commonly used species are from the crop families like Amaranthaceae, Amaryllidaceae, Apiaceae, Asteraceae, Brassicaceae, Chenopodiaceae, Cucurbitaceae, Fabaceae, and Lamiaceae.

Some members of the solanaceous family (tomato, brinjal, and pepper) are not considered edible as they contain various antinutrients (Di Gioia et al. 2015) and thus cannot be grown as the microgreens. Even among the edible species, there are various other factors like palatability, flavor, smell, texture, and color that are key traits for the consumer acceptability, while companies/producers of the microgreens look for attractive colors, shapes, flavor, and shelf life (Di Gioia et al. 2015). From the commercial perspective, the selection of microgreens species should be based on the availability of good quality untreated seeds with high and homogeneous germination and have least unit cost of the seeds (Di Gioia et al. 2017a). A comprehensive list of microgreens under cultivation across different countries is presented in Tables 7.2 and 7.3.

7.3 Growth Conditions and Quality of Microgreens

A number of factors that regulate the overall quality of microgreens and phytochemical contents are (1) genetic variability (between and within the taxa), (2) environmental impact (temperature, light quality, and quantity, photoperiod, etc.), and (3) genotype and environmental interaction. However, these factors have not yet been investigated very critically for a large number of species used in the production

Table 7.3 List of most commonly grown microgreens, their growth, harvest, and nutritive properties

S. no.	Crop species	Soaking/ presoak (h)	Suitable growth medium	Germ time (day)	Harvest time (day)	Color	Flavor	Nutrients
1.	Amaranth	No	S/H	2–3	8–12	Red/pink	Mild and sweet	Vitamin (K, E, C), Ca, Fe, beta carotenes
2.	Arugula	No	S/H	1–2	6–8	Green	Peppery and slightly buttery	Vitamin (A, C), Ca, Fe, P
3.	Barley	8–12	S/H	2–3	6–9	Bright green	Sweet	–
4.	Basil	No	H	3–4	8–12	Purple or green	Intense basil type	–
5.	Beets	4–10	S	3–4	11–21	Red stems and green top	Sweet and earthy	Vitamin (A, B, C, E, K), Ca, Mg, K, Fe, Zn, protein
6.	Broccoli	No	S/H	2–3	8–12	Green	Strong broccoli type	Vitamin (A and C), Ca, Fe, P
7.	Brussel sprouts	No	S/H	2–3	7–14	White/pink/ purple	Like broccoli and cabbage	Vitamin (B, C, K), folic acid, fiber
8.	Cabbage	No	S/H	2–3	6–14	Green	Strong brassica type	Vitamin (C, K, E), beta carotenes, Fe
9.	Cauliflower	No	S/H	2–3	8–14	Deep green	Strong brassica type	Vitamin (C, K, E), beta carotenes, Fe
10.	Chives	No	S/H	7–14	21–25	Green	Onion type	–
11.	Coriander	8–10	S/H	2–3	21–28	Green	Cilantro type	Vitamin (A, C), Ca, Fe, P
12.	Clover	No	S/H	1–2	8–12	Green	Mild, fresh	–
13.	Corn	12–16	H/S	2–3	12–16	Bright yellow to light green	Sugary and sweet	Vitamin (A, B, C, E), Ca, Mg
14.	Cress	No	S/H	2–3	7–14	Green	Intense peppery	Vitamin (B, C, K), folic acid, fiber
15.	Dill	No	S/H	1–2	10–14	Green	Sweet like dill	–
16.	Fennel	No	S/H	3–4	12–14	Green	Mild, anise like	–
17.	Kale	No	S/H	2–3	8–12	Pale green	Broccoli like, nutty, and rich	Antioxidants, fiber, vitamin (A, C, K), Fe, Cu
18.	Lettuce	No	S/H	3–4	14–16	Green	Lettuce like	Vitamin (B, C, K), folic acid, fiber
19.	Mustard	No	S/H	2–3	8–12	Green	Mustard like	Antioxidants, fiber, vitamin (A, C, E, K)
20.	Oat	1–4	S/H	2–3	6–9	Bright green	Fresh and mild	–

(continued)

Table 7.3 (continued)

S. no.	Crop species	Soaking/ presoak (h)	Suitable growth medium	Germ time (day)	Harvest time (day)	Color	Flavor	Nutrients
21.	Onion/leek	No	S/H	3–4	12	Green	Onion	–
22.	Oregano	No	S/H	7–14	20–22	Light pink to deep red	Oregano like	–
23.	Parsley	No	S/H	4–7	20–22	Light pink to deep red	Oregano like	–
24.	Pea	4–12	H/S	2–3	12–16	Green	Crunchy, sweet (like peas)	Vitamin (A, C), folic acid, fiber
25.	Radish	4–6	S/H	1–2	6–12	Red stem and deep green top	Spicy and slightly floral	Vitamin (A, B, C, E, K), folic acid, niacin, K, Fe, Zn, P, Ca, Mg, pantothenic acid, carotenes
26.	Rye	8–10	S/H	1–2	5–9	Green	Slightly bitter, like barley	Vitamin (B, C, K), folic acid, fiber
27.	Sunflower	8–12	S	2–3	8–12	Green	Crunchy, nutty, fresh	Vitamin (A, B, D, E), Ca, Fe, Mg, K, P
28.	Swiss chard	4–10	S	3–4	11–21	Dark red	Sweet and earthy, like Swiss chard microgreens	Vitamin (A, B, C, E, K), Ca, Mg, K, Fe, Zn, protein
29.	Turnip	No	S/H	2–3	8–12	Deep green	Fresh turnip and radish-like	Vitamin (C, K, E), beta carotenes, Fe
30.	Wheat	6–12	S/H	2–3	6–9	Bright green	Sweet with little or no bitterness	–
31.	Pearl millet	No	S/H	2–3	6–9	Bright green	Sweet with little or no bitterness	–
32.	Lentil	8–12	S/H	2–3	8–10	Green	Mild bitter, pea-like	Vitamin (A, B, C, E), low fat, folate, K, Fe, protein, beta carotenes
33.	Mung bean	8–12	S/H	1–2	6–8	Green	Mild beany taste, slight buttery	Vitamin (C, K, E), Fe, beta carotenes
34.	Chickpea	8–10	S/H	2–3	8–10	Bright green	Sweet and nut-like	Protein, fiber, folate, vitamin (A, C, K, B6)
35.	Fenugreek	No	S/H	2–3	10–14	Green	Subtle bitter taste, mild spicy, nutty	Vitamin C, protein, fibers, antioxidant, K, Fe

S soil, *H* hydroponic, *h* hour, *d* days
Source: https://www.hydrocentre.com.au/blog/types-of-microgreens/; https://microveggy.com/types-of-microgreens/

of microgreens. Very high variations in the bioactive contents largely depend upon both the genetics of the trait and also on the prevailing environmental conditions (Kader 2008). Hitherto, the effect of light quality and quantity is one of the most investigated parameters which is known to regulate the overall biochemical composition of the microgreens.

7.3.1 Light Spectra and the Biochemical Composition of Microgreens

The morphophysiology of microgreens is highly influenced by the light conditions as it significantly regulates the biosynthesis and accumulation of various phytochemicals (Delian et al. 2015). Light quality has more definite effects over light intensity or photoperiod in the regulation of growth and physiology of the microgreens (Bian et al. 2015). Instead of natural lighting, growers prefer to use high-pressure sodium (HPS) lamps (~150 μmol/m^2/s) (Vaštakaitė and Viršilė 2015). However, research is exploring the utility of light-emitting diode (LED)-based illumination for the optimal microgreens cultivation (Agarwal and Gupta 2016), as these can be matched with the plant photoreceptors to optimize the production of various phytochemicals (Morrow 2008). LED-based systems are environment friendly over HPS, and they allow even light dispersal over any conventional lighting systems (Agarwal and Gupta 2016; Morrow 2008).

Moreover, the light quality in terms of photon flux and photoperiod (wavelength) can help in the improvement of some biochemicals, thereby regulating the functional quality of microgreens (Kyriacou et al. 2016). Supplementation with green light and standard LED illumination (blue/red/far-red) has shown the improvement in the carotenoid content of the mustard microgreens and red pak choi/tatsoi microgreens, respectively (Brazaitytė et al. 2015a). Three-day application of supplementary red light (pre-harvest) has recorded better antioxidant levels in some microgreens (Samuolienė et al. 2012). Red, blue, or mix of theses lights were found more effective over white or yellow light alone in reducing the undesirable nitrates contents in the microgreens (Ohashi-Kaneko et al. 2007; Qi et al. 2007). Nevertheless, the precise molecular or biochemical mechanisms regulating the spectral quality-induced variations in the bioactive compounds of the microgreens have not been uncovered yet (Kyriacou et al. 2017).

Light quality is known to affect various plant growth, color, flavor, and nutrition-related parameters (Kyriacou et al. 2016). Alrifai et al. (2019) found red, blue, and combined lights are more effective than the white light for better photosynthesis and metabolism. Better antioxidant profile of lentil and wheat was recorded when supplemented with green light (510 nm) (Samuolienė et al. 2011), while better mineral profile was observed in beet microgreens (Brazaitytė et al. 2018). Green LED lighting produced different anthocyanin levels in the microgreens produced from the green and red genotypes of the same species (Carvalho and Folta 2016).

However, red and blue lights showed improved phenolic content and free radical scavenging activity in the green and red ocimum cultivars, respectively (Lobiuc et al. 2017). Amber light (595 nm) supplementation enhanced antioxidants in radish sprouts (Samuolienė et al. 2011), while supplementation of short-term red LED lighting could alter the antioxidant composition in some of the microgreens including ocimum, amaranth, brassica, spinach, broccoli, beetroot, and green peas (Samuolienė et al. 2012). In general, supplemental light wavelengths are reported to cause enhanced production of various bioactive compounds, which could play protective role against mild photooxidative stress, in a number of microgreens species.

Vaštakaitė et al. (2015b) imposed photostress by both insufficient and an excess of blue light, which has resulted in the biosynthesis of various protective antioxidants. Differential synthesis of various phytochemicals and antioxidant activity under similar supplemental lighting is dependent on genotype and the season of cultivation (Turner et al. 2020). The presence of relative cloud cover, day length of the microgreen growing period, and incident light angle are some of the key factors affecting both light quality and quantity which suggests the importance of the supplemental light while growing microgreens (Turner et al. 2020).

Ultraviolet (UV) spectra, which fall beyond the visible spectra, are also reported to influence the physiological responses of the plants, and UV-A (320–400 nm) spectrum is considered least harmful (Brazaitytė et al. 2015b). A number of studies have shown that by changing the spectral composition, certain targeted phytochemicals content of the microgreens can be modified (Table 7.4).

Besides the wavelength, even changes in the light pulse frequency can also influence the overall plant developmental and photosynthetic activities (Ani et al. 2014; Vaštakaitė et al. 2017, 2018). Same light quality with varying irradiance levels may cause differential effects on overall nutritional quality of microgreens. High-light conditions cause increased photosynthesis in the growing microgreens, which in turn reduces the susceptibility to photodamage. However, low-light conditions increase the number of light-harvesting complexes for the optimized light utilization (Walters 2005).

Photoperiod also affects the accumulation of various phytochemicals in the microgreens, and it interacts with both quality and intensity of the light used for growth and development of microgreens. Effect of light intensity on the growth and nutrition of microgreens is well known, but the effect of photoperiod has not been thoroughly investigated. However, the effect of photoperiod on the nutrient composition of baby spinach was reported by Lester et al. (2010, 2013). In case of pea-derived microgreens, Wu et al. (2007) studied the effects of 96-h continuous illumination based on blue, red, and white LEDs on biosynthesis and accumulation of various phytochemicals. In-depth research is required to unravel the mechanism regulating the induction of secondary metabolites synthesis and light-associated signal transduction pathways in different microgreens species (Kyriacou et al. 2016).

Environmental conditions of high-altitude regions (Leh, India), especially regions having wide temperature amplitude, PAR, and UV-B content, cause differential nutrient profile of the lentil and mung bean microgreens when compared to that of

Table 7.4 Effect of light quality and quantity on the growth and nutritional composition of various microgreens

S. no.	Microgreens species	Lighting	Effect	References
1.	Kale, broccoli, pea	Red (638 nm)	Increased (ascorbic acid, phenolics, anthocyanins)	Samuolienė et al. (2012)
2.	Mustard, borage, beet, parsley	Red (638 nm)	Reduced (anthocyanins)	Samuolienė et al. (2012)
3.	Mustard	463 μmol/m^2/s	Reduced (β-carotene) Increased (zeaxanthin)	Kopsell et al. (2012)
4.	Purple mint (*Perilla frutescens*)	Red (638 nm)	Increased (anthocyanins, ascorbic acid) Decreased (nitrate content)	Brazaitytė et al. (2013)
5.	Broccoli	Blue (470 nm; 41 μmol/m^2/s)	Increased (β-carotene, violaxanthin, glucoraphanin, K, Mg, Fe)	Kopsell and Sams (2013)
6.	Broccoli	Red (627 nm; 88%) + blue (470 nm; 12%); 350 μmol/m^2/s	Decreased (β-carotene, violaxanthin, glucoraphanin, K, Mg, Fe)	Kopsell and Sams (2013)
7.	Kohlrabi, mustard, red pak choi, tatsoi	330–440 μmol/m^2/s	Increased (leaf area, anthocyanins, phenolics, DPPH activity) Decreased (nitrate content)	Samuolienė et al. (2013b)
8.	Tatsoi, red pak choi	110–220 μmol/m^2/s	Increased (ascorbic acid, α-tocopherol)	Samuolienė et al. (2013b)
9.	Lettuce	Red + blue + white; 400–600 μmol/m^2/s	Increased (biomass)	Lin et al. (2013)
10.	Red pak choi, tatsoi, basil	Blue (447 nm) + red (638, 665 nm) + far-red (731 nm)	Increased (ascorbic acid, phenols, anthocyanins, flavanols, DPPH scavenging, leaf area) Decreased (hypocotyl length, plant height)	Vaštakaitė et al. (2015a)
11.	Mustard, red pak choi	Basal light (447, 638, 665, 731 nm), green (520 nm), yellow (595 nm), or orange (622 nm)	Increased (carotenoids in mustard) Decreased (carotenoids in red pak choi)	Brazaitytė et al. (2015a)
12.	Tatsoi	Supplemental yellow	Increased (violaxanthin, carotenoid)	Brazaitytė et al. (2015a)
13.	Basil, beet, pak choi	UV-A + basal lighting (12.4 μmol/m^2/s)	Increased (antioxidants)	Brazaitytė et al. (2015b)
14.	Pak choi	UV-A	Increased (leaf area, FW, DPPH activity, phenols, anthocyanins, ascorbic acid, α-tocopherol)	Brazaitytė et al. (2015b)

(continued)

Table 7.4 (continued)

S. no.	Microgreens species	Lighting	Effect	References
15.	Basil	UV-A (1, 7 or 14 days before harvest)	Increased (antioxidant contents)	Vaštakaitė et al. (2015a)
16.	Mustard, beet, parsley	Blue (33%)	Increased (chlorophylls, carotenoid)	Samuolienė et al. (2017)
17.	Mustard, beet, parsley	Blue (16%)	Increased (tocopherols)	Samuolienė et al. (2017)
18.	Ocimum	Blue	Increased (growth, chlorophyll *a*, anthocyanin)	Lobiuc et al. (2017)
19.	Pak choi, tatsoi	32 Hz, 455 nm, 627 nm	Increased (TPC in pak choi, red pak choi, tatsoi)	Vaštakaitė et al. (2017)
20.	Mustard	256, 1024 Hz and 470, 590 nm	Increased (phenolics content)	Vaštakaitė et al. (2017)
21.	Wild rocket	272 μmol/m^2/s	Increased (polyphenols, resveratrol, catechin, epicatechin)	Loedolff et al. (2017)
22.	Beet	Blue (455 nm)	Increased (P, K, Ca, Mg, S, and Mn) Decreased (Na, Fe, Zn, Cu, and B)	Brazaitytė et al. (2018)
23.	Kohlrabi	Blue (455 nm)	Increased (P, K, Ca, Mg, S, and Mn) No effect (Fe, Zn, Cu, or B)	Brazaitytė et al. (2018)
24.	Red pak choi, mustard, tatsoi, basil	Pulse of LEDs at specific frequencies or supplementing HPS lights of specific wavelength	Increased [phenols, anthocyanins, ascorbic acid (in basil), antiradical activity in all]	Vaštakaitė et al. (2017, 2018)
25.	Basil	(1) Blue (470 nm) + red (627 nm) at 1024 Hz (2) Blue (455 nm) at 256 Hz	(1) Increased (TPC, anthocyanins) (2) Increased (TPC)	Vaštakaitė et al. (2018)
26.	Basil	(1) 256 Hz for all wavelengths except 627 nm (2) 32 and 256 Hz	(1) Increased (DPPH activity) (2) Increased (ascorbic acid)	Vaštakaitė et al. (2018)
27.	Tatsoi	Blue	Decreased (nitrate, ascorbic acid)	Simanavičius and Viršilė (2018)
28.	Brassica species	600 μmol/m^2/s; blue: red (15:85)	Increased (FW, DW)	Jones-Baumgardt et al. (2019)
29.	Cabbage	Blue (15%)	Increased (yield, visual quality)	Ying et al. (2020)
30.	Kale, arugula, mustard	Blue (5%)	Increased (yield, visual quality)	Ying et al. (2020)

FW fresh weight, *DW* dry weight, *TPC* total phenolics content microgreens grown in plains (Delhi, India) (Priti et al. 2021). In general, better antioxidant profiles were recorded from the samples grown in Leh. Various enterprises have entered into the venture of growing the microgreens under indoor conditions, in a multilayer system, under artificial lighting having desired level of radiation (nearly 100 μmol/m^2/s of photosynthetically active radiation) for photosynthesis. At times, natural sunlight is integrated with supplemental lighting, with control on light intensity and quality, for the production of microgreens having enhanced nutritional composition (Kopsell and Sams 2013; Samuolienė et al. 2013b).

7.4 Biochemical Composition of Microgreens

Different microgreens species have varied flavor and are also quite rich in different bioactive contents, and hence, there is a need to identify the genotypes which can fulfill both the taste and nutritional priorities (Xiao et al. 2015a). Sprouts and microgreens are also used as dietary supplements (Kovacs 1996) and functional foods which can minimize the risk of various diet-related diseases (Tang et al. 2014). In this section, the details of biochemical composition of microgreens including vitamins, carotenoids, total sugars, minerals, and antioxidants are presented (Table 7.5).

7.4.1 Antioxidants and Vitamins

A study of 25 diverse microgreens species at USDA and University of Maryland revealed nearly 10 times more antioxidant contents over their mature counterparts (Xiao et al. 2012). The total antioxidant capacity (TAC) in radish microgreens increased nearly 1.7 times under high light (HL) (4.6 ± 0.6 mg/g DW) over normal light (NL) (2.6 ± 0.7 mg/g DW), while in kale the increase was nearly 2.5 times under HL (9.2 ± 1.8 mg/g DW) over NL (3.6 ± 0.5 mg/g DW) (Goble 2018). A set of 20 mung bean and lentil genotypes each, when grown as microgreens under plain-altitude (Delhi) and high-altitude (Leh) conditions, showed significant genotypic variations for ascorbic acid, tocopherol, carotenoids, flavonoid, total phenolics, antioxidant activities (DPPH, FRAP), peroxide activity, proteins, enzymes (peroxidase and catalase), micronutrients, and macronutrients contents (Priti et al. 2021).

The dark-green microgreens such as those derived from spinach, kale, and broccoli are known to possess relatively high phylloquinone (or vitamin K1), which is an essential component required for the coagulation of blood (Olson 1984). Xiao et al. (2012) have reported the phylloquinone content in the range of 0.6 (spinach) to 4.1 (amaranth) μg/g fresh weight (FW) among 25 microgreens species. The phylloquinone content in the mature amaranth, basil, and red cabbage was reported as 1.14, 0.41, and 0.04 μg/g FW, respectively (Haytowitz et al. 2002).

Table 7.5 Nutritional composition of some commonly grown microgreens

S. no.	Microgreens	Nutrient	Quantification	Light conditions	Duration (h)	References
1.	Amaranth	Lipophilic AoA	52.63–80.60 mmol TE/100 g DW	$B_{400–500}$, $R_{600–700}$, B-R	12.0	Kyriacou et al. (2019)
2.	Cress	Lipophilic AoA	87.76–99.13 mmol TE 100 g DW	$B_{400–500}$, $R_{600–700}$, B-R	12.0	Kyriacou et al. (2019)
3.	Mizuna	Lipophilic AoA	77.69–94.62 mmol TE/100 g DW	$B_{400–500}$, $R_{600–700}$, B-R	12.0	Kyriacou et al. (2019)
4.	Purslane	Lipophilic AoA	77.72–94.49 mmol TE 100 g DW	$B_{400–500}$, $R_{600–700}$, B-R	12.0	Kyriacou et al. (2019)
5.	Amaranth	Lutein	76.0–135.9 mg/kg DW	$B_{400–500}$, $R_{600–700}$, B-R	12.0	Kyriacou et al. (2019)
6.	Cress	Lutein	73.9–123.1 mg/kg DW	$B_{400–500}$, $R_{600–700}$, B-R	12.0	Kyriacou et al. (2019)
7.	Mizuna	Lutein	54.4–87 mg/kg DW	$B_{400–500}$, $R_{600–700}$, B-R	12.0	Kyriacou et al. (2019)
8.	Purslane	Lutein	91.5–135.2 mg/kg DW	$B_{400–500}$, $R_{600–700}$, B-R	12.0	Kyriacou et al. (2019)
9.	Mustard	Lutein	0.39–0.56 mg/g DW	R:G:B (74:18:8); R:FR:B (84:7:9); 105, 210, and 315 mmol/m^2/s	16.0	Craver et al. (2017)
10.	Basil	Lutein	47.80–74.40 µg/g	B_{455}, R_{638}, R_{665}, FR_{731}; 210 and 300 µmol/m^2/s	16.0	Samuolienė et al. (2016)
11.	Parsley	Lutein	76.31–106.62 µg/g	B_{455}, R_{638}, R_{665}, FR_{731}; 210 and 300 µmol/m^2/s	16.0	Samuolienė et al. (2016)
12.	Mustard	Lutein	3.13–3.44 mg/100 g FW	275 and 463 µmol/m^2/s	–	Kopsell et al. (2012)
13.	Kohlrabi	Lutein	0.52–0.63 mg/g DW	R:G:B (74:18:8), R:FR:B (84:7:9 and 84:7:9); 315, 210 and 105 mmol/m^2/s	16.0	Craver et al. (2017)
14.	Mizuna	Lutein	0.46–0.64 mg/g DW	R:G:B (74:18:8), R:FR:B (84:7:9 and 84:7:9); 315, 210, and 105 mmol/m^2/s	16.0	Craver et al. (2017)
15.	Golden pea tendrils	Lutein	2.7 mg/100 g FW	No light	–	Xiao et al. (2012)
16.	Popcorn shoots	Lutein	1.3 mg/100 g FW	No light	–	Xiao et al. (2012)

17.	Carrot	β-Carotene	5.8 mg/100 g FW	2500–4400 lux	11.5	Ghoora et al. (2020)
18.	Fennel	β-Carotene	9.1 mg/100 g FW	2500–4400 lux	11.5	Ghoora et al. (2020)
19.	Fenugreek	β-Carotene	3.1 mg/100 g FW	2500–4400 lux	11.5	Ghoora et al. (2020)
20.	French basil	β-Carotene	6.8 mg/100 g FW	2500–4400 lux	11.5	Ghoora et al. (2020)
21.	Mustard	β-Carotene	7.4 mg/100 g FW	2500–4400 lux	11.5	Ghoora et al. (2020)
22.	Onion	β-Carotene	3.8 mg/100 g FW	2500–4400 lux	11.5	Ghoora et al. (2020)
23.	Radish	β-Carotene	7.6 mg/100 g FW	2500–4400 lux	11.5	Ghoora et al. (2020)
24.	Roselle	β-Carotene	6.4 mg/100 g FW	2500–4400 lux	11.5	Ghoora et al. (2020)
25.	Spinach	β-Carotene	6.1 mg/100 g FW	2500–4400 lux	11.5	Ghoora et al. (2020)
26.	Sunflower	β-Carotene	4.5 mg/100 g FW	2500–4400 lux	11.5	Ghoora et al. (2020)
27.	Parsley	β-Carotene	43.54–53.45 μg/g	B_{455}, R_{638}, R_{665}, FR_{731}; 210 and 300 μmol/m^2/s	16.0	Samuolienė et al. (2016)
28.	Kohlrabi	β-Carotene	0.28–0.34 mg/g DW	R:G:B (74:18:8), R:FR:B (84:7:9 and 84:7:9); 315, 210, and 105 mmol/m^2/s	16.0	Craver et al. (2017)
29.	Mizuna	β-Carotene	0.22–0.35 mg/g DW	R:G:B (74:18:8), R:FR:B (84:7:9 and 84:7:9); 315, 210, and 105 mmol/m^2/s	16.0	Craver et al. (2017)
30.	Mustard	β-Carotene	0.21–0.34 mg/g DW	R:G:B (74:18:8), R:FR:B (84:7:9 and 84:7:9); 315, 210, and 105 mmol/m^2/s	16.0	Craver et al. (2017)
31.	Golden pea tendrils	β-Carotene	0.6 mg/100 g FW	No light	–	Xiao et al. (2012)
32.	Amaranth	Nitrate	2.1–5.6 mg/g FW	$B_{400–500}$, $R_{600–700}$, B-R	12.0	Kyriacou et al. (2019)
33.	Cress	Nitrate	4.1–5.6 mg/g FW	$B_{400–500}$, $R_{600–700}$, B-R	12.0	Kyriacou et al. 2019
34.	Mizuna	Nitrate	2.3–3.2 mg/g FW	$B_{400–500}$, $R_{600–700}$, B-R	12.0	Kyriacou et al. (2019)
35.	Purslane	Nitrate	2.6–4.1 mg/g FW	$B_{400–500}$, $R_{600–700}$, B-R	12.0	Kyriacou et al. (2019)
36.	Basil	DPPH	9.49–10.04 μmol/g	Basal (B_{447}, R_{638}, DR_{665}, FR_{731}) + UV (366, 390, 402 nm); 6.2 and 12.4 μmol/m^2/s	–	Brazaitytė et al. (2015b)
37.	Beet	DPPH	7.00–10.90 μmol/g	Basal (B_{447}, R_{638}, DR_{665}, FR_{731}) + UV (366, 390, 402 nm); 6.2 and 12.4 μmol/m^2/s	–	Brazaitytė et al. (2015b)

(continued)

Table 7.5 (continued)

S. no.	Microgreens	Nutrient	Quantification	Light conditions	Duration (h)	References
38.	Pak choi	DPPH	7.65–10.20 µmol/g	Basal (B_{447}, R_{638}, DR_{665}, FR_{731} + UV (366,390, 402 nm); 6.2 and 12.4 µmol/m^2/s	–	Brazaitytė et al. (2015b)
39.	Basil	DPPH	7.75–9.85 µmol/g	B_{455}, R_{638}, R_{665}, FR_{731}; 210 and 300 µmol/m^2/s	16.0	Samuolienė et al. (2016)
40.	Parsley	DPPH	5.68–6.83 µmol/g	B_{455}, R_{638}, R_{665}, FR_{731}; 210 and 300 µmol/m^2/s	16.0	Samuolienė et al. (2016)
41.	Basil	Total phenol	1.30–1.93 mg/g	Basal (B_{447}, R_{638}, DR_{665}, FR_{731}) + UV (366, 390, 402 nm)	–	Brazaitytė et al. (2015b)
42.	Beet	Total phenol	0.91–1.28 mg/g	Basal (B_{447}, R_{638}, DR_{665}, FR_{731}) + UV (366, 390, 402 nm); 6.2 and 12.4 µmol/m^2/s	–	Brazaitytė et al. (2015b)
43.	Pak choi	Total phenol	0.62–0.86 mg/g	Basal (B_{447}, R_{638}, DR_{665}, FR_{731}) + UV (366, 390, 402 nm); 6.2 and 12.4 µmol/m^2/s	–	Brazaitytė et al. (2015b)
44.	Basil	Total phenols	0.54–0.64 mg/g	B_{455}, R_{638}, R_{665}, FR_{731}; 210 and 300 µmol/m^2/s	16.0	Samuolienė et al. (2016)
45.	Parsley	Total phenol	0.46–0.57 mg/g	B_{455}, R_{638}, R_{665}, FR_{731}; 210 and 300 µmol/m^2/s	16.0	Samuolienė et al. (2016)
46.	Basil	Total anthocyanins	0.31–0.97 mg/g	Basal (B_{447}, R_{638}, DR_{665}, FR_{731}) + UV (366, 390, 402 nm); 6.2 and 12.4 µmol/m^2/s	–	Brazaitytė et al. (2015b)
47.	Beet	Total anthocyanins	0.28–1.02 mg/g	Basal (B_{447}, R_{638}, DR_{665}, FR_{731}) + UV (366, 390, 402 nm); 6.2 and 12.4 µmol/m^2/s	–	Brazaitytė et al. (2015b)
48.	Pak choi	Total anthocyanins	0.37–0.99 mg/g	Basal (B_{447}, R_{638}, DR_{665}, FR_{731}) + UV (366, 390, 402 nm); 6.2 and 12.4 µmol/m^2/s	–	Brazaitytė et al. (2015b)
49.	Basil	Ascorbic acid	1.31–2.52 mg/g	Basal (B_{447}, R_{638}, DR_{665}, FR_{731}) + UV (366, 390, 402 nm); 6.2 and 12.4 µmol/m^2/s	–	Brazaitytė et al. (2015b)
50.	Beet	Ascorbic acid	0.69–7.49 mg/g	Basal (B_{447}, R_{638}, DR_{665}, FR_{731}) + UV (366, 390, 402 nm); 6.2 and 12.4 µmol/m^2/s	–	Brazaitytė et al. (2015b)

51.	Pak choi	Ascorbic acid	0.30–1.25 mg/g	Basal (B_{447}, R_{638}, DR_{665}, FR_{731}) + UV (366,390, 402 nm); 6.2 and 12.4 μmol/m^2/s	–	Brazaitytė et al. (2015b)
52.	Basil	Ascorbic acid	2.51–5.85 mg/g	B_{455}, R_{638}, R_{665}, FR_{731}; 210 and 300 μmol/m^2/s	16.0	Samuolienė et al. (2016)
53.	Parsley	Ascorbic acid	0.94–13.39 mg/g	B_{455}, R_{638}, R_{665}, FR_{731}; 210 and 300 μmol/m^2/s	16.0	Samuolienė et al. (2016)
54.	Golden pea tendrils	TAA	25.1 mg/100 g FW	No light	–	Xiao et al. (2012)
55.	Popcorn shoots	TAA	31.8 mg/100 g FW	No light	–	Xiao et al. (2012)
56.	Red basil cultivars	Total carotenoids	0.10–0.15 mg/g	R:B (2:1), R:B (1:1), R:B (1:2); 120 μmol/m^2/s	12.0	Lobiuc et al. (2017)
57.	Green basil cultivars	Total carotenoids	0.09–0.11 mg/g	R:B (2:1), R:B (1: 1), R:B (1:2); 120 μmol/m^2/s	12.0	Lobiuc et al. (2017)
58.	Mustard	Total chlorophyll	14.64–20.28 mg/g DW	275 and 463 μmol/m^2/s	12.0	Kopsell et al. (2012)
59.	Kohlrabi	Total chlorophyll	6.21–8.47 mg/g DW	R:G:B (74:18:8), R:FR:B (84:7:9 and 84:7:9); 315, 210, and 105 mmol/m^2/s	16.0	Craver et al. (2017)
60.	Mizuna	Total chlorophyll	5.40–7.89 mg/g DW	R:G:B (74:18:8), R:FR:B (84:7:9 and 84:7:9); 315, 210, and 105 mmol/m^2/s	16.0	Craver et al. (2017)
61.	Mustard	Total chlorophyll	4.37–6.68 mg/g DW	R:G:B (74:18:8), R:FR:B (84:7:9 and 84:7:9); 315, 210, and 105 mmol/m^2/s	16.0	Craver et al. (2017)
62.	Basil	Chlorophyll index	30.5	Basal (B_{447}, R_{638}, DR_{665}, FR_{731}) + UV (366, 390, 7.6.402 nm); 6.2 and 12.4 μmol/m^2/s	–	Brazaitytė et al. (2015b)
63.	Beet	Chlorophyll index	25.2	Basal (B_{447}, R_{638}, DR_{665}, FR_{731}) + UV (366, 390, 402 nm); 6.2 and 12.4 μmol/m^2/s	–	Brazaitytė et al. (2015b)
64.	Pak choi	Chlorophyll index	34.4	Basal (B_{447}, R_{638}, DR_{665}, FR_{731}) + UV (366,390, 402 nm); 6.2 and 12.4 μmol/m^2/s	–	Brazaitytė et al. (2015b)
65.	Red basil cultivar	Anthocyanins	1.44–2.45 mg/g FW	R:B (2:1), R:B (1:1), R:B (1:2); 120 μmol/m^2/s	12.0	Lobiuc et al. (2017)

(continued)

Table 7.5 (continued)

S. no.	Microgreens	Nutrient	Quantification	Light conditions	Duration (h)	References
66.	Red basil cultivar	Caffeic acid	0.62–2.57 mg/g FW	R:B (2:1), R:B (1:1), R:B (1:2); 120 μmol/m^2/s	12.0	Lobiuc et al. (2017)
67.	Red basil cultivar	Rosmarinic acid	0.33–4.99 mg/g FW	R:B (2:1), R:B (1:1), R:B (1:2); 120 μmol/m^2/s	12.0	Lobiuc et al. (2017)
68.	Golden pea tendrils	Phylloquinone	0.7 mg/100 g FW	No light	–	Xiao et al. (2012)
69.	Popcorn shoots	Phylloquinone	0.9 mg/100 g FW	No light	–	Xiao et al. (2012)
70.	Golden pea tendrils	α-Tocopherol	4.9 mg/100 g FW	No light	–	Xiao et al. (2012)
71.	Carrot	α-Tocopherol	15.5 mg/100 g FW	2500–4400 lux	11.5	Ghoora et al. (2020)
72.	Fennel	α-Tocopherol	23.8 mg/100 g FW	2500–4400 lux	11.5	Ghoora et al. (2020)
73.	Fenugreek	α-Tocopherol	5.0 mg/100 g FW	2500–4400 lux	11.5	Ghoora et al. (2020)
74.	French basil	α-Tocopherol	16.5 mg/100 g FW	2500–4400 lux	11.5	Ghoora et al. (2020)
75.	Mustard	α-Tocopherol	31.6 mg/100 g FW	2500–4400 lux	11.5	Ghoora et al. (2020)
76.	Onion	α-Tocopherol	15.2 mg/100 g FW	2500–4400 lux	11.5	Ghoora et al. (2020)
77.	Radish	α-Tocopherol	58.6 mg/100 g FW	2500–4400 lux	11.5	Ghoora et al. (2020)
78.	Roselle	α-Tocopherol	10.3 mg/100 g FW	2500–4400 lux	11.5	Ghoora et al. (2020)
79.	Spinach	α-Tocopherol	17.1 mg/100 g FW	2500–4400 lux	11.5	Ghoora et al. (2020)
80.	Sunflower	α-Tocopherol	48.7 mg/100 g FW	2500–4400 lux	11.5	Ghoora et al. (2020)
81.	Popcorn shoots	α-Tocopherol	7.8 mg/100 g FW	No light	–	Xiao et al. (2012)
82.	Popcorn shoots	γ-Tocopherol	3.5 mg/100 g FW	No light	–	Xiao et al. (2012)
83.	Golden pea tendrils	γ-Tocopherol	3.0 mg/100 g FW	No light	–	Xiao et al. (2012)

AoA antioxidant activity, *B* blue, *DW* dry weight, *FR* far red, *FW* fresh weight, *h* hour, *R* red, *TAA* total ascorbic acid, *UV* ultraviolet

Vitamin C (ascorbic acid) is considered as an essential nutrient (Machlin and Bendich 1987), and the range of total ascorbic acid (TAA) was recorded from 20.4 (sorrel) to 147.0 (red cabbage) mg/100 g FW (Xiao et al. 2012). In mung bean microgreens, the mean vitamin C content was recorded 2.7-fold higher (Ebert et al. 2017) over their mature counterparts.

The vitamin E family includes various isomers of tocopherols (Brigelius-Flohé and Traber 1999) which are present in microgreens. Green daikon radish when grown as microgreen showed maximum tocopherol (α:87.4 and γ:39.4 mg/100 g FW), while golden pea tendrils exhibited minimum (α:4.9; γ:3.9 mg/100 g FW), which are quite higher than those of fully grown spinach (α:2.0; γ:0.2 mg/100 g FW) (USDA-ARS 2018b). β-Carotene acts as a precursor of vitamin A, having key role in the vision (Mayne 1996), and is also having antioxidant function (Sies and Stahl 1995). The β-carotene content varied from 0.6 mg/100 g FW (golden pea tendrils and popcorn shoots) to 12.1 mg/100 g FW (red sorrel), and hence, most of the microgreens are considered as richer source of β-carotene (Choe et al. 2018). Other carotenoids like lutein and zeaxanthin (Bone et al. 1997) act as antioxidants (Sujak et al. 1999). Very high lutein/zeaxanthin content was recorded in cilantro (10.1 mg/100 g FW), while lower values were observed for popcorn-derived microgreens (1.3 mg/100 g FW). Similarly, cilantro microgreens showed higher violaxanthin content (7.7 mg/100 g FW), while popcorn microgreens showed the lower values (0.9 mg/100 g FW) (Xiao et al. 2012).

In red cabbage microgreens, the average vitamin C content was found six folds more (147 and 23.5 mg/100 g FW), a 400-fold more vitamin E (24.1 and 0.06 mg/100 g FW), and nearly 60-fold more vitamin K (2.4 vs 0.04 μg/g FW) over their mature counterpart (Xiao et al. 2012). Thus, the recommended daily intake (European Food Safety Authority) of vitamin C (60 mg), E (13 mg), and vitamin K (70 μg) for a medium weight adult can be met from nearly 41 g red cabbage microgreens, 15 g of green radish microgreens, and 17 g of garnet amaranth, respectively (Di Gioia and Santamaria 2015).

7.4.2 Sugars

Relatively high sugar content (10.3 g/kg) was recorded for the microgreens of China rose radish, while red amaranth recorded 1.7 g/kg of fresh microgreens (Xiao et al. 2012). However, mature vegetables recorded higher sugar content (red amaranth recorded 17 g/kg (USDA-ARS 2018a). High light (HL)-induced biofortification strategy was used for the kale and radish microgreens (Xonti et al. 2020). Radish microgreens accumulated nearly 9 times more total starch under HL (191.9 ± 30.1 mg/g DW) over normal light (NL) conditions (20.9 ± 5.2 mg/g DW), whereas in kale the increase was nearly threefold under HL (106.2 ± 18.2 mg/g DW) over NL (35.7 ± 15.4 mg/g DW) (Goble 2018).

7.4.3 Mineral Content

Microgreens are considered as an excellent source of minerals (Weber 2017; Waterland et al. 2017). Broccoli microgreens have 1–2 times more minerals such as P, K, Mg, Mn, Zn, Fe, Ca, Na, and Cu over their mature counterparts (Weber 2017). Similarly, Waterland et al. (2017) also found more dietary mineral content in kale microgreens on a dry weight basis. Among various minerals, microgreens are considered as a good source of K and Ca (Di Gioia et al. 2017a). Especially, the brassica and basil microgreens contain very high nitrates (over 4000 mg/kg FW) under low sunlight, while Na content is generally very low, which makes microgreens as low-Na food (Di Gioia and Santamaria 2015).

Minerals in the microgreens are also directly related to their abundance in the growth medium or the nutrient solution. Thus, the overall nutritional composition of the microgreens can be enhanced through fortification of growing media with certain micronutrients, while some undesirable elements such as Na and nitrates can be reduced (Di Gioia and Santamaria 2015). The most abundant elements recorded were in the order of K, P, and Ca in mung bean microgreens and K, Ca, and P in the lentil microgreens (Priti et al. 2021).

Agronomic biofortification was attempted for Fe and Zn through enrichment of nutrient media by iron sulfate (0, 10, 20, 40 mg/L) and zinc sulfate (0, 5, 10, 20 mg/L) for Brassicaceae (arugula, red cabbage, and red mustard) microgreens. Application of Zn (10 mg/L) through media had resulted in 281% increase in Zn content over control, while Fe enrichment (20 mg/L) increased its content 278% over control. Thus, for biofortification of microgreens, soilless system or hydroponics is considered the most suitable and handy (Di Gioia et al. 2019). Application of more than 20 mM calcium (as calcium chloride) was found toxic for the cultivation of radish microgreens under hydroponic system. However, application of 5.0 and 10.0 mM Ca gave maximum shoots (%), hypocotyl length and also an increase is observed for the average fresh weight per plant and total Ca accumulation in radish microgreens (Goble 2018). Przybysz et al. (2016) demonstrated that microgreens may be enriched with Mg and Fe.

7.4.4 Others

Microgreens undergo the process of germination and hence are characterized with low phytate levels and more mineral bioavailability (Liang et al. 2009). The bioactive compounds such as polyphenols and glucosinolates which are known to have a role in the prevention of various chronic diseases (Del Rio et al. 2013; Dinkova-Kostova and Kostov 2012) are found more in red cabbage microgreens (71.01 and 17.15 μmol/g, respectively) than the mature ones (50.58 and 8.30 μmol/g, respectively) (Huang et al. 2016a). Despite several studies confirming the superior nutritional content of the microgreens over their mature counterparts, detailed investigations are required to analyze the genotypic and environmental factors regulating their nutritional composition (Choe et al. 2018).

7.5 Diverse Scope of Microgreens

7.5.1 Microgreens as Functional Foods

Microgreens are being used as a functional food in the prevention of diseases like obesity, cancer, cardiovascular diseases (CVD), and type 2 diabetes mellitus (Choe et al. 2018). Health-promoting effect of red cabbage microgreens was reported by Huang et al. (2016a). For the patients ailing with impaired kidney function, the hydroponic nutrient solution (in which microgreens are grown) can be tailored to have low or no potassium so that the resultant microgreens from such a system are low in potassium (Renna et al. 2018). Similarly, Se-supplemented hydroponic solution resulted in the Se fortified basil microgreens which are also having increased antioxidant capacity (Puccinelli et al. 2019). Rocket microgreens are known to be the excessive N accumulator; thus, they can be grown under hydroponic system having limited N content so that their content can be regulated in their produce (Bulgari et al. 2017).

The desulfoglucosinolate content in the red cabbage microgreens (17.15 μmol/g DW) was much higher over their mature counterparts (8.30 μmol/g DW) (Huang et al. 2016a), which can mediate NF-κB signaling pathway. The red cabbage microgreens showed the ability to lower the liver lipids by attenuating the C-reactive protein (CRP) and tumor necrosis factor (TNF-α) (Huang et al. 2016a). NF-κB can induce the pro-inflammatory genes like TNF-α, IL-1β, IL-6, and IL-8 (Tak and Firestein 2001). Polyphenols can interfere with the NF-κB signaling pathways by inhibiting phosphorylation or ubiquitination of kinases (Gupta et al. 2010), and they can also inhibit the interaction of NF-κB subunits with target DNA (Ruiz and Haller 2006). Microgreens contain flavonoids such as kaempferol and quercetin which can suppress the COX-2 activity (Mittal et al. 2014). Thus, microgreens can regulate the process of ROS generation and scavenging, thereby influencing NF-κB and other signaling pathways (Choe et al. 2018). Considerable flavonoids contents are reported in the brassica-based microgreens which may influence *Nrf2* pathway and inflammation (Busbee et al. 2013). Microgreens analyses confirmed them as the rich sources of natural AhR ligands like quercetin and I3C (indole-3-carbinol) which can regulate the AhR-mediated immune pathways. Thus, microgreens do have a significant role in the regulation of inflammation-associated pathways (Choe et al. 2018). Thus, the consumption of microgreens is supposedly having beneficial effect in the prevention of diseases like obesity, CVD, and diabetes via regulation of inflammation. The effects of microgreens could be due to the presence of compounds like I3C and metabolites like β-carotene and retinoic acid which can suppress the adipogenesis and lipid metabolism (Choi et al. 2013; Berry et al. 2012). Microgreens also have the potential to modulate cancer progression via regulation/inhibition of various pathways including modulation of xenobiotic metabolisms (Choe et al. 2018).

The gut microbiome is considered as a key component for the regulation of human health. Flavonoids (kaempferol, quercetin, apigenin, quercetin, catechin, puerarin, etc.) are known to regulate the gut microbiota composition and thus have role in the prevention of disease development (Clemente et al. 2012; Huang et al. 2016b). Microgreens being rich in flavonoids are likely to regulate the gut microbiome, which needs further in-depth studies. Microgreens rich in various bioactive compounds like flavonoids, indoles, and isothiocyanates are known to provide protection against inflammation and oxidative stress and thus prevent the various chronic diseases including cancers through miRNA and/or DNA methylation and histone modification pathways (Choe et al. 2018). Brassica microgreens are rich in compounds like sulforaphane, phenethyl isothiocyanate, and I3C which may regulate promoter and histone methylation and also the activities of different miRNAs (Wagner et al. 2013). Food-derived bioactive compounds like tocopherols, quercetin, curcumin, resveratrol, and lycopene are also known to affect DNA methylation and histone modification (Shankar et al. 2013; Simpkins et al. 1999; Huang et al. 2012) and thereby restore *Nrf2* expression, which impart the protection against prostate cancer (Yu et al. 2010).

7.5.2 Microgreens as Space Food

The extended stay of humans in space requires proper diet to the space travelers with least supply from the earth (Perchonok et al. 2012). A range of stress effects like weight loss, change in the blood composition, and radiation-induced stress are commonly encountered by the space travelers (Vergari et al. 2010; Cohu et al. 2014; Kyriacou et al. 2017). Prevention of such stress calls for the food-based antioxidant supply (Wan et al. 2006), for which microgreens seems an excellent option. Since, microgreens can be grown on board during the mission; therefore, future space missions aim to produce carotenoid-rich food as a part of space life support systems (SLSS) (Perchonok et al. 2012).

A major challenge for adapting agricultural practices in the space is reduced gravity (or microgravity) that impacts fluid and gas distribution around the plants (Kuang et al. 2000); transpiration rates tend to increase (under hypobaric conditions); irradiance levels are low ($\leq$300 μmol/m^2/s) requiring supplemental lighting which is energy demanding for the space farm (Salisbury and Bugbee 1988). Fresh microgreens can be directly harvested by crew members, and their production can be done on any synthetic media with little or no nutrient supplementation (Perchonok et al. 2012; Nyenhuis and Drelich 2015; Kyriacou et al. 2017). Microgreens in general have a low photon flux requirement compared to long-cycle crops. Further, the use of LED lights can reduce the overall power demand per unit of crop area (Poulet et al. 2014, 2016).

7.5.3 *Microgreens for the Skin Care Formulation*

Microgreens are also used in various skin care formulations due to the abundance of antioxidants and vitamins. The microgreen-enriched formulations provide cleansing, exfoliating and detoxification properties which help in the nourishment, repair, and protection of the skin (https://magazine.lneonline.com/breaking-news-microgreens/).

7.5.4 *Microgreens for Nutritional Security*

The trans-Himalayan part of cold-arid region covers nearly 80,000 km^2 land area. The Ladakh region of trans-Himalayas harbors more than 90% of the cold desert of India. In such remote areas, due to extreme long winter, the agricultural season is very short for a period from May to September months (Bhoyar et al. 2011a, 2012). In addition, altitudinal variations, seasonal climate, and weather make it very difficult to standardize the package of practices for the year-round cultivation of different crops in such harsh conditions (Bhoyar et al. 2011b; Singh et al. 2009). Among various climatic factors, temperature imposes serious restrictions on the cropping pattern and production techniques of this region (Bhoyar et al. 2010; Mishra et al. 2009). Human settlement in these far-flung areas is even up to 4200 m altitudes, which requires year-round healthy diets at affordable prices (Cohen and Garrett 2010). For enhanced crop production and to ensure the nutritional security in these harsh areas, various comprehensive research programs are required (Bhoyar et al. 2018; Mishra and Singh 2010). One novel but potential strategy is the optimization of nutrient-rich microgreen technology for such conditions (Singh et al. 2020). Although a range of crops such as beet, broccoli, flax, kale, peas, and radish can be used for microgreen lentil, brassica and mung bean may be the cheapest and quickest among all. In addition, growing these crop species is relatively easy for the microgreens purpose over many other crop species.

7.6 Food Safety of Microgreens

During germination, the seeds release a mix of carbohydrates and peptides which attract a number of microbes present in the rhizosphere, thus making microgreens more prone to the microbial contamination than their mature counterparts (Warriner et al. 2003). Microbial load was generally found more for the sprouts over microgreens (Xiao et al. 2014). However, more microbial contamination has been recorded for the hydroponically grown microgreens over soil or media-grown ones (Riggio et al. 2019), which could be due to the constant warm temperature and humid conditions maintained for the hydroponic system. Although studies on the

Table 7.6 Microbial contamination reported for some microgreens

S. no.	Microgreens	Microbial contamination	Inoculation/storage	References
1.	Radish	*E. coli* (O157:H7 and O104:H4)	–	Xiao et al. (2014)
2.	Eight different species	Shiga toxin-producing *E. coli*	Inoculated under hydroponics	Wright and Holden (2018)
3.	Swiss chard	*Salmonella enterica*	Contaminated water irrigation	Reed et al. (2018)
4.	Radish	*E. coli* (O157:H7)	Soil substitute and hydroponics	Xiao et al. (2015b)
5.	Rapini	Lower microbial populations	Recycled fiber mats	Di Gioia et al. (2017b)
6.	Radish	*Listeria monocytogenes*	Soil substitute and hydroponics	Wang et al. (2015)
7.	Kale, mustard	Murine norovirus (MNV)	Hydroponics	Wang and Kniel (2016)
8.	Arugula, kale, lettuce, mizuna	*E. coli* (O157:H7)	Stored in a refrigerator	Park et al. (2013)

survival and growth of pathogens on microgreens are limited (Table 7.6), such studies are abundant for sprouts (Turner et al. 2020).

Microbial contamination can be easily overcome by the use of good agricultural practices like use of uninfected seeds, seed treatment, use of clean utensils, and use of UV for the disinfection of hydroponic system (Riggio et al. 2019). Application of *Trichoderma harzianum* Rifai (strain KRL-AG2 G41) and *T. virens* (strain G-41) (ThTv) to either seed ball or to the growth media was found effective in reducing the damping-off (*Pythium aphanidermatum* (Edson) Fitzp.) in the beet microgreens at 14 days after planting (Pill et al. 2011). Safer microgreens can also be produced deploying blue and UV wavelength lights as these have the antimicrobial properties (Kim et al. 2016; Maclean et al. 2009; McKenzie et al. 2014; Turner et al. 2020). As microgreens are very delicate in nature, it is almost impossible to eliminate the microbial contamination using any sanitization treatment. A recent study revealed that the pathogenic bacteria like *Salmonella* spp. and *Listeria* spp. were not detected in the mungbean, lentil and Indian mustard microgreens when stored for certain duration under 4 °C conditions in the refrigerator. Similarly, total aerobic bacteria (TAB), yeast and mould (Y&M), *Shigella* spp., and *E. coli* were recorded well within the limit to cause any human illness in these microgreens. Washing of the microgreens for 2 min with double distilled water showed some reduction microbial load of these microgreens (Priti et al. 2022).

Although no food-borne outbreak associated with the microgreen consumption is reported, still they are considered as the vehicle of bacterial pathogens (Xiao et al. 2015b). It also warrants more attention to study the survival and proliferation of food-borne pathogens on the microgreens and stored under different conditions for different periods (Di Gioia et al. 2017a).

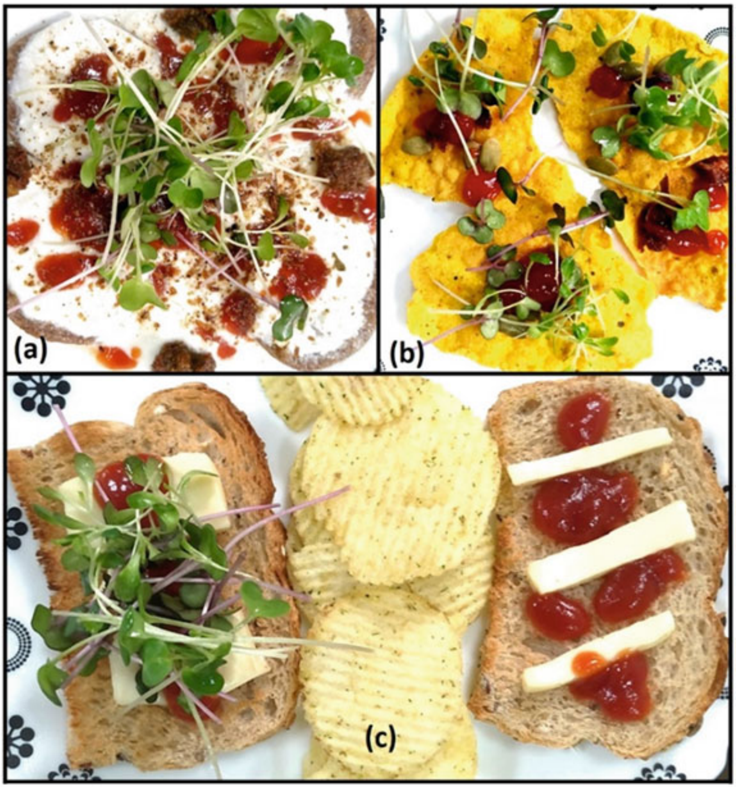

Fig. 7.2 Use of microgreens in various forms (**a**) with *paapdi chaat* (an Indian cuisine), (**b**) with nachos, and (**c**) with garlic bread

7.7 Consumption of Microgreens

Fresh microgreens form an extraordinary ingredient of taste and aesthetics for all kinds of energy drinks. Microgreens can invigorate any liquid creation, raising the bar for freshness, flavor, and overall nutritional composition, especially the antioxidant level. Mung bean and lentil-based microgreens are assumed to be the viable and cheapest option for the novel microgreens-based products. There are a number of ways in which the microgreens can be consumed either raw or after cooking or stir-frying (Fig. 7.2). Some of the most common recipes in which microgreens are used are as follows:

- *Green salads*: Microgreens are best when consumed raw as salads, since these are loaded with antioxidants, minerals, and delicate flavor.
- *Juices/smoothies*: Any microgreen is considered good for juicing or smoothies, but wheatgrass is considered the most used one in 1:3 ratio of microgreens:juice.

- *Sandwiches and wraps*: These are another raw option for consumption (radish, arugula microgreens).
- *Burgers*: Spring onion, radish, lentil, and mung bean microgreens.
- *Pizza*: Sprinkle of peppery microgreens.
- *Pasta* with raw or stir-fried microgreens.
- *Omelette with microgreens*: Any fresh microgreens will work.
- *Dhokla with microgreens*: Any fresh microgreens (preferably brassica) will work.
- *Noodles*: Flavored with microgreens.
- *Cooking with microgreens*: Some microgreens are good for cooking; while some need to be tossed in at the very last second (radish microgreens), others can stand up to a little heat.

The consumption of microgreens is not limited to any specific recipe, but can be consumed in a number of ways as per the regional food preparations (Fig. 7.2).

Microgreens as dry formulation have the ability to contribute to the nutritional security as they can be very easily made available at any part of the world (Ebert et al. 2015, 2017). The dehydration may be performed following cold raw dehydration process to retain full nutritional content of microgreens, and thus, these can be considered a raw food product. The dehydrated microgreens are unique because of their nutritional qualities. It can be used in smoothies, soups, salads, salad dressings, eggs, baked goods, etc. A number of products are now available in the market as dried formulations like tea (broccoli microgreen-based) or dressing. Microgreen-based energy drinks appear an easy way to add more healthy foods into our diet. These dried microgreen-based products are claimed to be packed with nutrients with added benefits of intense taste (https://drinkmicrotea.com).

7.8 Conclusions and Prospects

Balanced nutrition depends on the availability, accessibility, and utilization of quality foods, including microgreens. In recent decades, the consumption of calorie-rich diets which are high in fat and carbohydrates and low in protein has led to increased rates of diabetes, hypertension, and obesity in developing countries, prompting a call for serious changes in dietary patterns. Considering the burgeoning nutritional needs of our population, novel approaches like microgreen-based formulations seem a viable option for nutritional security. It has immense potential to be used as energy drinks and food additives at commercial scale. Thus, enhancing the quality of food using various microgreen-based formulations appears an option to tackle the nutritional security of our population.

The microgreens cultivation is now attracting the greenhouse growers so that the consumer need can be fulfilled especially in the urban settlements (Chandra et al. 2012). As a novel food crop, microgreens cultivation is still in infancy, especially in the developing and underdeveloped countries. However, constantly expanding research data for a number of microgreens species is unfolding their immense potential as superfood (Kyriacou et al. 2016; Xiao et al. 2012).

Currently, microgreens are mainly being used as a fresh flavor ingredient in the cuisines of upscale restaurants. As per the National Restaurant Association, microgreens are going to be considered as a culinary trend across the world. Nearly 51% of the chefs have predicted microgreens as a hot trend in the US eateries (Globe Newswire Report 2020). A few species of microgreens have been explored, and its cost of cultivation or the availability of untreated seeds has not yet been seriously considered. In addition, studies on the varietal or genotypic differences for the nutritional composition or for the shelf life studies have not been focused properly.

Research on postharvest storage should be intensified so as to have crop species-specific storage strategies. Augmentation of phytonutrient content through fortification of growth media should be explored as an alternative strategy of reaping more from same microgreens. Optimization of sanitization and drying techniques should be intensively studied which will help in the formulation of various novel storable food products. In-depth fundamental research for ensuring the food safety of microgreens and microgreens-based products should be done for their quick acceptance by the food industry.

Some of the key researchable areas include the following:

1. Variations in the nutritional composition of microgreens under different altitudinal and environmental conditions and under different drying conditions.
2. Identification of superior genotype(s) of microgreen when grown under different growth conditions (e.g., light, altitude, temperature, photoperiod).
3. Identification of factors responsible for the variations in the nutritional profile of microgreens when grown under different growth conditions using multiple OMICs approaches.
4. Optimization of cold dehydration and raw dehydration process of various microgreens for maximum nutrition retention.
5. Development of storable microgreen-based products such as microgreens powder and microgreen-based energy drink and its nutritional and medicinal characterization.
6. Region or country-specific selection and optimization of microgreens species with added cost economics for their large-scale commercialization.
7. Studies on the bioactive compounds of microgreens for their health-promoting effects in humans and estimation of bioavailability of microgreens bioactive components.

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