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A review on the effects of light-emitting diode (LED) light on the nutrients of sprouts and microgreens

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Abstract:

Background**:** Sprouts and microgreens, which are tender, flavourful, rich in nutrients, have a short growth cycle, and have been recognized as functional foods in the human diet. Culturing under artificial light sources could regulate the growth, the phytochemical compound content and antioxidant capacity of sprouts and microgreens.

Scope and Approach: In this review, the effects of light-emitting diode (LED) on growth, phytochemical compound content and antioxidant capacity, as well as the post-harvest quality of sprouts and microgreens were overviewed, and the underlying mechanisms were discussed. The future applications and research, which aim to improve the growth and nutritional quality of sprouts and microgreens, were also investigated.

Key Findings and Conclusions**:** LED light can promote the accumulation of different phytochemicals, such as phenolic compounds, vitamins, glucosinolates, chlorophyll and carotenoids. Meanwhile, the antioxidant capacity could also be significantly increased by growth under LED light, in particular UV-B light. The accumulation of mineral elements (Ca^{2+}, Fe^{2+}, K^{+}) increased after light exposure. The effects of LED light on the growth was species dependent. Therefore, growth under LED light is an efficient and promising strategy for producing sprouts and microgreens with higher nutritional values.

Keywords: sprouts; microgreens; light-emitting diode (LED); nutrition quality; light; functional foods

1. Introduction

Vegetables are rich in phytonutrients and dietary fibers, which are indispensable and beneficial for the human body. Recent researches have shown that regular intake of vegetables is associated with a reduced risk of illnesses, such as cardiovascular disease and cancer (Aune, et al., 2017; Moore & Thompson, 2015). Over the past two decades, the interest in fresh, nutritional and organic vegetables has increased as living standards have risen. In such cases, sprouts and microgreens are gaining increasing popularity. According to the recently published papers, the definition of sprouts is "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" (Di Gioia, Renna, & Santamaria, 2017). While, microgreens are defined as "tender immature greens, produced from the seeds of vegetables and herbs, having two fully developed cotyledon leaves with or without the emergence of a rudimentary pair of first true leaves" (Xiao, Lester, Luo, & Wang, 2012). There is a large variety of sprouts and microgreens, among which legumes (e.g. soybean, pea, cowpea, etc.) and *Brassica* species (e.g. radish, broccoli, red pak choi and buckwheat, etc.) sprouts and microgreens are the most commonly consumed.

One common feature of sprouts and microgreens is that they are both young and tender edible seedlings produced from the seeds of vegetables, herbs, or grains (The production methods of sprouts and microgreens were summarised in Supplemental methods and Figure 1) (Renna, Castellino, Leoni, Paradiso, & Santamaria, 2018). During seed germination, a series of physiological and biochemical processes occur: (1) the imbibed seeds germinate, the radicle and hypocotyl elongate and the cotyledon expands; (2) the content of anti-nutritional factors decreases (Bora, 2014); (3)

macromolecules (such as polysaccharides and fats) are transformed into small molecules (such as oligosaccharides and free amino acids), which increases their digestibility (Márton, Mándoki, Csapókiss, & Csapó, 2010); and (4) the content of bioactive phytochemicals and the antioxidant capacity increases (Di Gioia, Renna, & Santamaria, 2017). The nutrients of sprouts and microgreens include, but are not limited to, proteins, vitamins, phenolics, carotenoids, glucosinolate and minerals (Di Gioia, Renna, & Santamaria, 2017; Ebert, 2012). It is worth noting that the content of bioactive compounds in sprouts and microgreens are higher than those of their mature counterparts (Kyriacou, et al., 2016).

Light is one of the most important environmental factors for plants, as it provides not only the source of energy for photosynthesis but also the signal for a multitude of physiological responses. Light quality (wavelength), light quantity (intensity), direction and photoperiod (duration) are key components of light conditions (Ding, et al., 2011; Kami, Lorrain, Hornitschek, & Fankhauser, 2010). The use of artificial light sources (e.g. fluorescent lamps, halogen light, LED light and high-pressure sodium lamps), which emit photons over a spectral range from 250 nm to 750 nm, make the study of the effects of light on the nutrient quality of sprouts and microgreens more convenient and the results more conclusive. Recently, an increased number of studies have demonstrated the beneficial effects of LED light on plant growth and quality of crops, including the accumulation of phytonutrients in sprouts and microgreens (Ciska, Honke, & Kozłowska, 2008; Peng, Zou, Su, Fan, & Zhao, 2015; Pérez-Balibrea, Moreno, & García-Viguera, 2008; Qian, et al., 2016; Samuolienė

Giedrė, et al., 2017). Compared with conventional light sources, LED light offers cheap, cool and controllable sources of light that can selectively and quantitatively provide different spectra. LEDs provide photons that can activate discrete developmental pathways to change plant growth (e.g. leaf area, thickness, stem length) and quality (e.g. metabolites) through photoreceptors include phytochrome and cryptochrome (Folta & Carvalho, 2015; Folta & Childers, 2008; Heijde & Ulm, 2012; Quail, 2002; Smith, 2000). Therefore, this provides us with a new opportunity to manipulate the quality and quantity of vegetable products for markets and meet the demands of retailers.

Here we have reviewed the most relevant progressive studies, from 2005 to date, investigating the regulation of growth and nutrient quality of sprouts and microgreens grown under light-controlled environments. The objective of this study was to 1) summarise the effects of LED light (including other artificial lights) on growth, phytochemical compound content and antioxidant capacity of sprouts and microgreens; 2) discuss the underlying mechanisms; 3) assess the application potential and prospect of LED light in the production of sprouts and microgreens.

1.1 The artificial lighting systems in sprouts and microgreens production

The main light sources in sprouts or microgreen production are artificial lights, including high-pressure sodium lamps (HPSs), fluorescent lamps (FLs) and light-emitting diodes (LEDs), among others (Bantis, et al., 2018). HPSs, with their high electrical efficiencies, long operating life and a wide spectrum of light, are the most common artificial light sources used for the culture of many plant species in greenhouses (Islam, et al., 2012). FLs are widely used in growth chambers. When used as additional light sources, FLs can provide sustained photosynthetic photon fluence which is necessary for high productivity (Darko, Heydarizadeh, Schoefs, & Sabzalian, 2014). However, HPSs and FLs both have serious limitations. For example, HPSs require high voltage and emit intense radiant heat, in addition, they also contain only 5% blue light, which is low compared to natural sunlight (18% blue light) (Islam, et al., 2012). While FLs have limited photon output, less than ideal energy conversion to light and a short effective lifespan (Rehman, et al., 2017). These features bring several problems, in respect to the way the plants grow and develop, or overheating due to infrared radiation (D'Souza, Yuk, Khoo, & Zhou, 2015). In contrast, LEDs possess unique properties that are highly suitable for horticulture, including low radiant heat emissions; high emissions of monochromatic light; photon efficiency; long life expectancy, and flexibility, as well as the ability to be pulsate (D'Souza, Yuk, Khoo, & Zhou, 2015; Yeh & Chung, 2009). Therefore, LEDs have received widespread attention and have been widely used in plant factory and other controlled environment chambers.

1.2 The LED light spectra and plant photoreceptors

The range of wavelengths which modify the behavior of plants ranges from ultraviolet (UV) light (~280 nm) to far-red light (700–750 nm) (Figure 2) (Kami, et al., 2010; Rizzini, et al., 2011). Photoreceptors, which can sense a range of light wavelengths, help plants to sense and utilize radiation from near UV (~350nm) through the blue to red/far-red (~750nm) light (Möglich, Yang, Ayers, & Moffat, 2010). Blue (~450nm) and red (~650nm) light are strongly absorbed by plants, while green (~530 nm) and far-red (~735 nm) light are reflected a large extent (Kami, et al., 2010). Red/far-red light receptors phytochromes, UV-A/blue light receptors phototropins, cryptochromes and ZEITLUPE family proteins, as well as UV-B receptors UV RESPONSE LOCUS 8 (UVR8), form the three main systems that respond to light signals in plants (Chen, Chory, & Fankhauser, 2004; Rizzini, et al., 2011). In plants, there are two interconvertible forms of phytochromes: a red light-absorbing Pr form and a far-red light-absorbing Pfr form (Chen, Chory, & Fankhauser, 2004). Phytochromes have roles in seed germination, shade-avoidance responses, seedling development and floral induction (Mazzella, Cerdán, Staneloni, & Casal, 2001; Neff, Fankhauser, & Chory, 2000). In *Arabidopsis thaliana*, phototropins are responsible for phototropism (Inoue, Kinoshita, Takemiya, Doi, & Shimazaki, 2008), while cryptochromes are responsible for flowering, the entrainment of the circadian clock, the regulation of stomatal opening and root development (Li & Yang, 2007). UVR8 regulates a range of UV-B responses, including flavonoid biosynthesis, hypocotyl growth inhibition and leaf cell expansion (Jenkins, 2014). Although the specific green light photoreceptor remains to be identified in higher plants, the effects of green light on plant growth should not be ignored. Increasing evidences have shown the role of green light in photosynthesis and metabolism in plants. For instance, addition of small portion of green light (~20%) has been shown to enhance plant growth as green light penetrates deeper into the plant canopy and enhances photosynthesis at lower leaf levels (Kim, Goins, Wheeler, & Sager, 2004).

Therefore, an intricate photosensory system may work in conjunction to control plant physiological responses in response to spectral quality, intensity and duration (Neff, Fankhauser, & Chory, 2000). The downstream signalling components that interact with the photoreceptors remained to be gradually identified.

LEDs emit light with a narrow-brand wavelength, which depends on the properties of the semiconductor materials of the devices. With the improvement of semiconductor technology, the peak emission wavelength of LED ranges from UV (~250 nm) to infrared (~1000 nm) (Olle & Viršile, 2013). In other words, LED light could emit both broad-band light (white light) and monochromatic light (e.g., UV, blue, green, red and far-red light). When multiple LEDs are combined, monochromatic lights with different intensities or a combination of light with different spectral compositions could be emitted. Therefore, the accurate and flexible light spectra control ability of LEDs allows it to provide optimal light wavelengths that match the plant photoreceptors and photosynthetic pigments, and may contribute to optimize plant growth and metabolism.

1.3 Light spectra and intensity change photosynthesis

Photosynthesis is a process to convert light energy (photons) to biomass in plant, in which light intensity and spectra play fundamental roles. The highest photosynthesis and productivity of plants could be achieved at appropriate light intensity. When light intensity is lower than a certain compensation intensity, photosynthesis will be exceeded by respiration, and the plants will become a net consumer of oxygen. However, the photosynthesis and even plant growth could be damaged with the increase of light intensity, due to the photoinhibition (Ooms, Dinh, Sargent, & Sinton, 2016).

The most important light region for photosynthesis is 400 to 700 nm, known as photosynthetically active radiation (PAR). Due to the emitting of narrow wave band lights, the flexibility to control light spectral composition and the high PAR conversion efficiency (Both, et al., 2017), LEDs are perceived as tailor-made light sources and widely employed in analyzing photosynthesis under different light spectra. It has long been known that blue and red light regions are most efficiently absorbed by chlorophylls, the primary photosynthetic pigments, during the photosynthetic processes (Chen & Blankenship, 2011). Therefore, red and blue lights are currently two types of light spectra that have been most studied on plant photobiology . Red light was reported to promote photosynthesis and vegetative growth by increasing the content of chlorophyll, promoting the formation of photosynthetic apparatus and probably by inducing stomatal opening (Zhu, Geng, Chakravorty, Guan, Chen, & Assmann, 2019; Wang, Lu, Tong, & Yang, 2016).However, prolonged red light illumination may result in ‘red light syndrome’, which is characterized by low photosynthetic capacity, low maximum quantum yield of chlorophyll fluorescence (*Fv*/*Fm*), low carbohydrate content accumulation and impaired growth (Miao, Chen, Qu, Gao, & Hou, 2019)). Blue light, which is strongly absorbed by carotenoid pigments (lutein and β-carotene), was reported to increase the chlorophyll content and chlorophyll a/b ratio, promote stomatal opening, control the integrity of chloroplast protein, and enhance *Fv*/*Fm* (Huché-Thélier, et al., 2016) . Meanwhile, many studies showed that an optimized red: blue light ratio may be more beneficial for photosynthesis. For instance, the net photosynthetic rate increased upon the decrease of the red: blue ratio (Nanya, Ishigami, Hikosaka, & Goto, 2012), and the impaired photosynthetic parameters and chloroplast development induced by red light could be alleviated by adding blue light (Miao, Chen, Qu, Gao, & Hou, 2019).

On the other hand, other lights with wavelengths outside the red and blue light regions were also reported to play considerable roles in photosynthesis, which was once neglected. For example, green light was once ignored because it is absorbed weakly by the chlorophylls. The literature recently showed that green light could penetrate the leaf further than blue and red light, increasing carbon fixation and maybe yield (Terashima, Fujita, Inoue, Chow, & Oguchi, 2009; Terashima, Fujita, Inoue, Chow, & Oguchi, 2009; Smith, Mcausland, & Murchie, 2017). Moreover, green light could also reverse UV-B and blue light-mediated stomatal opening (Smith, Mcausland, & Murchie, 2017). Similarly, far-red light has long been considered as photosynthetically inefficient radiation, due to its poor ability in driving photosynthetic reaction. However, far-red light was now reported to be more active in enhancing photochemical efficiency than commonly believed, because of the synergistic effect between far-red light and light with shorter wavelengths (Zhen & van Iersel, 2017; Zhen, Haidekker, & van Iersel, 2019). UV light was traditionally considered harmful for photosynthesis, while the recent studies have changed this stereotype. Although, high UV radiation could impair the biosynthesis of carotenoids and damage the photosystem II, a moderate UV dose might have positive effects on photosynthesis by inducing the biosynthesis of flavonoids with photoprotective activity (Johnson & Day, 2010; Verdaguer, Jansen, Llorens, Morales, & Neugart, 2017; Guidi, et al., 2016).

Understanding the physiological responses induced by other lights (not only red and blue light) will expand our knowledge about how different portions of the light spectrum independently or cooperatively regulate plant morphogenesis, which can lead to the optimization of crop growth.

2. The effects of LED light on the growth of sprouts and microgreens

Photomorphogenic process, which is a default developmental process for the light-grown seedlings, is triggered by light in sprouts and microgreens during their development from seeds to edible vegetable products. Increasing numbers of studies have revealed the vital role of light signals on the growth of sprouts and microgreens (Table S1). Hypocotyls are one of the main edible parts of sprouts and microgreens, and the growth of hypocotyls could be affected by artificial lights. For instance, FLs light exposure was reported has negative effects on hypocotyl elongation. Compared with the dark conditions, illuminating with FLs light significantly reduced hypocotyl length of tartary buckwheat sprouts and soybean sprouts by 40% and 16%, respectively (Peng, Zou, Su, Fan & Zhao, 2015; Yuan, et al., 2015a). Similarly, FLs light illuminated bean sprouts, such as dolichos and cowpea sprouts, have been reported to have decreased radical length when compared with their counterparts grown in the dark (Martín-Cabrejas, et al., 2008). However, FLs light could significantly increase the diameter of soybean sprout hypocotyls by 12%, compared with the sprouts grown in the dark (Yuan, et al., 2015a). The results also showed that sprouts and microgreens grown in the dark show etiolation phenotype, with white and long hypocotyls. When grown under light, the shorten hypocotyl of light-grown sprouts and microgreens may be due to the inactivation of COP1 (CONSTITUTIVE PHOTOMORPHOGENIC 1), a repressor for photomorphogenesis, and the stabilization of HY5 (LONG HYPOCOTYL 5) and HYH (LONG HYPOCOTYL 5 HOMOLOG), transcription factors that promote photomorphogenesis (Deng, Caspar, & Quail, 1991). Furthermore, plant hormones, such as gibberellins and ethylene, may also contribute in mediating light-regulated hypocotyl elongation (Alabadí, et al., 2008; Yu & Huang, 2017). Compared with red and blue combined LED light, LED blue light alone could significantly increase hypocotyl length of buckwheat sprouts (Lee, et al., 2014). Similarly, supplementation of LED far-red light on the basis of LED red + blue light could significantly increase the hypocotyl length in kohlrabi microgreens and mustard microgreens (Gerovac, Craver, Boldt, & Lopez, 2016). UV light has been reported to suppress the growth of seedlings (Huché-Thélier,et al., 2016), while Brazaitytė et al. (2015a) reported that supplemental LED UV-A (402 nm) irradiation significantly increased the hypocotyl length of basil, beet and pak choi microgreens. The results of Wu et al. (2007) showed that LED blue light and red light both significantly increased stem length of pea microgreens, when compared with LED white light. The above conclusions, which are in contradiction with previous research results, may be caused by the lower light intensity under LED blue and red light. The study on *Brassicaceae* microgreens showed that the hypocotyl length of tatsoi, red pak choi and mustard microgreens grown under customized LED light was significantly shorter as compared with those of HPSs, even though the light intensity of the two treatments was the same (150 µmol m^{-2} s^{-1}) (Vaštakaitė & Viršilė, 2015).

The undesirable hypocotyl length of LED-grown *Brassicaceae* microgreens could be attributed to the high percentage of blue light of customized LED lamps (~16%), as it was reported that hypocotyl elongation could be prevented by the adding of blue light (Darko, Heydarizadeh, Schoefs, & Sabzalian, 2014). The effects of light quality on the leaf area in sprouts and microgreens differ between species. For example, LED red light was reported to have positive effects on leaf area of pea microgreens (Wu, et al., 2007), while having negative effects on leaf area of mustard and tatsoi microgreens (Brazaitytė, et al., 2016). LED light also has positive effects on leaf area. For instance, LED green light was reported to increase leaf area of mizuna microgreens, and the same is true for LED UV-A light in basil and pak choi microgreens (Brazaitytė, et al., 2015b; Gerovac, Craver, Boldt, & Lopez, 2016). As for the effects of light intensity, it was showed that high light intensity could decrease the leaf area in both kohlrabi and mustard microgreens (Gerovac, Craver, Boldt, & Lopez, 2016).

Fresh weight is one of the most important growth qualities of sprouts and microgreens. The effects of light on fresh weight varies depend upon the light spectra applied and varied among sprouts and microgreen species. For example, FLs light was reported to increase the fresh weight of mucuna sprouts, while decrease the fresh weight of cowpea sprouts (Martín-Cabrejas, et al., 2008). Similarly, LED UV-A light was shown to increase the fresh weight of basil microgreens, but decrease the fresh weight of beet microgreens (Brazaitytė, et al., 2015a). Both red and blue light are effective for enhancing plant growth because they are more efficiently absorbed by photosynthetic pigments than other regions of the light spectrum. Therefore, it is not surprising that the adding of LED red and/or blue light could increase fresh weight of sprouts and microgreens (Kopsell, Sams, Barickman, & Morrow, 2014; Lee, et al., 2014; Wu, et al., 2007). However, when compared with the dark, LED red and blue light showed inhibitory effects on fresh weight of common buckwheat sprouts (Nam, Lim, & Eom, 2018). Furthermore, light exposure might significantly decrease the yield of soybean sprouts. For example, a study on soybean sprouts with 1-7 days showed that the yield and dry weight of fluorescent light-grown sprouts were lower than that of dark-grown sprouts. The above-mentioned observations may result from the higher protein and lipid consumption and lower water absorption of light-grown sprouts. (Chen & Chang, 2015). The researches on the light intensity showed that LED light with higher light intensity could significantly increase the fresh weight of mustard microgreens (Gerovac, et al., 2016). The details of effects of LED light illumination on the growth of sprouts and microgreens are listed in the Table S1.

3. The effects of LED light on the nutrients content of sprouts and microgreens

The metabolite levels of sprouts and microgreens are mostly determined by the culturing conditions, especially when produced under artificial light and controlled-environment growing conditions. Here, we summarised the changes in main phytochemical compounds content and the antioxidant capacity of sprouts and microgreens grown under LED light, we also reviewed the changes of gene expression levels in response to the different LED light.

3.1 Phenolic compounds

Phenolic compounds, which are ubiquitous in plants, comprise an extremely rich group of secondary metabolites. They confer the colour, taste, and aroma of fruits and vegetables, and are an integral part of the human diet (Shahidi & Ambigaipalan, 2015). Numerous studies have highlighted the antioxidant properties and potential health-improving effects of a phenolic-rich diet, such as antioxidant, anti-inflammatory, anti-adhesive and antibacterial effects (Balasundram, Sundram, & Samman, 2006; Ferreira, Martins, & Barros, 2017; Rice-Evans, Miller, & Paganga, 1997). The content of phenolic compounds is an important quality index of sprouts and microgreens, and the accumulation of phenolic phytochemicals can be stimulated by cultivation under different LEDs (Table 1). Compared to the dark, light exposure increased the total phenolic content of soybean, Chinese kale, and pea sprouts, as well as sprouts of *Brassica oleracea* varieties (Kim, et al., 2006; Liu, et al., 2016; Qian, et al., 2016; Vale, Cidade, Pinto, & Oliveira, 2014). However, when grown in the growth chamber at controlled light cycle (16 h/8 h, light/dark), the total phenolic content decreased in galega kale, penca cabbage and broccoli sprouts, while increased in red cabbage sprouts (Vale, Cidade, Pinto, & Oliveira, 2014). The studies on the light quality showed that total phenolic content of Chinese kale sprouts and common buckwheat sprouts was significantly decreased under LED red light, while significantly increased under LED blue light, as compared with white light (Nam, Kim, & Eom, 2018; Qian, et al., 2016). In a study of pea sprouts, LED light of 585 nm was observed to decrease total phenolic content (Liu, et al., 2016). Several studies on tatsoi and basil microgreens reported an increase in total phenolic content under LED red light or supplemental LED red light (Brazaitytė, et al., 2016b; Samuolienė, et al., 2016).

Flavonoids represent one of the largest classes of phenolic compounds in fruits and vegetables (Zoratti, Karppinen, Escobar, Häggman, & Jaakola, 2014). In sprouts and microgreens, isoflavone, anthocyanin, rutin and quercetin are the most common phenolic compounds. Similar to the promoting effects on total phenolic content, light exposure significantly increased the content of the above-mentioned phenolic compounds (Table 1). For instance, light exposure was reported to boost isoflavone content in soybean and chickpea sprouts (Aisyah, Gruppen, Madzora, & Vincken, 2013; Gao, Yao, Zhu, & Ren, 2015). In addition, LED blue light showed promoting effects on total flavonoid content of common buckwheat sprouts, while LED red light showed the opposite effect (Nam, Kim & Eom, 2018). It is reported that secondary metabolites in plants are a response to the environmental stresses (Ramakrishna & Ravishankar, 2011). This has led to a series of studies on the effects of UV light on secondary metabolites in sprouts and microgreens. For example, UV-B lamps has been reported to increase total flavonoid content in broccoli sprouts by 92%, when compared with white light (Mewis, et al., 2012). UV-B light at 313 nm was reported to increase isoflavone content in soybean sprouts (Jiao, Yang, & Gu, 2016; Jiao, Yang, & Gu, 2017), while UV-B at 310 nm was reported to decrease isoflavone content in red clover sprouts (Grażyna, et al., 2018). In soybean sprouts, there were consistent strong positive correlations between the isoflavone content and radiation intensity of UV-B (from 0, 5, 10 and 20 μW cm^{-2}) (Ma, Wang, Yang, & Gu, 2018). Besides, nitric oxide signaling was reported involved in UV-B-induced isoflavone biosynthesis by regulating the gene expression of key enzymes related (i.e. phenylalanine ammonia lyase, PAL and chalcone synthase, CHS) (Jiao, Yang, Zhou, & Gu, 2016). Therefore, the influence of UV-B on isoflavone accumulation is dependent on the species, the UV-B wavelength as well as the radiation intensity (UV dose). In a study of tartary buckwheat sprouts, LED blue light followed by UV-C light enhanced the accumulation of bioactive compounds, while the opposite combination (UV-C followed by LED blue light) showed weaker effects (Ji, Wen, Zhou, & Ying, 2016). Thus, the content of phenolic compounds was not only dependent on the light quality but also the way they are combined.

The flavonoids is biosynthesized through a branched phenylpropanoid pathway, and most of the flavonoid synthesizing enzymes have been found. Recently, the transcriptional levels of flavonoid biosynthetic genes were investigated in sprouts and microgreens. For example, it was shown that the time duration and amount of light strongly affected the phenylpropanoids content in tartary buckwheat sprouts, the three anthocyanin compounds (namely cyanidin 3-*O* glucoside, cyanidin 3-*O*-rutinoside and delphindin-3-*O*-coumarylglucoside) in 4-day-old Hokkai T10 buckwheat sprouts grown under light/dark condition was nearly 4-fold more than those grown in the dark (Li, et al., 2012). The transcriptional results of flavonoid biosynthetic genes also showed that *FtFLS2*, *FtF3'H1*, *FtF3'H2* and *FtANS* were up-regulated by light. In addition, the transcription factor, *FtMYB*-like gene, was markedly induced in light-treated buckwheat sprouts, indicating that *FtMYB*-like gene was possibly involved in the light-regulated flavonoid biosynthesis (Li, et al., 2012). In another study, it was shown that rutin was the main phenolic compounds in Hokkai T8 buckwheat sprouts, and the maximum rutin content was observed at 4 day after LED exposure under blue light, as compared to the LEDA white and red light. Meanwhile, the cyanidin 3-O-rutinoside content under LED blue light was 2.8- and 10.6-fold higher than that under LED white and red light, respectively. The analysis of gene expression showed that the transcript levels of *FtC4H*, *FtCHI*, *FtFLS-2*, and *FtANS* was higher in sprouts grown under LED blue light (Thwe, et al., 2014). Studies on UV irradiation showed that UV-B and UV-A could increase the anthocyanin content of radish sprouts and soybean sprouts, respectively (Su, et al., 2016; Su, et al., 2017). The anthocyanin accumulation was significantly decreased by shading treatment in soybean sprouts, which was attributed to the down-regulation of anthocyanin biosynthesis genes (*GmDFR*, *GmANS* and *GmUFGT*) (Su, et al., 2017). Those results strongly suggested that the accumulation of anthocyanin was closely related to light exposure. On one hand, light is a necessary condition for the biosynthesis of anthocyanins. On the other hand, different light qualities exhibit different effects on anthocyanin biosynthesis, and short-wavelength light, such as blue light and UV light, might bemore effective to increase anthocyanin content (Qian, et al., 2016; Seo, Arasu, Kim, Park, & Kim, 2015; Thwe, et al., 2014). The details of effects of LED light on the phenolic compounds content in sprouts and microgreens are summarized in the Table 1.

In addition to light spectra, light intensity and light duration, pulsed light was reported has profound effects on the accumulation of phytochemicals in microgreen.

Vaštakaitė, et al. (2017) reported that adding monochromatic (455, 470, 505, 590 and 627nm) LEDs with frequencies at 2, 256, and 1024 Hz had most positive effects on total phenolic compounds in mustard microgreens grown under HPS lamps. On the contrary, adding the monochromatic LEDs at 32 Hz significantly decreased the total phenolic content in mustard microgreens. However, the monochromatic LED frequencies at 32 Hz were the most suitable for the accumulation of anthocyanins in red pak choi and tatsoi microgreens.

3.2 Vitamins

Vitamins are a class of organic compounds that cannot be synthesized by the human body and can only be absorbed from the diet. They are essential for human development and health, and the intake of vitamins help to reduce the risk of diseases, such as cardiovascular disease and coronary heart disease (Ashor, Lara, Mathers, & Siervo, 2014; Stampfer, et al., 1993). Vitamin C (ascorbic acid) is a dietary nutrient required as a co-factor for many enzymes, and is an especially effective antioxidant owing to its high electron□donating power (Jacob & Sotoudeh, 2002). Therefore, vitamin C is one of the most important vitamins in the human diet. Artificial light has been reported to significantly increase vitamin C content of sprouts and microgreens (Table S2). For example, compared to growth in the dark, white light and UV + red LED light significantly increased vitamin C content of broccoli sprouts and soybean sprouts by 87% and 79%, respectively (Pérez-Balibrea, Moreno, & García-Viguera, 2008; Xu, Dong, & Zhu, 2005). In addition, LED red light was reported to play a positive role in promoting vitamin C content of microgreens (Brazaitytė, Jankauskienė, & Novičkovas, 2013; Brazaitytė, et al., 2016). Moreover, it was shown that supplementary LED light, on the basis of HPS light, could also promote the content of vitamin C of tatsoi microgreens (Vaštakaitė & Viršilė, 2015).

Vitamin E, the major lipid-soluble component in the cell antioxidant defense system, has long been considered as a cytoprotective factor with roles in anti-ageing, arthritis, cataracts, Type 2 diabetic disease and kidney diseases (Jiang, 2014; Rizvi, et al., 2014). Alpha-tocopherols, the predominant form of vitamin E, was reported to be regulated by artificial light (LED and HPS lamps) in microgreens. As shown in Table S2, using the combination of LEDs or HPSs as the primary light source, supplemental green, blue and red LED light could promote the increase in vitamin E content of microgreens (Brazaitytė, et al., 2016; Samuolienė, et al., 2014; Samuolienė, et al., 2017). However, LED red light was reported to decrease the content of vitamin E in *Perilla frutescens* (L.) microgreens and red pak choi microgreens (Brazaitytė, Jankauskienė, & Novičkovas, 2013; Brazaitytė, et al., 2016). Therefore, the effects of LED light on vitamin E content depend on the light spectra and intensity and vary among microgreen species (Table S2).

3.3 Photosynthetic pigment contents

Following exposure to light, sprouts and microgreens undergo photomorphogenesis and inevitably synthesize photosynthetic pigments, such as chlorophyll and carotenoids. Chlorophylls are the most obvious and widespread pigments of plants, as they are required for photosynthesis. In addition, chlorophylls have been shown to play important roles in maintain human health, in view of their potent anti-inflammatory property and anti-oxidant activity (Lee, Nishizawa, Shimizu, & Saeki, 2017; Subramoniam, et al., 2012). Several preliminary studies revealed the effects of artificial light on chlorophyll and carotenoid content of sprouts and microgreens (Table S3). It was reported that 20% LED blue light with 80% LED red light treatment could significantly increase the content of total chlorophyll, chlorophyll a and chlorophyll b of broccoli microgreens (Kopsell, Sams, Barickman, & Morrow, 2014). Moreover, UV-A was also reported to increase total chlorophyll content in broccoli sprouts (Moreira-Rodríguez, Nair, Benavides, Cisneros-Zevallos, & Jacobo-Velázquez, 2017b). However, a recent study has revealed that LED blue light could decrease the total chlorophyll content of common buckwheat sprouts, as compared with the white light (Nam, Lim, & Eom 2018). Similarly, supplemental LED blue light significantly decreased the chlorophyll b content of broccoli microgreens (Kopsell, & Sams, 2013). Additionally, the total chlorophyll content of microgreens decreases when exposed to high-intensity light. For example, total chlorophyll content of mustard microgreens decreased by 27% under fluorescent light of 463 μmol m^{-2} s^{-1}, in comparison to 275 μmol m^{-2} s^{-1} exposure (Kopsell, Pantanizopoulos, Sams, & Kopsell, 2012).

Carotenoids (α-carotene, β-carotene, violaxanthin, neoxanthin and lutein, etc.) play fundamental roles in photosynthetic organisms. They act as accessory light-harvesting pigments, but they also perform photoprotective role by quenching triplet state chlorophyll molecules and scavenging singlet oxygen and other toxic oxygen species formed within the chloroplast (Young, 1991). Dietary carotenoids are thought to play an important role in maintaining good health and preventing human diseases, such as cancers, diabetes and eye disease (Johnson, 2002; Sluijs, et al., 2015). Generally, LED light is beneficial for the accumulation of carotenoids in sprouts and microgreens (Table S3). For example, the supplementation of LED yellow light (595 nm) could increase total carotenoids content of tatsoi microgreens by 16% (Brazaitytė, et al., 2015b). Similarly, supplemental blue, red and green LED light was reported to increase the content of α-carotene and β-carotene of microgreens (Brazaitytė, et al., 2015b; Brazaitytė, et al., 2016; Kopsell, Sams, Barickman, & Morrow, 2014; Samuolienė, et al., 2017). However, supplemental LED orange light (622 nm) decreased β-carotene content (Brazaitytė, et al., 2015b). Studies on *Brassicaceae* microgreens and beet microgreens showed that supplemental green, yellow and blue LED light could promote violaxanthin content, while supplemental LED orange light showed the opposite effect (Brazaitytė, et al., 2015b; Samuolienė, et al., 2017). It was also reported that supplemental LED green light increased neoxanthin content of red pak choi microgreens by 5%, while supplemental LED yellow light lead to a decrease in neoxanthin content by 69% (Brazaitytė et al., 2015b). A study on the effects of high light intensity reported that high light intensity could decrease neoxanthin content of mustard microgreens (Kopsell, Pantanizopoulos, Sams, & Kopsell, 2012). It was reported that lutein and β- carotene are two main carotenoid compositions in tartary buckwheat sprouts, and white florescent light exposure (16 h/8 h light/dark cycles) could significantly increase their content, even if the light intensity was very low (35 μmol m^{-2} s^{-1}) (Tuan, et al., 2013a). The total carotenoid content reached the maximum level at 9 or 6 days after sowing (DAS) in light-grown T8 or T10 tartary buckwheat sprouts, respectively. The transcription levels of carotenoid biosynthetic genes were analyzed during the sprouts' developmental stages, showing that the expression of *FtPSY*, *FtPDS*, *FtZDS*, *FtLCYB* and *FtLCYE* genes increased drastically from 3 DAS to 9 DAS and then decreased at 12 DAS in T10 tartary buckwheat sprouts, both in the dark and under light. And the higher expression levels of carotenoid biosynthetic genes and carotenoid content was observed in the light-grown T10 tartary buckwheat sprouts. While, in T8 tartary buckwheat sprouts, the expression of the above-mentioned genes decreased from 3 DAS to 9 or 6 DAS then increased at 12 DAS, whether in the presence of light or not. Although no difference was observed in the transcript levels of carotenoid biosynthetic-related genes between light and dark conditions, the carotenoid contents in the light-grown T8 tartary buckwheat sprouts were significantly higher. The discrepancy between gene expression and carotenoid content in T8 and T10 tartary buckwheat sprouts suggested that other isoforms of carotenoid biosynthetic genes may participate in controlling the flux into carotenoid biosynthesis. In addition, the accumulation of carotenoid was potentially controlled by additional determinants, such as the post-transcriptional and metabolic mechanisms (Tuan, et al., 2013a). At the same year, it was also reported that the total carotenoids content under LED white light (1282.63 μg g^{-1} dry weight) was much higher than that under LED blue (858.29 μg g^{-1} dry weight) and LED red (908.64 μg g^{-1} dry weight) light in T8 tartary buckwheat sprouts at 10 DAS. The accumulation of carotenoids was induced under white light from 2

DAS to 10 DAS, while it increased from 2 to 6 DAS (red light) or 8 DAS (blue light) then decreased at 10 DAS. At 8 DAS, the transcription levels of *FtPSY*, *FtLCYB*, *FtLCYE*, *FtCHXB*, *FtCHXE*, and *FtZEP* were higher in sprouts grown under white light than in those grown under blue and red lights, which might lead to the rich amount of carotenoids accumulation under white light (Tuan, et al., 2013b). LED red light, whether used alone or as a supplementary light, was reported to increase lutein content of tatsoi and basil microgreens, but decreased lutein content of mustard microgreens (Brazaitytė, et al., 2016; Samuolienė, et al., 2017). Therefore, the effects of LED red light on carotenoid accumulation might depend on both the species and the light conditions of this processing (Table S3).

3.4 Other nutritional compounds

In addition to the bioactive substances mentioned above, sprouts and microgreens also contain other nutrients and bioactive compounds (Table S4). Glucosinolates are an important group of secondary plant metabolites. They are sulfonated thioglycosides with a variable aglycone side chain, based on the structure of which glucosinolates are divided into three classes: aliphatic, indolyl and aromatic glucosinolates (Mewis, et al., 2012). Apart from the well-known role in plant defence response to insects and pathogens, glucosinolates also have health benefits in lowing the risk of myocardial infarction, cancer and coronary heart disease (Ma, et al., 2018; Traka, 2016). The biosynthesis of glucosinolates can be triggered by a series of biotic and abiotic factors (Kissen, et al., 2016). Therefore, UV irradiation was used as an effective strategy to accumulate high levels of glucosinolates in sprouts and microgreens. It was reported that UV-A, UV-B light doses and harvesting time differentially tailor glucosinolate profiles in broccoli sprouts, and UV-B could significantly increase the content of glucosinolate in broccoli sprouts (Moreira-Rodríguez, Nair, Benavides, Cisneros-Zevallos, & Jacobo-Velázquez, 2017a; 2017b) (Table S4). Light exposure has positive effect on glucosinolates accumulation in sprouts. For instance, compared with the dark, exposure to fluorescent light was reported to significantly increased the total glucosinolate content of broccoli sprouts by 35% (Pérez-Balibrea, Moreno, & García-Viguera, 2008). However, white light was reported to significantly decrease total glucosinolates content of white mustard sprouts by 8% (Ciska, Honke, & Kozłowska, 2008). The effects of different light qualities (white LED, red and blue lights) on glucosinolates content in Chinese kale sprouts were investigated, the results showed that the total glucosinolates content in the shoot under white and red LED light exhibited no striking change, but was significantly decreased under LED blue light, when compared to those grown in the dark (Qian, et al., 2016). However, Kopsell and Sams (2013) reported that supplemental LED blue light could significantly increase the glucosinolate content of broccoli microgreens. Combining red and blue LED light was also reported to increase the glucosinolate content of broccoli microgreens (Kopsell, Sams, Barickman, & Morrow, 2014). Recently, different cultivars of rapeseed sprouts are studied to identify the effects of blue/red light ratios on glucosinolate accumulation. The results showed that the glucosinolate content varied between different cultivars, but neither high blue ration (31.7% blue light/ 66.3% red light) nor low blue ratio (14.8%

blue/81.3% red light) could significantly alter the glucosinolate content. Therefore, the glucosinolates content of rapeseed sprouts might be optimized when treated with appropriate light treatment (Groenbaek, Tybirk, & Kristensen, 2018).

The total protein content of cowpea sprouts, jack bean sprouts and red cabbage sprouts were significantly increased under white light, as compared to those grown in the dark. However, the total protein content of mucuna sprouts and penca cabbage sprouts was significantly decreased under white light (Martín-Cabrejas, et al., 2008; Vale, et al., 2015). Therefore, the influence of white light on total protein content is species- and cultivars-dependent. In a study of mustard sprouts, 9 essential or semi essential amino acids and 12 nonessential amino acids were detected, and the contents of glycine, arginine, and isoleucine were up-regulated by light conditions, reached the maximum after 9 or 12 days. As for the total amino acids, the highest content was observed in dark-grown mustard sprouts (Li, et al., 2013). Among those detected amino acids, γ-aminobutyric acid (GABA) is a non-protein amino acid and has been considered a bioactive plant component. Glutamate decarboxylase (GAD) is the rate-limiting enzyme for GABA accumulation in GABA shunt. The expression of GAD-encoding genes showed higher expression level in the dark than under the light conditions (16 h/8 h, light/dark). However, GABA content in light-grown mustard sprouts was significantly higher than that of dark-grown sprouts. The discrepancy between the *GAD* expression level and GABA content of light-grown mustard sprouts may resulted from the activity of GABA transaminase and diamine oxidase (DAO), which catalyze the degradation of GABA and GABA polyamine degradation pathway, respectively (Shelp, 1997). This study provided a foundation for understanding the effects of light on GABA accumulation in sprouts, nevertheless, further studies are necessary to identify more regulators and genes that are associated with these compounds' biosynthesis.

Dietary fiber is reported to reduce the risk of colorectal adenoma and colorectal cancer (Aune, et al., 2011; Ben, et al., 2014), with vegetables being one of the main sources of dietary fiber. Vale, et al. (2015) reported that exposure to light determined a lower content of total dietary fiber in the four studied *Brassica oleracea* sprouts (red cabbage, broccoli, Galega kale and Penca cabbage). Similarly, Martín-Cabrejas, et al. (2008) reported that the soluble dietary fiber content was significantly decreased in cowpea sprouts and dolichos sprouts under 12 h/d and 24 h/d illumination, while significantly increased in jack bean sprouts and soybean sprouts under 24 h/d illumination. It is well-documented that high dietary nitrate consumption is associated with an increased risk of gastrointestinal cancer (Muscaritoli, Amabile, & Molfino, 2016). Approximately 80% of human dietary nitrates comes from vegetables, so ways to reduce the nitrate content in vegetables has become a primary concern. It was reported that LED red light could reduce nitrate content of *Perilla frutescen*s (L.) microgreens and radish microgreens, while increases were seen in basil microgreens. It is also reported that LED green light decreases nitrate content of radish microgreens, while increases nitrate content of basil microgreens (Samuolienė, et al., 2014). Mineral elements are also important nutrient of sprouts and microgreens and light could also manipulate the mineral elements content in sprouts and microgreens. For example, it was reported that, compared with the HPS treatment, compound LED light could significantly increase the content of minerals, such as Ca^{2+}, K^{+}, Na^{+} and P^{+}, in *Brassicaceae* microgreens (Vaštakaitė & Viršilė, 2015).

3.5 Antioxidant capacity

Antioxidants are compounds that, in low concentration, can prevent biomolecules (e.g. proteins, nucleic acids, polyunsaturated lipids, and sugars) from undergoing oxidative damage through free radical-mediated reactions (Bendary, Francis, Ali, Sarwat, & El Hady, 2013). They contribute to oxidative stress-related diseases, e.g. neurodegenerative diseases, cancer and heart disease (Apak, Özyürek, Güçlü, & Çapanoğlu, 2016). Various methods are used to measure the antioxidant activity of dietary antioxidants. The most commonly used methods for detecting antioxidant capacity of sprouts and microgreens include 2,2-diphenyl-1-picrylhydrazyl (DPPH) assay, ferric ion reducing antioxidant power (FRAP) assay, 2,2'-azino-bis-3-ethylbenzthiazoline-6-sulphonic acid (ABTS) assay and oxygen radical absorbance capacity (ORAC) assay (Table S5).

There are many studies show that sprouts and microgreens are good sources of dietary antioxidants. Generally, the antioxidant capacity of sprouts and microgreens reflects the composition and content of their bioactive compounds, such as phenolics, vitamins, chlorophyll, carotenoids and glucosinolates (Keum, Jeong, & Kong, 2004; Podsędek, 2007; Williamson, Faulkner, & Plumb, 1998). The structure-activity relationships (SAR) among those bioactive compounds hence provide us with a preliminary insight into their antioxidant capacity. Many studies showed that the antioxidant activity of sprouts and microgreens was positively correlated with flavonoids compounds content and was closely depended on the light conditions

(Table S5). For example, in the Chinese kale sprouts, the antioxidant capacity was significantly increased in sprouts under light exposure, and the highest antioxidant capacity was observed in sprouts grown under LED blue light, which was in accordance with the variation tendency of anthocyanin content (Qian, et al., 2016). In a study of soybean sprouts, the antioxidant activities of two varieties of soybean sprouts, yellow soybean sprouts (YSS, grown in the dark) and green soybean sprouts (GSS, grown under light), with different germination days were studied using DPPH, FRAP and ORAC analysis methods. The results showed that the GSS had lower DPPH radical scavenging capacity but higher ORAC value than YSS on day 7. It was reported that ORAC could measure both lipophilic and hydrophilic antioxidants, which is considered the most relevant to human biology among the antioxidant assay methods (e.g. DPPH, ORAC and FRAP) (Prior, Xianli, & Karen, 2005). Thus, it was speculated that ORAC value is more fundamentally representative of the antioxidant status of soybean sprouts than DPPH. And it is better to produce GSS from the viewpoint of antioxidant capacity because ORAC values were higher than those of YSS. (Chen & Chang, 2015). In another study, light illumination (12 h light and 12 h dark) significantly enhanced the DPPH radical scavenging activity and the FRAP value of polysaccharides from soybean sprouts, which indicating that light illumination during germination has a significant effect on structural and functional properties of polysaccharides derived from soybean sprouts (Yuan, et al., 2015b). In addition, the activity of antioxidant enzymes could also be significantly increased by UV-B (Jiao, Yang, Zhou, & Gu, 2016). The correlation analysis of phenolic compounds with antioxidant capacity showed that the antioxidant activities were correlated significantly and positively with phenolic content of lentil sprouts and pea sprouts (Liu, et al., 2016; Świeca, Gawlik-Dziki, Kowalczyk, & Złotek, 2012).

However, studies have also shown that light has no effect or even negative effect on the antioxidant capacity of sprouts and microgreens (Brazaitytė, Jankauskienė, & Novičkovas, 2013; Chen & Chang, 2015; Świeca, Gawlik-Dziki, Kowalczyk, & Złotek, 2012; Vale, Cidade, Pinto, & Oliveira, 2014).

3.6 Postharvest quality

Sprouts and microgreens are delicate and have a short shelf life due to high moisture content and rapid deterioration, which limits their commercial use. In addition, the nutritional quality of sprouts decreases during postharvest storage. Studies have shown that light treatments after harvesting of fruits and vegetables can play a role in delaying ageing, reducing nutrient loss and extending shelf life (Büchert, Gómez Lobato, Villarreal, Civello, & Martínez, 2011; Jin, Yao, Xu, Wang, & Zheng, 2015). However, little information is available describing the postharvest physiology of sprouts and microgreens, and the effects of light during this process have not yet been well quantified. Recently, several studies have shown that postharvest light treatment could affect the shelf life and the bioactive compounds content of the post-harvested sprouts and microgreens. For example, it was reported that continuous fluorescent light exposure during storage increased the content of ascorbic acid while having no effect on α-tocopherol, total phenolic concentrations or DPPH radical scavenging capacity of radish microgreens (Xiao, et al., 2014). Although UV-LEDs with wavelengths around 240-370 nm are commercially available, the application of UV-LEDs is restricted due to their lower output optical power and lack of complete monochromaticity (Bui & Hauser, 2015; Li, Dvořák, Nesterenko, Nuchtavorn, & Macka, 2018). Nevertheless, the use of UV florescent lamps have shown that postharvest UV-B radiation could further boost glucosinolates levels and extend the shelf life of broccoli microgreens (Lu, et al., 2018). Further studies are needed to investigate the effects of light exposure on the shelf life and nutrient contents of sprouts and microgreens.

4. Conclusions

LED, an innovative artificial light source for plants, is a promising lighting for improving the nutrient quality in sprouts and microgreens, both as a supplemental and a sole-source illumination. In these studies, it has been preliminarily established that a series of structural genes related to the biosynthesis of phytochemical compounds, such as flavonoids and carotenoids, are regulated in response to LED light in sprouts and microgreens. However, the expression patterns of the biosynthetic related genes cannot always explain their accumulation levels. Therefore, further work is necessary to thoroughly delineate the underlying mechanisms. Sprouts and microgreens are young seedlings that are sensitive to light and are a good model system for studying the metabolism. We would suggest the following topics that are worth considering for further exploration:

1) for the more efficient use of LED light and the improvement of the nutritional and health value of sprouts and microgreen vegetables, specific LED light recipes (the properly designed LED lighting system combining different spectral composition and light intensities) should be identified to increase the yield and maximize the content of phytochemical compounds to promote health or prevents diseases;

2) the integrated approaches of transcriptomic, proteomic and metabolomic analysis are needed to reveal the dynamics of the metabolism under LED light;

3) the role of photoreceptors (e.g. phytochromes) and light signal transduction pathways in regulating phytochemical compounds metabolism under LED light remained to be clarified;

4) further analysis should be carried out to identify the target genes and markers associated with secondary metabolites biosynthesis for future molecular breeding.

The studies on the regulatory effect of LED light spectra on the growth and metabolism of sprouts and microgreens will provide an increasingly mature system in which to provide adequate quantity and quality of vegetables, as well as to explore the basic responses of plant seedlings to light signals. Therefore, the application of LED light in vegetable production has enormous potential health benefits, and provides possibilities for feeding the expanding population sustainably and efficiently in the future.

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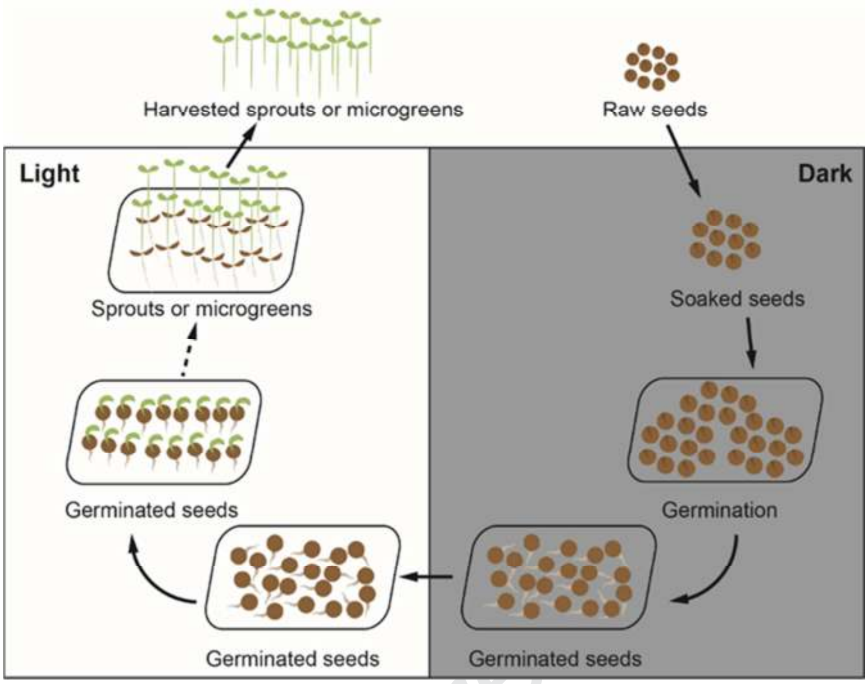
Figure captions:

Figure 1. The current production methods of sprouts and microgreens.

Figure 2. The effective spectra for plants and plant photoreceptors. UVR8, UV RESPONSE LOCUS 8.

1122 **Figure 1**



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1124 **Figure 2**

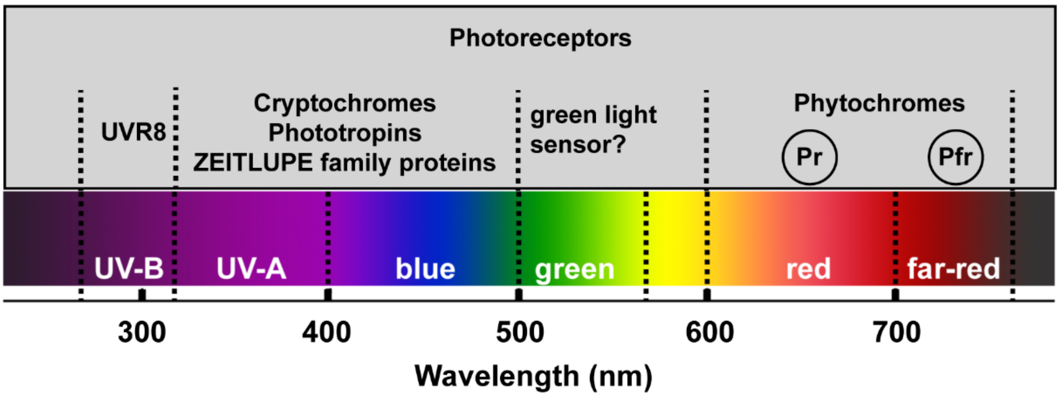

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Table 1. The effects of LED light on the phenolic compounds content of sprouts and microgreens.

Phytochemicals	**Quantification**	**Sprouts/microgreens**	**germination time**	**Light conditions**			**References**
				Light quality & light sources	**Light intensity or UV-irradiance**	**Photoperiod or illumination time (h)**	
Total Phenolic	+62%	Soybean sprouts (*Glycine max* L.)	6 days	Dark (Con[a]), Green and yellow (colored cellophane tapes and an acryl film)	NA[b]	96 h	(Kim, et al., 2006)
	-6%	Penca cabbage sprouts (*B. oleracea* L. var. *costata* DC)	12 days	Dark (Con), White (LNA[c])	NA	16 h light/8 h dark photoperiod	(Vale, Cidade, Pinto, & Oliveira, 2014)
	-17%	Broccoli sprouts (*B. oleracea* L. var. italic Plenck)	7 days				
	+30%	Red cabbage sprouts (*B. oleracea* L. var. *capitate* f. *rubra*)	12 days				
	-17%	Galega kale sprouts (*B. oleracea* L. var. *acephala* DC)	7 days				
	+34% under white light, +69% under blue light	Chinese kale sprouts (*Brassica oleracea*)	7 days	Dark (Con), White (440-660 nm), Red (660 nm), Blue (470 nm) (LED lamps)	30 μ mol m^{-2} s^{-1}	16 h light/8 h dark photoperiod	(Qian, et al., 2016)
	NQ[d] (significantly improved by red, blue and	Pea sprouts (*Pisum sativum* L.)	6 days	Dark (Con), Red (635 nm), Blue (460 nm), Yellow (585 nm),	30 μ mol m^{-2} s^{-1}	12 h light/12 h dark photoperiod	(Liu, et al., 2016)

white light)			white (LED lamps for red, blue and yellow light, fluorescent lamps for white light)			
+10% under blue light, -17% under red light	Common buckwheat sprouts (*Fagopyrum esculentum* Möench)	7 days	White (Con), Blue (460 nm), Red (625 nm), (LED lamps for blue and red light, fluorescent lamps for white light)	35 μ mol m^{-2} s^{-1}	16 h light/8 h dark photoperiod	(Nam, Kim, & Eom, 2018)
+40%	Lentil sprouts (*Lens culinaris*)	8 days	Dark, White (LNA)	NQ	24 h/day	(Świeca, Gawlik-Dziki, Kowalczyk, & Złotek, 2012)
-34%	Red pak choi microgreens (*Brassica rapa* var. *rosularis*)	10 days	Combination of LEDs (combination of 447 nm, 638 nm, 665 nm and 731 nm) (Con), Red (638 nm) (LED lamps)	300 μ mol m^{-2} s^{-1}	16 h light/8 h dark photoperiod	(Brazaitytė, et al., 2016)
+13%	Tatsoi microgreens (*Brassica rapa* var. *rosularis*)	10 days				
+58%	basil microgreens (*Ocimum basilicum* L.)	13 days	HPS light, HPS light supplemental red light (638 nm) (HPS lamps, LED lamps)	HPS: 300 μ mol m^{-2} s^{-1}, HPS 210 μ mol m^{-2} s^{-1} + LED 90 μ mol m^{-2} s^{-1}	16 h light/8 h dark photoperiod	(Samuolienė, et al., 2016)
NQ (significantly increased under white light)	Soybean sprouts (*Glycine max* L. Merrill)	3-7 days	Dark (Con), White (fluorescent lamps)	120 μ mol m^{-2} s^{-1}	12 h light/12 h dark	(Yuan et al., 2015)

Total Flavonoid	+56% under UV-C, +51% under UV-A, +24% under blue light	Tartary buckwheat sprouts (*Fagopyrum esculentum*)	3 days	Dark (Con), UV-C (254 nm), UV-A (365 nm), blue (Fluorescent lamps for blue light & UV lamps for UV light)	UV light: 70.32 W m^{-2}, blue light: 66.93 W m^{-2}	12 h light/12 h dark	(Ji, Wen, Zhou & Ying, 2016)
	NQ (significantly improved by all the light quality treatment)	Pea sprouts (*Pisum sativum* L.)	6 days	Dark (Con), Red (635 nm), Blue (460 nm), Yellow (585 nm), white (LED lamps for red, blue and yellow light, fluorescent lamps for white light)	30 μ mol m^{-2} s^{-1}	12 h light/12 h dark photoperiod	(Liu, et al., 2016)
	+12% under blue light, -13% under red light	Common buckwheat sprouts (*Fagopyrum esculentum* Mo¨ench)	7 days	White (Con), Blue (460 nm), Red (625 nm), (LED lamps for blue and red light, fluorescent lamps for white light)	35 μ mol m^{-2} s^{-1}	16 h light/8 h dark photoperiod	(Nam, Kim, & Eom, 2018)
	+92%	Broccoli sprouts (*B. oleracea* L.)	13 days	White (Con), UV-B (UV lamps)	0.6 kJ m^{-2} d^{-1}	240 min	(Mewis, et al., 2012)
	+55%	Lentil sprouts (*Lens culinaris*)	8 days	Dark (Con), White (LNA)	NA	24 h/day	(Świeca, Gawlik-Dziki, Kowalczyk, & Złotek, 2012)

Isoflavone	+176%	Soybean sprouts (*Glycine max* L. cv Yunhe)	4 days	Dark (Con), UV-B (313 nm) (UV-B light bulb)	4 μW cm^{-2}	NA	(Jiao, Yang, & Gu, 2016; 2017)
	+148%	Soybean sprouts (*Glycine max* L.)	6 days	Dark (Con), Green and yellow (colored cellophane tapes and an acryl film)	NA	96 h	(Kim, et al., 2006)
	+58%	Soybean sprouts (*Glycine max* L.)	4 days	Dark, UV-B (UV-B lamps)	10 μW cm^{-2}	6h light/18 h dark	(Ma, et al., 2018)
	-49%	Red clover sprouts (*Trifolium pratense* L.)	10 days	White (Con), UV-B (340 nm) (LNA)	NA	24 h/day	(Grażyna, et al., 2018)
	+20%	Soybean sprouts (*Glycine max* L. cv Aga3)	7 days	Dark (Con), White (greenhouse lamps)	8 μ mol m^{-2} s^{-1}	12 h light/12 h dark photoperiod	(Phommalth, Jeong, Kim, Dhakal, & Hwang, 2008)
Anthocyanin	+103%	Buckwheat sprouts (*Fagopyrum esculentum* Moench.)	NA	White (Con), UV-B (> 300 nm) (fluorescent lamps)	white light: 110 μ mol m^{-2} s^{-1} and 12 W m^{-2}, UV-B: 10 μ mol m^{-2} s^{-1} and 890 W m^{-2}	24 h	(Tsurunaga, et al., 2013)
	+465% under blue light, +454% under white light	Tartary buckwheat sprouts (*Fagopyrum sp.*)	11 days	Dark (Con), Blue (430 nm), White (380 nm) (LED lamps)	blue light: 177 μ mol m^{-2} s^{-1}, white light: 198 μ mol m^{-2} s^{-1}	16 h light/8 h dark photoperiod	(Seo, Arasu, Kim, Park, & Kim, 2015)
	NQ (significantly improved by all the light treatment,	Chinese kale sprouts (*Brassica oleracea*)	7 days	Dark (Con), White (440-660 nm), Red (660 nm), Blue (470 nm)	30 μ mol m^{-2} s^{-1}	16 h light/8 h dark photoperiod	(Qian, et al., 2016)

	especially blue light)			(LED lamps)			
	+610%	Tartary buckwheat sprouts (*Fagopyrum tataricum*)	10 days	Dark (Con), White light (LNA)	4000 LX	16 h light/8 h dark photoperiod	(Peng, Zou, Su, Fan, & Zhao, 2015)
	+65%	Tartary buckwheat sprouts (*Fagopyrum tataricum*, *cv* Hokkai T8)	4 days	White (380 nm) (Con), Blue (470 nm) (LED lamps)	50 μ mol m^{-2} s^{-1}	16 h light/8 h dark photoperiod	(Thwe, et al., 2014)
	NQ (significantly increased under UV-B)	Radish sprouts (*Raphanus sativus* L.)	4 days	Dark UV-B (UV lamps)	5.5 W m^{-2}	12 h light/12 h dark photoperiod	(Su, et al., 2016)
	NQ (significantly increased under UV-A)	Soybean sprouts (Glycine max L. 'Dongnong 690')	4 days	Dark UV-A (UV lamps)	5.5 W m^{-2}	36 h	(Su, et al., 2017)
	NQ (significantly increased under UV-B)	Radish sprouts (*Raphanus sativus* L.)	3 days	White (Con), UV-B (LED lamps for white light, UV lamps for UV-B)	white light: 50 μ mol m^{-2} s^{-1}, UV-B 10 W m^{-2}	36 h	(Wu, et al., 2016)
	+25%	*Perilla frutescens* (L.) microgreens	NA	White (Con), Red (638 nm) (LED lamps)	300 μ mol m^{-2} s^{-1}	18 h light/6 h dark photoperiod	(Brazaitytė, et al., 2013)
	+56%	Basil microgreens (*Ocimum basilicum* L.)	15 days	White (Con), Red:blue light ratio = 1:2 (LED lamps)	120 μ mol m^{-2} s^{-1}	12 h light/12 h dark photoperiod	(Lobiuc, et al., 2017)
Rutin	+43%	Buckwheat sprouts (*Fagopyrum esculentum* Moench.)	NA	White (Con), UV-B (> 300 nm) (fluorescent lamps)	white light: 110 μ mol m^{-2} s^{-1} and 12 W m^{-2}, UV-B: 10 μ mol m^{-2} s^{-1} and 890	24 h	(Tsurunaga, et al., 2013)

					W m^{-2}		
	+66%	Soybean sprouts (*Glycine max* L. Merrill)	6 days	Dark (Con), White (fluorescent lamp)	100 μ mol m^{-2} s^{-1}	12 h light/12 h dark photoperiod	(Yuan, et al., 2015)
	+8%	common buckwheat sprouts (*Fagopyrum esculentum*)	12 days	Red+blue (Con), Red (LED lamps)	red+blue light : 9.19 μ mol m^{-2} s^{-1},, red light: 4.75 μ mol m^{-2} s^{-1}	NA	(Lee, et al., 2014)
	+5%	Tartary buckwheat sprouts (*Fagopyrum tataricum*, *cv* Hokkai T8)	4 days	White (380 nm) (Con), Blue (470 nm) (LED lamps)	50 μ mol m^{-2} s^{-1}	16 h light/8 h dark photoperiod	(Thwe, et al., 2014)
Quercetin	+19%	Soybean sprouts (*Glycine max* L. Merrill)	6 days	Dark (Con), White (fluorescent lamp)	100 μ mol m^{-2} s^{-1}	16 h light/8 h dark photoperiod	(Yuan, et al., 2015)
	-31%	Lentil sprouts (*Lens culinaris*)	8 days	Dark (Con), White (LNA)	NQ	24 h/day	(Świeca, Gawlik-Dziki, Kowalczyk, & Złotek, 2012)
Luteolin	+138%	Lentil sprouts (*Lens culinaris*)	8 days	Dark (Con), White (LNA)	NQ	24 h/day	(Świeca, Gawlik-Dziki, Kowalczyk, & Złotek, 2012)

[a] Con: control group;
[b] NA: not available information;
[c] LNA: light source not available;
[d] NQ: not quantitative.

Highlights

1. Sprouts/microgreens are functional foods with multiple health benefits.
2. Sprouts/microgreens respond to spectra by altering the morphology and metabolism.
3. LEDs provide new opportunities to manipulate the quality of produce for markets.
4. An optimized LED light recipe unique for each plant species can be programmed.