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Review

Bioactive compounds and bioactivities of germinated edible seeds and sprouts: An updated review

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A B S T R A C T

Background: **Germination** has been widely employed to produce germinated **edible seeds** and sprouts for consumption in our daily life. Through simple germination procedures, many edible seeds can be germinated in a short time with improved nutritional and medicinal values. Understanding the main bioactive compounds and bioactivities of germinated edible seeds and sprouts can be helpful for their better utilization as functional foods.
Scope and approach: This review mainly summarizes recent studies about the bioactive compounds and bioactivities of germinated edible seeds and sprouts, and the potential molecular mechanisms of accumulating bioactive compounds in germination are discussed.
Key findings and conclusions: Germination can accumulate different bioactive compounds, such as **vitamins**, **γ-aminobutyric acid** and **polyphenols**, and this can be dependent on *de novo* synthesis and transformation. In addition, germinated edible seeds and sprouts possess many bioactivities, such as their **antioxidant capacity**, which is significantly increased after germination. Therefore, germination can be a green food engineering method to accumulate natural bioactive compounds, and those germinated edible seeds and sprouts rich in natural bioactive compounds can be consumed as functional foods to prevent chronic diseases.

1. Introduction

Edible seeds, such as pulses and cereal grains, are important dietary components for human. In addition, this year 2016 is "The International Year of Pulses", indicating the importance of edible seeds, especially pulses, in the current global nutrition. As indicated by FAO, of more than 50,000 edible plant species in the world, only a few hundred are important and nutritious food sources. Among them, pulses play an important role globally in human nutrition, being high in protein, vitamins, minerals and dietary fibre. Pulses generally have amino acid composition complementary to the major cereals, therefore, combined consumption of pulses and cereals increases the overall protein quality of the meal, which is most important for people in some developing countries. In addition, edible seeds contain different phytochemicals, and possess many biological functions, such as antioxidant, antidiabetic and antitumor effects (Hayat, Ahmad, Masud, Ahmed, & Bashir, 2014; Verspreet, Dornez, Van den Ende, Delcour, & Courtin, 2015). Recent studies show that germination can further enhance the nutritional and medicinal values of edible seeds. On one hand, it leads to the catabolism and degradation of main macronutrients, such as carbohydrates, protein and fatty acids, accompanied with the increase of simple sugars, free amino acids and organic acids (Shi, Nam, & Ma, 2010; Wang et al., 2005). On the other hand, it can reduce anti-nutritional and indigestible factors, such as protease inhibitors and lectin (Aguilera et al., 2013). Additionally, it can accumulate some secondary metabolites in edible seeds, such as vitamin C and polyphenols (Gan, Wang, Lui, Wu, & Corke, 2016). Furthermore, germinated edible seeds have been reported with many bioactivities, such as antioxidant, antidiabetic and anticancer effects. Therefore, germination is a good way to improve the health benefits of edible seeds, and edible bean sprouts, such as mung

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bean and soybean sprouts, are popular in some developing countries, such as some eastern Asian countries.

Based on Web of Science and Pubmed, we searched for English language articles on germination of edible seeds from 2000 to date. Germination of cereals has been reviewed in three recent papers (Hubner & Arendt, 2013; Omary, Fong, Rothschild, & Finney, 2012; Singh, Rehal, Kaur, & Jyot, 2015), where they are mainly focused on the influences of germination on macronutrients in cereals, but there is a lack of an updated review to highlight the importance of germination on bioactive compounds and bioactivities of edible seeds, mainly pulses and grains. Therefore, in this review, we first briefly described the germination strategies, and then summarized the bioactive compounds and their contents as well as the related analytic methods in germinated edible seeds and sprouts, followed by discussion of the potential mechanisms in the accumulation of bioactive compounds during germination, and finally highlighted the bioactivities of germinated edible seeds and sprouts, mainly focusing on antioxidant capacity.

1.1. Germination strategies

The germination strategies can be carried out in several simple procedures, mainly sterilization, soaking and sprouting. For different seeds, the germination strategies may vary, however, the basic principles and procedures are generally consistent, as described below.

1.2. Sterilization

In order to inhibit the growth of microbes, sterilization is performed before the soaking of seeds. According to the literature, sodium hypochlorite (NaClO) solutions with different concentrations are the most commonly used sterilization reagents for seed germination, especially 0.07% NaClO solution (Limon, Penas, Martinez-Villaluenga, & Frias, 2014). When using NaClO solutions, the sterilization is generally performed at room temperature for 5–30 min, with the seed weight (g)/solution volume (mL) ratio 1: 5 or 1: 6. In addition, ethanol or 70% ethanol is also reported to sterilize seeds, with the sterilization time no more than 3 min (Pajak, Socha, Galkowska, Roznowski, & Fortuna, 2014; Wu et al., 2012). However, few studies investigated the influences of sterilization on the germination results. On the other hand, some studies did not perform the sterilization step before soaking of seeds (e.g. Guajardo-Flores, Serna-Saldivar, & Gutierrez-Uribe, 2013; Guo, Li, Tang, & Liu, 2012), probably considering the potential hazardous effects of sterilization reagents on the seeds and food safety risks for consumption. Therefore, sterilization is not obligatory for seed germination, and whether sterilization is needed should be dependent on the condition of seeds, the frequency of changing water during the sprouting process and the purpose of germination.

1.3. Soaking

Before sprouting, seeds should be soaked in water to rehydrate, and the soaking temperature, time and the ratio of seed weight (g)/ water volume (mL) should be considered for seed soaking. Generally, seeds can be soaked at room temperature (about 20–30 °C), with the soaking time from several hours to 24 h and the ratio of seed weight (g)/water volume (mL) from 1: 1.5 to 1: 20. These differences of seed soaking condition should be associated with the intrinsic characteristics of different seeds, such as the capacity of absorbing water, the thickness of seed coats and the size of seeds.

1.4. Sprouting

After soaking, seeds can be put in special germinators or incubators for sprouting. There are several factors should be considered for seed sprouting, such as the light, temperature, humidity, watering and time. Sprouting of seeds is commonly performed in the dark and the sprouting temperature is generally kept at 20–30 °C. During sprouting, seeds should be watered everyday to keep relatively high humidity in order to support their growth, and water should be frequently changed, such as twice a day, in order to remove the metabolites of germinated seeds and to inhibit the growth of microbes. For the sprouting time, it is dependent on the purpose of germination. For common edible beans, 3–5 day is usually enough for bean sprouts to reach an edible length.

Overall, the germination is a very simple, inexpensive, environmental-friendly and safe way to cultivate the germinated seeds and sprouts within a short time. However, there are currently only several cultivated edible sprouts consumed in human diets, such as mung bean, soybean and peanut sprouts. In light of the cultivation advantages and accumulation of bioactive compounds and bioactivities during germination as discussed below, it is highlighted that germination can be an important bio-processing trend in the field of food science and technology to produce functional germinated seeds and sprouts.

2. Bioactive compounds

Recent studies indicate that germination can accumulate various bioactive compounds in germinated seeds and sprouts, such as vitamins, γ-aminobutyric acid (GABA) and polyphenols. These bioactive compounds can be *de novo* synthesized or transformed in the germination process. Here, we summarize the main bioactive compounds and their contents as well as their analytic methods in germinated edible seeds and sprouts, and pay special attention to the influence and potential mechanisms of germination on changes in these bioactive compounds.

2.1. Vitamins

Vitamins are a group of organic compounds widely distributed in the plant kingdom and play important functions in human health. Generally, they can be divided into water-soluble and fat-soluble vitamins. The former mainly includes vitamin B and C, and the latter contains vitamin A, D, E and K. Recent studies find that germination can significantly increase the content of some vitamins.

B vitamins include several members, including vitamin B1 (thiamine), vitamin B2 (riboflavin), vitamin B3 (niacin), vitamin B6 (pyridoxine), vitamin B9 (folate) and vitamin B12 (cobalamin), all of which play important roles in human health and diseases (Moran & Greene, 1979; Selhub, Troen, & Rosenberg, 2010). Germination has been found to increase the content of some B vitamins in different seeds (Table 1). Compared to raw seeds, folate was significantly increased in soybean and mung bean sprouts, by 65%–274% and 78%–326%, respectively (Shohag, Wei, & Yang, 2012), and vitamin B1 and B6 were about 11.8 mg/100 g DW in buckwheat sprouts, while they could not be detected in raw seeds (Kim, Kim, & Park, 2004). However, to our knowledge, the biosynthesis pathway of vitamin B has not been reported.

Vitamin C, also known as ascorbic acid, is associated with the diseases scurvy. Fruits and vegetables are the main natural sources of vitamin C, however, recent studies find that germination can significantly increase the content of vitamin C in some germinated edible seeds and sprouts, (Table 1), such as germinated buckwheat, chickpea, cowpea, lupin, mung bean and soybean or their sprouts.

Table 1
The contents of main vitamins in germinated edible seeds and sprouts.

Vitamins	Germinated edible seeds and sprouts	Germination time	Content		Unit	Analytical method	References
			Before germination	After germination			
B vitamins							
Vitamin B1 + B6	Buckwheat sprout (*Fagopyrum esculentum*)	7 day	N.D.	11.8	mg/100 g DW	HPLC	(Kim et al., 2004)
Vitamin B1	Sprouted wheat (*Triticum aestivum*)	5 day	5.81	5.18	μg/g DW	HPLC	(Zilic et al., 2014)
Vitamin B2		5 day	0.27	0.41	μg/g DW	HPLC	(Zilic et al., 2014)
Vitamin B3		5 day	72.8	86.7	μg/g DW	HPLC	(Zilic et al., 2014)
Vitamin B6		5 day	0.38	0.30	μg/g DW	HPLC	(Zilic et al., 2014)
Vitamin B9	Soybean sprout (*Glycine max* cv. HeiNong48)	2–10 day	203	~360–760	μg/100 g FW	HPLC	(Shohag et al., 2012)
	Soybean sprout (*Glycine max* cv. Bangladesh soybean-4)	2–10 day	231	~380–820	μg/100 g FW	HPLC	(Shohag et al., 2012)
	Mung bean sprout (*Vigna radiata* cv. Sulv3)	2–10 day	141	~270–600	μg/100 g FW	HPLC	(Shohag et al., 2012)
	Mung bean sprout (*Vigna radiata* cv. BARI mung-4)	2–10 day	169	~300–670	μg/100 g FW	HPLC	(Shohag et al., 2012)
Vitamin C							
	Germinated chickpea (*Cicer arietinum*)	24–120 h	N.D.	5.00–20.0	mg/100 g DW	DIPT	(Masood, Shah, & Zeb, 2014)
	Soybean sprout (*Glycine max* cv. HeiNong48)	2–10 day	N.D.	~12.0–25.0	mg/100 g FW	HPLC	(Shohag et al., 2012)
	Soybean sprout (*Glycine max* cv. Bangladesh soybean-4)	2–10 day	N.D.	~15.0–29.0	mg/100 g FW	HPLC	(Shohag et al., 2012)
	Germinated soybean (*Glycine max*)	1–5 day	N.D.	4.06–5.97	mg/g DW	DIPT	(Huang, Cai. & Xu, 2014)
	Soybean sprout (*Glycine max*)	1–9 day	N.D.	26.3–218	mg/kg FW	SBM	(Xu et al., 2005)
	Germinated lupin (*Lupinus albus*)	2–9 day	6.48	20.9–56.1	mg/100 g DW	MECC	(Frias et al., 2005)
	Germinated mung bean (*Vigna radiata* cv. emerald)	2–7 day	1.86	1.88–9.07	mg/100 g DW	MECC	(Fernandez-Orozco et al., 2008)
	Mung bean sprout (*Vigna radiate*)	1–9 day	11.7	~40.0–285	mg/100 g DW	DIPT	(Guo et al., 2012)
	Mung bean sprout (*Vigna radiata* cv. Sulv3)	2–10 day	N.D.	~11.0–25.0	mg/100 g FW	HPLC	(Shohag et al., 2012)
	Mung bean sprout (*Vigna radiata* cv. BARI mung-4)	2–10 day	N.D.	~13.0–27.0	mg/100 g FW	HPLC	(Shohag et al., 2012)
	Green mung bean sprout (*Vigna radiate*)	1–5 day	5.12	74.3–123	mg/100 g FW	DIPT	(Gan et al., 2016)
	Black mung bean sprout (*Vigna radiate*)	1–5 day	4.54	46.7–96.9	mg/100 g FW	DIPT	(Gan et al., 2016)
	Germinated mung bean (*Vigna radiate*)	24–120 h	N.D.	4.67–37.0	mg/100 g DW	DIPT	(Masood et al., 2014)
		1–5 day	N.D.	33.4–47.9	mg/g DW	DIPT	(Masood et al., 2014)
	Germinated cowpea (*Vigna unguiculata* L.)	4–6 day	N.D.	23.3–25.2	Mg/100 g DW	MECC	(Doblado, Frias, & Vidal-Valverde, 2007)
	Buckwheat sprout (*Fagopyrum esculentum*)	6 day	N.D.	50.1–64.8	Mg/100 g FW	HPLC	(Kim et al., 2006)
		7 day	N.D.	172	mg/100 g DW	HPLC	(Kim et al., 2004)
		4–14 day	10.0	21.7–26.5	mg/100 g DW	DIPT	(Lin et al., 2008)
		3–12 day	0.10	0.20–0.25	mg/g DW	DIPT	(Peng, Chen, Yang, Lin, & Peng, 2009)
	Tartary buckwheat sprout (*Fagopyrum tataricum*)	9 day	N.D.	27.1–40.2	mg/100 g FW	HPLC	(Kim et al., 2006)
	Tartary buckwheat sprout (*Fagopyrum tataricum*)	1–7 day	0.05	0.15–0.71	Mg/g DW	HPLC	(Zhou et al., 2015)
E vitamins							
α-tocopherol	Germinated lupin (*Lupinus albus*)	2–9 day	0.19	0.29–3.91	mg/100 g DW	HPLC	(Frias et al., 2005)
	Germinated soybean (*Glycine max* cv. Jutro)	2–4 day	2.94	2.94–8.37	mg/100 g DW	HPLC	(Fernandez-Orozco et al., 2008)
	Germinated soybean (*Glycine max* cv. merit)	2–6 day	1.00	1.12–1.93	mg/100 g DW	HPLC	(Fernandez-Orozco et al., 2008)
	Germinated mung bean (*Vigna radiata* cv. emerald)	2–7 day	0.11	0.30–0.45	mg/100 g DW	HPLC	(Fernandez-Orozco et al., 2008)
	Germinated wheat (*Triticum aestivum*)	Day 5	0.94	3.38	μg/g DW	HPLC	(Zilic et al., 2014)
	Tartary buckwheat sprout (*Fagopyrum tataricum*)	1–7 day	2.10	3.20–7.20	μg/g DW	HPLC	(Zhou et al., 2015)
β-tocopherol	Germinated soy bean (*Glycine max* cv. Jutro)	2–4 day	0.21	0.19–0.34	mg/100 g DW	HPLC	(Fernandez-Orozco et al., 2008)
	Germinated soy bean (*Glycine max* cv. merit)	2–6 day	0.25	0.33–0.40	mg/100 g DW	HPLC	(Fernandez-Orozco et al., 2008)

(*continued on next page*)

Table 1 (*continued*)

Vitamins	Germinated edible seeds and sprouts	Germination time	Content		Unit	Analytical method	References
			Before germination	After germination			
γ-tocopherol	Germinated lupin (*Lupinus albus*)	2–9 day	20.1	13.4–19.3	mg/100 g DW	HPLC	(Frias et al., 2005)
	Germinated soybean (*Glycine max* cv. Jutro)	2–4 day	12.9	13.1–34.1	mg/100 g DW	HPLC	(Fernandez-Orozco et al., 2008)
	Germinated soybean (*Glycine max* cv. merit)	2–6 day	4.10	5.23–7.51	mg/100 g DW	HPLC	(Fernandez-Orozco et al., 2008)
	Germinated mung bean (*Vigna radiata* cv. emerald)	2–7 day	9.16	2.55–7.45	mg/100 g DW	HPLC	(Fernandez-Orozco et al., 2008)
	Tartary buckwheat sprout (*Fagopyrum tataricum*)	1–7 day	118	103–16.8	μg/g DW	HPLC	(Zhou et al., 2015)
$\beta + \gamma$-tocopherol	Germinated wheat (*Triticum aestivum)*	5 day	1.71	3.98	μg/g DW	HPLC	(Zilic et al., 2014)
δ-tocopherol	Germinated lupin (*Lupinus albus*)	2–9 day	0.25	0.22–0.30	mg/100 g DW	HPLC	(Frias et al., 2005)
	Germinated soybean (*Glycine max* cv. Jutro)	2–4 day	2.88	2.85–5.96	mg/100 g DW	HPLC	(Fernandez-Orozco et al., 2008)
	Germinated soybean (*Glycine max* cv. merit)	2–6 day	1.65	2.90–8.46	mg/100 g DW	HPLC	(Fernandez-Orozco et al., 2008)
	Germinated mung bean (*Vigna radiata* cv. emerald)	2–7 day	0.60	0.25–0.52	mg/100 g DW	HPLC	(Fernandez-Orozco et al., 2008)
	Germinated wheat (*Triticum aestivum)*	5 day	1.26	3.29	μg/g DW	HPLC	(Zilic et al., 2014)
	Tartary buckwheat sprout (*Fagopyrum tataricum*)	1–7 day	7.30	5.40–3.90	μg/g DW	HPLC	(Zhou et al., 2015)
Total vitamin E	Germinated brown rice (*Oryza sativa*)	8–20 h	N.D.	26.5–39.4	mg/kg DW	HPLC	(Ng, Huang, Chen, & Su, 2013)

Abbreviations: MECC, micellar electrokinetic capillary electrophoresis; DIPT, 2,6-dichloroindophenol (DIP) titration; HPLC, high-performance liquid chromatography; SBM, Spectrophotometry-based method; AAA, amino acid analyzer; N.D., not detected; FW, fresh weight; DW, dry weight.

For example, a previous study found that the green and black mung bean sprouts increased 13.5–24.0 and 10.3–21.3 fold of vitamin C compared to respective raw seeds after germination for 1–5 day (Gan et al., 2016). Accumulation of vitamin C in germinated edible seeds and sprouts can be due to *de novo* synthesis, since most seeds before germination were found to have very low or even non-detectable vitamin C content (Table 1). Furthermore, the activity of L-galactono-γ-lactone dehydrogenase (GLDH), which is one of the key enzymes in ascorbic acid biosynthesis and catalyses the oxidation of L-galactono-1,4-lactone to ascorbic acid, has been found to be significantly increased during soybean seed germination, in parallel with the increase of ascorbic acid content (Wheeler, Jones, & Smirnoff, 1998; Xu, Dong, & Zhu, 2005).

E vitamins, or tocopherols, are fat-soluble antioxidant vitamins with four isomers, including α-tocopherol, β-tocopherol, γ-tocopherol and δ-tocopherol. Germination can distinctly change the content of E vitamin isomers in edible seeds (Table 1), however, the potential mechanisms remain unclear. γ-Tocopherol is the main vitamin E in several edible seeds reported, and it was significantly increased in germinated soybean, by 1.55%–164% compared to raw seeds (Fernandez-Orozco et al., 2008), but reduced in germinated lupin and mung bean (Fernandez-Orozco et al., 2008; Frias, Miranda, Doblado, & Vidal-Valverde, 2005). Therefore, the influence of germination on E vitamins is dependent on specific seeds.

Overall, germination is a valuable way to increase vitamins, especially vitamin C, in edible seeds, and those germinated edible seeds and sprouts rich in vitamins can be excellent natural sources of vitamins in human diets.

2.2. γ-Aminobutyric acid

γ-Aminobutyric acid (GABA) is a non-protein amino acid widely existing in both plants and animals. In mammals, it functions as an important depressive neurotransmitter in the nervous system, and it can also regulate blood pressure and heart rate, to relieve pain and anxiety, and to increase the secretion of insulin from the pancreas (Adeghate & Ponery, 2002; Mody, De Koninck, Otis, & Soltesz, 1994). Germination can accumulate GABA in many edible seeds (Table 2). Edible beans, such as adzuki bean, kidney bean, lentil, lupin, pea and soybean, have been reported to increase GABA content when compared to their raw beans. In addition, germinated cereal grains, such as brown rice, buckwheat, oat and waxy wheat, can also significantly accumulate GABA. For instance, germinated soybean and buckwheat sprouts have been reported to increase 0.50–2.60 and 0.60–37.5 fold of GABA compared to respective seeds (Lin, Peng, Yang, & Peng, 2008; Martinez-Villaluenga, Kuo, Lambein, Frias, & Vidal-Valverde, 2006). Besides, germination of sesame can increase GABA content.

In plants, GABA can be synthesized through different signaling pathways. It is primarily synthesized from L-glutamic acid via glutamate decarboxylase (GAD), which is a pyridoxal 5'-phosphate-dependent enzyme responsible for the conversion of L-glutamic acid to GABA (Bown & Shelp, 1997). In addition, it can be transformed via γ-aminobutyraldehyde intermediate from polyamine, in which process diamine oxidase (DAO) as well as aminoaldehyde dehydrogenase (AMADH) are the endogenous enzymes involved (Shelp et al., 2012). Studies find that the activity of GAD is significantly increased in germinated oat, soybean and brown rice (Matsuyama et al., 2009; Oh, 2003; Xu, Hu, Duan, & Tian, 2010). Besides, the activity of DAO is also reported to be increased in germinated fava bean (Yang, Chen, & Gu, 2011). Therefore, accumulation of GABA in germinated edible seeds and sprouts can be due to the increased activity of endogenous enzymes involved in the metabolic pathways of GABA.

2.3. Polyphenols

Polyphenols are a group of small molecules characterized by their structure with at least one phenol unit. In the plant kingdom, polyphenols mainly exist in soluble or bound forms. Compared to

Table 2
The contents of GABA in germinated edible seeds and sprouts.

Germinated edible seeds and sprouts	Germination time	Content		Unit	Analytical methods	References
		Before germination	After germination			
Germinated lentil (*Lens culinaris*)	6 day	N.D.	0.32	mg/g DW	HPLC	(Kuo, Rozan, Lambein, Frias, & Vidal-Valverde, 2004)
Soybean sprout (*Glycine max* L. var. merit)	2–6 day	0.26	0.18–1.09	mg/g DW	HPLC	(Martinez-Villaluenga et al., 2006)
Soybean sprout (*Glycine max* L. var. jutro)	2–4 day	0.25	0.38–0.90	mg/g DW	HPLC	(Martinez-Villaluenga et al., 2006)
Germinated soybean (*Glycine max)*	30–102 h	0.29	0.31–2.31	μmol/g DW	AAA	(Xu & Hu, 2014)
Lupin sprout (*Lupinus angustifolius* L. var. zapaton)	2–9 day	0.46	0.77–1.69	mg/g DW	HPLC	(Martinez-Villaluenga et al., 2006)
Kidney bean sprout (Phaseolus vulgaris)	4–8 day	N.D.	0.43–0.95	mg/g DW	HPLC	(Limon et al., 2014)
Germinated kidney bean (*Phaseolus vulgaris* L, var. La Granja)	6 day	N.D.	0.44	mg/g DW	HPLC	(Kuo et al., 2004)
Germinated pea *(Pisum sativum)*	6 day	N.D.	1.04	mg/g DW	HPLC	(Kuo et al., 2004)
Adzuki bean sprout (*Vigna angulariz)*	1–7 day	21.3	17.0–63.3	mg/100 g DW	HPLC	(Li, Liu, & Zheng, 2011)
Germinated oat (*Avena nuda* L.)	1–7 day	0.54–1.41	5.71–20.4	mg/100 g DW	AAA	(Xu et al., 2010)
Germinated wheat (*Triticum aestivum* L.)	6–48 h	3.40	3.40–16.0	mg/100 g DW	AAA	(Hung, Maeda, & Morita, 2015)
Buckwheat sprout (*Fagopyrum esculentum*)	3–7 day	2.50	16.5–81.9	mg/100 g DW	AAA	(Kim et al., 2004)
Buckwheat sprout (*Fagopyrum esculentum*)	4–14 day	2.00	3.20–77.0	mg/100 g DW	HPLC	(Lin et al., 2008)
Buckwheat sprout (*Fagopyrum esculentum*)	3–12 day	0.02	0.12–0.90	mg/g DW	HPLC	(Peng et al., 2009)
Buckwheat sprout (*Fagopyrum esculentum*)	6 day	N.D.	3.99–4.77	mg/100 g FW	HPLC	(Kim et al., 2006)
Tartary buckwheat sprout (*Fagopyrum. tataricum*)	9 day	N.D.	4.11–5.76	mg/100 g FW	HPLC	(Kim et al., 2006)
Germinated brown rice (*Oryza sativa*)	6–48 h	N.D.	~0.20–1.40	g/kg DW	SBM	(Zhang et al., 2014)
Germinated brown rice, nonpigmented (*Oryza sativa*)	8–20 h	N.D.	28.4–62.3	mg/kg DW	SBM	(Ng et al., 2013)
Germinated brown rice, pigmented (*Oryza sativa*)	8–20 h	N.D.	10.3–48.8	mg/kg DW	SBM	(Ng et al., 2013)
Germinated Ecuadorian brown rice (*Oryza sativa*)	48–96 h	4.34–8.26	44.6–139	mg/100 g DW	HPLC	(Caceres, Martinez-Villaluenga, Amigo, & Frias, 2014)
Germinated black rice (*Oryza sativa*, Heinuo)	72 h	14.9	41.8–574	mg/100 g DW	GC-MS	(Ding et al., 2016)
Germinated white rice (*Oryza sativa*, Xianhui 207)	72 h	14.5	92.5–544	mg/100 g DW	GC-MS	(Ding et al., 2016)
Germinated waxy wheat (*Triticum aestivum)*	6–48 h	84.0	101–155	mg/kg DW	AAA	(Hung et al., 2012)
Sesame sprout	1–5 day	24.1	~23.0–95.3	μg/g DW	HPLC	(Liu et al., 2011)

Abbreviations: HPLC, high-performance liquid chromatography; SBM, Spectrophotometry-based method; AAA, amino acid analyzer; GC-MS, Gas chromatography–mass spectrometry; N.D., not detected; FW, fresh weight; DW, dry weight.

fruits and vegetables, many edible seeds, such as beans and grains, have a much higher percentage of bound phenolics. In plants, most soluble phenolics are synthesized in the intracellular endoplasmic reticulum, and stored in vacuoles, while bound phenolics are formed by the transportation of soluble phenolics to the cell wall, and conjugated with cell wall macromolecules such as cellulose and protein through the ester and glycosidic bonds, therefore, contributing to cell wall formation (Agati, Azzarello, Pollastri, & Tattini, 2012). Recent studies indicate that germination can change the level of total phenolics in germinated edible seeds and sprouts, while having a distinct impact on their soluble and bound phenolics. In the following part, it is, therefore, summarized and compared the total phenolic content as well as main phenolic compounds in the soluble and bound phenolics in germinated edible seeds and sprouts. Besides, the potential molecular signaling pathways involved in the metabolism of phenolic compounds during germination are discussed.

The influence of germination on total phenolic contents has been investigated in many edible seeds, such as edible beans and cereal grains. Most studies found that germination can gradually accumulate soluble phenolics in germinated edible seeds and sprouts compared with raw seeds (Table 3). For example, a previous study found that the mung bean sprouts after germination for 5 days had about 5.0–5.5 fold of soluble phenolics compared to mung bean seeds (Gan et al., 2016). The increase of soluble phenolics during germination can be attributed to the *de novo* synthesis and transformation (Kim et al., 2013; Randhir, Lin, & Shetty, 2004; Tang, Dong, Guo, Li, & Ren, 2014; Wu, Song, & Huang, 2011; Wu et al., 2012). Glucose is the original precursor for the synthesis of phenolic compounds, and several important molecular signaling pathways, including the oxidative pentose phosphate pathway, glycolysis, acetate/malonate pathway, shikimate pathway, phenylpropanoid pathway and hydrolysable tannin pathway, are involved in the synthesis and transformation of different phenolic compounds (Fig. 1). However, several studies also report a decrease of soluble phenolics in germinated edible seeds and sprouts (Table 3), and this contradiction can be partly associated with the results expressed as wet weight or dry weight, considering that the water content during germination is gradually increased during the germination process (Guo et al., 2012).

On the other hand, although the bound phenolics have been less investigated in germinated edible seeds and sprouts (Table 3), some germinated edible seeds, especially cereal grains, still contain a high level of bound phenolics (Hung, Hatcher, & Barker, 2011, 2012; Ti et al., 2014). In addition, several studies reported that bound phenolics first decreased and then increased after germination

Table 3
Total phenolic content and main phenolic compounds in the soluble and bound phenolics of germinated edible seeds and sprouts.

Germinated edible seeds and sprouts	Germination time	Total phenolic content		Unit	Main phenolic compounds in germinated edible seeds and sprouts	References
		Before germination	After germination			
Soluble phenolics						
Germinated jack bean (*Canavalia ensiformis* L.)	4 day	2.3	3.6	mg GAE/g DW	N.D.	(Aguilera et al., 2013)
Germinated sword bean (*Canavalia gladiata*)	1–4 day	~40	~30 - 58	mg GAE/ 100 g FW	N.D.	(Wu et al., 2012)
Germinated chickpea (*Cicer arietinum* L.)	1–4 day	~58	~80 -100	mg GAE/ 100 g FW	Formononetin, biochanin A, biochanin A glucoside, pseudobaptigenin,pratensein, genistein, formononetin glucoside malonylate and isoformononetin glucoside malonylate	(Wu et al., 2012)
Soybean sprout (*Glycine max* cv. HeiNong48)	2–10 day	~220	~120 - 150	mg GAE/ 100 g FW	N.D.	(Shohag et al., 2012)
	2–10 day	~190	~210 - 380	mg GAE/ 100 g DW	N.D.	(Shohag et al., 2012)
Soybean sprout (*Glycine max* cv. Bangladesh soybean-4)	2–10 day	~235	~125–170	mg GAE/ 100 g FW	N.D.	(Shohag et al., 2012)
	2–10 day	~210	~250 - 400	mg GAE/ 100 g DW	N.D.	(Shohag et al., 2012)
Germinated soybean (*Glycine max* L.)	24–120 h	0.1	0.41–1.20	mg GAE/g DW	Daidzein, glycitein, genistein and their 7-*o*-β-glucosides	(Huang, Cai, & Xu, 2014)
Germinated soy bean (*Glycine max* cv. jutro)	2–4 day	2.85	2.65–3.00	mg CE/ g DW	N.D.	(Fernandez-Orozco et al., 2008)
Germinated soy bean (*Glycine max* cv. merit)	2–6 day	2.98	3.06–3.49	mg CE/ g DW	N.D.	(Fernandez-Orozco et al., 2008)
Germinated black soybean (*Glycine max* (L.) Merr.)	1–4 day	~70	~60 -100	mg GAE/ 100 g FW	daidzin, daidzein glucoside malonylated, genistin, genistein glucoside malonylated and genistein	(Wu et al., 2012)
Germinated hyacinth bean (*Lablab purpureus* (L.) Sweet)	1–4 day	~15	~35 - 40	mg GAE/ 100 g FW	N.D.	(Wu et al., 2012)
Germinated dolichos (*Lablab purpureus* L.)	4 day	0.72	1.7	mg GAE/g DW	N.D.	(Aguilera et al., 2013)
Germinated lentil (*Lens culinaris* L. var. Castellana)	2–6 day	N.D.	N.D.	N.D.	*p*-Hydroxybenzoic acid, *p*-hydroxybenzoic aldehyde, vanillic aldehyde, *p*-coumaric acid and its derivative, ferulic acid	(Lopez-Amoros, Hernandez, & Estrella, 2006)
Germinated lentil (*Lens culinaris* L. var. Salmantina)	3–8 day	~450	~130 - 250	mg GAE/ 100 g DW	N.D.	(Aguilera et al., 2014)
Germinated dark beans (*Phaseolus vulgaris* L.)	7 day	N.D.	N.D.	N.D.	Anthocyanins, ferulyl aldaric acid, biochanin B-7-glucoside, quercetin-3-rutinoside, kaempferol, kaempferol-3-glucoside, quercetin-3-glucoside acetate, myricetin-3-glucoside, genistein derivatives and naringenin-7-glucoside	(Lopez et al., 2013)
Germinated kidney bean (*Phaseolus vulgaris* L., var. Pinta)	3–8 day	~370	~110 - 420	mg GAE/ 100 g DW	N.D.	(Aguilera et al., 2014)
Black bean sprout (*Phaseolus vulgaris* L.)	1–5 day	~0.90	~0.30–0.50	mg GAE/g DW	Soyasaponin, myricetin-3-*o*-glucoside and quercetin-3-*o*-galactoside	(Guajardo-Flores et al., 2013)
Germinated bean (*Phaseolus vulgaris* L. variety La Granja)	2–6 day	N.D.	N.D.	N.D.	*p*-Hydroxybenzoic acid, *p*-hydroxybenzoic aldehyde, vanillic acid, *p*-coumaric acid and its derivative, trans ferulic acid, quercetin-3-rutinoside, quercetin-3-rhamnoside, kaempferol-3-rutinoside and kaempferol-3-glucoside	(Lopez-Amoros et al., 2006)
Germinated kidney bean (*Phaseolus vulgaris* L.)	1–4 day	~34	~40 - 60	mg GAE/	N.D.	(Wu et al., 2012)

Table 3 (*continued*)

Germinated edible seeds and sprouts	Germination time	Total phenolic content		Unit	Main phenolic compounds in germinated edible seeds and sprouts	References
		Before germination	After germination			
				100 g FW		
Germinated pea (*Pisum sativum* L. variety Elsa)	2–6 day	N.D.	N.D.	N.D.	*p*-Hydroxybenzoic acid, *p*-hydroxybenzoic aldehyde, *p*-coumaric acid and ferulic acid	(Lopez-Amoros et al., 2006)
Germinated mucuna (*Stizolobium niveum* L.)	4 day	37.4	46.3	mg GAE/g DW	N.D.	(Aguilera et al., 2013)
Germinated adzuki bean (*Vigna angulariz* (Willd.) Ohwi & H. Ohashi)	1–4 day	~43	~35 - 80	mg GAE/ 100 g FW	N.D.	(Wu et al., 2012)
Mung bean sprout (*Vigna radiata* cv. Sulv3)	2–10 day	~150	~75 - 120	mg GAE/ 100 g FW	N.D.	(Shohag et al., 2012)
	2–10 day	~120	~155- 325	mg GAE/ 100 g DW	N.D.	(Shohag et al., 2012)
Mung bean sprout (*Vigna radiata* cv. BARI mung-4)	2–10 day	~170	~75 - 125	mg GAE/ 100 g FW	N.D.	(Shohag et al., 2012)
	2–10 day	~140	~175 - 320	mg GAE/ 100 g DW	N.D.	(Shohag et al., 2012)
Mung bean sprout (*Vigna radiata*)	1–7 day	N.D.	N.D.	N.D.	Vitexin, isovitexin, rutin, kaempferol-3-*o*-rutinoside, isoquercitrin, genistein, daidzein and isorhamnetin	(Tang et al., 2014)
Mung bean sprout (*Vigna radiata*)	1–9 day	171	~230 - 925	mg GAE/ 100 g DW	Quercetin-3-*o*-glucoside	(Guo et al., 2012)
Mung bean sprout (*Vigna radiata* L. Wilczek)	5 day	~0.40	~3.4	mg GAE/g DW	Gallic acid, ferulic acid, chlorogenic acid, sinapic acid and quercetin	(Pajak et al., 2014)
Green mung bean sprout (*Vigna radiata*)	1–5 day	209	192–1148	mg GAE/ 100 g DW	Gallic acid, *p*-coumaric acid, catechin, rutin, vitexin and isovitexin	Gan et al., 2016
Black mung bean sprout (*Vigna radiata*)	1–5 day	180	140–902	mg GAE/ 100 g DW	Gallic acid, *p*-coumaric acid, catechin, vitexin and isovitexin	Gan et al., 2016
Germinated mung bean (*Vigna radiata* cv. emmerald)	2–7 day	1.09	1.43–3.46	mg CE/ g DW	N.D.	(Fernandez-Orozco et al., 2008)
Germinated mung bean (*Vigna radiata* (L.) R. Wilczek)	1–4 day	~40	~60–80	mg GAE/ 100 g FW	N.D.	(Wu et al., 2012)
Germinated mung bean (*Vigna radiate* L.)	24–120 h	0.23	0.32–0.44	mg GAE/g DW	N.D.	(Huang et al., 2014)
Germinated cowpea (*Vigna unguiculata* L.)	4 day	3.3	3.7	mg GAE/g DW	N.D.	(Aguilera et al., 2013)
Germinated cowpea (*Vigna unguiculata* subsp. sesquipedalis)	1–4 day	~58	~45–70	mg GAE/ 100 g FW	N.D.	(Wu et al., 2012)
Germinated black-eyed pea (*Vigna unguiculata* subsp. unguiculata)	1–4 day	~30	~45–65	mg GAE/ 100 g FW	N.D.	(Wu et al., 2012)
Sprouted wheat (CWRS) (*Triticum aestivum)*	2 day	1230	1763	µg FE/g DW	Sinapic acid, syringic acid, vanillic acid, caffeic acid, *p*-coumaric acid and ferulic acid	(Hung et al., 2011)
Sprouted wheat (CWAD) (*Triticum aestivum)*	2 day	1212	1414	µg FE/g DW	Sinapic acid, syringic acid, caffeic acid, *p*-coumaric acid and ferulic acid	(Hung et al., 2011)
Sprouted wheat (*Triticum aestivum)*	5 day	1830	1957	mg GAE/kg DW	Ferulic acid and isoferulic acid	(Zilic et al., 2014)

(*continued on next page*)

Table 3 (*continued*)

Germinated edible seeds and sprouts	Germination time	Total phenolic content		Unit	Main phenolic compounds in germinated edible seeds and sprouts	References
		Before germination	After germination			
Germinated waxy wheat (*Triticum aestivum)*	6–48 h	~780	~800–1300	mg FAE/kg DW	N.D.	(Hung et al., 2012)
Wheat sprout (*Triticum aestivum* L.)	110 h	53.1	110	mg GAE/ 100 g DW	Ethyl gallate	(Alvarez-Jubete et al., 2010)
Germinated wheat (*Triticum aestivum* L.)	6–48 h	~1.20	~1.20–2.00	µg FE/g DW	N.D.	(Hung et al. 2015)
Buckwheat sprout (*Fagopyrum esculentum* Moench)	96 h	323	670	mg GAE/ 100 g DW	Syringic acid derivative, caffeic acid and its derivative, 3-coumaric acid derivative, catechin, luteolin glycoside, apigenin glycoside and quercetin glycosides	(Alvarez-Jubete et al., 2010)
	3–9 day	1.57	2.97–7.79	mg GAE/g DW	Rutin and quercetin	(Peng et al., 2009)
	4–14 day	176	164–694	mg GAE/ 100 g DW	Rutin and quercetin	(Lin et al., 2008)
Buckwheat sprouts (*Fagopyrum esculentum)*	5 day	N.D.	N.D.	N.D.	Orientin, isoorientin, vitexin, isovitexin, quercetin-3-*o*-robinobioside and rutin	(Nam et al., 2015).
Germinated buckwheat (*Fagopyrum esculentum* Moench)	12–72 h	3.03	3.11–8.42	mg GAE/g DW	Gallic acid, 3,4-dihydroybenzoic acid, 2,3,4-trihydroxybenzoic acid, *p*-hydroxybenzoic acid, chlorogenic acid, vanillic acid, caffeic acid, syringic acid, *p*-coumaric acid, ferulic acid, sinapic acid, *trans*-3-hydroxycinnamic acid, orientin, isoorientin, vitexin, isovitexin, rutin, kamperol-3-rutinoside, quercitrin, myricetin, luteolin, quercetin and kaempferol	(Zhang et al., 2015)
Germinated brown rice (*Oryza sativa*)	17–48 h	100	159–188	mg GAE/ 100 g DW	Protocatechuic acid, chlorogenic acid, caffeic acid, syringic acid and ferulic acid	(Ti et al., 2014)
Germinated canaryseed (*Phalaris canariensis* L.)	24–120 h	37.4	49.0–427	mg GAE/ 100 g DW	Gallic acid, *p*-hydroxybenzoic acid, *p*-coumaric acid and ferulic acid	(Chen, Yu, Wang, Gu, & Beta, 2016).
Germinated black peanuts (*Arachis hypogaea* L.)	1–3 day	145	159–194	mg GAE/ 100 g FW	Coumaric acid derivatives, sinapinic acid derivative, feruloyl malic acid derivative and stilbene derivatives	(Wu et al., 2011)
Germinated red peanuts (*Arachis hypogaea* L.)	1–3 day	127	156–228	mg GAE/ 100 g FW	Coumaric acid derivatives, sinapinic acid derivative, feruloyl malic acid derivative and stilbene derivatives	(Wu et al., 2011)
Germinated reddish brown peanuts (*Arachis hypogaea* L.)	1–3 day	130	160–253	mg GAE/ 100 g FW	Coumaric acid derivatives, catechin, sinapinic acid derivative, feruloyl malic acid derivative and *cis*-resveratrol	(Wu et al., 2011)
Sunflower sprout (*Helianthus annuus* L.)	5 day	~3.80	~9.00	mg GAE/g DW	Gallic acid, protocatechuic acid, caffeic acid, sinapic acid and quercetin	(Pajak et al., 2014)
	N.D.	N.D.	N.D.	N.D.	Cynarin	(Sun et al., 2012)
Sesame sprout (*Sesamum indicum* L.)	1–5 day	0.51	~1.20–13.4	mg GAE/g DW	Sesamin	(Liu et al., 2011)
Bound phenolics						
Germinated lentil (*Lens culinaris* L. var. Salmantina)	3–8 day	~40	~10–80	mg GAE/ 100 g DW	N.D.	(Aguilera et al., 2014)
Germinated kidney bean (*Phaseolus vulgaris* L. var. Pinta)	3–8 day	~30	~15–45	mg GAE/ 100 g DW	N.D.	(Aguilera et al., 2014)
Mung bean sprout (*Vigna radiata*)	1–9 day	43.9	~30–70	mg GAE/ 100 g DW	N.D.	(Guo et al., 2012)
Mung bean sprout (*Vigna radiata* L. Wilczek)	5 day	N.D.	N.D.	N.D.	Caffeic acid, *p*-coumaric acid, ferulic acid, sinapic acid, quercetin and apigenin	(Pajak et al., 2014)
Green mung bean sprout (*Vigna radiata*)	1–5 day	164	47.0–181	mg GAE/	Caffeic acid, ferulic acid, *p*-coumaric acid, vitexin and isovitexin	(Gan et al., 2016)

Table 3 (*continued*)

Germinated edible seeds and sprouts	Germination time	Total phenolic content		Unit	Main phenolic compounds in germinated edible seeds and sprouts	References
		Before germination	After germination			
				100 g DW		
Black mung bean sprout (*Vigna radiata*)	1–5 day	167	24.6–72.7	mg GAE/ 100 g DW	Caffeic acid, ferulic acid, *p*-coumaric acid, vitexin and isovitexin	(Gan et al., 2016)
Germinated brown rice (*Oryza sativa*)	17–48 h	73.7	90.3–107	mg GAE/ 100 g DW	Syringic acid, coumaric acid and ferulic acid	(Ti et al., 2014)
Sprouted wheat (CWRS) (*Triticum aestivum*)	2 day	2330	2116	μg FAE/ g DW	4-Hydroxybenzoic acid, caffeic acid, syringic acid, *p*-coumaric acid, ferulic acid, sinapic acid and vanillic acid	(Hung et al., 2011)
Sprouted wheat (CWAD) (*Triticum aestivum*)	2 day	2291	2141	μg FAE/ g DW	4-Hydroxybenzoic acid, caffeic acid, syringic acid, *p*-coumaric acid, ferulic acid, sinapic acid and vanillic acid	(Hung et al., 2011)
Sprouted wheat (*Triticum aestivum*)	5 day	1431	1627	mg GAE/kg DW	Ferulic acid, isoferulic acid, *p*-coumaric acid and caffeic acid	(Zilic et al., 2014)
Germinated wheat (*Triticum aestivum* L.)	6–48 h	~2.60	~2.40–2.80	μg FAE/ g DW	N.D.	(Hung et al. 2015)
Germinated waxy wheat (*Triticum aestivum*)	6–48 h	~2200	~1850 –2200	mg FAE/kg DW	N.D.	(Hung et al., 2012)
Germinated canaryseed (*Phalaris canariensis* L.)	24–120 h	18.1	14.4–39.9	mg GAE/ 100 g DW	Protocatechuic acid, *p*-hydroxybenzoic acid, vanillic acid, caffeic acid, syringic acid, *p*-coumaric acid and ferulic acid	(Chen et al., 2016)
Sunflower sprout (*Helianthus annuus* L.)	5 day	N.D.	N.D.	N.D.	Caffeic acid, ferulic acid, quercetin, luteolin	(Pajak et al., 2014)

Abbreviations: GAE, gallic acid equivalence; FAE, ferulic acid equivalence; CE, catechin equivalence; FW, fresh weight; DW, dry weight; ND, not detected; CWRS, Canadian western red spring wheat. CWAD, Canadian western amber durum wheat.

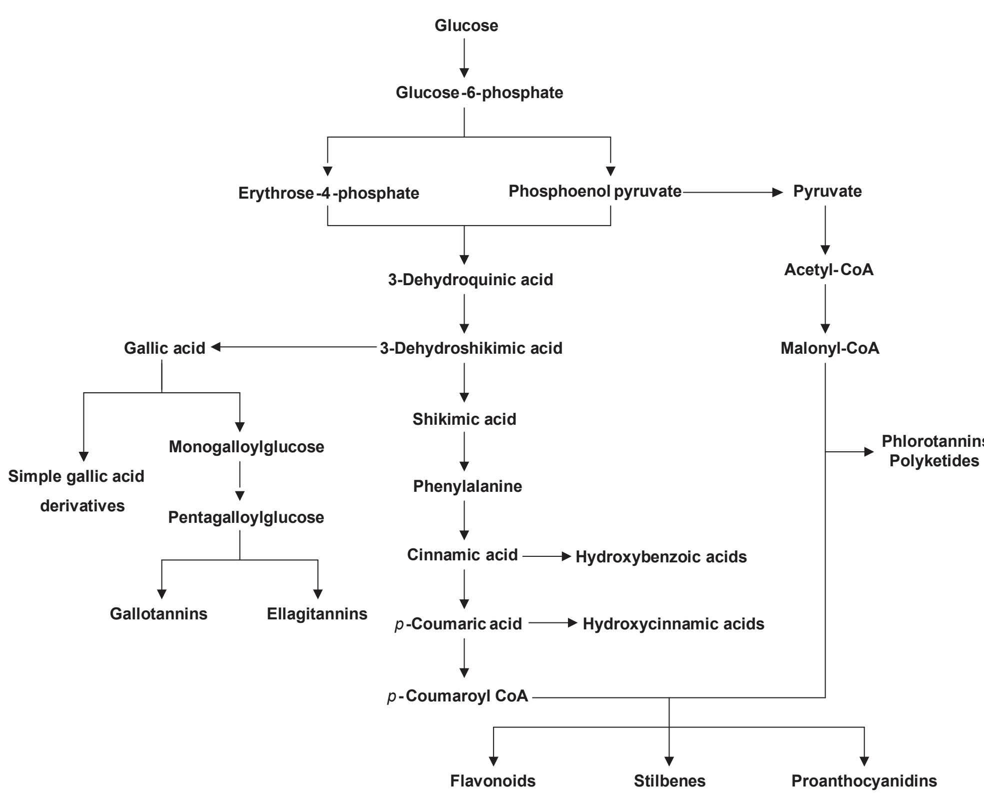

Fig. 1. The proposed molecular signaling pathway of the synthesis and transformation of polyphenols in germinated edible seeds and sprouts.

Table 4
Antioxidant capacity of the soluble and bound extracts in germinated edible seeds and sprouts.

Germinated edible seeds and sprouts	Soluble/bound extract	Germination time	Analytic method	Antioxidant capacity		Unit	References
				Before germination	Before germination		
Germinated jack bean (*Canavalia ensiformis* L.)	Soluble	4 day	DPPH	~1.50	~1.70	μmol TE/g DW	(Aguilera et al., 2013)
	Soluble	4 day	FRAP	~2.00	~3.00	μmol TE/g DW	(Aguilera et al., 2013)
Germinated sword bean (*Canavalia gladiata* (Jacq.) DC.)	Soluble	1–4 day	ORAC	~600	~800–1600	μmol TE/100 g FW	(Wu et al., 2012)
Germinated chickpea (*Cicer arietinum* L.)	Soluble	1–4 day	ORAC	~800	~2000–2600	μmol TE/100 g FW	(Wu et al., 2012)
Germinated soy bean (*Glycine max* cv. jutro)	Soluble	2–4 day	ABTS	37.3	40.2–41.9	μmol TE/g DW	(Fernandez-Orozco et al., 2008)
	Soluble	2–7 day	PRTC	3.25	3.32–4.15	μmol TE/g DW	(Fernandez-Orozco et al., 2008)
Germinated soy bean (*Glycine max* cv. merit)	Soluble	2–6 day	ABTS	63.0	68.4–71.8	μmol TE/g DW	(Fernandez-Orozco et al., 2008)
	Soluble	2–7 day	PRTC	2.90	2.69–4.93	μmol TE/g DW	(Fernandez-Orozco et al., 2008)
Germinated soybean (*Glycine max* L.)	Soluble	24–120 h	DPPH	0.01	0.03–0.13	μmol TE/g DW	(Huang et al., 2014)
Soybean sprout (*Glycine max* cv. HeiNong48)	Soluble	2–10 day	FRAP	~1.16	~0.50–0.79	mmol Fe(II)/100 g FW	(Shohag et al., 2012)
Soybean sprout (*Glycine max* cv. Bangladesh soybean-4)	Soluble	2–10 day	FRAP	~1.32	~0.52–0.90	mmol Fe(II)/100 g FW	(Shohag et al., 2012)
Germinated black soybean (*Glycine max* (L.) Merr.)	Soluble	1–4 day	ORAC	~1700	~1400–2200	μmol TE/100 g FW	(Wu et al., 2012)
Germinated dolichos (*Lablab purpureus* L.)	Soluble	4 day	DPPH	~1.90	~2.30	μmol TE/g DW	(Aguilera et al., 2013)
	Soluble	4 day	FRAP	~4.00	~6.00	μmol TE/g DW	(Aguilera et al., 2013)
Germinated hyacinth bean (*Lablab purpureus* (L.) Sweet)	Soluble	1–4 day	ORAC	~650	~700–1650	μmol TE/100 g FW	(Wu et al., 2012)
Germinated lentil (*Lens culinaris* L. var. Salmantina)	Soluble	3–8 day	ORAC	~20.0	~20.0–53.0	μmol TE/g DW	(Aguilera et al., 2014)
Germinated kidney bean (*Phaseolus vulgaris* L. var. Pinta)	Soluble	3–8 day	ORAC	~25.0	~13.0–46.0	μmol TE/g DW	(Aguilera et al., 2014)
Black bean sprout (*Phaseolus vulgaris* L.)	Soluble	1–5 day	ORAC	~27.0	~9.00–15.0	μmol TE/g DW	(Guajardo-Flores et al., 2013)
Germinated kidney bean (*Phaseolus vulgaris* L.)	Soluble	1–4 day	ORAC	~900	~900–1700	μmol TE/100 g FW	(Wu et al., 2012)
Germinated mucuna (*Stizolobium niveum* L.)	Soluble	4 day	DPPH	~8.30	~10.8	μmol TE/g DW	(Aguilera et al., 2013)
	Soluble	4 day	FRAP	~55.0	~80.0	μmol TE/g DW	(Aguilera et al., 2013)
Germinated adzuki bean (*Vigna angulariz* Ohwi & H. Ohashi)	Soluble	1–4 day	ORAC	~800	~500–2000	μmol TE/100 g FW	(Wu et al., 2012)
Germinated mung bean (*Vigna radiata* cv. emmerald)	Soluble	2–7 day	ABTS	27.0	27.9–43.5	μmol TE/g DW	(Fernandez-Orozco et al., 2008)
Mung bean sprout (*Vigna radiata* L. Wilczek)	Soluble	5 day	ABTS	0.86	11.3	mg TE/g DW	(Pajak et al., 2014)
	Soluble	5 day	DPPH	0.11	1.41	mg TE/g DW	(Pajak et al., 2014)
Germinated mung bean (*Vigna radiate* L.)	Soluble	24–120 h	DPPH	0.03	0.12–0.20	μmol TE/g DW	(Huang et al., 2014)
Mung bean sprout (*Vigna radiata* cv. Sulv3)	Soluble	2–10 day	FRAP	~0.85	~0.35–0.60	mmol Fe(II)/100 g FW	(Shohag et al., 2012)
Mung bean sprout (*Vigna radiata* cv. BARI mung-4)	Soluble	2–10 day	FRAP	~1.00	~0.40–0.77	mmol Fe(II)/100 g FW	(Shohag et al., 2012)
Mung bean sprout (*Vigna radiata* L. Wilczek)	Soluble	5 day	FRAP	0.13	1.20	mmol Fe(II)/100 g DW	(Pajak et al., 2014)
Mung bean sprout (*Vigna radiata*)	Total	1–9 day	Hydro-PSC	452	~700–2657	mmol Vc/100 g DW	(Guo et al., 2012)
Green mung bean sprout (*Vigna radiata*)	Soluble	1–5 day	FRAP	8.28	8.77–32.9	μmol Fe (II)/g DW	(Gan et al., 2016)
	Bound	1–5 day	FRAP	11.8	1.03–12.4	μmol Fe (II)/g DW	(Gan et al., 2016)
	Soluble	1–5 day	ABTS	10.9	8.57–25.8	μmol TE/g DW	(Gan et al., 2016)
	Bound	1–5 day	ABTS	4.25	0.51–4.35	μmol TE/g DW	(Gan et al., 2016)
Black mung bean sprout (*Vigna radiata*)	Soluble	1–5 day	FRAP	7.83	5.68–18.7	μmol Fe (II)/g DW	(Gan et al., 2016)
	Bound	1–5 day	FRAP	15.5	1.11–4.61	μmol Fe (II)/g DW	(Gan et al., 2016)
	Soluble	1–5 day	ABTS	6.80	6.07–21.3	μmol TE/g DW	(Gan et al., 2016)
	Bound	1–5 day	ABTS	5.84	0.52–1.89	μmol TE/g DW	(Gan et al., 2016)
Germinated mung bean (*Vigna radiata* (L.) R. Wilczek)	Soluble	1–4 day	ORAC	~400	~1300–2500	μmol TE/100 g FW	(Wu et al., 2012)
Germinated mung bean (*Vigna radiata* cv. emmerald)	Soluble	2–7 day	PRTC	2.65	3.08–9.21	μmol TE/g DW	(Fernandez-Orozco et al., 2008).
Germinated cowpea (*Vigna unguiculata* L.)	Soluble	4 day	DPPH	~4.90	~8.30	μmol TE/g DW	(Aguilera et al., 2013)
	Soluble	4 day	FRAP	~9.00	~17.0	μmol TE/g DW	(Aguilera et al., 2013)
Germinated cowpea (*Vigna unguiculata* subsp. sesquipedalis)	Soluble	1–4 day	ORAC	~1100	~950–2300	μmol TE/100 g FW	(Wu et al., 2012)
Germinated black-eyed pea (*Vigna unguiculata* subsp. unguiculata)	Soluble	1–4 day	ORAC	~700	~800–2200	μmol TE/100 g FW	(Wu et al., 2012)

Table 4 (*continued*)

Germinated edible seeds and sprouts	Soluble/bound extract	Germination time	Analytic method	Antioxidant capacity		Unit	References
				Before germination	Before germination		
Germinated brown rice (*Oryza sativa*)	Soluble	17–48 h	FRAP	108	112–139	mg TE/100 g DW	(Ti et al., 2014)
	Bound	17–48 h	FRAP	82.3	88.3–106	mg TE/100 g DW	(Ti et al., 2014)
	Soluble	17–48 h	ORAC	29.4	32.1–48.5	μmol TE/g DW	(Ti et al., 2014)
	Bound	17–48 h	ORAC	9.20	13.4–24.2	μmol TE/g DW	(Ti et al., 2014)
Buckwheat sprout (*Fagopyrum esculentum* Moench)	Soluble	96 h	DPPH	620	666	mg TE/100 g DW	(Alvarez-Jubete et al., 2010)
	Soluble	96 h	FRAP	436	739	mg TE/100 g DW	(Alvarez-Jubete et al., 2010)
Germinated buckwheat (*Fagopyrum esculentum* Moench)	Soluble	12–72 h	DPPH	6.32	6.86–24.5	mg TE/kg DW	(Zhang et al., 2015)
	Soluble	12–72 h	ABTS	13.0	14.3–46.0	mg TE/kg DW	(Zhang et al., 2015)
	Soluble	12–72 h	FRAP	18.1	17.3–63.9	mg Fe (II)/kg DW	(Zhang et al., 2015)
	Soluble	12–72 h	ORAC	80.5	80.0–257	mg TE/kg DW	(Zhang et al., 2015)
Tartary buckwheat sprout (*Fagopyrum tataricum*)	Soluble	1–7 day	DPPH	2.60	3.50–5.40	μmol TE/g DW	(Zhou et al., 2015)
	Soluble	1–7 day	ABTS	0.90	0.80–2.20	μmol TE/g DW	(Zhou et al., 2015)
	Soluble	1–7 day	SORAC	5.80	4.70–10.9	μmol TE/g DW	(Zhou et al., 2015)
Sprouted wheat (*Triticum aestivum* L.)	Soluble	5 day	ABTS	22.5	23.5	mmol TE/kg DW	(Zilic et al., 2014)
	Bound	5 day	ABTS	24.7	26.9	mmol TE/kg DW	(Zilic et al., 2014)
	Soluble	110 h	DPPH	44.1	73.7	mg TE/100 g DW	(Alvarez-Jubete et al., 2010)
	Soluble	110 h	FRAP	110	210	mg TE/100 g DW	(Alvarez-Jubete et al., 2010)
Germinated canaryseed (*Phalaris canariensis* L.)	Soluble	24–120 h	DPPH	0.89	1.20–4.17	μmol TE/g DW	(Chen et al., 2016)
	Soluble	24–120 h	ABTS	2.10	2.34–18.2	μmol TE/g DW	(Chen et al., 2016)
	Soluble	24–120 h	ORAC	7.49	10.6–83.6	μmol TE/g DW	(Chen et al., 2016)
	Bound	24–120 h	DPPH	0.52	0.43–0.82	μmol TE/g DW	(Chen et al., 2016)
	Bound	24–120 h	ABTS	1.74	1.52–4.48	μmol TE/g DW	(Chen et al., 2016)
	Bound	24–120 h	ORAC	5.56	4.73–13.4	μmol TE/g DW	(Chen et al., 2016)
Germinated black peanuts (*Arachis hypogaea* L.)	Soluble	1–3 day	ORAC	2336	2279–2984	μmol TE/100 g FW	(Wu et al., 2011)
	Soluble	1–3 day	HORAC	651	594–691	mg GAE/100 g FW	(Wu et al., 2011)
	Soluble	1–3 day	SORAC	54.9	12.5–30.0	units SOD/100 g FW	(Wu et al., 2011)
	Soluble	1–3 day	DPPH	3.54	5.09–6.96	mg GAE/100 g FW	(Wu et al., 2011)
Germinated red peanuts (*Arachis hypogaea* L.)	Soluble	1–3 day	ORAC	690	1339–2084	μmol TE/100 g FW	(Wu et al., 2011)
	Soluble	1–3 day	HORAC	127	217–364	mg GAE/100 g FW	(Wu et al., 2011)
	Soluble	1–3 day	SORAC	36.4	37.6–66.3	units SOD/100 g FW	(Wu et al., 2011)
	Soluble	1–3 day	DPPH	4.87	6.46–10.5	mg GAE/100 g FW	(Wu et al., 2011)
Germinated reddish brown peanuts (*Arachis hypogaea* L.)	Soluble	1–3 day	ORAC	1384	1915–3384	μmol TE/100 g FW	(Wu et al., 2011)
	Soluble	1–3 day	HORAC	230	357–586	mg GAE/100 g FW	(Wu et al., 2011)
	Soluble	1–3 day	SORAC	94.3	40.7–105	units SOD/100 g FW	(Wu et al., 2011)
	Soluble	1–3 day	DPPH	3.90	9.78–18.8	mg GAE/100 g FW	(Wu et al., 2011)
Sunflower sprout (*Helianthus annuus* L.)	Soluble	5 day	ABTS	7.75	18.4	mg TE/g DW	(Pajak et al., 2014)
	Soluble	5 day	DPPH	5.91	11.5	mg TE/g DW	(Pajak et al., 2014)
	Soluble	5 day	FRAP	1.20	11.1	mmol Fe(II)/100 g DW	(Pajak et al., 2014)

Abbreviations: ABTS, ABTS free radical scavenging capacity; DPPH, DPPH free radical scavenging capacity; FRAP, ferric-reducing antioxidant power; Hydro-PSC, hydrophilic peroxyl radical scavenging capacity; HORAC, hydroxyl radical absorbance capacity; ORAC, oxygen radical absorbance capacity; PRTC, peroxyl radical-trapping capacity; SORAC, superoxide radical absorbance capacity; TE, trolox equivalent; GAE, gallic acid equivalent; SOD, superoxide dismutase; DW, dry weight; FW, fresh weight.

(Aguilera et al., 2014; Guo et al., 2012; Hung et al., 2012), while they were also found to continually increase in germinated brown rice (Ti et al., 2014), germinated brown wheat as well as common wheat sprouts (our unpublished data). It is hypothesized that the content of bound phenolics is dependent on their release and conjugation rate. During the early stage of germination, carbohydrates and proteins are degraded, accompanied with the increase of simple sugars and free amino acids (Liu, Guo, Zhu, & Liu, 2011; Wang et al., 2005), and the bound phenolics conjugated with the cell wall components, therefore, are also released. With the germination time increase, new plant cells are proliferated with new cell walls formed and the synthesized soluble phenolics can be secreted to the cell wall to form new bound phenolics. Therefore, bound phenolics are involved in a dynamic process, and their release and conjugation rate may be distinct in different germinated seeds and sprouts.

Phenolic acids and flavonoids are the most common phenolic compounds detected in germinated edible seeds and sprouts

Table 5
Other bioactivities of germinated edible seeds and sprouts.

Germinated edible seeds and sprouts	Bioactivities	Main bioactive components	References
Germinated soybean (*Glycine max*)	Anticancer effect	Bioactive soy peptide, protein hydrolates and phytochemicals	(Mora-Escobedo, Robles-Ramirez, Ramon-Gallegos, & Reza-Aleman, 2009; Robles-Ramirez, Ramon-Gallegos, Reyes-Duarte, & Mora-Escobedo, 2012)
Kidney bean sprout (*Phaseolus vulgaris* var. Pinto)	ACE-inhibitory effect	Bioactive peptides	(Limon et al., 2014)
Germinated black beans (*Phaseolus vulgaris* L.)	Antiproliferative effect	Genistein, flavonols and group B saponins	(Guajardo-Flores et al., 2013)
Dark beans sprout (*Phaseolus vulgaris* L.)	Anticancer effect	Phenolic compounds	(Lopez et al., 2013)
Dark mung bean sprout (*Vigna radiata*)	Antibacterial effect	N.D.	(Randhir et al., 2004)
Germinated mung Bean (*Vigna radiata*)	Antistress effect	N.D.	(Yeap et al., 2014)
Mung bean sprout (*Vigna radiata*)	Antidiabetic effect	D-*chiro*-inositol (DCI)	(Yao, Chen, Wang, Wang, & Ren, 2008).
Buckwheat sprout (*Fagopyrum esculentum*)	Hypolipidemic effect	N.D.	(Lin et al., 2008; Peng et al., 2009)
Germinated barley (*Hordeum vulgare* L.)	Anticancer effect	N.D.	(Kanauchi, Mitsuyama, Andoh, & Iwanaga, 2008).
	Antiinflammatory effect	N.D.	(Kanauchi et al., 1998)
Germinated brown rice (*Oryza sativa*)	Reproductive protective effect	N.D.	(Muhammad, Ismail, Mahmud, Salisu, & Zakaria, 2013)
	Anticancer effect	GABA	(Latifah et al., 2010; Oh & Oh, 2004)
	Hypolipidemic effect	N.D.	(Miura et al., 2006; Roohinejad et al., 2009; Roohinejad et al., 2010)
	Neuro-protective effect	N.D.	(Mamiya et al., 2004)
	Psychosomatic health-enhancing effect	N.D.	(Sakamoto et al., 2007)
Sunflower sprout (*Helianthus annuus*)	Antiglycative effect	Cynarin	(Sun et al., 2012)

Abbreviations: ACE, angiotensin-converting enzyme; GABA, γ-aminobutyric acid; N.D., not detected.

(Table 3), in which many phenolic compounds are the same in fruits and vegetables. In addition, some germinated edible seeds and sprouts had total phenolic content (30–253 mg GAE/100 g FW, Table 3) generally comparable with some common fruits (11.9–586 mg GAE/100 g FW) and vegetables (114–311 mg GAE/100 g FW) (Fu et al., 2011; Lin & Tang, 2007). Therefore, germinated edible seeds and sprouts can be an alternative choice of fruits and vegetables for providing phenolic compounds in our diets.

2.4. Other bioactive compounds

Besides the bioactive compounds mentioned above, several other bioactive compounds have also been reported in germinated edible seeds and sprouts. Melatonin (*N*-acetyl-5-methoxytryptamine) is an indolamine ubiquitously found in animals, plants, fungi and bacteria, and plays many important physiological functions in different organisms, such as the regulation of the circadian rhythm and growth (Gamble, Berry, Frank, & Young, 2014; Park, 2011). Recent studies find that germination can increase the content of melatonin in edible seeds. Aguilera et al. (2014) find that melatonin level is significantly increased in germinated lentils (*Lens culinaris* L.) and kidney beans (*Phaseolus vulgaris* L.), and reaches the highest content, about 2.50 and 9.50 ng/g DW for lentils and kidney beans, respectively, after 6 day of germination under 24 h dark in both beans. D-*chiro*-Inositol (DCI) is a coenzyme of glycosylphosphatidyl inositol protein that is involved in the insulin signaling pathway and glucose transport, therefore, it is an important insulin mediator with antidiabetic effect (Adams et al., 2014; Ostlund et al., 1993). Germination can increase the content of DCI in germinated edible seeds and sprouts. In the mung bean sprout, DCI content is gradually increased from 0 to 80 h of germination, with the highest level of 4.79 mg/g DW, which is 74% higher than in the seeds, and then decreased after 80 h of germination time (Yao, Cheng, & Ren, 2011).

3. Bioactivities

3.1. Antioxidant capacity

Antioxidant capacity is the most extensively investigated bioactivity in germinated edible seeds and sprouts, and it is found that germination can change the antioxidant capacity in many edible seeds. Although different evaluation methods are used to evaluate the antioxidant capacity in germinated edible seeds and sprouts, most of these studies reach a consistent result that germination can significantly enhance the antioxidant capacity of the soluble extracts in germinated edible seeds and sprouts when compared with raw seeds (Table 4). This can be attributed to the increase of some antioxidant components in germinated seeds and sprouts, such as antioxidant vitamins and polyphenols. However, still several studies reported a decrease or fluctuation of antioxidant capacity in germinated edible seeds and sprouts (Aguilera et al., 2014; Alvarez-Jubete, Wijngaard, Arendt, & Gallagher, 2010; Guajardo-Flores et al., 2013; Shohag et al., 2012; Wu et al., 2012), and this might be partly associated with the results based on fresh weight, affected by the moisture content.

On the other hand, the antioxidant capacity in the bound extracts of germinated edible seeds and sprouts has been less investigated (Table 4). In the germinated brown rice, the bound extract had significant antioxidant capacity, which was higher than the raw seeds (Ti et al., 2014). Furthermore, in the sprouted wheat, antioxidant capacity in bound extract was even higher than that in the soluble extract after a 5 - day germination time (Zilic et al., 2014). It is speculated that the antioxidant capacity of bound extracts can be associated with the bound phenolics, and the change of bound phenolics can directly affect antioxidant capacity. Owing to lack of more data about antioxidant capacity of bound extracts in geminated edible seeds and sprouts, further studies are necessary to focus on this research area, since ignorance of bound extracts might cause underestimation of the total antioxidant capacity in some germinated edible seeds and sprouts.

3.2. Other bioactivities

Besides antioxidant capacity, germinated edible seeds and sprouts have also been reported with a number of bioactivities (Table 5), such as antiinflammatory, antibacterial, antidiabetic and anticancer effects, and these bioactivities can be associated with the accumulation of different bioactive components, such as polyphenols, in germinated edible seeds and sprouts. The bioactivities of germinated edible seeds and sprouts suggest that they may possess potential health benefits and can be consumed as parts of our diets for the prevention of some chronic diseases.

4. Conclusion

Numerous studies have proven that germination is a valuable way to accumulate bioactive compounds, especially vitamins, GABA and polyphenols, in edible seeds. In addition, germination can be widely applied to other seeds, such as vegetable, fruit, flower and medicinal plant seeds, in order to improve their phytochemical composition and biological functions. The antioxidant capacity is significantly increased in the soluble extracts of many germinated edible seeds and sprouts. However, their bound extracts may be also rich in polyphenols and antioxidant capacity, which has been less studied and need further investigation. Furthermore, germination can contribute to human nutrition and health, such as prevention of malnutrition and chronic diseases as it can increase the content of some nutrients, bioactive components and bioactivities of edible seeds. Further studies on their health benefits are essential in order to better understand their beneficial effects on humans. Overall, germinated edible seeds and sprouts rich in bioactive compounds can be considered as functional foods for the prevention of some chronic diseases.

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