Can sprouting reduce phytate and improve the nutritional composition and nutrient bioaccessibility in cereals and legumes?

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INTRODUCTION

The nutritional value of cereals and legumes can be negatively impacted by phytate through its ability to bind with minerals and prevent their absorption and utilisation in the body (Bouajila et al., 2020). Phytate is present in most plants as the primary storage form of phosphorus. Low mineral availability in cereals and legumes may increase the risk of mineral deficiencies worldwide as they are staple food crops in many diets (Gibson et al., 2018). Therefore, methods that reduce phytate could benefit the availability of minerals and the nutritional status of the global population. It has been reported that the process of sprouting can decrease

REVIEW

Can sprouting reduce phytate and improve the nutritional composition and nutrient bioaccessibility in cereals and legumes?

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Abstract
Sprouting is a traditional processing method which has been used for centuries to improve the nutritional value of cereals and legumes. There has been growing interest in sprouted products in recent years due to a high demand for more natural and healthy foods. Phytate is the primary storage form of phosphorus in plants. It is long recognised to affect human health as it forms insoluble complexes with minerals such as iron and zinc in cereals and legumes, thereby preventing their absorption in the body. Sprouting activates the enzyme phytase, which degrades phytate, thereby improving mineral bioaccessibility and bioavailability. The extent of phytate reduction varies depending on the sprouting conditions, cereal/legume species, cultivar and native phytase activity. Sprouting has been associated with increased iron, zinc and calcium bioaccessibility in many studies, but this appears to differ in cereals and legumes, which possibly is due to the presence of other ‘antinutrients’. Protein digestibility also appears to be positively correlated with phytate reduction albeit less than for minerals. It is not possible to accurately predict the influence of sprouting on nutrient bioavailability because so few studies have been conducted. Further research is required to determine whether the commercial production of sprouted cereals and legumes can increase the nutritional value and health benefits of commercial end products.

KEYWORDS
bioaccessibility, cereals, legumes, minerals, phytate, sprouting
Phytate content and increase the availability of minerals (Luo et al., 2014). This review explores the potential of sprouting as a commercial method to reduce phytate content and to improve the nutritional value of cereals and legumes.

**NUTRITIONAL COMPOSITION OF CEREALS AND LEGUMES**

Cereals and legumes are important sources of key nutrients including fibre, starch, protein and minerals for many populations, as evident in Table 1. The nutrients displayed in Table 1, as identified in the literature, indicate that fibre levels in cereals typically range from 3.7 to 31 g/100 g, with the highest level reported in oats and the lowest level found in rice (Hemalatha et al., 2007b; Wilhelmson et al., 2001). Protein content can range from 7.5 to 19 g/100 g, and was also most abundant in oats and least abundant in rice and millet (Donkor et al., 2012; Sharma & Gujral, 2020; Tian et al., 2010). The highest starch content is reported in millet where content is reported to range from 63.7 to 77.8 g/100 g, whilst barley contained the lowest starch content at 28.2 g/100 g (Donkor et al., 2012; Torbica et al., 2021). Similar concentrations of zinc were reported between cereals (typically 1–5 mg/100 g), and whilst significantly higher levels of iron have been reported in sorghum, there appears to be considerable variation between sorghum cultivars (reported iron range 3.7–14.9 mg/100 g) (Afify et al., 2011; Nour et al., 2010). Similar variations in calcium content by variety were noted in millet, ranging from 4.2 to 325 mg/100 g with the highest amount reported in finger millet and the lowest in proso millet (Hemalatha et al., 2007b; Torbica et al., 2021). Growing conditions can also influence nutrient levels since higher mineral levels were reported in wheat grown under organic conditions compared to those with fewer than three phosphate groups (i.e. IP1–IP4) do not impact zinc absorption and those with fewer than three phosphate groups (i.e. IP1-IP2) do not impact iron absorption (Gibson et al., 2010).

**WHAT IS PHYTATE?**

Phytate (myo-inositol hexaphosphate [IP6]) also known as phytic acid normally constitutes 0.2%–2% of the dry weight in cereals and legumes with 60%–90% of the total phosphorus present bound to phytate (Feizollahi et al., 2021). It is mostly located in the aleurone layer in cereals, which is the innermost layer of the bran, except for in maize which contains the majority of phytate in the germ (Pallauf & Rimbach, 1997). Phytate in legumes is mostly contained within protein bodies located in the cotyledon or endosperm (Schlemmer et al., 2009). Phytate levels vary depending on the growing conditions, fertiliser applied, species cultivar and stage of plant maturation (Gibson et al., 2018). Phytate chelates with minerals including iron, zinc, magnesium, calcium, manganese and copper to form insoluble complexes that cannot be digested by humans due to the lack of intestinal phytase enzymes (Figure 1) (Kumar et al., 2010). In vivo, the enzyme phytase is required to release these bound minerals and break down phytate to myo-inositol and/or lower myo-inositol phosphates with less chelating power (Egli et al., 2002). It is understood that myo-inositol phosphates with fewer than five phosphate groups (i.e. IP1-IP4) do not impact zinc absorption and those with fewer than three phosphate groups (i.e. IP1-IP2) do not impact iron absorption (Gibson et al., 2010).

**INFLUENCE OF PHYTATE ON NUTRIENT INTAKE AND NUTRITIONAL STATUS**

The terms bioaccessibility and bioavailability are used to describe the amount of nutrients from food that are absorbed and utilised by the body and ultimately both influence the nutritional quality of the food (Pongrac et al., 2016). Bioaccessibility refers to the amount of nutrients that are released from the food matrix following digestion, while bioavailability refers to the amount of nutrients that are absorbed into the bloodstream following digestion and can be utilised through normal metabolic pathways (Etchevery et al., 2012). Dietary components can inhibit or enhance the bioaccessibility and bioavailability of nutrients from food (Hemalatha
The formation of phytate-mineral complexes reduces mineral bioavailability as humans are unable to digest these complexes and release bound minerals (Lemmens et al., 2019b). Phytate is the major inhibitor of iron and zinc absorption from cereals and legumes resulting in low bioavailability of these minerals (Poorvisha et al., 2020). This can increase the risk of mineral deficiencies especially where these foods are major dietary staples, such as in developing countries and for individuals consuming plant-based diets.

### TABLE 1

| Source    | Fibre g/100 g | Starch g/100 g | Protein g/100 g | Iron mg/100 g | Zinc mg/100 g | Calcium mg/100 g | References |
|-----------|---------------|----------------|-----------------|---------------|---------------|------------------|------------|
| Cereal    |               |                |                 |               |               |                  |            |
| Wheat     | 10.9–15.4     | 41.9–60.4      | 10.5–17.5       | 1.9–5.4       | 1.1–4.6       | 29–50.3          | Hemalatha et al. (2007b), Hussain et al. (2010), Anjum et al. (2012), Donkor et al. (2012), Latunde-Dada et al. (2014), Luo et al. (2014), Zilic et al. (2016), Liu et al. (2017), Baranzelli et al. (2018), Montemurro et al. (2019), Wang et al. (2020) |
| Oat       | 11.3–31       | 40.6–63.4      | 8.3–19          | 2.9–4.0       | 1.9–3.1       | 20.8–53.2        | Wilhelmson et al. (2001), Hübner et al. (2010), Tian et al. (2010), Donkor et al. (2012), Aparicio-García et al. (2021), Torbica et al. (2021) |
| Rye       | 12.9          | 30.4–57.2      | 11.4–16.3       | 3.2           | 1.6           | 14.7             | Donkor et al. (2012), Torbica et al. (2021) |
| Barley    | 15.2–21.5     | 28.2–61.5      | 11.6–15.7       | 2.4–3.7       | 1.0–2.0       | 17.1–18.9        | Hübner et al. (2010), Donkor et al. (2012), Montemurro et al. (2019), Torbica et al. (2021) |
| Sorghum   | 10.2–12.1     | 33.7–67.1      | 10.2–17.2       | 3.7–14.9      | 1.2–5.0       | 3.4–21           | Hemalatha et al. (2007b), Nour et al. (2010), Affy et al. (2011), Tizazu et al. (2011), Donkor et al. (2012), Ogbanna et al. (2012), Torbica et al. (2021) |
| Millet    | 4.6–18.9      | 63.7–77.8      | 7.5–12.2        | 2.1–6.4       | 1.7–1.9       | 4.2–325          | Hemalatha et al. (2007b), Suma and Urooj (2014), Sharma and Gujral (2020), Torbica et al. (2021) |
| Rice      | 3.7           | 54.7           | 7.8             | 1.3–3.7       | 1.1–1.7       | 7.3–37.5         | Hemalatha et al. (2007b), Donkor et al. (2012), Luo et al. (2014) |
| Legume    |               |                |                 |               |               |                  |            |
| Chickpea  | 24.3–27.3     | 32.5–51.8      | 14.8–25.2       | 3.0–7.7       | 2.0–6.8       | 79.1–222         | El-Adawy (2002), Iqbal et al. (2006), Hemalatha et al. (2007b), Ghavidel and Prakash (2007), Bains et al. (2014), Chandra-Hioe et al. (2016), Erba et al. (2019), Montemurro et al. (2019), Njoumi et al. (2019), Atudorei et al. (2020) |
| Lentil    | 16.5–24       | 21.5–38.2      | 19.1–30.1       | 3.1–8.5       | 2.8–4.4       | 69–120           | Iqbal et al. (2006), Ghavidel and Prakash (2007), Fouad and Rehab (2015), Pal et al. (2017), Kamboj and Nanda (2018), Montemurro et al. (2019), Njoumi et al. (2019), Atudorei et al. (2020), Viktorinová et al. (2020) |
| Green gram (Mung bean) | 19.8–22.3 | 46.7–53.8 | 24–27.7 | 4.4–11.1 | 2.4–4.0 | 72.8–136 | Hemalatha et al. (2007b), Ghavidel and Prakash (2007), Oghbaei and Prakash (2017), Kamboj and Nanda (2018) |
| Soybean   | –             | 4.3–6.7        | 39.4–44.4       | 2.7–10.4      | 1.7–4.4       | 140–240          | Luo et al. (2014), Sharma et al. (2014), Kamboj and Nanda (2018) |
| Faba bean | 34.9          | –              | 22.7            | 2.5–4.7       | 1.5–3.9       | 132              | Luo et al. (2009), Luo and Xie (2014), Luo et al. (2014), Chandra-Hioe et al. (2016), Njoumi et al. (2019) |
Cereals have been reported as the primary source of zinc in most vegetarian diets with legumes as the secondary source (Hemalatha et al., 2007a). Low mineral bioavailability could also influence the nutritional status of entire populations since cereals and cereal products are the primary dietary sources of iron and primary or secondary sources of zinc in the UK, Australia, New Zealand and the US populations (Lim et al., 2013). Micronutrient deficiencies are a global health concern that affect over two billion people worldwide causing both physical and mental health implications and with iron and zinc being two of the most prevalent deficiencies (Ritchie & Roser, 2017). Therefore, strategies to improve the bioavailability of minerals from cereals and legumes are required to reduce the risk of mineral deficiencies and enhance the nutritional status of the population. One such strategy could be the development of methods to reduce the phytate content of cereals and legumes and thereby improve the bioavailability of minerals (Samtiya et al., 2020). Although phytate has been linked with beneficial health effects including antioxidant, anti-carcinogenic and anti-diabetic properties, the level of phytate required to provide these positive health effects in humans is unclear and requires further research (Kumar et al., 2010). The present review considers how the inhibitory effects of phytate can be minimised, with a specific focus on sprouting.

SPROUTING AS A TRADITIONAL AND RE-EMERGING TECHNOLOGY

Sprouting is a traditional process that has been used for centuries to soften grain kernels and improve the nutritional value of cereals and legumes (Singh et al., 2015). More than 5000 years ago, Chinese physicians were the first to utilise the nutritional and medicinal properties achieved through sprouting for the treatment of several health disorders (Pagand et al., 2017). The population of Asian countries such as China, Japan, Thailand and India uses sprouted brown rice in their daily cooking and in the production of rice products (Ding & Feng, 2019). Since the 1980s, the interest around sprouting has reached the Western world due to high demand for healthy and natural foods (Benincasa et al., 2019). This has led to a growing trend in the number of global sprouted products launched with a 4.5-fold increase in new sprouted products in 2019 compared to 2009 (Weel & Heirbaut, 2020).

Sprouting, which is also known as germination, occurs when the dry grain takes up water and starts to grow into a new plant as a sprout emerges from the grain (Montemurro et al., 2019). According to the EU Regulation No 208/2013, ‘Sprouts’ are ‘the product obtained from the germination of seeds and their development in water or another medium, harvested before the development of true leaves and which are intended to be eaten whole, including the seed’ (Benincasa et al., 2019). Commercially, once the grains are selected and cleaned, highly controlled processes are used to produce sprouted products, which consist of three main steps including soaking, sprouting and drying, as displayed in Figure 2 (Villeneuve et al., 2015). Firstly, grains are soaked in water until they reach a moisture that will activate enzymes, which are dormant in raw grains (Guzmán-Ortiz et al., 2019). After the soaking water is drained, the grains are sprouted under controlled conditions to increase metabolic processes and mobilise energy reserves to support the growing plant (Mäkinen & Arendt, 2015). These activated enzymes break down proteins into amino acids, carbohydrates into simple sugars and lipids into fatty acids, thereby improving the digestibility of grains (Marton et al., 2010). Furthermore, higher levels of vitamins, soluble dietary fibre, phenolic compounds, antioxidant activity and degradation of antinutrients including phytate can result in greater nutritional value and bioavailability of nutrients compared with non-sprouted grains (Ding & Feng, 2019). The final step involves drying the grains once the desired nutritional and functional properties are achieved. The intention is to halt the biochemical processes, ensure microbiological safety and maximise the flavour compounds present (Kaukovirta-Norja et al., 2004).

The degree of changes that occur during sprouting depends on the process parameters including moisture content, temperature–time combinations and atmospheric conditions (Montemurro et al., 2019). A significant increase in the moisture content is required to initiate sprouting (Kaukovirta-Norja et al., 2004). The minimum grain moisture level that has been reported in studies to initiate sprouting has varied from 35% in wheat to 45% in oats and barley (Hübner et al., 2010; Lemmens et al., 2019a). This uptake of water is further influenced by the permeability of the grain coat, water
solute concentration and grain composition since protein is the primary absorbent of water, thereby grains with higher protein content may absorb more water (Ikram et al., 2021). Table 2 provides an overview of the soaking, sprouting and drying conditions used in studies to date which have characterised sprouting cereals and legumes. The temperatures applied during soaking and sprouting are considered the most important environmental conditions that impact the sprouting process (Ding & Feng, 2019). As evident in Table 2, the temperatures varied between studies with a soaking range of 15–33°C and a sprouting range of 10–32°C. Ikram et al. (2021) suggested that the optimal sprouting temperatures typically range from 20 to 30°C as sprouting resists very high or very low temperatures. However, this will differ depending on grain species, species cultivar, genetic differences, source and age of the grain (Villeneuve et al., 2015). Such moisture levels are maintained by sprouting grains in a moist environment and/or periodically spraying them with water (Table 2) since the growing plant continues to take up water after soaking (Benincasa et al., 2019). Regular ventilation is also recommended during sprouting as optimal sprouting occurs under natural atmospheric conditions achieved either manually (Villeneuve et al., 2015) or automatically using a sprouting system (Bouajila et al., 2020). The temperature at which grains are dried at can also influence the enzyme activity and nutritional value of the end product since higher temperatures will inactivate enzymes (Lemmens et al., 2019b). In Table 2, the grains studied were dried at 40–70°C for 3–48 h or freeze-dried and the studies were mostly conducted under small-scale laboratory conditions (e.g. household germination systems). It is worth noting that the soaking, sprouting and drying conditions displayed in Table 2 may have different outcomes when applied to large-scale production since grains could be exposed to different temperatures and atmospheric conditions.

The process parameters applied in large-scale production will also depend on nutritional, sensory and functional properties required for commercial utilisation.

INFLUENCE OF SPROUTING CONDITIONS ON PHYTASE AND PHYTATE LEVELS IN CEREALS AND LEGUMES

The process of sprouting can decrease phytate concentrations present through the activation of, and de novo synthesis of, phytase as well as the leaching of water-soluble phytate during soaking (Gibson et al., 2018). As mentioned, the primary role of phytase activated during sprouting is to release myo-inositol, phosphate and other minerals for plant growth (Lemmens et al., 2019b), which also led to phytate reduction in various cereals and legumes following sprouting (Table 3). As evident in Table 3, there are variations in phytate reductions between studies which could be a result of the different sprouting conditions used (Table 2). Whilst soaking led to a 2%–58% decrease in phytate, some studies did not associate this with an increase in phytase activity, indicating that phytate was leached into the soaking water (Egli et al., 2002; Poorvisha et al., 2020). Soaking time was positively correlated with phytate reduction in wheat and faba beans when soaked for 4–24 h (Luo et al., 2009; Masud et al., 2007); however, the largest decrease (−58%) was recorded when wheat was soaked for 4 h (Poorvisha et al., 2020). Egli et al. (2002) reported that grains and legumes soaked for 16 h led to contrasting effects in phytate reduction: wheat (+1%), oats (0%), rye (−22%), barley (−6%), sorghum (+1%), buckwheat (−9%), millet (−13%), chickpeas (−15%), lentils (−3%), mung beans (+7%) and soybeans (−3%), whereas sorghum soaked for 20 h decreased phytate by 32% and millet soaked...
| Source | Soaking | Sprouting | Equipment | Periodically sprayed with water | Drying | References |
|--------|---------|-----------|-----------|-------------------------------|--------|------------|
| Wheat  | 4–36a   | 0.25–10b  | Micro-malting system (n = 2) | Y (n = 6) | 40–60°C for 3–25 h (n = 8) | Lemmens et al. (2019a), Azeke et al. (2021), Poorvisha et al. (2020), Montemurro et al. (2019), Poudel et al. (2019) Singkhornart et al. (2013), Stern et al. (2021), Anjum et al. (2012), Egli et al. (2002), Nagaoka (2005) |
|        | 15-33b  | 15-32b    | Tray/plate with damp cloths (n = 4) | N/NS (n = 4) | Freeze-dried (n = 2) | |
|        |         |           | Household germination system (n = 2) | | | |
|        |         |           | Germination vessel (n = 1) | | | |
|        |         |           | Not specified (n = 1) | | | |
| Oat    | 16–24   | 1–6       | Micro-malting system (n = 1) | Y (n = 1) | 45–55°C for 23–24 h (n = 2) | Hübner et al. (2010), Tian et al. (2010), Egli et al. (2002) |
|        | 16-25b  | 10–25    | Wet cellulose pads (n = 1) | N/NS (n = 2) | Freeze-dried (n = 1) | |
|        |         |           | Household germination system (n = 1) | | | |
| Rye    | 1–16    | 1–5       | Tray with damp cloths (n = 1) | Y (n = 2) | Freeze-dried (n = 2) | Centeno et al. (2001), Egli et al. (2002) |
|        | 15-25   | 22–25    | Household germination system (n = 1) | | | |
| Barley | 1–24    | 1–12b    | Micro-malting system (n = 1) | Y (n = 5) | 45–55°C for 23–25 h (n = 3) | Hübner et al. (2010), Centeno et al. (2001), Montemurro et al. (2019), Singkhornart et al. (2013), Egli et al. (2002), Bouajila et al. (2020) |
|        | 15–25b  | 10–25    | Tray with damp cloths (n = 2) | N/NS (n = 1) | Freeze-dried (n = 3) | |
|        |         |           | Household germination system (n = 2) | | | |
|        |         |           | Steel hydroponic unit (n = 1) | | | |
| Sorghum| 8–48a   | 1–10     | Moistened jute bags (n = 1) | Y (n = 3) | 45–60°C for 3–24 h (n = 4) | Nour et al. (2010), Afify et al. (2011), Tizazu et al. (2011), Ogbanna et al. (2012), Azeke et al. (2011), Egli et al. (2002) |
|        | 22–25b  | 15-30b   | Tray with damp cloths (n = 1) | N/NS (n = 3) | Sun-dried (n = 1) | |
|        |         |           | Household germination system (n = 1) | | Freeze-dried (n = 1) | |
|        |         |           | Not specified (n = 3) | | | |
| Buckwheat | 1–16 | 0.5–3  | Plastic bucket with damp gauze (n = 1) | Y (n = 2) | Freeze-dried (n = 2) | Zhang et al. (2015), Egli et al. (2002) |
|        | 15–25   | 25       | Household germination system (n = 1) | | | |
| Millet | 12–24a  | 0.5–10   | Wet jute bags with damp cloths (n = 1) | Y (n = 3) | 45–60°C for 18–24 h (n = 4) | Badau et al. (2005), Sharma and Gujral (2020), Hejazi and Orsat (2016), Egli et al. (2002), Suma and Urooj (2014), Hemalatha et al. (2007a), Azeke et al. (2011) |
|        | 15–25b  | 15–32   | Wet muslin cloths (n = 2) (n = 1) | N/NS (n = 4) | Freeze-dried (n = 2) | |
|        |         |           | Household germination system (n = 1) | | NS (n = 1) | |
|        |         |           | Plastic trays with damp cloths (n = 1) | | | |
| Source     | Soaking       | Sprouting       | Equipment                                                                 | Periodically sprayed with water | Drying                      | References                                                                 |
|------------|---------------|-----------------|---------------------------------------------------------------------------|---------------------------------|-----------------------------|----------------------------------------------------------------------------|
| Chickpea   | 8–24          | 15-25b          | 0.5-4b 16.5-30b                                                           | Y (n = 4)                       | 40–70°C for 4–25 h (n = 6) | Hemalatha et al. (2007a), El-Adawy (2002), Ghavidel and Prakash (2007), Erba et al. (2019), Montemurro et al. (2019), Khalil et al. (2007), Egli et al. (2002), Sofi et al. (2020) |
|            | 6–24b         | 16.5–25b        | 1–6b 16-25b                                                              | Y (n = 4)                       | 50°C for 16–48 h (n = 4)   | Ghavidel and Prakash (2007), Montemurro et al. (2019), Fouad and Rehab (2015), Pai et al. (2017), Viktorinová et al. (2020), Egli et al. (2002), Bautista-Expósito et al. (2021) |
|            | 12–16         | 22–30b          | 0.5–4 25–30b                                                             | Y (n = 2)                       | 50°C for 16–18 h (n = 1)   | Egli et al. (2002), Hemalatha et al. (2007a), Ghavidel and Prakash (2007), Wang et al. (2015), Luo et al. (2013) |
|            | 12–16         | 25–30           | 1–4 25–30                                                                | Y (n = 2)                       | Freeze-dried (n = 2)       | Egli et al. (2002), Wang et al. (2015)                                    |
|            | 4–24b         | 20–25b          | 1–6 20–30                                                                | Y (n = 2)                       | 60°C (n = 1)                | Luo and Xie (2014), Luo et al. (2009), Bautista-Expósito et al. (2021), Luo et al. (2013) |

Abbreviation: NS, not specified.

*Indicates were grains were rinsed instead of soaked by Azeke et al. (2011).

Indicates were some sprouting times/temperatures were not provided.
for 12 h decreased phytate by 46% (Afify et al., 2011; Badau et al., 2005). Temperature and pH during soaking and sprouting also play an important role in phytate reduction. Higher phytate degradation can be achieved at optimal phytase conditions of 38–55°C and pH 4.4–6 in cereals and pH 4.5–8 in legumes; however, this may be less practical in commercial production compared to small-scale studies (Bohn et al., 2008). Soaking millet in acidic conditions caused further reductions in phytate compared to water soaked millet as the pH was in the range of optimal phytase activity (Jha et al., 2015). Similarly, when wheat was hydrothermally treated at 40°C for 8 h, phytate decreased further from 0.65 to 0.47 g/100 g (Lemmens et al., 2019a). However, moderate soaking temperatures (15–30°C) are recommended as temperatures exceeding 30°C can result in greater mineral loss through leaching of water-soluble minerals (Lemmens et al., 2019b).

Sprouting time can also play an important role in the reduction of phytate. Phytate breakdown was positively correlated with sprouting time in wheat (Poudel et al., 2019), oats (Tian et al., 2010), rye (Centeno et al., 2001), barley (Bouajila et al., 2020), sorghum (Nour et al., 2010), buckwheat (Zhang et al., 2015), millet (Sharma et al., 2011), chickpea (Hemalatha et al., 2007a), lentil (Bouajila et al., 2020), green gram/mung bean (Egli et al., 2002), soybean (Luo and Xie, 2014), and faba bean (Luo et al., 2009, 2013).

**TABLE 3** Summary overview of the minimum and maximum phytate values before and after sprouting cereals and legumes as identified in the literature (see supplemental table in Appendix S2 for full details)

| Source         | Phytate (g/100 g) | Phytate change (%) |
|----------------|-------------------|--------------------|
|                | Raw (min) | Raw (max) | Sprouted (min) | Sprouted (max) | Min  | Max  |
| Wheat          | 0.30      | 2.27      | 0.04          | 1.40          | +38  | −87  |
| Oat            | 0.35      | 0.88      | 0.11          | 0.94          | +7   | −69  |
| Rye            | 0.19      | 0.79      | 0.03          | 0.71          | −10  | −84  |
| Barley         | 0.19      | 1.08      | 0.01          | 0.95          | −5   | −97  |
| Sorghum        | 0.20      | 1.50      | 0.09          | 1.11          | +3   | −81  |
| Buckwheat      | 1.42      | 1.52      | 1.26          | 1.46          | +3   | −17  |
| Millet         | 0.22      | 2.98      | 0.09          | 1.63          | −2   | −91  |
| Chickpea       | 0.48      | 1.90      | 0.16          | 1.80          | +6   | −73  |
| Lentil         | 0.09      | 1.30      | 0.04          | 1.13          | −3   | −74  |
| Green gram/mung bean | 0.22  | 0.89      | 0.14          | 0.89          | +7   | −76  |
| Soybean        | 0.98      | 1.40      | 0.42          | 1.44          | +3   | −58  |
| Faba bean      | 0.26      | 0.86      | 0.11          | 0.77          | −8   | −68  |

Note: Some values were interpreted from data in a graphical manner so may be subject to variation.
& Gujral, 2020), chickpeas (Khalil et al., 2007), lentils (Fouad & Rehab, 2015), green gram (Hemalatha et al., 2007a) and faba beans (Luo et al., 2009). Some studies correlated this phytate reduction during sprouting with higher phytase activity through activated and de novo synthesised phytase (Bouajila et al., 2020; Centeno et al., 2001). Egli et al. (2002) reported that phytase increased in legumes but decreased in cereals sprouted for 3 days despite a reduction in phytate. A 24-hour lag phase was reported before phytase activity increased significantly in wheat, rice, millet and sorghum, which delayed the rate of phytate breakdown (Azeke et al., 2011). Conversely, endogenous phytase was rapidly activated during the initial stages of sprouting which led to the largest reductions of phytate content in the first 2 days (Lemmens et al., 2019a). Following the initial increase in these studies, phytase activity decreased after sprouting for 5 days, possibly due to enzymatic degradation by activated protease and/or inhibition by liberated phosphate (Azeke et al., 2011; Bouajila et al., 2020). However, despite this reduced phytase activity, phytate content continued to decrease in these studies for up to 5 days following the initial phytase reduction.

Similar to soaking, sprouting temperatures closer to the optimal conditions for phytase activity can increase the rate of phytase activation and phytate reduction (Guzmán-Ortiz et al., 2019). Hence, in the study of Sung et al. (2005), it took 7 days for phytase to reach its maximum activity when barley was sprouted at 15°C compared to 4 days at 20–25°C. In turn, the rate at which phosphorus was liberated through phytate degradation was highest at 25°C and lowest at 15°C. Furthermore, Stern et al. (2021) did not report any significant reductions in phytate content when wheat was sprouted at 16°C for 36 h. This indicates that lower temperatures may require longer sprouting times to reduce phytate to a similar level that is achieved at higher temperatures and shorter sprouting times. Hübner et al. (2010) also reported an influence of sprouting temperature on phytate reduction in oats, but not in barley. However, these results were not consistent as oats sprouted for 2 days reduced phytate by 6% at 10°C and 18% at 20°C, whereas after 6 days phytate decreased by 32% at 10°C and 24% at 20°C. Therefore, sprouting temperatures may have conflicting effects on phytate reduction at different sprouting times. This could be influenced by changes in phytase activity at different temperatures since it was reported that once phytase reaches its maximum activity, the rate of phytate reduction is higher at temperatures exceeding 20°C (Sung et al., 2005).

The influence of sprouting on phytate reduction can also depend on the native phytase activity between different grain species (Gibson et al., 2018). Phytate levels vary in cereals since high levels were reported in rye, wheat, barley and buckwheat whilst lower levels were found in oats, millet and sorghum (Egli et al., 2002). Legumes were also found to contain low native phytase activity including chickpeas and lentils (Montemurro et al., 2019). Despite lower phytase activities, phytate decreased in sprouted oats and chickpeas by up to 69% and 73%, respectively (Khalil et al., 2007; Tian et al., 2010). Thermal drying applied in these studies could also influence phytate reduction in cereals and legumes since phytase is still active at typical drying temperatures (40–60°C); although, sufficient moisture is required for high enzymatic activity (Hübner et al., 2010). Therefore, any changes would occur at the initial stages of drying when the moisture content is high enough to favour phytase activity (Lemmens et al., 2019b). Variations in phytate reduction between cereal and legume cultivars have also been reported in barley (Bouajila et al., 2020), sorghum (Nour et al., 2010), millet (Sharma & Gujral, 2020), chickpeas (Khalil et al., 2007) and lentils (Pal et al., 2017). Overall, longer sprouting times and higher temperatures favour phytate reduction, but this can have a detrimental effect on the nutritional quality of grains, for example, the loss of water-soluble nutrients during soaking (Lemmens et al., 2019b). Therefore, sprouting conditions used to reduce phytate will depend on the nutritional and functional properties that are desired in the final product.

### INFLUENCE OF SPROUTING ON THE NUTRITIONAL COMPOSITION OF CEREALS AND LEGUMES

#### Influence of sprouting on the macronutrient composition

Sprouting can induce changes in the nutritional composition of cereals and legumes through enzymatic hydrolysis of existing compounds and de novo synthesis of new compounds (Singh et al., 2015). The activation of α-amylase degrades starch into sugars that serve as an energy source for the growing plant including glucose, maltose and sucrose (Ikram et al., 2021). Sprouting reduced starch by up to 3.3-fold and increased sugar content by up to 7.8-fold in sprouted wheat, barley, chickpeas, lentils and quinoa (Montemurro et al., 2019). Tian et al. (2010) reported that sugar content decreased in oats sprouted for 24 h possibly due to a faster rate of sugar consumption than starch degradation. Following this, sprouting time was positively correlated with starch reduction and increased sugar content for up to 5 days. Glucose and sucrose levels increased from 5- to 7-fold in two wheat varieties sprouted for 36 h, but the increase in maltose differed significantly between the two varieties (Stern et al., 2021). Higher sugar content increases the natural sweetness of cereals and legumes that could reduce the requirement for added sugar in sprouted products (Pagand et al., 2017).
Sprouting can also increase the digestibility of starch as rapidly digestible starch increased, whereas slowly digestible starch and resistant starch decreased in millet sprouted for 2 days (Sharma & Gujral, 2020). Higher starch digestibility in this study was associated with the activation of α-amylase and reduction of amylase inhibitors. Furthermore, partial removal of phytate and tannins in this study created space within the matrix that increased the susceptibility of starch to enzyme degradation. Similarly, reduced antinutrient levels were correlated with higher starch digestibility in green gram, cowpeas, chickpeas and lentils sprouted for 24 h, which was further enhanced when these legumes were dehulled (Ghavidel & Prakash, 2007). Conversely, it was also reported that sprouting can induce more crystalline starch structures, which are more resistant to enzymatic hydrolysis, and thereby may increase resistant starch (Cornejo et al., 2015). Resistant starch can provide prebiotic benefits as it escapes digestion in the small intestine and is fermented by colonic bacteria (Bede & Zaixiang, 2021). Stern et al. (2021) did not report any significant changes in resistant starch in wheat sprouted for 36 h whereas, Marti et al. (2017) reported higher levels of slowly digestible starch in bread prepared from 100% wheat flour that was sprouted for 48 h, although research in this area is limited. The impact of sprouting on starch digestibility can depend on the time, pH and temperatures applied during soaking, sprouting and drying (Bede & Zaixiang, 2021).

Dietary fibre is an important component of cereals and legumes, which can be grouped into soluble fibre, including beta-glucan and arabinoxylan (AX), and insoluble fibre, including cellulose and lignans (Hübner & Arendt, 2013). The cell walls of wheat and rye mainly consist of AX whilst barley, oats, sorghum and millet mainly consist of beta-glucan (Lemmens et al., 2019b). Sprouting solubilises fibre due to the activation of endogenous enzymes, which led to a decrease in insoluble fibre and an increase in soluble fibre from 1- to 2-fold in sprouted wheat, barley, chickpeas, lentils and quinoa, although total dietary fibre decreased (Montemurro et al., 2019). Ghavidel and Prakash (2007) also reported a reduction in insoluble fibre and higher levels of soluble fibre in green gram, cowpeas, chickpeas and lentils sprouted for 24 h, whilst total dietary fibre increased slightly possibly due to the loss of dry matter through respiration during sprouting. Oats contain high levels of betaglucan that decreased in sprouted oats due to the activation of beta-glucanase (Aparicio-García et al., 2021; Hübner et al., 2010). Therefore, short sprouting times are recommended to retain soluble fibre and beta-glucan in oats (Hübner et al., 2010). Sprouting can also solubilise AX from water-unextractable AX (insoluble) to water-extractable AX (soluble), with conflicting impacts on total AX reported (Benincasa et al., 2019). Donkor et al. (2012) found that total AX increased in buckwheat, sorghum, wheat and brown rice but decreased in barley, oats and rye when sprouted for 5 days (Donkor et al., 2012). These conflicting results could be influenced by different levels of xylanases, which are activated during sprouting to hydrolyse AX into arabinose, xylose and oligosaccharides (Lemmens et al., 2019b). AX and beta-glucan breakdown products as well as the higher levels of fermentable sugars in sprouted products may provide prebiotic effects through improved colon fermentation (Hübner & Arendt, 2013).

Sprouting can increase the digestibility of protein, but it can also change the protein content and amino acid composition (Ikram et al., 2021). Sprouting increased the protein content by around 10% in chickpeas and lentils but decreased it by 12% in quinoa (Darwish et al., 2020; Erba et al., 2019; Viktorinová et al., 2020). The decrease in protein may be due to the leaching of water-soluble peptides during soaking (Ikram et al., 2021). The influence of sprouting on protein content can also depend on the balance between enzymatic degradation of protein and protein synthesis (Benincasa et al., 2019). The amino acid composition can be altered during sprouting as the level of essential amino acids including lysine, histidine, isoleucine, leucine, threonine and valine increased from 8% to 55%, whilst methionine and phenylalanine decreased by 50% and 43%, respectively, in oats sprouted for 3 days (Tian et al., 2010). However, when these oats were sprouted for 6 days, methionine and phenylalanine increased by 43% and 27%, respectively. Tang et al. (2020) observed a similar pattern as essential amino acids decreased after oats were sprouted for 12 h but increased after 24 h. Sprouting can also induce changes in the lipid content and fatty acid composition of cereals and legumes through the activation of lipase and lipoygenase (Poudel et al., 2019). Lipids are catabolised during sprouting to provide energy and carbon sources for biochemical processes (Lemmens et al., 2019b). The levels of palmitoleic, linoleic, α-linolenic and cis-11-eicosenoic acid increased by up to 17% in oats sprouted for 4 days, whilst oleic acid decreased by 3% (Aparicio-García et al., 2021). Whereas, oleic acid increased by up to 26% in several varieties of lentils when sprouted for 2 days, linoleic and α-linolenic acid decreased by up to 17% (Pal et al., 2017). Ikram et al. (2021) reported that higher sprouting temperatures can increase the rate of lipid breakdown.

Influence of sprouting on the micronutrient composition

The vitamin content in cereals and legumes is important for plant growth and can increase during sprouting as a result of biosynthesis (Lemmens et al., 2019b). The levels of B-vitamins were altered in wheat sprouted for 5 days including niacin (+19%), riboflavin
Phenolic compounds are important contributors to the antioxidant activity in cereals and legumes and made from sprouted wheat compared to the control. Phenolic compounds are altered during sprouting due to de novo synthesis (Gan et al., 2019). However, vitamin C is very heat sensitive as a slight decrease was observed in oats sprouted at 30°C, whilst it increased at 20–25°C (Krapf et al., 2019). Vitamin C content was positively correlated with sprouting time as it increased by 1.3- to 3.5-fold in chickpeas and quinoa that were sprouted for 1–4 days (Darwish et al., 2020; Khalil et al., 2007). Vitamin E is an important antioxidant which increased by 2.7-fold in wheat sprouted for 5 days (Zilic et al., 2014). Pagand et al. (2017) also reported that vitamin E contents increased in wheat, millet and soybeans that were sprouted for at least 4 days. Therefore, increased vitamin E levels in sprouted cereals and legumes were associated with relatively long sprouting times as it was suggested that sprouting time is the main determinant of vitamin E content during sprouting (Lemmens et al., 2019b).

The accumulation of bioactive compounds in sprouted cereals and legumes has gained attention, including γ-aminobutyric acid (GABA), which is a non-protein amino acid that is an important neurotransmitter in the nervous system (Gan et al., 2019). Sprouting increased GABA from 6- to 34-fold in wheat, barley, chickpeas, lentils and quinoa (Montemurro et al., 2019). Baranzelli et al. (2018) also reported that GABA increased by 2.2-fold in wheat sprouted for 24 h. However, the high temperatures applied during baking in this study decreased GABA content in bread, although it remained higher in bread made from sprouted wheat compared to the control. Phenolic compounds are important contributors to the antioxidant activity in cereals and legumes and possess anti-carcinogenic and anti-inflammatory properties (Hübner & Arendt, 2013). Phenolic compounds exist in both free and bound forms, the proportion of which are altered during sprouting as free phenolics increase and bound phenolics decrease (Benincasa et al., 2019). Zilic et al. (2014) reported that sprouting wheat for 5 days increased free phenolic compounds, which are more bioavailable than bound forms, by 28%. Total phenolic compounds also increased in this study by 10%. Shorter sprouting times can also increase these compounds since sprouting oats for 48 h increased total phenolics by 1.6-fold and free phenolics by 4.1-fold (Xu et al., 2009). The enhancement of phenolic compounds during sprouting contributed to the increase in antioxidant capacity of wheat, oats, barley, buckwheat, chickpeas, quinoa, lentils and flaxseed (Montemurro et al., 2019; Pajał et al., 2019; Xu et al., 2009; Zhang et al., 2015). Conversely, antioxidant activity decreased in sprouted lentils which may be a result of the heat applied in the additional processes when these lentils were steamed, pressed and dried (Viktorinova et al., 2020). Therefore, sprouting can improve the health benefits of cereals and legumes through increased levels of vitamins and bioactive compounds; although, this will depend on the process conditions and differences between species and cultivars.

**INFLUENCE OF SPROUTING ON THE BIOACCESSIBILITY AND BIOAVAILABILITY OF NUTRIENTS**

**Measurement of nutrient bioaccessibility and bioavailability**

Sprouting is suggested as a promising technique to improve the bioaccessibility and bioavailability of minerals through phytate degradation (Benincasa et al., 2019). However, whilst there is some published data on the impact of sprouting on mineral bioaccessibility, research regarding mineral bioavailability is limited. Therefore, this review focuses on mineral bioaccessibility. A summary of the published data examining the influence of sprouting on the bioaccessibility of iron, zinc and calcium in various cereals and legumes is displayed in Table 4. The mineral bioaccessibility in these studies was measured using an in vitro procedure that simulates human digestion in the mouth, stomach and small intestine (Lemmens et al., 2019a). Cereals and legumes were digested with enzymes including pepsin and pancreatin under similar conditions to the intestinal environment (Hemalatha et al., 2007a). Mineral bioaccessibility was then calculated as the percentage of soluble mineral in the digested sample compared to the undigested sample. This in vitro method is an effective and reproducible model to determine the potential impact of processing methods such as sprouting on the bioaccessibility of minerals (Etcheverry et al., 2012). However, this method has also been referred to as a measurement of mineral bioavailability which implies that there is some misunderstanding between the in vitro measurements of bioaccessibility and bioavailability (Afify et al., 2011; Luo et al., 2014). Bioavailability can be assessed in vitro by measuring the uptake or transport of minerals from the digested sample by a human epithelial cell line, most commonly Caco-2 cells (Etcheverry et al., 2012). Therefore, a clear understanding of the
| Source         | Iron bioaccessibility (%) | Zinc bioaccessibility (%) | Calcium bioaccessibility (%) |
|---------------|--------------------------|---------------------------|------------------------------|
|               | Raw Soaked 1 2 3         | Raw Soaked 1 2 3          | Raw 1 2 3                   |
| Cereal        |                          |                           |                              |
| Wheat         | 4.8 – – 7.8 – +63        | 5.3 – – 8.4 – +59         | – – – – –                   |
|               | 4.6 – – 21.9 – +376      | 2.5 – – 25.3 – +912       | – – – – –                   |
|               | 4.6 – – 4.5 – -2         | 18.0 – – 33.6 – +87       | 10.7 – 10.5 – -2           |
| Rice          | 5.6 – – 19.0 – +239      | 16.3 – – 29.4 – +80       | 32.4 – 41.5 – +28          |
| Sorghum       | 9.1 15.5 – – 17.4 +91    | 7.4 10.2 – – 12.1 – +56  | 73.0 – 73.0 0              |
|               | 8.0 14.6 – – 16.7 +109   | 8.9 9.1 – – 18.3 – +106   | – – – – –                   |
| Pearl Millet  | 3.2 – – 2.5 – -22        | – – – – – – – – – – –     | 32.2 42.3 41.9 32.6 36.2 +12 |
| Finger Millet | 24.6 – 26.3 29.5 – +20   | 3.9 – 2.8 2.4 – -39       | – – – – –                   |
| Legume/Seed   |                          |                           |                              |
| Chickpea      | 6.4 – 8.8 8.9 – +39      | 45.1 – 40.5 40.1 – -11    | – – – – –                   |
| Green Gram    | 5.1 – 7.0 8.2 – +61      | 37.5 – 23.2 21.0 – -44    | – – – – –                   |
| Soybean       | 6.2 – 30.7 – +395        | 14.2 – 3.9 – -73          | 35.9 – 39.7 – +11          |
| Faba bean     | 6.3 – 31.5 – +400        | 15.2 – 2.7 – -82          | 32.8 – 38.7 – +18          |
|               | 32.2 42.3 41.9 32.6 36.2 | – – – – – – – – – – –     | – – – – –                   |
| Green Faba bean| 32.2 50.5 – – 51.2 +59  | 31.6 38.4 – – 49.3 +56   | – – – – –                   |
| White Faba bean| 28.6 58.8 – – 58.9 +106 | 33.4 44.2 – – 58.7 +76   | – – – – –                   |
| Golden Flaxseed| – – – – – – – – – – – | 35.6 41.5 – – 31.0 38.8 +25 |
| Brown Flaxseed| – – – – – – – – – – – | – – – – – – – – – – –     | – – – – –                   |

**Note:** Percentage change in bioaccessibility was calculated using the raw and maximum sprouting time values. Bioaccessibility values were selected from 1 to 3 days sprouting as this was the most frequent timeframe used in the literature. Some values were interpreted from data in a graphical manner so may be subject to variation.
difference between the in vitro measurements of bio-accessibility and bioavailability, and the harmonisation of laboratory methods used to perform these measurements are required to ensure accurate and comparable data is provided. Protein digestibility has also been considered as phytate has been linked with inhibitory effects on digestible protein (Hejazi et al., 2016). The studies displayed in Table 5 also used an in vitro simulated human digestion procedure to calculate the percentage of digestible protein in cereals and legumes (Sharma & Gujral, 2020).

**Table 5** Protein digestibility in raw, soaked and sprouted (1–3 days) cereals and legumes as identified in the literature and the percentage change between raw and sprouted cereals and legumes

| Source        | Raw | Soaked | 1   | 2   | 3   | Change (%) | References                  |
|---------------|-----|--------|-----|-----|-----|------------|------------------------------|
| Cereal        |     |        |     |     |     |            |                              |
| Sorghum       | 35.7 | –      | 40.7 | 44.0 | 48.0 | +35        | Nour et al. (2010)           |
|               | 35.9 | –      | 40.9 | 43.0 | 48.0 | +34        |                              |
| Finger Millet | 33.9 | –      | 43.6 | 45.0 | 50.5 | +49        | Hejazi and Orsat (2016)      |
|               | 74.0 | –      | 81.0 | 90.5 | –   | +22        | Sharma and Gujral (2020)     |
| Foxtail Millet| 74.0 | –      | 86.5 | 91.5 | –   | +24        |                              |
| Barnyard Millet| 74.0 | –    | 89.0 | 92.0 | –   | +24        |                              |
| Amaranth      | 72.0 | 73.9   | 82.7 | 84.0 | –   | +17        |                              |
| Legume        |     |        |     |     |     |            |                              |
| Chickpea      | 83.6 | –      | –   | –   | 87.6 | +5         | El-Adawy (2002)              |
|               | 64.2 | –      | 73.4 | –   | –   | +14        | Ghavidel and Prakash (2007)  |
| Lentil        | 65.6 | –      | 75.1 | –   | –   | +15        |                              |
| Green Gram    | 61.0 | –      | 72.7 | –   | –   | +19        |                              |
| Cowpea        | 63.8 | –      | 72.9 | –   | –   | +14        |                              |

Note: Percentage change in digestibility was calculated using the raw and maximum sprouting time values. Digestibility values were selected from 1 to 3 days sprouting as this was the most frequent timeframe used in the literature. Some values were interpreted from data in a graphical manner so may be subject to variation.

**Influence of sprouting on mineral bioaccessibility in cereals**

It is noted that raw cereals have very low levels of bioaccessible iron and zinc with variations between cereal species and cultivars (Table 4). Calcium bioaccessibility also varied between raw cereals but was mostly higher than iron and zinc bioaccessibility (Table 4). Sprouting decreased phytate content in all these studies, but the increase in mineral bioaccessibility varied. A phytate reduction of 51% in sprouted wheat that was hydrothermally processed increased bioaccessible iron from 4.8% to 7.8% and bioaccessible zinc from 5.3% to 8.4% (Lemmens et al., 2019a). However, when this sprouted wheat flour was milled into smaller particle sizes (<200 µm), the iron and zinc bioaccessibility increased further to 21.9% and 25.3%, respectively. Lemmens et al. (2019a) correlated this increase in mineral bioaccessibility with phytate reduction and the release of minerals from aleurone cells with rigid walls when flour was milled into smaller particle sizes. Furthermore, an almost complete phytate breakdown (~95%) increased the bioaccessibility of iron and zinc to 36.6% and 27.4%, respectively (Lemmens et al., 2018). This indicates that larger phytate reductions and/or cell wall disruption is required to significantly improve mineral bioaccessibility since very low levels can still exert inhibitory effects, especially on iron (Kumar et al., 2010). Conversely, Afify et al. (2011) reported that lower phytate reductions (~30%) in different sprouted sorghum varieties increased both iron and zinc bioaccessibility by up to 50%–100%. Soaking had a larger impact than sprouting on iron bioaccessibility in this study as it increased by up to 83% due to the leaching of phytate. Luo et al. (2014) did not report phytate levels but found that sprouting increased the
bioaccessibility of iron (+239%), zinc (+80%) and calcium (+28%) in rice but had a less significant influence on bioaccessible iron (−2%), zinc (+80%) and calcium (−2%) in wheat. The impact of sprouting on bioaccessible iron also varied between millet varieties as it increased in finger millet (+20%), but differed in two pearl millet varieties, ‘K’ (−22%) and ‘MRB’ (+3%) (Hemalatha et al., 2007a; Suma & Urooj, 2014). However, increased iron bioaccessibility in sprouted finger millet was correlated with a 51% reduction in tannins as phytate only decreased by 5% (Hemalatha et al., 2007a). Therefore, the large variations that occur between mineral bioaccessibilities in cereals are also influenced by the presence of other dietary inhibitors and the impact of sprouting on these inhibitors.

Influence of sprouting on mineral bioaccessibility in legumes

The bioaccessible mineral contents in raw legumes also varied with higher levels of bioaccessible zinc and calcium compared to iron (Table 4). Sprouting had a positive influence on iron and calcium bioaccessibility but led to conflicting results regarding zinc bioaccessibility. Iron and calcium bioaccessibility increased by up to 400% and 25%, respectively, whereas zinc bioaccessibility decreased by up to 82% (Ghavidel & Prakash, 2007; Luo et al., 2014). However, Luo and Xie (2014) reported that sprouting increased the level of bioaccessible zinc in green faba beans (+56%) and white faba bean (+76%). This could be a result of longer sprouting times and/or larger phytate reductions (~30%) compared to chickpeas and green gram (~10%) (Hemalatha et al., 2007a). Soybeans sprouted for 2 days decreased the bioaccessibility of zinc by 3.6-fold (Luo et al., 2014), whilst it increased by 3.7-fold in soybeans sprouted for 4 days which was correlated with a phytate reduction of 58% (Wang et al., 2015). Decreased phytate levels in sprouted flaxseed were also linked with an increase in calcium bioaccessibility in both golden (+17%) and brown (+25%) flaxseed (Pimenta et al., 2020). However, this was also linked with a reduction in oxalates during sprouting, which highlights the influence of other dietary factors on mineral bioaccessibility.

Influence of other dietary components on mineral bioaccessibility during sprouting

Mineral bioaccessibility can also be negatively impacted by tannins, oxalates, fibre and calcium, whilst vitamin C can enhance iron absorption (Platel & Srinivasan, 2016). Similarly to phytate, the impact of sprouting on these dietary components can influence mineral bioaccessibility. Sprouting reduced the levels of tannins and oxalates which was positively correlated with enhanced mineral bioaccessibility (Hemalatha et al., 2007a; Pimenta et al., 2020). The influence of fibre on mineral bioaccessibility will depend on the ratio of soluble to insoluble fibre since it was reported that zinc absorption can be negatively impacted by soluble and insoluble fibre, whereas iron absorption is only negatively impacted by insoluble fibre (Platel & Srinivasan, 2016). Conversely, soluble fibre was also reported to benefit mineral absorption in pearl millet (Jha et al., 2015). A high-fibre concentration in sprouted faba beans was associated with little improvement in iron bioaccessibility, despite a phytate reduction of 68% (Luo et al., 2009). Furthermore, lower concentrations of these inhibitors in rice were correlated with higher levels of bioaccessible zinc compared to other cereals (Hemalatha et al., 2007b). Therefore, the influence of sprouting on these inhibitors can play an important role in mineral bioaccessibility.

Influence of sprouting on protein digestibility in cereals and legumes

Protein digestibility was significantly higher in raw cereals and legumes compared to mineral bioaccessibility, as evident in Table 5. Sprouting increased the level of digestible protein by 5%–49% and displayed a positive correlation with sprouting time in sorghum, millet and amaranth (Hejazi & Orsat, 2016; Nour et al., 2010; Sharma & Gujral, 2020). As previously discussed, sprouting activates enzymes that break down proteins into amino acids, thereby increasing the digestibility of protein (Benincasa et al., 2019). Furthermore, protein digestibility was positively correlated with phytate reduction indicating inhibitory effects of phytate on digestible protein (Sharma & Gujral, 2020). As evident in Table 5, sorghum contained approximately half the level of digestible protein than other cereals and legumes (Nour et al., 2010). Since the phytate content was significantly lower in sorghum, this indicates that other dietary components can negatively impact protein digestibility, such as tannins and trypsin inhibitors (Lemmens et al., 2019b). However, the positive correlation between protein digestibility and tannin reduction was also reported in millet, green gram, cowpeas, lentils and chickpeas (Ghavidel & Prakash, 2007; Hejazi & Orsat, 2016; Sharma & Gujral, 2020). Conversely, sprouting increased tannin content in amaranth whilst the levels of phytate and oxalate decreased (Hejazi et al., 2016). Therefore, the positive correlation between phytate reductions on the digestibility of protein was generally consistent throughout all studies. Whilst protein digestibility improved in vitro, the digestibility of amino acids in vivo increased in sprouted faba beans but decreased in sprouted chickpeas which highlights the importance of conducting in vivo studies (Rubio et al., 2002).
Influence of sprouting on mineral bioavailability in cereals and legumes

As mentioned, the influence of sprouting on mineral bioavailability was investigated in some studies however research in this area is limited as the emphasis has been on bioaccessibility studies. Pongrac et al. (2016) did not report any improvement in iron bioavailability in vitro using Caco-2 cell lines, despite a reduction of phytate in sprouted buckwheat. Similarly, a reduction of phytate in sprouted flaxseed did not increase bioavailable calcium in rats (Pimenta et al., 2020). This study reported an increase in calcium bioaccessibility in vitro, which suggests that larger phytate reductions are required to correlate calcium bioaccessibility and bioavailability. However, similar phytate reductions (~20%) improved calcium and iron bioavailability in vitro from 57% to 81% in green gram, cowpeas, lentils and chickpeas (Ghavidel & Prakash, 2007). The level of bioavailable calcium and iron increased further when these legumes were dehulled following sprouting, particularly bioavailable iron which doubled in chickpeas and lentils. Mineral bioavailability values could be influenced by the analysis method, but these results demonstrate that sprouting has the potential to improve mineral bioavailability. However, it is difficult to draw any definitive conclusions from a limited number of studies.

COMMERCIAL APPLICATION AND CONSUMER ACCEPTABILITY OF SPROUTED PRODUCTS

Sprouting has been used for centuries to produce malts with distinctive functionality and flavours for the brewing and distilling industry, most commonly known as malt- ing (Rimsten et al., 2002). In recent years, the putative health promoting properties of sprouted products have increased their application by the food industry (Zilic et al., 2014). Sprouted products can be added to breakfast items, yogurts, salads, smoothies or milled into flour for bakery products including: bread, noodles, pasta, biscuits and tortillas (Ikram et al., 2021; Luo & Xie, 2014). The increased digestibility and lower viscosity of sprouted products have also been utilised in the preparation of weaning and geriatric foods as they are suitable for those who have lower digestion capacity (Luo et al., 2014). Therefore, the diverse changes that occur from sprouting provide many opportunities for their application in the food industry. Global sprouted product launches from 2012 to 2017 were categorised as 26% in bakery products, 24% snacks, 13% breakfast cereals and 8% side dishes (Weel & Heirbaut, 2020). However, the increase in enzymatic activity during sprouting can negatively impact the baking properties and consumer acceptability of bakery products produced from sprouted flour (Baranzelli et al., 2018). Sprouted flour has been linked with decreased dough development, stability, water absorption and a sticky and wet crumb (Lemmens et al., 2019b). However, the impact of sprouting on the functional properties of flour can depend on the sprouting time and their level of substitution in composite flours. Poudel et al. (2019) reported that the functional properties of bread were not impacted when composite flours were substituted with 10% of wheat flour sprouted for 48 h but decreased when wheat was sprouted for 72 h. Shorter sprouting times (up to 48 h) in this study were associated with improved mixing properties, loaf volume and firmness. Similarly, the rheological properties of sourdough bread decreased as sprouting time increased up to 36 h (Stern et al., 2021). However, longer sprouting times in this study did not impact the sensory evaluation or consumer acceptability of sourdough bread, except for the crumb. Wheat flour sprouted for 48 h decreased the water absorption, development time and stability of dough when it was added to composite flours from 15% to 100% (Marti et al., 2017). On the other hand, this study also reported that a 50% substitution with sprouted wheat flour produced the best bread volume and crumb porosity compared with the control. A higher loaf volume was also reported in whole wheat bread made from sprouted flour which consumers preferred as it was sweeter and moister and less bitter and grainy (Johnston et al., 2019). Furthermore, tortillas made with 100% sprouted wheat flour scored higher for bakery attributes including volume, diameter, brightness and opacity and obtained higher sensory scores for colour, texture and flavour compared with the control and lower substitutions (Liu et al., 2017). However, it was recommended to add 50% sprouted wheat flour in tortillas due to weaker gluten strength at higher substitutions. Sprouting chickpeas for 48 h enhanced the functional properties of chickpea flour, whilst thermal and pasting properties decreased with sprouting time (Sofi et al., 2020). Therefore, despite alterations in baking properties, sprouted flour has the potential to produce high quality products for the bakery sector. Controlled spraying conditions including short spraying times could enable the correct balance between phytate reduction, nutritional advantages and baking performance required for commercial application (Cardone et al., 2020).

FUTURE PERSPECTIVES

Sprouting conditions play a vital role in phytate reduction and impact the nutritional value of sprouted products. However, conditions studied have varied greatly in previous small-scale studies. Harmonisation of sprouting methods is difficult since the influence of sprouting can differ depending on species, cultivars and growing conditions. Furthermore, the desirable nutritional
and functional properties will depend on the end use of the sprouted product. However, research is required to determine the extent to which similar sprouting conditions can be achieved in large-scale production to produce high-quality products with comparable nutritional benefits for commercial utilisation. Further work needs to be carried out to harmonise bioaccessibility and bioavailability methods to determine the influence of phytate reduction on mineral and protein bioavailability using in vitro or in vivo studies. Also, the influence of sprouting and phytate reduction on the bioavailability of vitamins and bioactive compounds needs to be considered. If applicable, food manufacturers should consider the transferability of higher nutrient bioavailability in sprouted ingredients to sprouted end products such as bakery products. In turn, the ability of sprouted products to provide biological health benefits including reduced risk of micronutrient inadequacies needs consideration on a global scale. Finally, the communication of nutritional and health benefits from sprouted products to consumers via food labels requires regulatory attention.

CONCLUSION

In conclusion, this review highlights the potential of sprouting to reduce phytate content and improve the bioaccessibility of minerals and protein in cereals and legumes. This is significant since cereals and legumes are primary or secondary sources of iron and zinc in many diets but have low bioavailability due to the presence of phytate. Sprouting provides a natural means of reducing phytate and enhancing the nutritional value of cereals and legumes. Nutritional, functional and sensory changes that occur during sprouting provide many opportunities for their application in the food industry and beyond.

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CONFLICTS OF INTEREST

HE is a KTP Associate for a project between Queens University Belfast and Linwoods Health Foods under the supervision of PW, AN and BG. PW is employed by Linwoods Health Foods who manufacturer sprouted grains and seeds. AN and BG are employed by Queens University Belfast who are the Knowledge Based Partner Institution for this KTP project.

DATA AVAILABILITY STATEMENT

All data is openly availability in a public repository.

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IMPACT OF SPROUTING ON NUTRITIONAL VALUE

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