



Review

Rice Germination and Its Impact on Technological and Nutritional Properties: A Review

Lucas Ávila do NASCIMENTO¹, Abhilasha ABHILASHA², Jaspreet SINGH², Moacir Cardoso ELIAS¹, Rosana COLUSSI³

¹Department of Agroindustrial Science and Technology, Federal University of Pelotas, Pelotas, University Campus, s/n, 96010-900, Pelotas, RS, Brazil; ²Riddet Institute and Massey Institute of Food Science and Technology, Massey University, Palmerston North, New Zealand; ³Center for Chemical, Pharmaceutical and Food Sciences, Federal University of Pelotas, Pelotas, University Campus, s/n, 96010-900, Pelotas, RS, Brazil)

Abstract: Grain germination is a process involving numerous factors that influence the biochemical processes inside the plant cells. This review covered the abiotic factors that lead to the germination and significantly impact the nutritional properties and digestion behavior of rice grains. The macro- and micro-nutrients can be changed depending on the intensity of the applied variables during germination. For instance, germination time can increase the protein content in the grain and concurrently reduce its protein digestibility. In most cases, the number of bioactive compounds present in rice grains are increased regardless of germination conditions. Germination can promote the complexation of nutrients and thus negatively interfere with the digestibility of macronutrients. This review highlighted the influence of the germination process on the nutritional quality of rice grains, providing information about the germination conditions and their impacts on the anabolic and catabolic reactions of the grain, emphasizing the health benefits.

Key words: germinated rice; nutritional aspect; germination condition; digestibility; advantage

Rice is a staple food for most of the world's population due to its quantity and quality of the nutrients and the diverse forms to the consumer (Korres et al, 2017; Li and Yang, 2020). Rice in its whole form has more fiber, resistant starch, and diversity of proteins and lipids compared to its polished form, which possesses mainly starch with some protein fractions. Some pigmented rice varieties also contain compounds with antioxidant activity that are beneficial to health (Krishnan et al, 2021). Since rice is consumed in various forms, several rice products have been developed by applying different treatments directly to the grain, such as parboiling, annealing and quick-cooking rice processes, including some that induce germination (Sirisoontaralak et al,

2015; Liu et al, 2020; Saniso et al, 2020; Zhong et al, 2020). These treatments change not only the quantity of nutrients (free amino-acids, vitamins and such others) present in the grain but also their nutritional quality and organoleptic properties (Chaijan and Panpipat, 2020). Along with the processes mentioned above, germination increases the bioavailability of nutrients such as carbohydrates and proteins; likewise, some bioactive compounds such as gamma-aminobutyric acid (GABA) and antioxidants are found to increase. Germination also leads to increased fiber levels, and stimulates the production of bioactive compounds, and sometimes also leads to reduction in compounds that are expendable or harmful to human nutrition, such as phytates (Xia et al, 2017).

Received: 27 August 2021; **Accepted:** 25 January 2022

Corresponding author: Rosana COLUSSI (rosana_colussi@yahoo.com.br)

Copyright © 2022, China National Rice Research Institute. Hosting by Elsevier B V

This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>)

Peer review under responsibility of China National Rice Research Institute

<http://dx.doi.org/10.1016/j.rsci.2022.01.009>

Many studies on induced germination, especially the effects of different soaking conditions, germination time and temperature, applied stresses and drying conditions on germination have been published (Ding et al, 2016; Lahkar and Tanti, 2018; Xia and Li, 2018; Kamjijam et al, 2020). The effects reported in terms of nutritional and technological aspects are the most diverse, following logical and blunt theories of clarification. Ding et al (2018) effectively used ultrasound during the germination process of red rice to increase the levels of GABA and metabolites beneficial to health. Nascimento et al (2020) found that the stress application (salinity, low temperature and the combination) can promote a significant increase in the GABA content. Li and Yang (2020) studied the behavior of rice with cold tolerance genes at 30 °C and 15 °C during germination, and found that with resistance genes, the increased enzyme activity and soluble sugar occurred at the highest temperature, even with the exogenous addition of phytohormones to break dormancy, which can facilitate the germination starts. Nguyen et al (2020) found that the amount of bioactive compounds resulting from the sucrose addition during the rice germination period is equivalent to the amount of total flavonoids and anthocyanins already present in red brown rice.

This review aimed to discuss relevant studies about rice germination conditions, nutritional transformations and their impacts on nutritional and digestibility properties.

Germination

In the most applied definition of germinated grains proposed by the American Association of Cereal Chemists (AACC) (2008), malted or germinated grains containing all of the original bran, germ and endosperm shall be considered whole grains as long as sprout growth does not exceed kernel length and nutrient values have not diminished. These grains should be labelled as 'malted or germinated whole grain', which has been approved and endorsed by the United States Department of Agriculture (USDA).

Malting has immense relevance and applicability in the beverage industry, such as beers (Mayer et al, 2016) and whiskeys (Jeleń et al, 2019). Controlled-induced germination has been studied over the past few years, including on rice grains (Ng et al, 2013; Ding et al, 2018), as an efficient method to improve the bioavailability of bioactive compounds and reduce the anti-nutritional functions of cereals (Benincasa et al,

2019). Controlled-induced germination has also been used as an alternative to obtain grains with specific characteristics, both nutritional and technological (Cáceres et al, 2017; Ding et al, 2018). For this type of germination to occur, the germ of the grain must be present and intact in order to produce phytohormones responsible for cell division and elongation (Finnie et al, 2019).

It is possible to verify the efficiency of these processes in several cereal grains. Guan et al (2019) demonstrated the germination efficacy regarding the accumulation of bioactive phytochemicals in barley. Lee et al (2015) also proved with *in vivo* tests the efficiency of some of these bioactive phytochemicals in reducing the concentration of glucose and hepatic triglycerides. Cardone et al (2020) found that although the germination process reduces the hardness and the hectoliter weight of wheat grains, the properties of starch and gluten are not altered after 48 h of germination. It promotes improvement in the fermentation of the dough and the final volume of the bread. Aparicio-García et al (2020) demonstrated that the germination process increases the antioxidant capacity and enzymatic potential of α -amylase and proteases without any reduction in the β -glucan load retained in the oat flour. Fraś et al (2018) reported that it is possible to develop bread with antioxidant capacity and abundant fibers, with similar characteristics to oat flour products on the current market.

Germination conditions applied for rice

Although the minimum conditions necessary for the grain to start germination are the same, each species has its specific requirements, varying in time, temperature, intensity or other factors such as luminosity and nutrients, as shown in Table 1 (Singh et al, 2017; Kamjijam et al, 2020). These conditions directly influence metabolic reactions and consequently, the germination process varies (Zhou et al, 2020).

Germination starts as soon as the grain is in favorable circumstances, such as moisture content ranging between 15% and 45%, temperature above 4 °C, in the absence of germination inhibitors and the presence of atmospheric air. Some seeds, including rice, also need light because it is a vital part of the energy production by plants and the signal for countless physiological responses (Dziki et al, 2015). Therefore, the first stage of the germination process is soaking the grains/seeds in water, where water will penetrate the seed through the pores and micropyle

Table 1. Temperature, time, relative humidity (RH), processing method and drying condition applied during rice germination.

| Rice variety | Temperature (°C) | Time (h) | RH (%) | Processing method | Drying | Reference |
|--|------------------|----------|--------|---|--|--|
| Daohuaxiang | 37 | 36 | 100 | Steeped in hydrogen peroxide solution at a ratio of 1:2 | NA | Xia et al, 2017 |
| Xianhui 207, Heinuo | 28 | 72 | 100 | Normoxia and hypoxia only at 6 final hours | Freeze-dried under vacuum | Ding et al, 2016 |
| Joha | 21–28 | 360 | 100 | Hydroponic culture | Hot air oven 80 °C/72 h | Lahkar and Tanti, 2018 |
| Sanquiding SZ | 37 | 52 | 90 | Darkness in a climatic cabinet | NA | Xia and Li, 2018 |
| KDML105, Riceberry | 30 | 144 | NA | Darkness and washed every 24 h | Freeze dryer | Kamjijam et al, 2020 |
| | 26–30 | 36 | > 95 | Normal and ultrasound | Hot air dryer 80 °C/2 h | Ding et al, 2018 |
| OM457, TN11, Huong Dua | 35 | 72 | 90 | Sprayed water every 12 h, in the dark | NA | Nguyen et al, 2020 |
| Baekokchal | 30 | 36 | 95 | NA | NA | You et al, 2016 |
| Ipum | 30 | 48 | 95 | NA | Hot air oven 50 °C until 10% MC | Li et al, 2017 |
| Zhengxian, Nanjing, Yannuo | 25 | 120 | 100 | Water changed every 6 h | Hot air oven 50 °C until 14% MC | Wu et al, 2013 |
| NA | 25–35 | 48 | 80 | NA | Freeze-dried | Wang et al, 2020 |
| 02428, YZX | 15 | 96 | NA | NA | Freeze-dried | Yang et al, 2019 |
| Ingwizabukungu, Intsingirabigege, Jyambere, Mpembuke, Ndamirabahinzi, Nemeyubutaka, Zong geng | 15–30 | NA | NA | Field crops | Freeze-dried under vacuum | Mukamuhirwa et al, 2020 |
| Khao Niaw Dam Peuak Dam | 37 | 48 | 66 | Closed system | Hot air oven 80 °C/5 h | Owolabi et al, 2020 |
| San-Pah-Tawng1, Pathum-Thani1, Phitsanulok2 | 30 | 50 | 85 | Dark | Hot air oven 40 °C/12 h | Kupkanchanukul et al, 2018 |
| Pusa Basmati 1 | 28 | 192 | NA | NA | NA | Sinha et al, 2020 |
| IET-23466, Dhan-201, IET-23448, MAS-946, IET-23445, IET-23463, IET-23455, PR-123, PR-115 e IET-23449 | 28–30 | 48 | 95 | Washed every 4 h | NA | Kaur et al, 2017 |
| KDML105 | 35 | 24 | 95 | Washed every 4 h | Hot air oven | Jongyingcharoen and Cheevitsopon, 2016 |
| Ipumbyeo | 37 | 48 | 80 | Washed every 24 h | Hot air oven 50 °C/48 h | Kim et al, 2017 |
| Sanpatong 1, Khao Jow Hawm Phitsanulok 1, KDML105, Niaw Sanpatong, Rice Department 6, Luem Pua | 25–28 | 96 | 100 | Water changed every 4 h | Hot air oven 40 °C until 12% MC | Yodpitak et al, 2019 |
| Mottaikaruppan | 30 | 120 | NA | Sprayed water | Solar dried | Velupillai et al, 2009 |
| Hom Mali 105, Hom Deang Sukhothai 1, Hom Dam Sukhothai 2 | Room temperature | 168 | NA | NA | Hot air oven 45 °C/ 24 h | Pramai et al, 2018 |
| KDML105 | 48 | 30 | NA | Flowing air | Hot air oven 73 °C/2 h | Tuntipopipat et al, 2015 |
| KDML105 | 30 | 72 | 100 | Water changed every 4 h | Hot air oven and a hybrid dryer; multiple conditions | Tumpanuvatr et al, 2018 |
| Qiutian Xiaoting | 37 | 48 | 90 | Darkness in a climatic cabinet | Hot air oven 40 °C/24 h | Xia and Li, 2018 |

NA, Not available; MC, Moisture content.

and will be stored inside the grain due to interactions predominantly with proteins and fibers. The water absorption index is stabilized during the second stage, which is the rupture of the pericarp in the region of the germ, and subsequently the appearance of the radicle. The water absorption rate rises again during the third stage and the radicle cells multiply during their development (Nelson et al, 2013).

Briefly, throughout the germination process, the seed synthesizes and/or releases a series of plant hormones such as gibberellic acid, abscisic acid and

ethylene that serve as signals for the activation and release of enzymes, such as amylases, lipases and proteases (also referred to as functional proteins). These enzymes will disrupt specific bonds between the monomers that compose each nutrient, simultaneously synthesizing new tissues (Guzmán-Ortiz et al, 2019). As mentioned earlier, there are many conditions such as time, temperature, relative humidity, stress application and dry conditions that can influence the rice germination and the germinated rice properties (Fig. 1). These conditions will be discussed in detail in

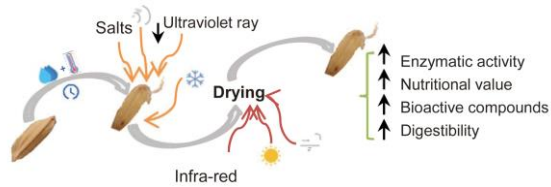


Fig. 1. Illustration of conditions that can influence rice germination and germinated rice properties.

the following sections.

Germination time

The changes in the seed as a result of germination depend on the conditions to which the rice is subjected and the time for which it remains in such conditions.

The need for the plant being generated to survive includes physical-chemical and structural changes in its cells. As soon as the germination process starts, the first structural changes could be noticed (Fig. 2) (Nonogaki et al, 2010). Physiologically, the plant lacks to reinforce its cell wall to confer rigidity to the root system, to expand and reach the soil surface, which takes some time, commonly around 15 h, for the radicle and hypocotyl to lengthen; before that, the germination shows low indexes of efficiency (Liu et al, 2016; Singh et al, 2017).

These transformations result in changes in the nutritional and technological properties of the grains. Kamjijam et al (2020) demonstrated that the content of essential amino acids (alanine, arginine, glycine, methionine, proline, serine, tyrosine, tryptophan and valine) in rice grains increases with germination and reaches maximum levels between 72 and 96 h. Chaijan and Panpipat (2020) studied on the feasibility of obtaining a germinated extract of Thai indigenous rice, and observed a substantial increase in GABA content during germination (35 °C, in the dark) between the 36th and 48th hour, increasing from approximately 1.5 to 55.0 mg/kg, a value that did not change until the end of the process (96 h). On the other hand, Singh et al (2017) reported that the lipid content in the flours of germinated cereals decreases



Fig. 2. Structural changes in rice grain (cultivar BRS Pampeira) during germination process at 30 °C and 80% relative humidity (Nonogaki et al, 2010).

throughout the germination process of 48 h, but there is no significant difference in the first 12 h. Kupkanchanakul et al (2018) indicated that the lipid content decreases with germination at 30 °C for 50 h.

Starch digestibility is intensified with germination (You et al, 2016). Nascimento et al (2020) showed that 36 h of germination process and the application of stress during germination of brown rice increase the starch digestibility by more than 30%. Li et al (2017a) found that the relative crystallinity and enthalpy of retrogradation of brown rice starch decrease with germination. Wu et al (2013) noticed a slight reduction in the gelatinization temperature of the starch in the flour and the starch, isolated after 48 h of germination in brown rice grains.

The germination time can significantly influence the final product. However, the longer the germination time is, the more significant the changes are in the product, which may not coincide with the desired organoleptic or nutritional characteristics. Therefore, it is necessary to optimize the germination time to reach the desired characteristics without affecting consumer acceptance or nutritional quality.

Germination temperature

The germination temperature significantly influence the germination capacity of grains since it is a limiting factor in the activity of the enzymes present, mainly proteases, amylases (α - and β -) and glucanases (Krapf et al, 2020). Wang et al (2020) found that the increase of temperature from 25 °C to 30 °C increases the germination rate by approximately 40%.

Some grains have mechanisms of adaptation or resistance to an abiotic factor, such as harsh winter or scorching summer, thus perpetuating in various regions. This resistance or adaptation to the climatological aspect directly influences the physical-chemical characteristics of the plant cell, and additionally, influences the nutritional and technological aspects of the grain (Kenchanmane Raju et al, 2018).

Prieto et al (2020) reported that the activity of essential signaling effectors in response to cold stress results in a reduction in the neutral lipids and the long-chain base's content; concurrently, the phospholipid content is increased, promoting greater fluidity of the membrane, which is assumed to facilitate the digestion of macronutrients. Moreover, lipid contained in the whole grain is changed, with polyunsaturated and unsaturated lipids predominating in comparison with saturated ones.

In contrast, extreme heat conditions affect the

metabolism of proteins and starch. As the fatty acids produced in the plastids enter the biosynthetic pathway of phospholipids or triacylglycerols and undergo several reactions, they reduce the nutritional and technological quality of starch and proteins, interfering in the applications (Marion and Saulnier, 2020). Also, Ohdaira et al (2015) reported an increase in the storage protein content of rice grains when subjected to germination at high temperatures; however, the prolamin values are reduced in the grains.

Stress application

When a plant is affected by stress, it automatically activates secondary mechanisms and/or metabolic pathways to combat reactive oxygen species. For example, the intracellular imbalance caused by different stresses is formed to make sure that the species can survive (Li et al, 2017b). Mukamuhirwa et al (2020) found that water deficit stress during germination increases the protein content and reduce the productivity but does not affect the amylose content. Thi Thu et al (2020) showed that even at the minimum saline concentration tested (6 dS/m NaCl) during the germination of rice grains, there is a reduction in seedling and root development. Moreover, the authors highlighted some positive points as the reduction in phytic acid and an increase in the content of phenolic compounds.

Drying

Grain drying operations are carried out to prolong the shelf life of the products, and there is a constant search for greater retention of the nutritional and technological properties. In germinated foods, another important reason why drying must be fast and effective is the reduction and/or limitation of the proliferation of microorganisms from the conditions of mild temperature and high relative humidity (Gan et al, 2017). Ge et al (2021) reported that infrared drying achieves greater efficiency concerning the retention of phenolic compounds than drying by heated air. According to Poudel et al (2019), the temperature of 60 °C is effective in reducing the action of lipases in germinated grains, such as esterase and lipoxygenase compared to p-nitrophenyl butyrate and p-nitrophenyl palmitate substrates, respectively. Likewise, sun-drying reproduces positive effects in drying germinated rice grains, increasing the content of γ -oryzanol, phenolic compounds with antioxidant activity, without causing loss in GABA content (Cáceres et al, 2017). However, research on drying

action to reduce the microbiological content in germinated grains is scarce.

Chemical compositions and their digestibility of germinated rice

Rice has a high content of starch, protein, minerals and vitamin B, and the amount of these nutrients vary according to variety, growth condition and other treatment conditions. Some examples of nutritional variations caused by germination are showed in Table 2 (Bao et al, 2004; Korres et al, 2017).

However, nutrients are not evenly distributed throughout the grain. The hull, which can be responsible for 16% to 28% of the dry grain weight, is constituted by cellulose, hemicellulose and lignin in addition to a large amount of silicon (Chaves et al, 2009). In the pericarp, right below the hull, the aleurone layer and the forehead are located as proteins, fibers, minerals and pigments (Lang et al, 2019). The endosperm is basically composed of starch and some protein fractions and provides energy for seed germination (Xia et al, 2017). In the germ, a large amount of lipids and enzymes, important for its development, are stored (Cho and Lim, 2016). For this reason, it is recommended to consume whole grains for a balanced diet in the amount of carbohydrates, proteins, fibers and minerals (Patil and Khan, 2011). During the metabolic processes, interactions between starch and proteins are disrupted, which can facilitate the digestion of these nutrients, and at the same time, new tissues with high levels of fibers and bioactive compounds are formed (Ng et al, 2013; Nascimento et al, 2020).

Carbohydrate

Rice is associated with a high glycemic index due to the ease of digestion of its starch by the human gastrointestinal tract (He et al, 2020). However, the related data are considering only polished rice, as it has the highest consumption worldwide. When consumed in its brown form, its digestibility decreases, being even lower than that of other cereals such as wheat (Xu et al, 2021), barley (Tamura et al, 2019) and oats (Shah et al, 2018). Generally, according to its digestibility, starch is classified into rapid digestion (RDS), slow digestion (SDS) and resistant starch (RS). RDS, SDS and RS differ in the digestion time, which can be up to 20 min in the duodenum, between 20 and 120 min in the small intestine, and beyond 120 min in the small intestine, respectively (He et al, 2020; Cui et al, 2021; Tang et al, 2021).

Table 2. Changes in proximal composition caused by germination in rice grains.

| Rice variety | Carbohydrate | Protein | Lipid | Bioactive compounds | Vitamin | Enzyme | Reference |
|---|--------------|---------|-------|---------------------|------------|--------|--|
| Daohuaxiang | NA | ↑ | NA | ↑ | NA | NA | Xia et al, 2017 |
| Xianhui 207, Heinuo | NA | NA | ↓ | GABA↑ | NA | NA | Ding et al, 2016 |
| KDML105, Riceberry | NA | ↑ | NA | GABA↑ | NA | NA | Kamjijam et al, 2020 |
| OM457, TN11 | NA | NA | NA | TPF↑ | NA | NA | Nguyen et al, 2020 |
| Zhengxian, Nanjing, Yannuo | ↓ | NA | NA | NA | NA | NA | Wu et al, 2013 |
| NA | NA | WM | WM | NA | NA | ↑ | Wang et al, 2020 |
| HATRI192 | NA | NA | NA | TPF↑↓ | NA | ↓ | Thi Thu et al, 2020 |
| HATRI62 | NA | NA | NA | TPF↑↓ | NA | ↑ | |
| Khao Niaw Dam Peuak Dam | ↓ | NA | ↑ | NA | NA | NA | Owolabi et al, 2020 |
| San-Pah-Tawng 1 | ↓ | ↑ | ↑ | NA | NA | NA | Kupkanchanakul et al, 2018 |
| Pathum-Thani 1, Phitsanulok 2 | ↓ | ↑ | ↓ | NA | NA | NA | |
| Pusa Basmati 1 | NA | NA | TAG↓ | NA | NA | NA | Sinha et al, 2020 |
| IET-23466, Dhan-201, IET-23448, MAS-946, IET-23445, IET-23463, IET-23455, PR-123, PR-115, IET-23449 | NA | NA | NA | ↑ | NA | NA | Kaur et al, 2017 |
| KDML105, Qiutianxiaoting | NA | NA | NA | GABA↑ | NA | NA | Jongyingcharoen and Cheevitsopon, 2016; Xia and Li, 2018 |
| Ilpumbyeo | NA | NA | NA | ↑ | Vitamin E↑ | NA | Kim et al, 2017 |
| Mottaikaruppan | NA | ↓ | NA | NA | NA | ↑ | Veluppillai et al, 2009 |
| Hom Mali 105, Hom Deang Sukhothai 1, Hom Dam Sukhothai 2 | NA | NA | ↑ | ↑ | ↑ | NA | Pramai et al, 2018 |
| KDML105 | NA | NA | NA | ↑ | NA | NA | Tuntipopipat et al, 2015; Tumpanuvat et al, 2018 |

NA, Not available; WM, Without modification; GABA, Gamma-aminobutyric acid; TPF, Total phenolics and flavonoids; TAG, Triacylglycerols; ↑↓ indicates that the levels can increase or decrease depending on the treatment applied.

Carbohydrates suffer the most changes due to germination, because the hydrolytic enzymes are the first to be activated in response to germination conditions. Initially, alpha-amylase is responsible for the fragmentation of starch reserved in the grains, decreasing it until the maltose (disaccharide). Another amylolytic enzyme pullulanase reduces it to glucose monomers used for cellular respiration and energy production (McKie and McCleary, 2015). These actions significantly alter the original conformation, as well as the properties of the starch.

Germination is an effective process in increasing the digestibility of fast-digesting and slow-digesting starch, suggesting a loosening between the starch-protein and starch-lipid complexes (You et al, 2016). This impact on starch digestibility is not suitable in controlling type 2 diabetes; however, it is a positive outcome for those who seek high levels of glycogen quickly, as athletes practicing sports of short duration and high intensity (Kirk, 2009).

In general, starch represents about 90% of the dry weight in polished rice grains, and this value decreases to around 75% for the brown rice (Bonto et al, 2021). Owolabi et al (2020) stated that the initial carbohydrate content in purple rice grains (58.1%) is influenced by soaking and germination, increased to approximately 63.9% in the first step. With the initiation of

germination, the content shows a linear reduction until 24 h of germination, without significant changes during 24–36 h. Then, the carbohydrate content increases again, reaching a value close to 63.6% after 36 h of germination. Zhou et al (2020) found that total carbohydrate content decreases by approximately 3% with germination in all the studied cases, with a maximum value of 87.15% (pre-germination) and a minimum of 83.79% (post-germination). Given the above, the relationship between germination and the carbohydrates in the grain is changed due to utilization as the first source of energy and subsequent structural function. Carbonhydrate content is reduced at the initiation of the germination process and structural carbohydrates (cellulose, hemicellulose and xylose) is increased as the grain develops.

The amylases are the most relevant catalysts when the subject is starch digestion. These enzymes act by hydrolyzing the glycosidic bond between the amylose and amylopectin monosaccharides and release simple sugars, sometimes reducers (Ding et al, 2018). These reactions make the particles smaller, along with some micro-holes that can be perceived on the starch structure, facilitating the action of digestive enzymes (Wu et al, 2013). You et al (2016) demonstrated an increase of about 20% in starch digestibility in brown rice grains compared to the non-germinated grains.

Similar effects have been reported by Chung et al (2012), where starch digestibility is increased by 10% in germinated brown rice compared to non-germinated brown rice (Fig. 3).

Protein

Vegetable proteins are classified according to their solubility in different solvents (Osborne, 1895), including glutelins, prolamines, globulins and albumins, which are solubilized in dilute alkaline solutions, 70% ethanol, saline and water, respectively (Shukla and Cheryan, 2001). The amino acids necessary for the formation of proteins derive from synthesis and proteolysis reactions. In the first day of germination, the synthesis reaction of free amino acids predominates using nitrogen captured from the soil and stored in the form of nitrate. Subsequently, the nitrogen used for the formation of new amino acids is derived by breaking down existing proteins, also referred to as reserve proteins (Shen et al, 2015). For a protein to be nutritious, it depends not only on its quantitative value but on other factors, such as the quality, availability and digestibility of its amino acids.

In rice, glutelins are in greater quantity, about 68%, distributed throughout the grain, and smaller fractions of albumin and globulins, about 11% and 14% respectively, are present in the aleurone and germ layer, comprising the total protein content ranging from 6.5% to 12.5% (Khatun et al, 2020). Structural proteins found in the aleurone layer perform synthetic

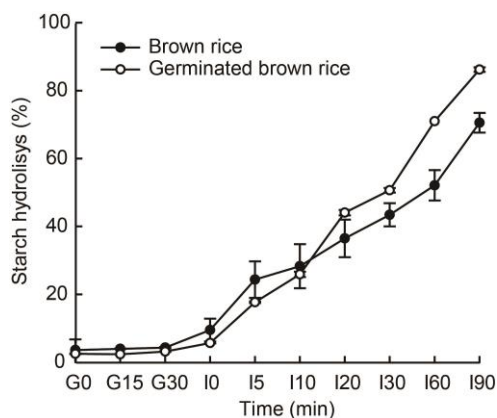


Fig. 3. Starch digestibility of brown rice and germinated brown rice at 30 °C and 80% relative humidity during 36 h (cultivar BRS Pampeira).

The digestibility was done according to the method proposed by Dartois et al (2010). G0, G15 and G30 represent aliquots removed during simulated gastric digestion during 0, 15 and 30 min of gastric digestion, and I0, I5, I10, I20, I30 I60 and I90 represent aliquots removed during simulated intestinal digestion during 0, 5, 10, 20, 30, 60 and 90 min of intestinal digestion.

and secretion functions, while storage proteins are distributed in the endosperm, commonly attached to the starch structure (Acosta-Estrada et al, 2014). However, proteins in rice have a low amount of cysteine and methionine, the latter classified as essential for humans (Maphosa and Jideani, 2017).

Furthermore, the digestibility of rice protein is lower compared to proteins of animal origin due to its conformation, location within the cell, and complexation with other nutrients and antinutrients (phytate, tannins, enzyme inhibitors, etc.) (Ohanenye et al, 2020). Seed germination is an alternative to increase the nutritional value of proteins. The total protein content of waxy and low amylose rice cultivars is significantly increased after 12 h of germination; however, it is increased after 48 h of germination for the high amylose cultivar (Kupkanchanakul et al, 2018). According to Kamjijan et al (2020), the amount of essential amino acids, such as leucine, lysine and tryptophan, increases during the first 48 h of germination. Some substances, such as phytates, in which inorganic phosphorus is stored inside the plant cell, influence the nutritional quality. Phytates act as a high chelating agent for minerals such as iron, zinc and calcium, and can alter the protein conformation and consequently reduce their solubility, directly affecting their digestibility (Mohammadi et al, 2021). Fortunately, Liang et al (2008) proved the efficiency of the germination of rice grains in reducing phytic acid.

Proteolysis is responsible for releasing amino acids from storage proteins, precursors in the formation of new proteins that meet the needs of the plant organism during its development. For instance, cysteine is released from the storage proteins of cereals, contributing to the formation of methionine that acts in antioxidant systems in plants (Szewińska et al, 2016).

Proteases namely endopeptidases are present in the aleurone layer and the scutellum, where they are secreted to perform their hydrolytic functions. However, they present low levels of metabolic activity during the initial hours of germination, becoming evident from the first day of germination (Lemmens et al, 2021). Their activity is observed more efficiently under specific conditions. Schwalb et al (2012) reported that the degradation of the peptide substrate is more significant at temperatures around 20 °C and in an acidic medium (pH close to 4).

The function of peptidases is to reduce proteins through the hydrolysis of peptide bonds present between the amino acids. Thus, the activity of

peptidases, which is accentuated during germination, weakens internal structures and causes the dismantling of protein/starch complexes, mainly in the endosperm of the grain, facilitating their digestion and absorption (Wu et al, 2013; Guzmán-Ortiz et al, 2019).

In contrast, germination can provide substrates for the Maillard reaction, which can interfere with protein digestibility (Lamberts et al, 2008). The combination of reducing amino acids and monosaccharides, formed during the induced germination process, is favored at temperatures above 40 °C, a condition to which the grains usually are exposed during the drying process (Sirisoontarak et al, 2015). The complexation of these compounds can hinder protein digestion by the human digestive system (Nascimento et al, 2020).

Cornejo et al (2015) reported that after 24 h of germination, there is a reduction of protein digestion. Joye (2019) indicated that protein digestibility is facilitated by germination due to the plant's need to synthesize new proteins with other functions. Therefore, the action of proteases during germination facilitates the access of enzymes of the human gastrointestinal system during digestion.

Lipid

Lipids are related to chronic non-communicable diseases, such as obesity, diabetes and heart complications (Zhang et al, 2020). However, some of the lipids are essentials for the proper functioning of the human body, such as omegas (3, 6, and 9) that are not produced endogenously and are related to combating inflammatory diseases, regulation of protein synthesis, reduction of low-density lipoproteins and increase of high-density lipoproteins (Mason and Sherratt, 2017). Lipids are present mainly in seafood and some plant seeds (such as flaxseed, rapeseed and sunflower), and a smaller amount of lipids is found in rice grains (Punia et al, 2019). Other health-beneficial compounds associated with lipids are γ -oryzanol, tocopherols, tocotrienols and carotenoids, due to their lipophilic character and extraction together with oil (Torres-Luna et al, 2019).

Triglycerides or triacylglycerols (TAGs) are the forms of lipids in grains, mainly in the bran layers. In rice, lipids are also found in the germ and endosperm in the form of phospholipids and free fatty acids (Go et al, 2020).

A large part of the lipids present in endosperm and germ are complicated with other nutrients or are encouraged to be post-treated, which involve excessive heat and/or pre-gelatinization. These

treatments reduce the bioavailability of the lipids due to the difficult access by the digestive or endogenous metabolic enzymes (Cui et al, 2021).

Rice oil, extracted from bran and germ, has high levels of saturated fatty acids, such as palmitic acid (16:0), and unsaturated fatty acids such as oleic (18:1) and linolenic acid (18:2) (Sinha et al, 2020). The synthesis and accumulation of lipids, begin shortly after pollination, in a maximum of 12 d (Sinha et al, 2020). With germination, reserved lipids are degraded by the action of lipolytic enzymes and oxidation reactions to generate energy by β -oxidation and the glyoxylate pathway (Khan et al, 2017). The fatty acids generated, especially polyunsaturated ones, are prone to suffer oxidation and peroxidation reactions catalyzed by the action of lipoxygenases, forming compounds that interfere with the organoleptic characteristics of the oil, mainly hydroperoxides (Sinha et al, 2020).

Young et al (2012) reported that the total lipid content of paddy rice grains is increased after germination for 72 h, from approximately 1.6% to 2.0%. However, with the removal of the hull, the total lipid content of brown rice pre- and post-germination shows no difference, remaining at approximately 2.2%. Sinha et al (2020) demonstrated that the TAG content is significantly decreased after the sixth day of germination, while the diacylglycerols (DAG) (except for palmitic acid), polar and free fatty acids, are not changed. The degradation of TAG is catalyzed by TAG lipases to supply non-esterified fatty acids and glycerols, and generate energy in the second instance for the grain. Sinha et al (2020) demonstrated that the initial TAG content (60 $\mu\text{mol/g}$) is decomposed after the fourth day of germination, with approximately 40 $\mu\text{mol/g}$ remaining on the sixth day and 20 $\mu\text{mol/g}$ on the eighth day. Free fatty acids, especially palmitic acid, are consequently increased after the fourth day.

Pramai et al (2018) compared the profile of metabolites in rice grains (white, black and red) before and after germination for 7 d and found an increase in fatty acid content with germination, being greater in black rice grains, mainly α -linolenic acid.

Minerals

Minerals are essential to regulate physiological functions both in plant and animal metabolism. In plants, potassium (K) can regulate the closure of stomata. Magnesium (Mg) is related to photosynthesis since Mg is the central atom of the structure of chlorophyll. Calcium (Ca) exerts the function of

signalization to the abiotic stresses.

Silicon (Si) is the main mineral in rice, located mainly in the husk. However, it is of low importance in human nutrition due to husking before consumption. The other minerals present in considerable quantities are phosphorus (P), K and Mg, while the essential minerals iron (Fe) and zinc (Zn) are in insignificant amounts, in addition to the low bioavailability (Huang et al, 2020). Furthermore, the mineral content in grains is considerably affected by the planting site due to variations in soil composition (Qian et al, 2019).

Huang et al (2020) reported the average amount of minerals presents in brown rice, with the clear presence of P (4 652 mg/kg) and K (3 810 mg/kg) followed by Mg (1 558 mg/kg), and a very low amount of Zn (34 mg/kg) and Fe (12 mg/kg). With germination or pre-germination, content, solubility or bioavailability of minerals change. As Mohd Esa et al (2011) demonstrated, germination reduces the initial amount of K and Ca; although it does not interfere with Mg and Zn.

Bioactive compounds

Bioactive compounds, mainly countless phenolic compounds, have an aromatic ring in their chemical structure, such as polyphenols, carotenoids and phytosterols (Chu et al, 2020). Bioactive compounds are concentrated in the husk and bran layers of rice grain, mainly in pigmented cultivars (Verma and Srivastav, 2020). During germination, some of these compounds are used to combat the free radicals

formed, synthesize new compounds or mix with tissues and other nutrients. Also, there is the stimulus for synthesizing new bioactive compounds such as tocopherols, tocotrienols, GABA and γ -oryzanol (Cho and Lim, 2016; Liang et al, 2020). Rice germination parameters and their influence on bioactive compounds are shown in Table 3.

Kaur et al (2017) observed the increase in the content of total phenolics and flavanol in all the ten rice cultivars during germination. The total phenolic content doubles after germination for cultivar IET-23466. Young et al (2012) found that germination increases the γ -oryzanol content in the brown rice, from 6 to 8 mg/g approximately, and higher than 10 mg/g in the isolated sprout, but there is no significant effects in paddy rice.

Kamjijan et al (2020) evaluated the effect of germination on GABA content of grains from two different rice cultivars. GABA content increases exponentially, initially bordering on nullity (20 mg/kg), and reaches the peak (approximately 330 mg/kg) between 72 and 96 h of germination. However, there is a decrease after this period, but it remains higher than the initial content. Nevertheless, it is worth mentioning that the behavior, although similar for both cultivars, obtained different results.

Ding et al (2018) indicated that when an ultrasound humidifier is applied after the grain immersion stage or for 5 min after 66 h of germination in red rice, a maximum GABA content of approximately 750 mg/kg for both treatments is achieved. Jongyingcharoen and

Table 3. Rice germination parameters and their influence on bioactive compounds.

| Rice variety | Germination condition | Bioactive compounds increased | Reference |
|--|--|--|--|
| Daohuaxiang | 36 h at 37 °C at 100% RH, stressed by hydrogen peroxide | Antioxidant activity | Xia et al, 2017 |
| Xianhui 207, Heinuo | 72 h at 28 °C at 100% RH, stressed by normoxia and hypoxia | GABA | Ding et al, 2016 |
| Sanqjuding, SZ | 52 h at 37 °C at 90% RH, darkness | GABA | Xia and Li, 2018 |
| KDML105, Riceberry | 144 h at 30 °C, darkness | GABA | Kamjijam et al, 2020 |
| OM457, TN11, Huong Dua | 72 h at 35 °C at 90% RH, darkness | Total phenolics and flavonoids | Nguyen et al, 2020 |
| IET-23466, Dhan-201, IET-23448, MAS-946, IET-23445, IET-23463, IET-23455, PR-123, PR-115 e IET-23449 | 48 h at 28 °C to 30 °C at 95% RH | Total phenolics and flavonoids | Kaur et al, 2017 |
| KDML105 | 4 h at 35 °C at 95% RH | GABA | Jongyingcharoen and Cheevitsopon, 2016 |
| Ipumbyeo | 48 h at 37 °C at 80% RH | Vitamin E | Kim et al, 2017 |
| Sanpatong 1, Khao Jow Hawm Phitsanulok 1, KDML105, Niaw Sanpatong, Rice Department 6, Luem Pua | 96 h at 25 °C to 28 °C at 100% RH, cold plasma treatment | Vitamin E, γ -oryzanol, antioxidant activity, total phenolics | Yodpitak et al, 2019 |
| Hom Mali 105, Hom Deang Sukhothai 1, Hom Dam Sukhothai 2 | 168 h at room temperature | GABA, γ -oryzanol, total phenolics | Pramai et al, 2018 |
| KDML105 | 30 h at 48 °C | GABA, γ -oryzanol, phenolic acids | Tuntipopipat et al, 2015 |
| Qiutian Xiaoting | 8 h at 37 °C at 90% RH, darkness | GABA | Xia and Li, 2018 |

RH, Relative humidity; GABA, Gamma-aminobutyric acid.

Cheevitsopon (2016) found that shortest immersion time (4 h) and the longest germination time (20 h) provide the best results for GABA content (197.1 mg/kg).

Regarding the total phenolic content, its free and bound/insoluble forms must be considered. Free forms are found in plant cell vacuoles, while insoluble forms are linked to macromolecules such as insoluble carbohydrates (pectin and cellulose) and structural proteins (Rasera et al, 2020). Ti et al (2014) found that the total phenolic content in brown rice increases, as well as the free and bound phenolic compounds during germination. Initially, they contribute with 57.7% and 42.3%, respectively, for the total phenolic content. After 30 h of germination, free phenolics account for 66% and bound for 34%. The enzymatic activity promotes the breakdown of interactions between phenolics and macromolecules, making them free.

Vitamins

The vitamins commonly found in rice grains are vitamins B (B3 and B5) and E (Ghosh et al, 2019). Rice is not a vitamin source food for human due to the low amounts. However, vitamin fractions, especially in the bran layers, such as the tocopherol and tocotrienol isomers, have a homologous function to vitamin E (Kim et al, 2017). The dehulling and polishing processes of rice grains, and subsequent cooking, make the content of vitamins even lower (Kyritsi et al, 2011). The deficit of vitamins in the human organism causes serious health problems that can become a public health issue if rice becomes the only source of nutrients (Bonto et al, 2018). Treatments like biofortification and processes that retain or stimulate the production of nutrients in food are becoming popular. Some examples are rice fortification with vitamin B (Kyritsi et al, 2011), grain biofortification with pro-vitamin A and carotenoids (Nkhata et al, 2020), parboiling process (Jannasch et al, 2020) and germination (Kim et al, 2017).

Germination increased the total vitamin E content, including the compounds α -tocopherol, α -tocotrienol and β -tocotrienol (Kim et al, 2017). Yodpitak et al (2019) found that the germination process increases the vitamin E content, and the levels can vary significantly depending on the germination time and the cultivar.

Enzymes

Enzymatic action is essential for plant development and grain formation. Enzymes catalyse countless

reactions such as degradation of nutrients, lysis and hydrolysis, oxidation-reduction, and conversion/synthesis of compounds (van Hung et al, 2020). The germination process is dependent on enzymatic action, such as on phytohormones, which starts with the breaking of seed dormancy by water absorption. Amylases, proteases and lipases stand out in the first stages of germination.

Starch is the source of reserve energy for the seed, and therefore it is the first nutrient utilised during germination. Li et al (2019) investigated how α -amylase acts during the germination of rice grains and demonstrated that after 24 h of germination, the action of these enzymes is approximately 70 mg/(g min), increasing to 85 and 105 mg/(g min) in the next 24 and 48 h, respectively. α -amylase and β -amylase are the main amylolytic enzymes activated during germination (Charoenthaikij et al, 2009). These enzymes act on the α -(1-4) bonds of amylose and amylopectin; this action is blocked on the α -(1-6) bonds present in the maltose molecules resulting from this degradation, where pullulanase action is necessary to reduce glucose (required during cellular respiration and energy production) as well as to generate new tissues (Miao et al, 2015).

According to Szewińska et al (2016), cysteine protease is the most abundant among the proteases that act during the germination process on the degradation of storage proteins. Veluppillai et al (2009) followed the action of proteases in general during germination and proved that these enzymes are activated in the first 24 h of germination, and remain with the stable activity until 48 h, and then their activity is increased exponentially until the 120 h of germination. However, it is not known when the growth ends after the fifth day of germination.

Benefits of germinated rice to health

There are countless benefits by the consumption of germinated grains. The consumption of germinated brown rice rich in GABA, a regulator of anxiety (He et al, 2019), has a calming effect (Hayat et al, 2015), and prevents type 2 diabetes by stimulating insulin production (Ohm et al, 2016) and anti-inflammatory effect in adenocarcinoma cells (Caco-2) taken from the human colon (Tuntipopipat et al, 2015). Germinated brown rice is rich in γ -oryzanol and other lipophilic compounds such as tocopherols and tocotrienols, which are related to cholesterol regulation (Burlando and Cornara, 2014), antioxidant effect (Yang and

Jiang, 2019), neuroprotective (Alzoubi et al, 2019) and anti-inflammatory effects (Torres-Luna et al, 2019). Other antioxidant compounds, such as phenolic compounds (phenolic acids and flavonoids), are also related to reductions of cardiovascular diseases and some types of cancer (Sybron et al, 2019).

As shown, the nutritional and digestibility profiles change with germination and vary according to the conditions applied, providing unique properties in the grains that can be used technologically and nutritionally as functional foods (Sofi et al, 2020). In this way, products obtained from germinated rice have gained increasing prominence, such as bread (Cornejo et al, 2015), cupcakes (Müller et al, 2021), noodles (Sofi et al, 2020), cookies (Chung et al, 2014), and other bakery products, in addition to the germinated parboiled grain itself (Nascimento et al, 2020).

Perspective

The nutritional quality of germinated rice alters depending on the germination conditions and the genotype used. However, it is impossible to mention one best condition for all rice cultivars. Each cultivar has specific requirements for improving the physical-chemical, technological and nutritional characteristics when it is about interactions between genetic characteristics with biotic and abiotic environmental factors. Thus, the germination process applied to the rice grains can be an alternative method to achieve desirable attributes that meet the nutrient demands of the consuming population. Interestingly, the pre-germination of seeds results in multiple benefits for planting crops and multiple technological and nutritional benefits when properly applied to rice grains. This review showed the important advances and the need for further studies, and offered enough important and comprehensive information for those who wish to delve into the application of germination in the industrialization of rice foods.

ACKNOWLEDGEMENTS

We thank FAPERGS (Research Support Foundation of the State of Rio Grande do Sul), CAPES (Coordination of Improvement of Higher Education Personnel), CNPq (National Council for Scientific and Technological Development) and SCT-RS (Secretary of Science and Technology of the State of Rio Grande do Sul) for the financial support.

REFERENCES

Acosta-Estrada B A, Gutiérrez-Urbe J A, Serna-Saldívar S O. 2014. Bound phenolics in foods: A review. *Food Chem*, **152**: 46–55.

- Alzoubi K H, Halboup A M, Alomari M A, Khabour O F. 2019. The neuroprotective effect of vitamin E on waterpipe tobacco smoking-induced memory impairment: The antioxidative role. *Life Sci*, **222**: 46–52.
- Aparicio-García N, Martínez-Villaluenga C, Frias J, Peñas E. 2020. Changes in protein profile, bioactive potential and enzymatic activities of gluten-free flours obtained from hulled and dehulled oat varieties as affected by germination conditions. *LWT*, **134**: 109955.
- Bao J S, Kong X L, Xie J K, Xu L J. 2004. Analysis of genotypic and environmental effects on rice starch: 1. Apparent amylose content, pasting viscosity, and gel texture. *J Agric Food Chem*, **52**(19): 6010–6016.
- Benincasa P, Falcinelli B, Lutts S, Stagnari F, Galieni A. 2019. Sprouted grains: A comprehensive review. *Nutrients*, **11**(2): 421.
- Bonto A P, Camacho K S I, Camacho D H. 2018. Increased vitamin B5 uptake capacity of ultrasonic treated milled rice: A new method for rice fortification. *LWT*, **95**: 32–39.
- Bonto A P, Tiozon R N Jr, Sreenivasulu N, Camacho D H. 2021. Impact of ultrasonic treatment on rice starch and grain functional properties: A review. *Ultrason Sonochem*, **71**: 105383.
- Burlando B, Cornara L. 2014. Therapeutic properties of rice constituents and derivatives (*Oryza sativa* L.): A review update. *Trends Food Sci Technol*, **40**(1): 82–98.
- Cáceres P J, Peñas E, Martínez-Villaluenga C, Amigo L, Frias J. 2017. Enhancement of biologically active compounds in germinated brown rice and the effect of sun-drying. *J Cereal Sci*, **73**: 1–9.
- Cardone G, Grassi S, Scipioni A, Marti A. 2020. Bread-making performance of durum wheat as affected by sprouting. *LWT*, **134**: 110021.
- Chaijan M, Panpipat W. 2020. Nutritional composition and bioactivity of germinated Thai indigenous rice extracts: A feasibility study. *PLoS One*, **15**(8): e0237844.
- Charoenthaikij P, Jangchud K, Jangchud A, Piyachomkwan K, Tungtrakul P, Prinyawiwatkul W. 2009. Germination conditions affect physicochemical properties of germinated brown rice flour. *J Food Sci*, **74**(9): C658–C665.
- Chaves T F, de Queiroz Z F, de Sousa D N R, Girão J H S, Rodrigues E A. 2009. Use of rice husk ash (CCA) obtained from thermal energy generation As a Zn(II) adsorbent in aqueous solutions. *Química Nova*, **32**(6): 1378–1383. (in Portuguese)
- Cho D H, Lim S T. 2016. Germinated brown rice and its bio-functional compounds. *Food Chem*, **196**: 259–271.
- Chu C, Du Y M, Yu X T, Shi J, Yuan X L, Liu X M, Liu Y H, Zhang H B, Zhang Z F, Yan N. 2020. Dynamics of antioxidant activities, metabolites, phenolic acids, flavonoids, and phenolic biosynthetic genes in germinating Chinese wild rice (*Zizania latifolia*). *Food Chem*, **318**: 126483.
- Chung H J, Cho D W, Park J D, Kweon D K, Lim S T. 2012. *In vitro* starch digestibility and pasting properties of germinated brown rice after hydrothermal treatments. *J Cereal Sci*, **56**(2): 451–456.
- Chung H J, Cho A, Lim S T. 2014. Utilization of germinated and heat-moisture treated brown rices in sugar-snap cookies. *LWT*, **57**(1): 260–266.

- Cornejo F, Caceres P J, Martínez-Villaluenga C, Rosell C M, Frias J. 2015. Effects of germination on the nutritive value and bioactive compounds of brown rice breads. *Food Chem*, **173**: 298–304.
- Cui J, Zheng B, Liu Y F, Chen L, Li B, Li L. 2021. Insights into the effect of structural alternations on the digestibility of rice starch-fatty acid complexes prepared by high-pressure homogenization. *LWT*, **136**: 110294.
- Dartois A, Singh J, Kaur L, Singh H. 2010. Influence of guar gum on the *in vitro* starch digestibility-rheological and microstructural characteristics. *Food Biophys*, **5**(3): 149–160.
- Ding J Z, Yang T W, Feng H, Dong M Y, Slavin M, Xiong S B, Zhao S M. 2016. Enhancing contents of γ -aminobutyric acid (GABA) and other micronutrients in dehulled rice during germination under normoxic and hypoxic conditions. *J Agric Food Chem*, **64**(5): 1094–1102.
- Ding J Z, Hou G G, Dong M Y, Xiong S B, Zhao S M, Feng H. 2018. Physicochemical properties of germinated dehulled rice flour and energy requirement in germination as affected by ultrasound treatment. *Ultrason Sonochem*, **41**: 484–491.
- Dziki D, Gawlik-Dziki U, Kordowska-Wiater M, Domań-Pytka M. 2015. Influence of elicitation and germination conditions on biological activity of wheat sprouts. *J Chem*, **2015**: 649709.
- Finnie S, Brovelli V, Nelson D. 2019. Sprouted grains as a food ingredient. Amsterdam: Elsevier: 113–142.
- Fraś A, Gołębiowski D, Gołębiowska K, Mańkowski D R, Gzowska M, Boros D. 2018. *Triticale*-oat bread as a new product rich in bioactive and nutrient components. *J Cereal Sci*, **82**: 146–154.
- Gan R Y, Lui W Y, Wu K, Chan C L, Dai S H, Sui Z Q, Corke H. 2017. Bioactive compounds and bioactivities of germinated edible seeds and sprouts: An updated review. *Trends Food Sci Technol*, **59**: 1–14.
- Ge X Z, Saleh A S M, Jing L Z, Zhao K, Su C Y, Zhang B, Zhang Q, Li W H. 2021. Germination and drying induced changes in the composition and content of phenolic compounds in naked barley. *J Food Compos Anal*, **95**: 103594.
- Ghosh S, Datta K, Datta S K. 2019. Rice vitamins. In: Bao J S. *Rice: Chemistry and Technology* (Fourth Edition). Duxford, United Kingdom. Woodhead Publishing and AACC International Press: 195–220.
- Go A W, Pham T Y N, Truong C T, Quijote K L, Angkawijaya A E, Agapay R C, Gunarto C, Ju Y H, Santoso S P. 2020. Improved solvent economy and rate of rice bran lipid extraction using hydrolyzed rice bran with hexane as solvent. *Biomass Bioenerg*, **142**: 105773.
- Guan Q, Ding X W, Jiang R, Ouyang P L, Gui J, Feng L, Yang L, Song L H. 2019. Effects of hydrogen-rich water on the nutrient composition and antioxidative characteristics of sprouted black barley. *Food Chem*, **299**: 125095.
- Guzmán-Ortiz F A, Castro-Rosas J, Gómez-Aldapa C A, Mora-Escobedo R, Rojas-León A, Rodríguez-Marín M L, Falfán-Cortés R N, Román-Gutiérrez A D. 2019. Enzyme activity during germination of different cereals: A review. *Food Rev Int*, **35**(3): 177–200.
- Hayat A, Jahangir T M, Khuhawar M Y, Alamgir M, Hussain Z, Haq F U, Musharraf S G. 2015. HPLC determination of gamma amino butyric acid (GABA) and some biogenic amines (BAs) in controlled, germinated, and fermented brown rice by pre-column derivatization. *J Cereal Sci*, **64**: 56–62.
- He H, Zheng B, Wang H W, Li X X, Chen L. 2020. Insights into the multi-scale structure and *in vitro* digestibility changes of rice starch-oleic acid/linoleic acid complex induced by heat-moisture treatment. *Food Res Int*, **137**: 109612.
- He Y J, Ouyang J Y, Hu Z Y, Yang J, Chu Y, Huang S W, Yang Y C, Liu C H. 2019. Intervention mechanism of repeated oral GABA administration on anxiety-like behaviors induced by emotional stress in rats. *Psychiatry Res*, **271**: 649–657.
- Huang S, Wang P T, Yamaji N, Ma J F. 2020. Plant nutrition for human nutrition: Hints from rice research and future perspectives. *Mol Plant*, **13**(6): 825–835.
- Jannasch A, Brownmiller C, Lee S O, Mauromoustakos A, Wang Y J. 2020. Simultaneous fortification of rice with folic acid and β -carotene or vitamin A by limited-water parboiling. *J Cereal Sci*, **96**: 103096.
- Jeleń H H, Majcher M, Szwengiel A. 2019. Key odorants in peated malt whisky and its differentiation from other whisky types using profiling of flavor and volatile compounds. *LWT*, **107**: 56–63.
- Jongyingcharoen J S, Cheevitsopon E. 2016. Development of UV-treated cooked germinated brown rice and effect of UV-C treatment on its storability, GABA content, and quality. *LWT*, **71**: 243–248.
- Joye I. 2019. Protein digestibility of cereal products. *Foods*, **8**(6): 199.
- Kamijiam B, Bednarz H, Suwannaporn P, Jom K N, Niehaus K. 2020. Localization of amino acids in germinated rice grain: Gamma-aminobutyric acid and essential amino acids production approach. *J Cereal Sci*, **93**: 102958.
- Kaur M, Asthir B, Mahajan G. 2017. Variation in antioxidants, bioactive compounds and antioxidant capacity in germinated and ungerminated grains of ten rice cultivars. *Rice Sci*, **24**(6): 349–359.
- Kenchanmane Raju S K, Barnes A C, Schnable J C, Roston R L. 2018. Low-temperature tolerance in land plants: Are transcript and membrane responses conserved? *Plant Sci*, **276**: 73–86.
- Khan F I, Lan D, Durrani R, Huan W, Zhao Z, Wang Y. 2017. The lid domain in lipases: Structural and functional determinant of enzymatic properties. *Front Bioeng Biotechnol*, **5**: 16.
- Khatun A, Waters D L E, Liu L. 2020. The impact of rice protein on *in vitro* rice starch digestibility. *Food Hydrocoll*, **109**: 106072.
- Kim M Y, Lee S H, Jang G Y, Li M S, Lee Y R, Lee J, Jeong H S. 2017. Changes of phenolic-acids and vitamin E profiles on germinated rough rice (*Oryza sativa* L.) treated by high hydrostatic pressure. *Food Chem*, **217**: 106–111.
- Kirk S E. 2009. Hypoglycemia in *Athletes* with diabetes. *Clin Sports Med*, **28**(3): 455–468.
- Korres N E, Norsworthy J K, Burgos N R, Oosterhuis D M. 2017. Temperature and drought impacts on rice production: An agronomic perspective regarding short- and long-term adaptation measures. *Water Resour Rural Dev*, **9**: 12–27.

- Krapf J, Ding L D, Brühan J, Lorimer L, Walther G, Flöter E. 2020. Effect of sprouting temperature on selected properties of wheat flour and direct expanded extrudates. *J Food Process Eng*, **43**(4): e13365.
- Krishnan V, Rani R, Awana M, Pitale D, Kulshreshta A, Sharma S, Bollinedi H, Singh A, Singh B, Singh A K, Praveen S. 2021. Role of nutraceutical starch and proanthocyanidins of pigmented rice in regulating hyperglycemia: Enzyme inhibition, enhanced glucose uptake and hepatic glucose homeostasis using *in vitro* model. *Food Chem*, **335**: 127505.
- Kupkanchanakul W, Kadowaki M, Kubota M, Naivikul O. 2018. Effect of pre-germination at varying stages of embryonic growth length on chemical composition and protein profile of Thai rice (*Oryza sativa* L.). *Agric Nat Resour*, **52**(1): 59–65.
- Kyritsi A, Tzia C, Karathanos V T. 2011. Vitamin fortified rice grain using spraying and soaking methods. *LWT Food Sci Technol*, **44**(1): 312–320.
- Lahkar L, Tanti B. 2018. *Morpho*-physicochemical and cooking characteristics of traditional aromatic Joha rice (*Oryza sativa* L.) of Assam, India. *Biocatal Agric Biotechnol*, **16**: 644–654.
- Lamberts L, Rombouts I, Brijs K, Gebruers K, Delcour J A. 2008. Impact of parboiling conditions on Maillard precursors and indicators in long-grain rice cultivars. *Food Chem*, **110**(4): 916–922.
- Lang G H, da Silva Lindemann I, Ferreira C D, Hoffmann J F, Vanier N L, de Oliveira M. 2019. Effects of drying temperature and long-term storage conditions on black rice phenolic compounds. *Food Chem*, **287**: 197–204.
- Lee J H, Lee S Y, Kim B, Seo W D, Jia Y Y, Wu C Y, Jun H J, Lee S J. 2015. Barley sprout extract containing policosanols and polyphenols regulate AMPK, SREBP2 and ACAT2 activity and cholesterol and glucose metabolism *in vitro* and *in vivo*. *Food Res Int*, **72**: 174–183.
- Lemmens E, Deleu L J, de Brier N, Smolders E, Delcour J A. 2021. Mineral bio-accessibility and intrinsic saccharides in breakfast flakes manufactured from sprouted wheat. *LWT*, **143**: 111079.
- Li C, Oh S G, Lee D H, Baik H W, Chung H J. 2017. Effect of germination on the structures and physicochemical properties of starches from brown rice, oat, sorghum, and millet. *Int J Biol Macromol*, **105**: 931–939.
- Li C H, Zhu J G, Sha L N, Zhang J S, Zeng Q, Liu G. 2017. Rice (*Oryza sativa* L.) growth and nitrogen distribution under elevated CO₂ concentration and air temperature. *Ecol Res*, **32**(3): 405–411.
- Li Q, Yang A. 2020. Comparative studies on seed germination of two rice genotypes with different tolerances to low temperature. *Environ Exp Bot*, **179**: 104216.
- Li Q, Yang A, Zhang W H. 2019. Higher endogenous bioactive gibberellins and α -amylase activity confer greater tolerance of rice seed germination to saline-alkaline stress. *Environ Exp Bot*, **162**: 357–363.
- Liang H L, Cheng P W, Lin H L, Hao C L, Ke L Y, Chou H Y, Tseng Y H, Yen H W, Shen K P. 2020. Extract of pre-germinated brown rice protects against cardiovascular dysfunction by reducing levels of inflammation and free radicals in a rat model of type II diabetes. *J Funct Foods*, **75**: 104218.
- Liang J F, Han B Z, Nout M J R, Hamer R J. 2008. Effects of soaking, germination and fermentation on phytic acid, total and *in vitro* soluble zinc in brown rice. *Food Chem*, **110**(4): 821–828.
- Liu Q Q, Kong Q, Li X L, Lin J F, Chen H, Bao Q B, Yuan Y J. 2020. Effect of mild-parboiling treatment on the structure, colour, pasting properties and rheology properties of germinated brown rice. *LWT*, **130**: 109623.
- Liu S J, Xu H H, Wang W Q, Li N, Wang W P, Lu Z, Møller I M, Song S Q. 2016. Identification of embryo proteins associated with seed germination and seedling establishment in germinating rice seeds. *J Plant Physiol*, **196/197**: 79–92.
- Maphosa Y, Jideani V A. 2017. The role of legumes in human nutrition. In: Hueda M C. *Functional Food: Improve Health Through Adequate Food*. InTech: 69127.
- Marion D, Saulnier L. 2020. Minor components and wheat quality: Perspectives on climate changes. *J Cereal Sci*, **94**: 103001.
- Mason R P, Sherratt S C R. 2017. *Omega*-3 fatty acid fish oil dietary supplements contain saturated fats and oxidized lipids that may interfere with their intended biological benefits. *Biochem Biophys Res Commun*, **483**(1): 425–429.
- Mayer H, Ceccaroni D, Marconi O, Sileoni V, Perretti G, Fantozzi P. 2016. Development of an all rice malt beer: A gluten free alternative. *LWT Food Sci Technol*, **67**: 67–73.
- McKie V A, McCleary B V. 2015. A rapid, automated method for measuring α -amylase in pre-harvest sprouted (sprout damaged) wheat. *J Cereal Sci*, **64**: 70–75.
- Miao M, Li R, Huang C, Jiang B, Zhang T. 2015. Impact of β -amylase degradation on properties of sugary maize soluble starch particles. *Food Chem*, **177**: 1–7.
- Mohammadi F, Marti A, Nayebezhadeh K, Hosseini S M, Tajdar-Oranj B, Jazaeri S. 2021. Effect of washing, soaking and pH in combination with ultrasound on enzymatic rancidity, phytic acid, heavy metals and coliforms of rice bran. *Food Chem*, **334**: 127583.
- Mohd Esa N, Abdul Kadir K K, Amom Z, Azlan A. 2011. Improving the lipid profile in hypercholesterolemia-induced rabbit by supplementation of germinated brown rice. *J Agric Food Chem*, **59**(14): 7985–7991.
- Mukamuhirwa A, Persson Hovmalm H, Ortiz R, Nyamangyoku O, Prieto-Linde M L, Ekholm A, Johansson E. 2020. Effect of intermittent drought on grain yield and quality of rice (*Oryza sativa* L.) grown in Rwanda. *J Agron Crop Sci*, **206**(2): 252–262.
- Müller C P, Hoffmann J F, Ferreira C D, Diehl G W, Rossi R C, Ziegler V. 2021. Effect of germination on nutritional and bioactive properties of red rice grains and its application in cupcake production. *Int J Gastron Food Sci*, **25**: 100379.
- Nascimento L Á D, Ávila B P, Colussi R, Elias M C. 2020. Effect of abiotic stress on bioactive compound production in germinated brown rice. *Cereal Chem*, **97**(4): 868–876.
- Nelson K, Stojanovska L, Vasiljevic T, Mathai M. 2013. Germinated grains: A superior whole grain functional food? *Can J Physiol Pharmacol*, **91**(6): 429–441.
- Ng L T, Huang S H, Chen Y T, Su C H. 2013. Changes of tocopherols, tocotrienols, γ -oryzanol, and γ -aminobutyric acid levels in the germinated brown rice of pigmented and

- nonpigmented cultivars. *J Agric Food Chem*, **61**(51): 12604–12611.
- Nguyen B C Q, Shahinozzaman M, Tien N T K, Thach T N, Tawata S. 2020. Effect of sucrose on antioxidant activities and other health-related micronutrients in gamma-aminobutyric acid (GABA)-enriched sprouting Southern Vietnam brown rice. *J Cereal Sci*, **93**: 102985.
- Nkhata S G, Chilungo S, Memba A, Mponela P. 2020. Biofortification of maize and sweetpotatoes with provitamin A carotenoids and implication on eradicating vitamin A deficiency in developing countries. *J Agric Food Res*, **2**: 100068.
- Nonogaki H, Bassel G W, Bewley J D. 2010. Germination: Still a mystery. *Plant Sci*, **179**(6): 574–581.
- Ohanenye I C, Tsopmo A, Ejike C E C C, Udenigwe C C. 2020. Germination as a bioprocess for enhancing the quality and nutritional prospects of legume proteins. *Trends Food Sci Technol*, **101**: 213–222.
- Ohdaira Y, Takeda H, Sasaki R. 2015. Effects of temperature on the digestible protein content of grains during ripening in a seed-protein mutant rice cultivar LGCsoft. *Plant Prod Sci*, **13**(2): 132–140.
- Ohm J B, Lee C W, Cho K. 2016. Germinated wheat: Phytochemical composition and mixing characteristics. *Cereal Chem*, **93**(6): 612–617.
- Osborne T B. 1895. The proteids of barley. *J Am Chem Soc*, **17**(7): 539–567.
- Owolabi I O, Dat-arun P, Takahashi Yupanqui C, Wichienchot S. 2020. Gut microbiota metabolism of functional carbohydrates and phenolic compounds from soaked and germinated purple rice. *J Funct Foods*, **66**: 103787.
- Patil S B, Khan M K. 2011. Germinated brown rice as a value added rice product: A review. *J Food Sci Technol*, **48**(6): 661–667.
- Poudel R, Finnie S, Rose D J. 2019. Effects of wheat kernel germination time and drying temperature on compositional and end-use properties of the resulting whole wheat flour. *J Cereal Sci*, **86**: 33–40.
- Pramai P, Abdul Hamid N A, Mediani A, Maulidiani M, Abas F, Jiamyangyuen S. 2018. Metabolite profiling, antioxidant, and α -glucosidase inhibitory activities of germinated rice: Nuclear-magnetic-resonance-based metabolomics study. *J Food Drug Anal*, **26**(1): 47–57.
- Prieto J A, Estruch F, Cárcoles-Sáez I, del Poeta M, Rieger R, Stenzel I, Randez-Gil F. 2020. Pho85 and PI(4,5)P₂ regulate different lipid metabolic pathways in response to cold. *Biochim Biophys Acta Mol Cell Biol Lipids*, **1865**(2): 158557.
- Punia S, Sandhu K S, Siroha A K, Dhull S B. 2019. Omega 3-metabolism, absorption, bioavailability and health benefits: A review. *PharmaNutrition*, **10**: 100162.
- Qian L L, Zhang C D, Zuo F, Zheng L N, Li D, Zhang A W, Zhang D J. 2019. Effects of fertilizers and pesticides on the mineral elements used for the geographical origin traceability of rice. *J Food Compos Anal*, **83**: 103276.
- Rasera G B, Hilkner M H, de Castro R J S. 2020. Free and insoluble-bound phenolics: How does the variation of these compounds affect the antioxidant properties of mustard grains during germination? *Food Res Int*, **133**: 109115.
- Saniso E, Prachayawarakorn S, Swasdisevi T, Soponronnarit S. 2020. Parboiled rice production without steaming by microwave-assisted hot air fluidized bed drying. *Food Bioprod Process*, **120**: 8–20.
- Schwalb T, Wieser H, Koehler P. 2012. Studies on the gluten-specific peptidase activity of germinated grains from different cereal species and cultivars. *Eur Food Res Technol*, **235**(6): 1161–1170.
- Shah A, Masoodi F A, Gani A, Ashwar B. 2018. Dual enzyme modified oat starch: Structural characterisation, rheological properties, and digestibility in simulated GI tract. *Int J Biol Macromol*, **106**: 140–147.
- Shen S Q, Wang Y, Li M, Xu F F, Chai L H, Bao J S. 2015. The effect of anaerobic treatment on polyphenols, antioxidant properties, tocopherols and free amino acids in white, red, and black germinated rice (*Oryza sativa* L.). *J Funct Foods*, **19**: 641–648.
- Shukla R, Cheryan M. 2001. Zein: The industrial protein from corn. *Ind Crops Prod*, **13**(3): 171–192.
- Singh A, Sharma S, Singh B. 2017. Effect of germination time and temperature on the functionality and protein solubility of sorghum flour. *J Cereal Sci*, **76**: 131–139.
- Sinha K, Kaur R, Singh N, Kaur S, Rishi V, Bhunia R K. 2020. Mobilization of storage lipid reserve and expression analysis of lipase and lipoxygenase genes in rice (*Oryza sativa* var. Pusa Basmati 1) bran during germination. *Phytochemistry*, **180**: 112538.
- Sirisoontaralak P, Nakornpanom N N, Koakietdumrongkul K, Panumaswiwath C. 2015. Development of quick cooking germinated brown rice with convenient preparation and containing health benefits. *LWT Food Sci Technol*, **61**(1): 138–144.
- Sofi S A, Singh J, Mir S A, Dar B N. 2020. *In vitro* starch digestibility, cooking quality, rheology and sensory properties of gluten-free pregelatinized rice noodle enriched with germinated chickpea flour. *LWT*, **133**: 110090.
- Sybron A, Rai D K, Vaidya K R, Hossain M B, Benkeblia N. 2019. Effects of ripening stage on the content and antioxidant capacities of phenolic compounds of arils, seeds and husks of ackee fruit *Blighia sapida* Koenig. *Sci Hortic*, **256**: 108632.
- Szawińska J, Simińska J, Bielawski W. 2016. The roles of cysteine proteases and phytocystatins in development and germination of cereal seeds. *J Plant Physiol*, **207**: 10–21.
- Tamura M, Imaizumi R, Saito T, Watanabe T, Okamoto T. 2019. Studies of the texture, functional components and *in vitro* starch digestibility of rolled barley. *Food Chem*, **274**: 672–678.
- Tang Z Y, Fan J, Zhang Z Z, Zhang W, Yang J T, Liu L, Yang Z B, Zeng X F. 2021. Insights into the structural characteristics and *in vitro* starch digestibility on steamed rice bread as affected by the addition of okara. *Food Hydrocoll*, **113**: 106533.
- Thi Thu H P, Thu T N, Nguyen Thao N D, Minh K L, Tan K D. 2020. Evaluate the effects of salt stress on physico-chemical characteristics in the germination of rice (*Oryza sativa* L.) in response to methyl salicylate (MeSA). *Biocatal Agric Biotechnol*, **23**: 101470.
- Ti H H, Zhang R F, Zhang M W, Li Q, Wei Z C, Zhang Y, Tang X J, Deng Y Y, Liu L, Ma Y X. 2014. Dynamic changes in the free and bound phenolic compounds and antioxidant activity of

- brown rice at different germination stages. *Food Chem*, **161**: 337–344.
- Torres-Luna C, Hu N P, Tammareddy T, Domszy R, Yang J, Wang N S, Yang A. 2019. Extended delivery of non-steroidal anti-inflammatory drugs through contact lenses loaded with Vitamin E and cationic surfactants. *Cont Lens Anterior Eye*, **42**(5): 546–552.
- Tumpanuvat T, Jittanit W, Surojanametakul V. 2018. Effects of drying conditions in hybrid dryer on the GABA rice properties. *J Stored Prod Res*, **77**: 177–188.
- Tuntipopipat S, Muangnoi C, Thiyajai P, Srichamnong W, Charoenkiatkul S, Praengam K. 2015. A bioaccessible fraction of parboiled germinated brown rice exhibits a higher anti-inflammatory activity than that of brown rice. *Food Funct*, **6**(5): 1480–1488.
- van Hung P, Hoang Yen N T, Lan Phi N T, Ha Tien N P, Thu Trung N T. 2020. Nutritional composition, enzyme activities and bioactive compounds of mung bean (*Vigna radiata* L.) germinated under dark and light conditions. *LWT*, **133**: 110100.
- Veluppillai S, Nithyanantharajah K, Vasantharuba S, Balakumar S, Arasaratnam V. 2009. Biochemical changes associated with germinating rice grains and germination improvement. *Rice Sci*, **16**(3): 240–242.
- Verma D K, Srivastav P P. 2020. Bioactive compounds of rice (*Oryza sativa* L.): Review on paradigm and its potential benefit in human health. *Trends Food Sci Technol*, **97**: 355–365.
- Wang H W, Xiao N Y, Ding J T, Zhang Y Y, Liu X L, Zhang H. 2020. Effect of germination temperature on hierarchical structures of starch from brown rice and their relation to pasting properties. *Int J Biol Macromol*, **147**: 965–972.
- Wu F F, Chen H Y, Yang N, Wang J P, Duan X, Jin Z Y, Xu X M. 2013. Effect of germination time on physicochemical properties of brown rice flour and starch from different rice cultivars. *J Cereal Sci*, **58**(2): 263–271.
- Xia Q, Li Y F. 2018. Mild high hydrostatic pressure pretreatments applied before soaking process to modulate wholegrain brown rice germination: An examination on embryo growth and physicochemical properties. *Food Res Int*, **106**: 817–824.
- Xia Q, Wang L P, Xu C C, Mei J, Li Y F. 2017. Effects of germination and high hydrostatic pressure processing on mineral elements, amino acids and antioxidants *in vitro* bioaccessibility, as well as starch digestibility in brown rice (*Oryza sativa* L.). *Food Chem*, **214**: 533–542.
- Xu H B, Zhou J P, Yu J L, Wang S, Wang S J. 2021. Mechanisms underlying the effect of gluten and its hydrolysates on *in vitro* enzymatic digestibility of wheat starch. *Food Hydrocoll*, **113**: 106507.
- Yang C, Jiang Q. 2019. Vitamin E δ -tocotrienol inhibits TNF- α -stimulated NF- κ B activation by up-regulation of anti-inflammatory A20 via modulation of sphingolipid including elevation of intracellular dihydroceramides. *J Nutr Biochem*, **64**: 101–109.
- Yang M, Yang J, Su L, Sun K, Li D X, Liu Y Z, Wang H, Chen Z Q, Guo T. 2019. Metabolic profile analysis and identification of key metabolites during rice seed germination under low-temperature stress. *Plant Sci*, **289**: 110282.
- Yodpitak S, Mahatheeranont S, Boonyawan D, Sookwong P, Roytrakul S, Norkaew O. 2019. Cold plasma treatment to improve germination and enhance the bioactive phytochemical content of germinated brown rice. *Food Chem*, **289**: 328–339.
- Young H, Guk I, Myoung T, Woo K S, Park D S, Kim J H, Kim D J, Lee J, Lee Y R, Jeong H S. 2012. Chemical and functional components in different parts of rough rice (*Oryza sativa* L.) before and after germination. *Food Chem*, **134**: 288–293.
- You S Y, Oh S G, Han H M, Jun W J, Hong Y S, Chung H J. 2016. Impact of germination on the structures and *in vitro* digestibility of starch from waxy brown rice. *Int J Biol Macromol*, **82**: 863–870.
- Zhang R F, Ma Q, Tong X, Liu L, Dong L H, Huang F, Deng Y Y, Jia X C, Chi J W, Zhang M W. 2020. Rice bran phenolic extract supplementation ameliorates impaired lipid metabolism in high-fat-diet fed mice through AMPK activation in liver. *J Funct Foods*, **73**: 104131.
- Zhong Y J, Xiang X Y, Zhao J C, Wang X H, Chen R Y, Xu J G, Luo S J, Wu J Y, Liu C M. 2020. Microwave pretreatment promotes the annealing modification of rice starch. *Food Chem*, **304**: 125432.
- Zhou L H, Lu Y, Zhang Y D, Zhang C Q, Zhao L, Yao S, Sun X C, Chen T, Zhu Z, Zhao Q Y, Zhao C F, Liang W H, Lu K, Wang C L, Liu Q Q. 2020. Characteristics of grain quality and starch fine structure of *japonica* rice kernels following preharvest sprouting. *J Cereal Sci*, **95**: 103023.

(Managing Editor: FANG Hongmin)