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

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13

14 **Abstract:**

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

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

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

33

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

36

37

## 38 **1. Introduction**

39 Vegetables are rich in phytonutrients and dietary fibers, which are indispensable  
40 and beneficial for the human body. Recent researches have shown that regular intake  
41 of vegetables is associated with a reduced risk of illnesses, such as cardiovascular  
42 disease and cancer (Aune, et al., 2017; Moore & Thompson, 2015). Over the past two  
43 decades, the interest in fresh, nutritional and organic vegetables has increased as living  
44 standards have risen. In such cases, sprouts and microgreens are gaining increasing  
45 popularity. According to the recently published papers, the definition of sprouts is “the  
46 product obtained from the germination of seeds and their development in water or  
47 another medium, harvested before the development of true leaves and which is intended  
48 to be eaten whole, including the seed” (Di Gioia, Renna, & Santamaria, 2017). While,  
49 microgreens are defined as “tender immature greens, produced from the seeds of  
50 vegetables and herbs, having two fully developed cotyledon leaves with or without the  
51 emergence of a rudimentary pair of first true leaves” (Xiao, Lester, Luo, & Wang,  
52 2012). There is a large variety of sprouts and microgreens, among which legumes (e.g.  
53 soybean, pea, cowpea, etc.) and *Brassica* species (e.g. radish, broccoli, red pak choi and  
54 buckwheat, etc.) sprouts and microgreens are the most commonly consumed.

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

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

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

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

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

## 100 **1.1 The artificial lighting systems in sprouts and microgreens production**

101 The main light sources in sprouts or microgreen production are artificial lights,  
102 including high-pressure sodium lamps (HPSs), fluorescent lamps (FLs) and  
103 light-emitting diodes (LEDs), among others (Bantis, et al., 2018). HPSs, with their  
104 high electrical efficiencies, long operating life and a wide spectrum of light, are the  
105 most common artificial light sources used for the culture of many plant species in

106 greenhouses (Islam, et al., 2012). FLs are widely used in growth chambers. When  
107 used as additional light sources, FLs can provide sustained photosynthetic photon  
108 fluence which is necessary for high productivity (Darko, Heydarizadeh, Schoefs, &  
109 Sabzalian, 2014). However, HPSs and FLs both have serious limitations. For example,  
110 HPSs require high voltage and emit intense radiant heat, in addition, they also contain  
111 only 5% blue light, which is low compared to natural sunlight (18% blue light) (Islam,  
112 et al., 2012). While FLs have limited photon output, less than ideal energy conversion  
113 to light and a short effective lifespan (Rehman, et al., 2017). These features bring  
114 several problems, in respect to the way the plants grow and develop, or overheating  
115 due to infrared radiation (D'Souza, Yuk, Khoo, & Zhou, 2015). In contrast, LEDs  
116 possess unique properties that are highly suitable for horticulture, including low  
117 radiant heat emissions; high emissions of monochromatic light; photon efficiency;  
118 long life expectancy, and flexibility, as well as the ability to be pulsed (D'Souza, Yuk,  
119 Khoo, & Zhou, 2015; Yeh & Chung, 2009). Therefore, LEDs have received  
120 widespread attention and have been widely used in plant factory and other controlled  
121 environment chambers.

## 122 **1.2 The LED light spectra and plant photoreceptors**

123 The range of wavelengths which modify the behavior of plants ranges from  
124 ultraviolet (UV) light (~280 nm) to far-red light (700–750 nm) (Figure 2) (Kami, et  
125 al., 2010; Rizzini, et al., 2011). Photoreceptors, which can sense a range of light  
126 wavelengths, help plants to sense and utilize radiation from near UV (~350nm)  
127 through the blue to red/far-red (~750nm) light (Möglich, Yang, Ayers, & Moffat,

128 2010). Blue (~450nm) and red (~650nm) light are strongly absorbed by plants, while  
129 green (~530 nm) and far-red (~735 nm) light are reflected a large extent (Kami, et al.,  
130 2010). Red/far-red light receptors phytochromes, UV-A/blue light receptors  
131 phototropins, cryptochromes and ZEITLUPE family proteins, as well as UV-B  
132 receptors UV RESPONSE LOCUS 8 (UVR8), form the three main systems that  
133 respond to light signals in plants (Chen, Chory, & Fankhauser, 2004; Rizzini, et al.,  
134 2011). In plants, there are two interconvertible forms of phytochromes: a red  
135 light-absorbing Pr form and a far-red light-absorbing Pfr form (Chen, Chory, &  
136 Fankhauser, 2004). Phytochromes have roles in seed germination, shade-avoidance  
137 responses, seedling development and floral induction (Mazzella, Cerdán, Staneloni, &  
138 Casal, 2001; Neff, Fankhauser, & Chory, 2000). In *Arabidopsis thaliana*,  
139 phototropins are responsible for phototropism (Inoue, Kinoshita, Takemiya, Doi, &  
140 Shimazaki, 2008), while cryptochromes are responsible for flowering, the entrainment  
141 of the circadian clock, the regulation of stomatal opening and root development (Li &  
142 Yang, 2007). UVR8 regulates a range of UV-B responses, including flavonoid  
143 biosynthesis, hypocotyl growth inhibition and leaf cell expansion (Jenkins, 2014).  
144 Although the specific green light photoreceptor remains to be identified in higher  
145 plants, the effects of green light on plant growth should not be ignored. Increasing  
146 evidences have shown the role of green light in photosynthesis and metabolism in  
147 plants. For instance, addition of small portion of green light (~20%) has been shown  
148 to enhance plant growth as green light penetrates deeper into the plant canopy and  
149 enhances photosynthesis at lower leaf levels (Kim, Goins, Wheeler, & Sager, 2004).



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

154 LEDs emit light with a narrow-band wavelength, which depends on the  
155 properties of the semiconductor materials of the devices. With the improvement of  
156 semiconductor technology, the peak emission wavelength of LED ranges from UV  
157 (~250 nm) to infrared (~1000 nm) (Olle & Viršile, 2013). In other words, LED light  
158 could emit both broad-band light (white light) and monochromatic light (e.g., UV,  
159 blue, green, red and far-red light). When multiple LEDs are combined,  
160 monochromatic lights with different intensities or a combination of light with  
161 different spectral compositions could be emitted. Therefore, the accurate and flexible  
162 light spectra control ability of LEDs allows it to provide optimal light wavelengths  
163 that match the plant photoreceptors and photosynthetic pigments, and may contribute  
164 to optimize plant growth and metabolism.

### 165 **1.3 Light spectra and intensity change photosynthesis**

166 Photosynthesis is a process to convert light energy (photons) to biomass in plant,  
167 in which light intensity and spectra play fundamental roles. The highest  
168 photosynthesis and productivity of plants could be achieved at appropriate light  
169 intensity. When light intensity is lower than a certain compensation intensity,  
170 photosynthesis will be exceeded by respiration, and the plants will become a net  
171 consumer of oxygen. However, the photosynthesis and even plant growth could be

172 damaged with the increase of light intensity, due to the photoinhibition (Ooms, Dinh,  
173 Sargent, & Sinton, 2016).

174 The most important light region for photosynthesis is 400 to 700 nm, known as  
175 photosynthetically active radiation (PAR). Due to the emitting of narrow wave band  
176 lights, the flexibility to control light spectral composition and the high PAR  
177 conversion efficiency (Both, et al., 2017), LEDs are perceived as tailor-made light  
178 sources and widely employed in analyzing photosynthesis under different light spectra.  
179 It has long been known that blue and red light regions are most efficiently absorbed  
180 by chlorophylls, the primary photosynthetic pigments, during the photosynthetic  
181 processes (Chen & Blankenship, 2011). Therefore, red and blue lights are currently  
182 two types of light spectra that have been most studied on plant photobiology . Red  
183 light was reported to promote photosynthesis and vegetative growth by increasing the  
184 content of chlorophyll, promoting the formation of photosynthetic apparatus and  
185 probably by inducing stomatal opening (Zhu, Geng, Chakravorty, Guan, Chen, &  
186 Assmann, 2019; Wang, Lu, Tong, & Yang, 2016). However, prolonged red light  
187 illumination may result in 'red light syndrome', which is characterized by low  
188 photosynthetic capacity, low maximum quantum yield of chlorophyll fluorescence  
189 ( $F_v/F_m$ ), low carbohydrate content accumulation and impaired growth (Miao, Chen,  
190 Qu, Gao, & Hou, 2019)). Blue light, which is strongly absorbed by carotenoid  
191 pigments (lutein and  $\beta$ -carotene), was reported to increase the chlorophyll content and  
192 chlorophyll a/b ratio, promote stomatal opening, control the integrity of chloroplast  
193 protein, and enhance  $F_v/F_m$  (Huché-Thélier, et al., 2016) . Meanwhile, many studies

194 showed that an optimized red: blue light ratio may be more beneficial for  
195 photosynthesis. For instance, the net photosynthetic rate increased upon the decrease  
196 of the red: blue ratio (Nanya, Ishigami, Hikosaka, & Goto, 2012), and the impaired  
197 photosynthetic parameters and chloroplast development induced by red light could be  
198 alleviated by adding blue light (Miao, Chen, Qu, Gao, & Hou, 2019).

199 On the other hand, other lights with wavelengths outside the red and blue light regions  
200 were also reported to play considerable roles in photosynthesis, which was once  
201 neglected. For example, green light was once ignored because it is absorbed weakly by  
202 the chlorophylls. The literature recently showed that green light could penetrate the leaf  
203 further than blue and red light, increasing carbon fixation and maybe yield (Terashima,  
204 Fujita, Inoue, Chow, & Oguchi, 2009; Terashima, Fujita, Inoue, Chow, & Oguchi,  
205 2009; Smith, Mcausland, & Murchie, 2017). Moreover, green light could also reverse  
206 UV-B and blue light-mediated stomatal opening (Smith, Mcausland, & Murchie,  
207 2017). Similarly, far-red light has long been considered as photosynthetically  
208 inefficient radiation, due to its poor ability in driving photosynthetic reaction.  
209 However, far-red light was now reported to be more active in enhancing photochemical  
210 efficiency than commonly believed, because of the synergistic effect between far-red  
211 light and light with shorter wavelengths (Zhen & van Iersel, 2017; Zhen, Haidekker, &  
212 van Iersel, 2019). UV light was traditionally considered harmful for photosynthesis,  
213 while the recent studies have changed this stereotype. Although, high UV radiation  
214 could impair the biosynthesis of carotenoids and damage the photosystem II, a  
215 moderate UV dose might have positive effects on photosynthesis by inducing the  
216 biosynthesis of flavonoids with photoprotective activity (Johnson & Day, 2010;  
217 Verdaguer, Jansen, Llorens, Morales, & Neugart, 2017; Guidi, et al., 2016).

218 Understanding the physiological responses induced by other lights (not only red and  
219 blue light) will expand our knowledge about how different portions of the light  
220 spectrum independently or cooperatively regulate plant morphogenesis, which can lead  
221 to the optimization of crop growth.**2. The effects of LED light on the growth of**  
222 **sprouts and microgreens**

223 Photomorphogenic process, which is a default developmental process for the  
224 light-grown seedlings, is triggered by light in sprouts and microgreens during their  
225 development from seeds to edible vegetable products. Increasing numbers of studies  
226 have revealed the vital role of light signals on the growth of sprouts and microgreens  
227 (Table S1). Hypocotyls are one of the main edible parts of sprouts and microgreens,  
228 and the growth of hypocotyls could be affected by artificial lights. For instance, FLs  
229 light exposure was reported has negative effects on hypocotyl elongation. Compared  
230 with the dark conditions, illuminating with FLs light significantly reduced hypocotyl  
231 length of tartary buckwheat sprouts and soybean sprouts by 40% and 16%,  
232 respectively (Peng, Zou, Su, Fan & Zhao, 2015; Yuan, et al., 2015a). Similarly, FLs  
233 light illuminated bean sprouts, such as dolichos and cowpea sprouts, have been  
234 reported to have decreased radical length when compared with their counterparts  
235 grown in the dark (Martín-Cabrejas, et al., 2008). However, FLs light could  
236 significantly increase the diameter of soybean sprout hypocotyls by 12%, compared  
237 with the sprouts grown in the dark (Yuan, et al., 2015a). The results also showed that  
238 sprouts and microgreens grown in the dark show etiolation phenotype, with white and  
239 long hypocotyls. When grown under light, the shorten hypocotyl of light-grown

240 sprouts and microgreens may be due to the inactivation of COP1 (CONSTITUTIVE  
241 PHOTOMORPHOGENIC 1), a repressor for photomorphogenesis, and the  
242 stabilization of HY5 (LONG HYPOCOTYL 5) and HYH (LONG HYPOCOTYL 5  
243 HOMOLOG), transcription factors that promote photomorphogenesis (Deng, Caspar,  
244 & Quail, 1991). Furthermore, plant hormones, such as gibberellins and ethylene, may  
245 also contribute in mediating light-regulated hypocotyl elongation (Alabadí, et al.,  
246 2008; Yu & Huang, 2017). Compared with red and blue combined LED light, LED  
247 blue light alone could significantly increase hypocotyl length of buckwheat sprouts  
248 (Lee, et al., 2014). Similarly, supplementation of LED far-red light on the basis of  
249 LED red + blue light could significantly increase the hypocotyl length in kohlrabi  
250 microgreens and mustard microgreens (Gerovac, Craver, Boldt, & Lopez, 2016). UV  
251 light has been reported to suppress the growth of seedlings (Huché-Thélier, et al.,  
252 2016), while Brazaitytė et al. (2015a) reported that supplemental LED UV-A (402 nm)  
253 irradiation significantly increased the hypocotyl length of basil, beet and pak choi  
254 microgreens. The results of Wu et al. (2007) showed that LED blue light and red light  
255 both significantly increased stem length of pea microgreens, when compared with  
256 LED white light. The above conclusions, which are in contradiction with previous  
257 research results, may be caused by the lower light intensity under LED blue and red  
258 light. The study on *Brassicaceae* microgreens showed that the hypocotyl length of  
259 tatsoi, red pak choi and mustard microgreens grown under customized LED light was  
260 significantly shorter as compared with those of HPSs, even though the light intensity  
261 of the two treatments was the same ( $150 \mu\text{mol m}^{-2} \text{s}^{-1}$ ) (Vaštakaitė & Viršilė, 2015).

262 The undesirable hypocotyl length of LED-grown *Brassicaceae* microgreens could be  
263 attributed to the high percentage of blue light of customized LED lamps (~16%), as it  
264 was reported that hypocotyl elongation could be prevented by the adding of blue light  
265 (Darko, Heydarizadeh, Schoefs, & Sabzalian, 2014). The effects of light quality on  
266 the leaf area in sprouts and microgreens differ between species. For example, LED red  
267 light was reported to have positive effects on leaf area of pea microgreens (Wu, et al.,  
268 2007), while having negative effects on leaf area of mustard and tatsoi microgreens  
269 (Brazaitytė, et al., 2016). LED light also has positive effects on leaf area. For instance,  
270 LED green light was reported to increase leaf area of mizuna microgreens, and the  
271 same is true for LED UV-A light in basil and pak choi microgreens (Brazaitytė, et al.,  
272 2015b; Gerovac, Craver, Boldt, & Lopez, 2016). As for the effects of light intensity, it  
273 was showed that high light intensity could decrease the leaf area in both kohlrabi and  
274 mustard microgreens (Gerovac, Craver, Boldt, & Lopez, 2016).

275 Fresh weight is one of the most important growth qualities of sprouts and  
276 microgreens. The effects of light on fresh weight varies depend upon the light spectra  
277 applied and varied among sprouts and microgreen species. For example, FLs light was  
278 reported to increase the fresh weight of mucuna sprouts, while decrease the fresh  
279 weight of cowpea sprouts (Martín-Cabrejas, et al., 2008). Similarly, LED UV-A light  
280 was shown to increase the fresh weight of basil microgreens, but decrease the fresh  
281 weight of beet microgreens (Brazaitytė, et al., 2015a). Both red and blue light are  
282 effective for enhancing plant growth because they are more efficiently absorbed by  
283 photosynthetic pigments than other regions of the light spectrum. Therefore, it is not

284 surprising that the adding of LED red and/or blue light could increase fresh weight of  
285 sprouts and microgreens (Kopsell, Sams, Barickman, & Morrow, 2014; Lee, et al.,  
286 2014; Wu, et al., 2007). However, when compared with the dark, LED red and blue  
287 light showed inhibitory effects on fresh weight of common buckwheat sprouts (Nam,  
288 Lim, & Eom, 2018). Furthermore, light exposure might significantly decrease the  
289 yield of soybean sprouts. For example, a study on soybean sprouts with 1-7 days  
290 showed that the yield and dry weight of fluorescent light-grown sprouts were lower  
291 than that of dark-grown sprouts. The above-mentioned observations may result from  
292 the higher protein and lipid consumption and lower water absorption of light-grown  
293 sprouts. (Chen & Chang, 2015). The researches on the light intensity showed that  
294 LED light with higher light intensity could significantly increase the fresh weight of  
295 mustard microgreens (Gerovac, et al., 2016). The details of effects of LED light  
296 illumination on the growth of sprouts and microgreens are listed in the Table S1.

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

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

#### 304 **3.1 Phenolic compounds**

305 Phenolic compounds, which are ubiquitous in plants, comprise an extremely rich

306 group of secondary metabolites. They confer the colour, taste, and aroma of fruits and  
307 vegetables, and are an integral part of the human diet (Shahidi & Ambigaipalan,  
308 2015). Numerous studies have highlighted the antioxidant properties and potential  
309 health-improving effects of a phenolic-rich diet, such as antioxidant,  
310 anti-inflammatory, anti-adhesive and antibacterial effects (Balasundram, Sundram, &  
311 Samman, 2006; Ferreira, Martins, & Barros, 2017; Rice-Evans, Miller, & Paganga,  
312 1997). The content of phenolic compounds is an important quality index of sprouts  
313 and microgreens, and the accumulation of phenolic phytochemicals can be stimulated  
314 by cultivation under different LEDs (Table 1). Compared to the dark, light exposure  
315 increased the total phenolic content of soybean, Chinese kale, and pea sprouts, as well  
316 as sprouts of *Brassica oleracea* varieties (Kim, et al., 2006; Liu, et al., 2016; Qian, et  
317 al., 2016; Vale, Cidade, Pinto, & Oliveira, 2014). However, when grown in the  
318 growth chamber at controlled light cycle (16 h/8 h, light/dark), the total phenolic  
319 content decreased in galega kale, penca cabbage and broccoli sprouts, while increased  
320 in red cabbage sprouts (Vale, Cidade, Pinto, & Oliveira, 2014). The studies on the  
321 light quality showed that total phenolic content of Chinese kale sprouts and common  
322 buckwheat sprouts was significantly decreased under LED red light, while  
323 significantly increased under LED blue light, as compared with white light (Nam,  
324 Kim, & Eom, 2018; Qian, et al., 2016). In a study of pea sprouts, LED light of 585  
325 nm was observed to decrease total phenolic content (Liu, et al., 2016). Several studies  
326 on tatsoi and basil microgreens reported an increase in total phenolic content under  
327 LED red light or supplemental LED red light (Brazaitytė, et al., 2016b; Samuolienė,



328 et al., 2016).

329 Flavonoids represent one of the largest classes of phenolic compounds in fruits  
330 and vegetables (Zoratti, Karppinen, Escobar, Häggman, & Jaakola, 2014). In sprouts  
331 and microgreens, isoflavone, anthocyanin, rutin and quercetin are the most common  
332 phenolic compounds. Similar to the promoting effects on total phenolic content, light  
333 exposure significantly increased the content of the above-mentioned phenolic  
334 compounds (Table 1). For instance, light exposure was reported to boost isoflavone  
335 content in soybean and chickpea sprouts (Aisyah, Gruppen, Madzora, & Vincken,  
336 2013; Gao, Yao, Zhu, & Ren, 2015). In addition, LED blue light showed promoting  
337 effects on total flavonoid content of common buckwheat sprouts, while LED red light  
338 showed the opposite effect (Nam, Kim & Eom, 2018). It is reported that secondary  
339 metabolites in plants are a response to the environmental stresses (Ramakrishna &  
340 Ravishankar, 2011). This has led to a series of studies on the effects of UV light on  
341 secondary metabolites in sprouts and microgreens. For example, UV-B lamps has  
342 been reported to increase total flavonoid content in broccoli sprouts by 92%, when  
343 compared with white light (Mewis, et al., 2012). UV-B light at 313 nm was reported  
344 to increase isoflavone content in soybean sprouts (Jiao, Yang, & Gu, 2016; Jiao, Yang,  
345 & Gu, 2017), while UV-B at 310 nm was reported to decrease isoflavone content in  
346 red clover sprouts (Grażyna, et al., 2018). In soybean sprouts, there were consistent  
347 strong positive correlations between the isoflavone content and radiation intensity of  
348 UV-B (from 0, 5, 10 and 20  $\mu\text{W cm}^{-2}$ ) (Ma, Wang, Yang, & Gu, 2018). Besides, nitric  
349 oxide signaling was reported involved in UV-B-induced isoflavone biosynthesis by

350 regulating the gene expression of key enzymes related (i.e. phenylalanine ammonia  
351 lyase, PAL and chalcone synthase, CHS) (Jiao, Yang, Zhou, & Gu, 2016). Therefore,  
352 the influence of UV-B on isoflavone accumulation is dependent on the species, the  
353 UV-B wavelength as well as the radiation intensity (UV dose). In a study of tartary  
354 buckwheat sprouts, LED blue light followed by UV-C light enhanced the  
355 accumulation of bioactive compounds, while the opposite combination (UV-C  
356 followed by LED blue light) showed weaker effects (Ji, Wen, Zhou, & Ying, 2016).  
357 Thus, the content of phenolic compounds was not only dependent on the light quality  
358 but also the way they are combined.

359 The flavonoids is biosynthesized through a branched phenylpropanoid pathway,  
360 and most of the flavonoid synthesizing enzymes have been found. Recently, the  
361 transcriptional levels of flavonoid biosynthetic genes were investigated in sprouts and  
362 microgreens. For example, it was shown that the time duration and amount of light  
363 strongly affected the phenylpropanoids content in tartary buckwheat sprouts, the three  
364 anthocyanin compounds (namely cyanidin 3-*O* glucoside, cyanidin 3-*O*-rutinoside  
365 and delphindin-3-*O*-coumarylglucoside) in 4-day-old Hokkai T10 buckwheat sprouts  
366 grown under light/dark condition was nearly 4-fold more than those grown in the dark  
367 (Li, et al., 2012). The transcriptional results of flavonoid biosynthetic genes also  
368 showed that *FtFLS2*, *FtF3'H1*, *FtF3'H2* and *FtANS* were up-regulated by light. In  
369 addition, the transcription factor, *FtMYB*-like gene, was markedly induced in  
370 light-treated buckwheat sprouts, indicating that *FtMYB*-like gene was possibly  
371 involved in the light-regulated flavonoid biosynthesis (Li, et al., 2012). In another

372 study, it was shown that rutin was the main phenolic compounds in Hokkai T8  
373 buckwheat sprouts, and the maximum rutin content was observed at 4 day after LED  
374 exposure under blue light, as compared to the LEDA white and red light. Meanwhile,  
375 the cyanidin 3-O-rutinoside content under LED blue light was 2.8- and 10.6-fold  
376 higher than that under LED white and red light, respectively. The analysis of gene  
377 expression showed that the transcript levels of *FtC4H*, *FtCHI*, *FtFLS-2*, and *FtANS*  
378 was higher in sprouts grown under LED blue light (Thwe, et al., 2014). Studies on  
379 UV irradiation showed that UV-B and UV-A could increase the anthocyanin content  
380 of radish sprouts and soybean sprouts, respectively (Su, et al., 2016; Su, et al., 2017).  
381 The anthocyanin accumulation was significantly decreased by shading treatment in  
382 soybean sprouts, which was attributed to the down-regulation of anthocyanin  
383 biosynthesis genes (*GmDFR*, *GmANS* and *GmUFGT*) (Su, et al., 2017). Those results  
384 strongly suggested that the accumulation of anthocyanin was closely related to light  
385 exposure. On one hand, light is a necessary condition for the biosynthesis of  
386 anthocyanins. On the other hand, different light qualities exhibit different effects on  
387 anthocyanin biosynthesis, and short-wavelength light, such as blue light and UV light,  
388 might be more effective to increase anthocyanin content (Qian, et al., 2016; Seo, Arasu,  
389 Kim, Park, & Kim, 2015; Thwe, et al., 2014). The details of effects of LED light on  
390 the phenolic compounds content in sprouts and microgreens are summarized in the  
391 Table 1.

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

394 Vaštakaitė, et al. (2017) reported that adding monochromatic (455, 470, 505, 590 and  
395 627nm) LEDs with frequencies at 2, 256, and 1024 Hz had most positive effects on  
396 total phenolic compounds in mustard microgreens grown under HPS lamps. On the  
397 contrary, adding the monochromatic LEDs at 32 Hz significantly decreased the total  
398 phenolic content in mustard microgreens. However, the monochromatic LED  
399 frequencies at 32 Hz were the most suitable for the accumulation of anthocyanins in  
400 red pak choi and tatsoi microgreens.

### 401 **3.2 Vitamins**

402 Vitamins are a class of organic compounds that cannot be synthesized by the  
403 human body and can only be absorbed from the diet. They are essential for human  
404 development and health, and the intake of vitamins help to reduce the risk of diseases,  
405 such as cardiovascular disease and coronary heart disease (Ashor, Lara, Mathers, &  
406 Siervo, 2014; Stampfer, et al., 1993). Vitamin C (ascorbic acid) is a dietary nutrient  
407 required as a co-factor for many enzymes, and is an especially effective antioxidant  
408 owing to its high electron-donating power (Jacob & Sotoudeh, 2002). Therefore,  
409 vitamin C is one of the most important vitamins in the human diet. Artificial light has  
410 been reported to significantly increase vitamin C content of sprouts and microgreens  
411 (Table S2). For example, compared to growth in the dark, white light and UV + red  
412 LED light significantly increased vitamin C content of broccoli sprouts and soybean  
413 sprouts by 87% and 79%, respectively (Pérez-Balibrea, Moreno, & García-Viguera,  
414 2008; Xu, Dong, & Zhu, 2005). In addition, LED red light was reported to play a  
415 positive role in promoting vitamin C content of microgreens (Brazaitytė,

416 Jankauskienė, & Novičkovas, 2013; Brazaitytė, et al., 2016). Moreover, it was shown  
417 that supplementary LED light, on the basis of HPS light, could also promote the  
418 content of vitamin C of tatsoi microgreens (Vaštakaitė & Viršilė, 2015).

419 Vitamin E, the major lipid-soluble component in the cell antioxidant defense  
420 system, has long been considered as a cytoprotective factor with roles in anti-ageing,  
421 arthritis, cataracts, Type 2 diabetic disease and kidney diseases (Jiang, 2014; Rizvi, et  
422 al., 2014). Alpha-tocopherols, the predominant form of vitamin E, was reported to be  
423 regulated by artificial light (LED and HPS lamps) in microgreens. As shown in Table  
424 S2, using the combination of LEDs or HPSs as the primary light source, supplemental  
425 green, blue and red LED light could promote the increase in vitamin E content of  
426 microgreens (Brazaitytė, et al., 2016; Samuolienė, et al., 2014; Samuolienė, et al.,  
427 2017). However, LED red light was reported to decrease the content of vitamin E in  
428 *Perilla frutescens* (L.) microgreens and red pak choi microgreens (Brazaitytė,  
429 Jankauskienė, & Novičkovas, 2013; Brazaitytė, et al., 2016). Therefore, the effects of  
430 LED light on vitamin E content depend on the light spectra and intensity and vary  
431 among microgreen species (Table S2).

### 432 **3.3 Photosynthetic pigment contents**

433 Following exposure to light, sprouts and microgreens undergo  
434 photomorphogenesis and inevitably synthesize photosynthetic pigments, such as  
435 chlorophyll and carotenoids. Chlorophylls are the most obvious and widespread  
436 pigments of plants, as they are required for photosynthesis. In addition, chlorophylls  
437 have been shown to play important roles in maintain human health, in view of their

438 potent anti-inflammatory property and anti-oxidant activity (Lee, Nishizawa, Shimizu,  
439 & Saeki, 2017; Subramoniam, et al., 2012). Several preliminary studies revealed the  
440 effects of artificial light on chlorophyll and carotenoid content of sprouts and  
441 microgreens (Table S3). It was reported that 20% LED blue light with 80% LED red  
442 light treatment could significantly increase the content of total chlorophyll,  
443 chlorophyll a and chlorophyll b of broccoli microgreens (Kopsell, Sams, Barickman,  
444 & Morrow, 2014). Moreover, UV-A was also reported to increase total chlorophyll  
445 content in broccoli sprouts (Moreira-Rodríguez, Nair, Benavides, Cisneros-Zevallos,  
446 & Jacobo-Velázquez, 2017b). However, a recent study has revealed that LED blue  
447 light could decrease the total chlorophyll content of common buckwheat sprouts, as  
448 compared with the white light (Nam, Lim, & Eom 2018). Similarly, supplemental  
449 LED blue light significantly decreased the chlorophyll b content of broccoli  
450 microgreens (Kopsell, & Sams, 2013). Additionally, the total chlorophyll content of  
451 microgreens decreases when exposed to high-intensity light. For example, total  
452 chlorophyll content of mustard microgreens decreased by 27% under fluorescent light  
453 of  $463 \mu\text{mol m}^{-2} \text{s}^{-1}$ , in comparison to  $275 \mu\text{mol m}^{-2} \text{s}^{-1}$  exposure (Kopsell,  
454 Pantanizopoulos, Sams, & Kopsell, 2012).

455 Carotenoids ( $\alpha$ -carotene,  $\beta$ -carotene, violaxanthin, neoxanthin and lutein, etc.)  
456 play fundamental roles in photosynthetic organisms. They act as accessory  
457 light-harvesting pigments, but they also perform photoprotective role by quenching  
458 triplet state chlorophyll molecules and scavenging singlet oxygen and other toxic  
459 oxygen species formed within the chloroplast (Young, 1991). Dietary carotenoids are

460 thought to play an important role in maintaining good health and preventing human  
461 diseases, such as cancers, diabetes and eye disease (Johnson, 2002; Sluijs, et al.,  
462 2015). Generally, LED light is beneficial for the accumulation of carotenoids in  
463 sprouts and microgreens (Table S3). For example, the supplementation of LED yellow  
464 light (595 nm) could increase total carotenoids content of tatsoi microgreens by 16%  
465 (Brazaitytė, et al., 2015b). Similarly, supplemental blue, red and green LED light was  
466 reported to increase the content of  $\alpha$ -carotene and  $\beta$ -carotene of microgreens  
467 (Brazaitytė, et al., 2015b; Brazaitytė, et al., 2016; Kopsell, Sams, Barickman, &  
468 Morrow, 2014; Samuolienė, et al., 2017). However, supplemental LED orange light  
469 (622 nm) decreased  $\beta$ -carotene content (Brazaitytė, et al., 2015b). Studies on  
470 *Brassicaceae* microgreens and beet microgreens showed that supplemental green,  
471 yellow and blue LED light could promote violaxanthin content, while supplemental  
472 LED orange light showed the opposite effect (Brazaitytė, et al., 2015b; Samuolienė, et  
473 al., 2017). It was also reported that supplemental LED green light increased  
474 neoxanthin content of red pak choi microgreens by 5%, while supplemental LED  
475 yellow light lead to a decrease in neoxanthin content by 69% (Brazaitytė et al., 2015b).  
476 A study on the effects of high light intensity reported that high light intensity could  
477 decrease neoxanthin content of mustard microgreens (Kopsell, Pantanizopoulos, Sams,  
478 & Kopsell, 2012). It was reported that lutein and  $\beta$ - carotene are two main carotenoid  
479 compositions in tartary buckwheat sprouts, and white florescent light exposure (16 h/8  
480 h light/dark cycles) could significantly increase their content, even if the light  
481 intensity was very low ( $35 \mu\text{mol m}^{-2} \text{s}^{-1}$ ) (Tuan, et al., 2013a). The total carotenoid

482 content reached the maximum level at 9 or 6 days after sowing (DAS) in light-grown  
483 T8 or T10 tartary buckwheat sprouts, respectively. The transcription levels of  
484 carotenoid biosynthetic genes were analyzed during the sprouts' developmental stages,  
485 showing that the expression of *FtPSY*, *FtPDS*, *FtZDS*, *FtLCYB* and *FtLCYE* genes  
486 increased drastically from 3 DAS to 9 DAS and then decreased at 12 DAS in T10  
487 tartary buckwheat sprouts, both in the dark and under light. And the higher expression  
488 levels of carotenoid biosynthetic genes and carotenoid content was observed in the  
489 light-grown T10 tartary buckwheat sprouts. While, in T8 tartary buckwheat sprouts,  
490 the expression of the above-mentioned genes decreased from 3 DAS to 9 or 6 DAS  
491 then increased at 12 DAS, whether in the presence of light or not. Although no  
492 difference was observed in the transcript levels of carotenoid biosynthetic-related  
493 genes between light and dark conditions, the carotenoid contents in the light-grown  
494 T8 tartary buckwheat sprouts were significantly higher. The discrepancy between  
495 gene expression and carotenoid content in T8 and T10 tartary buckwheat sprouts  
496 suggested that other isoforms of carotenoid biosynthetic genes may participate in  
497 controlling the flux into carotenoid biosynthesis. In addition, the accumulation of  
498 carotenoid was potentially controlled by additional determinants, such as the  
499 post-transcriptional and metabolic mechanisms (Tuan, et al., 2013a). At the same year,  
500 it was also reported that the total carotenoids content under LED white light (1282.63  
501  $\mu\text{g g}^{-1}$  dry weight) was much higher than that under LED blue (858.29  $\mu\text{g g}^{-1}$  dry  
502 weight) and LED red (908.64  $\mu\text{g g}^{-1}$  dry weight) light in T8 tartary buckwheat sprouts  
503 at 10 DAS. The accumulation of carotenoids was induced under white light from 2



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

#### 514 **3.4 Other nutritional compounds**

515 In addition to the bioactive substances mentioned above, sprouts and  
516 microgreens also contain other nutrients and bioactive compounds (Table S4).  
517 Glucosinolates are an important group of secondary plant metabolites. They are  
518 sulfonated thioglycosides with a variable aglycone side chain, based on the structure  
519 of which glucosinolates are divided into three classes: aliphatic, indolyl and aromatic  
520 glucosinolates (Mewis, et al., 2012). Apart from the well-known role in plant defence  
521 response to insects and pathogens, glucosinolates also have health benefits in lowering  
522 the risk of myocardial infarction, cancer and coronary heart disease (Ma, et al., 2018;  
523 Traka, 2016). The biosynthesis of glucosinolates can be triggered by a series of biotic  
524 and abiotic factors (Kissen, et al., 2016). Therefore, UV irradiation was used as an  
525 effective strategy to accumulate high levels of glucosinolates in sprouts and

526 microgreens. It was reported that UV-A, UV-B light doses and harvesting time  
527 differentially tailor glucosinolate profiles in broccoli sprouts, and UV-B could  
528 significantly increase the content of glucosinolate in broccoli sprouts  
529 (Moreira-Rodríguez, Nair, Benavides, Cisneros-Zevallos, & Jacobo-Velázquez, 2017a;  
530 2017b) (Table S4). Light exposure has positive effect on glucosinolates accumulation  
531 in sprouts. For instance, compared with the dark, exposure to fluorescent light was  
532 reported to significantly increased the total glucosinolate content of broccoli sprouts  
533 by 35% (Pérez-Balibrea, Moreno, & García-Viguera, 2008). However, white light was  
534 reported to significantly decrease total glucosinolates content of white mustard  
535 sprouts by 8% (Ciska, Honke, & Kozłowska, 2008). The effects of different light  
536 qualities (white LED, red and blue lights) on glucosinolates content in Chinese kale  
537 sprouts were investigated, the results showed that the total glucosinolates content in  
538 the shoot under white and red LED light exhibited no striking change, but was  
539 significantly decreased under LED blue light, when compared to those grown in the  
540 dark (Qian, et al., 2016). However, Kopsell and Sams (2013) reported that  
541 supplemental LED blue light could significantly increase the glucosinolate content of  
542 broccoli microgreens. Combining red and blue LED light was also reported to  
543 increase the glucosinolate content of broccoli microgreens (Kopsell, Sams, Barickman,  
544 & Morrow, 2014). Recently, different cultivars of rapeseed sprouts are studied to  
545 identify the effects of blue/red light ratios on glucosinolate accumulation. The results  
546 showed that the glucosinolate content varied between different cultivars, but neither  
547 high blue ratio (31.7% blue light/ 66.3% red light) nor low blue ratio (14.8%

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

551 The total protein content of cowpea sprouts, jack bean sprouts and red cabbage  
552 sprouts were significantly increased under white light, as compared to those grown in  
553 the dark. However, the total protein content of mucuna sprouts and penca cabbage  
554 sprouts was significantly decreased under white light (Martín-Cabrejas, et al., 2008;  
555 Vale, et al., 2015). Therefore, the influence of white light on total protein content is  
556 species- and cultivars-dependent. In a study of mustard sprouts, 9 essential or semi  
557 essential amino acids and 12 nonessential amino acids were detected, and the contents  
558 of glycine, arginine, and isoleucine were up-regulated by light conditions, reached the  
559 maximum after 9 or 12 days. As for the total amino acids, the highest content was  
560 observed in dark-grown mustard sprouts (Li, et al., 2013). Among those detected  
561 amino acids,  $\gamma$ -aminobutyric acid (GABA) is a non-protein amino acid and has been  
562 considered a bioactive plant component. Glutamate decarboxylase (GAD) is the  
563 rate-limiting enzyme for GABA accumulation in GABA shunt. The expression of  
564 GAD-encoding genes showed higher expression level in the dark than under the light  
565 conditions (16 h/8 h, light/dark). However, GABA content in light-grown mustard  
566 sprouts was significantly higher than that of dark-grown sprouts. The discrepancy  
567 between the *GAD* expression level and GABA content of light-grown mustard sprouts  
568 may resulted from the activity of GABA transaminase and diamine oxidase (DAO),  
569 which catalyze the degradation of GABA and GABA polyamine degradation pathway,

570 respectively (Shelp, 1997). This study provided a foundation for understanding the  
571 effects of light on GABA accumulation in sprouts, nevertheless, further studies are  
572 necessary to identify more regulators and genes that are associated with these  
573 compounds' biosynthesis.

574 Dietary fiber is reported to reduce the risk of colorectal adenoma and colorectal  
575 cancer (Aune, et al., 2011; Ben, et al., 2014), with vegetables being one of the main  
576 sources of dietary fiber. Vale, et al. (2015) reported that exposure to light determined a  
577 lower content of total dietary fiber in the four studied *Brassica oleracea* sprouts (red  
578 cabbage, broccoli, Galega kale and Penca cabbage). Similarly, Martín-Cabrejas, et al.  
579 (2008) reported that the soluble dietary fiber content was significantly decreased in  
580 cowpea sprouts and dolichos sprouts under 12 h/d and 24 h/d illumination, while  
581 significantly increased in jack bean sprouts and soybean sprouts under 24 h/d  
582 illumination. It is well-documented that high dietary nitrate consumption is associated  
583 with an increased risk of gastrointestinal cancer (Muscaritoli, Amabile, & Molfino,  
584 2016). Approximately 80% of human dietary nitrates comes from vegetables, so ways  
585 to reduce the nitrate content in vegetables has become a primary concern. It was  
586 reported that LED red light could reduce nitrate content of *Perilla frutescens* (L.)  
587 microgreens and radish microgreens, while increases were seen in basil microgreens.  
588 It is also reported that LED green light decreases nitrate content of radish microgreens,  
589 while increases nitrate content of basil microgreens (Samuolienė, et al., 2014).  
590 Mineral elements are also important nutrient of sprouts and microgreens and light  
591 could also manipulate the mineral elements content in sprouts and microgreens. For

592 example, it was reported that, compared with the HPS treatment, compound LED  
593 light could significantly increase the content of minerals, such as  $\text{Ca}^{2+}$ ,  $\text{K}^+$ ,  $\text{Na}^+$  and  $\text{P}^+$ ,  
594 in *Brassicaceae* microgreens (Vaštakaitė & Viršilė, 2015).

### 595 **3.5 Antioxidant capacity**

596 Antioxidants are compounds that, in low concentration, can prevent  
597 biomolecules (e.g. proteins, nucleic acids, polyunsaturated lipids, and sugars) from  
598 undergoing oxidative damage through free radical-mediated reactions (Bendary,  
599 Francis, Ali, Sarwat, & El Hady, 2013). They contribute to oxidative stress-related  
600 diseases, e.g. neurodegenerative diseases, cancer and heart disease (Apak, Özyürek,  
601 Güçlü, & Çapanoğlu, 2016). Various methods are used to measure the antioxidant  
602 activity of dietary antioxidants. The most commonly used methods for detecting  
603 antioxidant capacity of sprouts and microgreens include  
604 2,2-diphenyl-1-picrylhydrazyl (DPPH) assay, ferric ion reducing antioxidant power  
605 (FRAP) assay, 2,2'-azino-bis-3-ethylbenzthiazoline-6-sulphonic acid (ABTS) assay  
606 and oxygen radical absorbance capacity (ORAC) assay (Table S5).

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

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

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

### 645 **3.6 Postharvest quality**

646 Sprouts and microgreens are delicate and have a short shelf life due to high  
647 moisture content and rapid deterioration, which limits their commercial use. In  
648 addition, the nutritional quality of sprouts decreases during postharvest storage.  
649 Studies have shown that light treatments after harvesting of fruits and vegetables can  
650 play a role in delaying ageing, reducing nutrient loss and extending shelf life (Büchert,  
651 Gómez Lobato, Villarreal, Civello, & Martínez, 2011; Jin, Yao, Xu, Wang, & Zheng,  
652 2015). However, little information is available describing the postharvest physiology  
653 of sprouts and microgreens, and the effects of light during this process have not yet  
654 been well quantified. Recently, several studies have shown that postharvest light  
655 treatment could affect the shelf life and the bioactive compounds content of the  
656 post-harvested sprouts and microgreens. For example, it was reported that  
657 continuous fluorescent light exposure during storage increased the content of ascorbic  
658 acid while having no effect on  $\alpha$ -tocopherol, total phenolic concentrations or DPPH  
659 radical scavenging capacity of radish microgreens (Xiao, et al., 2014). Although  
660 UV-LEDs with wavelengths around 240-370 nm are commercially available, the  
661 application of UV-LEDs is restricted due to their lower output optical power and lack  
662 of complete monochromaticity (Bui & Hauser, 2015; Li, Dvořák, Nesterenko,

663 Nuchtavorn, & Macka, 2018). Nevertheless, the use of UV florescent lamps have  
664 shown that postharvest UV-B radiation could further boost glucosinolates levels and  
665 extend the shelf life of broccoli microgreens (Lu, et al., 2018). Further studies are  
666 needed to investigate the effects of light exposure on the shelf life and nutrient  
667 contents of sprouts and microgreens.

#### 668 **4. Conclusions**

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

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



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

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

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

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

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706

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1117 **Figure captions:**

1118 **Figure 1.** The current production methods of sprouts and microgreens.

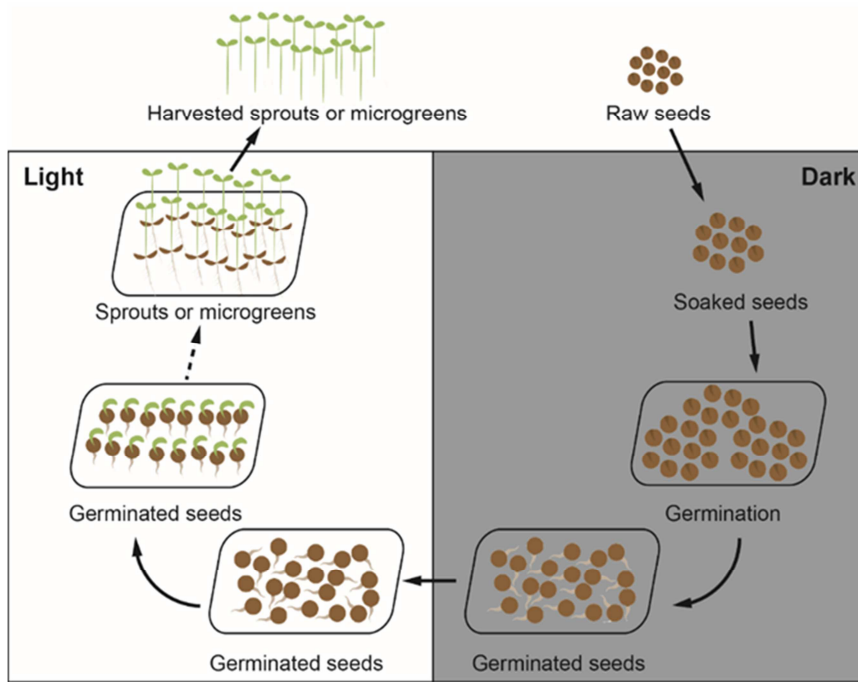
1119 **Figure 2.** The effective spectra for plants and plant photoreceptors. UVR8, UV

1120 RESPONSE LOCUS 8.

1121

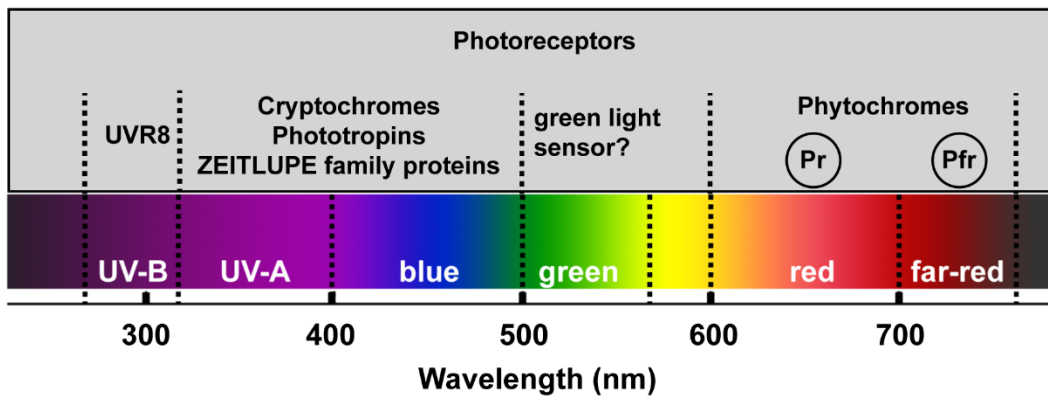
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1122 **Figure 1**



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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 illumination (h) or time	
<b>Total Phenolic</b>	+62%	Soybean sprouts ( <i>Glycine max</i> L.)	6 days	Dark (Con <sup>a</sup> ), Green and yellow (colored cellophane tapes and an acryl film)	NA <sup>b</sup>	96 h	(Kim, et al., 2006)
	-6%	Penca cabbage sprouts ( <i>B. oleracea</i> L. var. <i>costata</i> DC)	12 days	Dark (Con), White (LNA <sup>c</sup> )	NA	16 h light/8 h dark photoperiod	(Vale, Cidade, Pinto, & Oliveira, 2014)
	-17%	Broccoli sprouts ( <i>B. oleracea</i> L. var. <i>italic</i> Plenck)	7 days				
	+30%	Red cabbage sprouts ( <i>B. oleracea</i> L. var. <i>capitate f. rubra</i> )	12 days				
	-17%	Galega kale sprouts ( <i>B. oleracea</i> L. var. <i>acephala</i> DC)	7 days				
	+34% under white light, +69% under blue light	Chinese kale sprouts ( <i>Brassica oleracea</i> )	7 days	Dark (Con), White (440-660 nm), Red (660 nm), Blue (470 nm) (LED lamps)	30 $\mu$ mol m <sup>-2</sup> s <sup>-1</sup>	16 h light/8 h dark photoperiod	(Qian, et al., 2016)
	NQ <sup>d</sup> (significantly improved by red, blue and	Pea sprouts ( <i>Pisum sativum</i> L.)	6 days	Dark (Con), Red (635 nm), Blue (460 nm), Yellow (585 nm),	30 $\mu$ mol m <sup>-2</sup> s <sup>-1</sup>	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 sprouts ( <i>Fagopyrum esculentum</i> Möench)	buckwheat	7 days		White (Con), Blue (460 nm), Red (625 nm), (LED lamps for blue and red light, fluorescent lamps for white light)	$35 \mu \text{ mol m}^{-2} \text{ s}^{-1}$	16 h light/8 h dark photoperiod		(Nam, Kim, & Eom, 2018)
+40%	Lentil sprouts ( <i>Lens culinaris</i> )		8 days		Dark, White (LNA)	NQ	24 h/day		(Świeca, Gawlik-Dziki, Kowalczyk, & Złotek, 2012)
-34%	Red pak microgreens ( <i>Brassica rapa</i> var. <i>rosularis</i> )	choi	10 days		Combination of LEDs (combination of 447 nm, 638 nm, 665 nm and 731 nm) (Con), Red (638 nm) (LED lamps)	$300 \mu \text{ mol m}^{-2} \text{ s}^{-1}$	16 h light/8 h dark photoperiod		(Brazaitytė, et al., 2016)
+13%	Tatsoi microgreens ( <i>Brassica rapa</i> var. <i>rosularis</i> )		10 days		HPS light, HPS supplemental red light (638 nm) (HPS lamps, LED lamps)	HPS: $300 \mu \text{ mol m}^{-2} \text{ s}^{-1}$ , HPS $210 \mu \text{ mol m}^{-2} \text{ s}^{-1}$ + LED $90 \mu \text{ mol m}^{-2} \text{ s}^{-1}$	16 h light/8 h dark photoperiod		(Samuolienė, et al., 2016)
+58%	basil microgreens ( <i>Ocimum basilicum</i> L.)		13 days		Dark (Con), White (fluorescent lamps)	$120 \mu \text{ mol m}^{-2} \text{ s}^{-1}$	12 h light/12 h dark		(Yuan et al., 2015)
NQ (significantly increased under white light)	Soybean sprouts ( <i>Glycine max</i> L. Merrill)		3-7 days						



<b>Total Flavonoid</b>	+56% UV-C, +51% UV-A, +24% under blue light	under	Tartary sprouts ( <i>Fagopyrum esculentum</i> )	buckwheat	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 <sup>-2</sup> , blue light: 66.93 W m <sup>-2</sup>	12 h light/12 h dark	(Ji, Wen, Zhou & Ying, 2016)
	NQ (significantly improved by all the light quality treatment)		Pea sprouts ( <i>Pisum sativum</i> 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 <sup>-2</sup> s <sup>-1</sup>	12 h light/12 h dark photoperiod	(Liu, et al., 2016)
	+12% blue light, -13% under red light	under	Common sprouts ( <i>Fagopyrum esculentum</i> Moench)	buckwheat	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 <sup>-2</sup> s <sup>-1</sup>	16 h light/8 h dark photoperiod	(Nam, Kim, & Eom, 2018)
	+92%		Broccoli sprouts ( <i>B. oleracea</i> L.)		13 days	White (Con), UV-B (UV lamps)	0.6 kJ m <sup>-2</sup> d <sup>-1</sup>	240 min	(Mewis, et al., 2012)
	+55%		Lentil sprouts ( <i>Lens culinaris</i> )		8 days	Dark (Con), White (LNA)	NA	24 h/day	(Świeca, Gawlik-Dziki, Kowalczyk, & Złotek, 2012)

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

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

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

<sup>a</sup> Con: control group;

<sup>b</sup> NA: not available information;

<sup>c</sup> LNA: light source not available;

<sup>d</sup> 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.