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REVIEW ARTICLE

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Impact of germination on the techno-functional properties, nutritional composition, and health-promoting compounds of brown rice and its products: A review

Chiemela Enyinnaya Chinma[1,2] | **Olajide Emmanuel Adedeji**[3] | **Olusola Samuel Jolayemi**[4] | **Vanessa Chinelo Ezeocha**[5] | **Muna Abdulsalam Ilowefah**[6] | **Cristina M. Rosell**[7,8] | **Janet Adeyinka Adebo**[9] | **Jonathan D Wilkin**[10] | **Oluwafemi Ayodeji Adebo**[2]

[1]Department of Food Science and Technology, Federal University of Technology Minna, Minna, Nigeria

[2]Food Innovation Research Group, Department of Biotechnology and Food Technology, University of Johannesburg, Gauteng, South Africa

[3]Department of Food Science and Technology, Federal University Wukari, Wukari, Nigeria

[4]Department of Food Science and Technology, Federal University of Technology Akure, Akure, Nigeria

[5]Department of Food Science and Technology, Michael Okpara University of Agriculture Umudike, Umudike, Nigeria

[6]Department of Food Technology, Faculty of Engineering and Technology, Sabha University, Sabha, Libya

[7]Institute of Agrochemistry and Food Technology (IATA-CSIC), Paterna, Spain

[8]Department of Food and Human Nutritional Science, University of Manitoba, Winnipeg, Canada

[9]Food Evolution Research Laboratory, School of Tourism and Hospitality, College of Business and Economics, University of Johannesburg, Johannesburg, South Africa

[10]Division of Engineering and Food Science, School of Applied Sciences, Abertay University, Dundee, UK

Correspondence

Chiemela Enyinnaya Chinma, Department of Food Science and Technology, Federal University of Technology Minna, Minna, Nigeria. Email: chinmachiemela@futminna.edu.ng

Cristina M. Rosell, Institute of Agrochemistry and Food Technology (IATA-CSIC), C/Agustin Escardino, 7, 46980 Paterna, Spain. Email: crosell@iata.csic.es; cristina.rosell@umanitoba.ca

Oluwafemi Ayodeji Adebo, Food Innovation Research Group, Department of Biotechnology and Food Technology, University of Johannesburg, Doornfontein

Abstract: Rice is a popular grain and forms part of the daily diet of people throughout the world. However, the consumption of rice and its products is sometimes limited by its high glycemic index due to its high starch content, low protein content and quality, and low bioavailability of minerals due to the presence of anti-nutritional factors. This has partly stimulated research interest in recent times toward the use of bioprocessing techniques such as germination as cheap and natural means to improve the nutritional quality, digestibility, and health properties of cereals, including rice, to partially achieve nutrition and food security in the developing regions of the world. This review highlights the impact of germination on the nutritional quality, health-promoting properties, and techno-functional characteristics of germinated brown rice grains and their products. The review demonstrated that germinated rice grains and their products have improved nutritional quality and digestibility, modified functional properties, and showed antioxidant, anti-inflammatory, anti-diabetic,

Campus, P. O. Box 17011, Gauteng, South Africa. Email: oadebo@uj.ac.za

anti-obesity, anti-cancer, and anti-cardiovascular activities. Germination appears to be a suitable bioprocessing method to improve the nutritional quality and bioactive constituents and modify the techno-functional properties of rice grains for diverse food applications and improved global nutrition and food safety.

KEYWORDS
digestibility, germinated rice, macro and micronutrients, phytic acid, techno-functional properties

1 | INTRODUCTION

Rice (*Oryza sativa* L.), one of the most important cereals in the world, serves as the main staple food for diverse people across different continents (Li et al., 2017). The adaptability of rice to different agroecological conditions is responsible for its wide cultivation and utilization in many parts of the globe (Saleh et al., 2019). Rice provides 15%–20% of the global energy and protein requirements (Ding et al., 2018) and contains some micro-nutrients and bioactive compounds with health-promoting properties (Owolabi et al., 2019; Saki et al., 2017; Wunjuntuk et al., 2015). Different kinds of rice—rough/paddy, brown, and white—are obtained during rice processing depending on the severity of milling (Wang, Xiao et al., 2020). White rice has wide acceptability due to its excellent eating, cooking, and textural qualities (Saleh et al., 2019); however, due to the increase in consumers' interest in the consumption of highly nutritious and health-promoting foods, the utilization of brown rice as a raw material for food production is gradually gaining attention (Qi et al., 2019).

In the last decade, there has been an increasing research interest in the modification of rice grain to improve its nutritional qualities and functionalities. Many studies have demonstrated the use of bioprocessing, such as germination and enzymatic pretreatment (Chinma et al., 2015; Xia & Li , 2018), and thermal and non-thermal methods (Chen et al., 2016; Ding et al., 2018; Hu et al., 2016), to achieve an improved rice grain and subsequent products. Among these, germination, as a method of rice grain modification, has gained more research and industrial attention due to its high efficiency and low cost (Wang, Xiao et al., 2020).

The germination of rice grain involves the pre-hydration and subsequent conditioning of the grain based on parameters such as relative humidity, temperature, and time (Lin et al., 2015), which encourage the degradation of complex materials and the synthesis of new compounds, which result in the modification of the embryo (Chen et al., 2016). This phenomenon is accompanied by changes in the enzymatic activities, nutritional and phytochemical composition, physicochemical, and functional properties of the grain (Chungcharoen et al., 2015; Hu et al., 2016; Lee et al., 2019; Xia et al., 2016). The utilization of subsequent germinated rice grain for the production of value-added products with improved bioactivity, nutritional, and physicochemical properties has been exploited (Caceres et al., 2019; Chaijan & Panpipat, 2020; Cornejo et al., 2015; Kim et al., 2012; Li et al., 2019). Some authors have reviewed changes in rice grain quality, in terms of its nutritional, physicochemical, and antioxidant properties after germination (do Nascimento et al., 2022; Imam et al., 2012; Kadiri 2017; Xia et al., 2018), without emphasis on the impact of germination on the techno-functional properties or providing in-depth knowledge on the health-promoting properties of germinated rice grain and its products. This present review, therefore, goes in-depth on the techno-functional, nutritional, and health-promoting properties of germinated rice grain and its products, with a focus on the production of functional foods from germinated brown rice.

1.1 | Effects of germination on macronutrients of brown rice

1.1.1 | Protein and amino acid content of brown rice

Protein is a large organic molecule containing several amino acid (AA) units linked together by peptide bonds that form its building blocks. Some functional characteristics conferred on foods by protein include the ability to act as buffering agents, emulsifiers, fat mimics, gels and foams, and emulsion stabilizers (McClements & Grossmann, 2022). Most dietary proteins are genetically encoded with 20 α-AAs capable of being covalently linked to form varying sizes of peptides. Physiologically, some peptides have been shown to lower blood pressure and manage hypertension (Shobako et al., 2018). Germination is a multiphasic biochemical process that can alter the protein content and overall AA profile of rice in time, temperature, and oxygen-dependent conditions

(Wunthunyarat et al., 2020). These alterations are due to the activation of protease enzymes that aerobically catalyze the hydrolysis of nitrogenous biopolymers into free amino acids (Xia et al., 2016). While there might be no substantial increases in crude protein content during germination due to selective depolymerization and breakdown activities of proteases, dramatic increases in total free amino acids are not uncommon (Xu et al., 2012). Protein tends to decrease after one day of rice germination indicating nitrogen breakdown and transfer to embryonic tissues in contrast to a more passive increase in later days (Tortayeva et al., 2014). However, proteins with low molecular weights of 35 kDa or less were shown to be largely intact during the initial stages of brown rice germination, but proteins of higher molecular weights were hydrolyzed (Mohan et al., 2010). In addition to gamma-aminobutyric acid (GABA), other AAs constitute the most essential functional components of brown rice. However, during brown rice germination, reductions in the contents of certain AAs such as glutamic acid, threonine, and aspartic acid have been reported (Moongngarm & Saetung, 2010). According to Choi et al. (2009), germinated brown rice from large embryos contained high amounts of glutamic acid, aspartic acid, and GABA, whereas glutamic acid, alanine, and cysteine are the most abundant amino acids in normal embryonic brown rice. The authors reiterated that germination alters the concentration of various AAs, with a considerable drop in aspartic and glutamic acid, but an increase in alanine and GABA after 60 h of germination.

Following a comprehensive metabolomic characterization of germinated rice under hypoxic and normoxic conditions, varying amounts of six essential amino acids, including lysine, L-phenylalanine, threonine, isoleucine, methionine, and valine, and other health-benefiting amino acids including GABA, proline, serine, and L-alanine were identified (Ding et al., 2016). Comparative assessment of free AAs in raw brown rice, germinated brown rice, and soaked hypoxic-treated germinated rice showed significant reductions of aspartic acid, asparagine, glutamic acid, and serine following germination (Komatsuzaki et al., 2007), whereas other AAs increased. In contrast, Tortayeva et al. (2014) reported that cysteine showed no significant difference after 7 days of germination, while there was an increase in aspartic acid. The nutritional implication of aspartic acid is linked with its neuroprotective role and ammonia-producing capacities while aspartic acid, glutamic acid, glycine, and alanine are key flavor-enhancing or delectable compounds according to the organoleptic assessment of rice (Ohtsubo et al., 2005). In addition, a study has revealed the elimination of allergenic proteins of varying molecular weights from rice between 5 and 7 days of germination (Tortayeva et al., 2014). Germination in conjunction with soaking has also been found handy in regulating the rate and type of AA production, such that certain proteins are synthesized by a sequence of chemical and biological events, while others are enzymatically hydrolyzed (Owolabi et al., 2019).

1.1.2 | Starch/carbohydrate contents of brown rice

Starch is the main reserve ingredient in cereal grains, accounting for over 80% of the dry weight (Wani et al., 2012). Understanding the starch/carbohydrate content of rice is critical for evaluating its nutritional value, energy contents, potential postprandial glucose release upon ingestion, and techno-functional qualities when processed into different products. Starch is mostly stored in the endosperm and is hydrolyzed during germination, thus, nourishing the sprouting seedling by making soluble sugars available (Wu et al., 2013). According to Xu et al. (2012), germinated brown rice contains less starch (721.1 g/kg) than raw grains (798.9 g/kg). This is because germination stimulates endogenous amylase activities (Chinma et al., 2015) leading to the quantitative depletion of the starch component. Amylase-type enzymes (e.g., α-amylase, β-amylase, and glucoamylase) are the most prominent enzymes in starch hydrolysis and the most frequently stimulated enzyme types during starch hydrolysis. Structurally, starch is a homopolysaccharide composed of repeating units of dehydroglucose linked together by α-1,4 linear chain called amylose and a branching chain by α-1,6 called amylopectin (Haq et al., 2019). All forms of amylases are capable of degrading native starch granules and converting starch into energy-producing mono- and oligosaccharides that are useful during cereal germination for the expansion of plumules. Wu et al. (2013) recorded a significant reduction in amylose and total starch concentrations during aerobic germination of brown rice, mainly due to enzyme-mediated starch degradation. Xu et al. (2012) similarly observed a significant decrease in the amylose content of germinated brown rice starch compared to ungerminated samples. A reduction in amylose content is the key step in starch content reduction during rice germination depending on the nature of the enzymes and germination conditions. Germination has been reported to increase the total reducing sugar in brown rice (Xu et al., 2012).

Higher levels of total reducing sugars corresponding with the activities of α-amylase and α-glucosidase were observed during the germination of waxy rice, especially on the third day, while non-waxy rice produces higher contents of sugars and oligosaccharides (Saman et al., 2008). Ayernor and Ocloo (2007) reported a decrease in starch, reducing and non-reducing sugar concentrations, accompanied by a dramatic rise in amylase activities over 9 days of germination of paddy rice. Similarly, Veluppillai et al. (2009) equally reported a linear increase in amylase activities and sugar content up to the third day of germination. These changes appeared non-linear afterward, due to an asymmetric rate of sugar production and utilization as germination continues. Rice flours from both raw brown rice and germinated brown rice displayed higher reducing sugar and α-amylase activity as steeping duration and pH of steeping water increased (Charoenthaikij et al., 2009). Meanwhile, the total starch contents of glutinous and non-glutinous germinated rice, according to Charoenthaikij et al. (2009), were lower than their respective raw samples. The findings revealed that as steeping time increased or steeping water pH decreased, germinated brown rice flours from both non-glutinous brown rice and glutinous brown rice had significantly higher reducing sugar content and α-amylase activity (Charoenthaikij et al., 2009). The maximum content of reducing sugars in the study was recorded at a pH of 3 after 72 and 48 h for non-glutinous brown rice and glutinous brown rice, respectively (Charoenthaikij et al., 2009).

Ding et al. (2016) reported some carbohydrate-based metabolites found in normoxic- and hypoxic-germinated brown rice to include D-glucose, D-fructose, maltose, and D-turanose. Ofoedu et al. (2021) explored the effects of altering malting conditions on the characteristics of malt, wort, and beer from various locally produced Nigerian rice cultivars. Varying amounts and types of sugars (glucose 10.84–11.63, maltose 14.63–15.34, maltotetraose 0.44–0.63, maltotriose 12.26–16.40, raffinose 0.05–0.07, and sucrose 2.23–2.83) were recorded based on germination period, steeping duration, and kilning temperature (Ofoedu et al., 2021). During germination of brown rice, a significant quantitative depletion of maltose, cellobiose, glucose, sorbitol, and gluconic acid by 11.4, 10, 3, 2.6, 1.7, and 2.3 times, respectively, was reported compared to a non-germinated sample and thereafter increased (Kim et al., 2020). The glucose level of brown rice germinated for over 40 h was very similar to the starting values. Sucrose declined constantly throughout the germination process, and after 48 h, it was almost eight times lower than that of non-germinated brown rice, thus leading to fructose and myoinositol buildup. According to the findings of Chuenprasert et al. (2021), the optimal temperature and germination time of two upland rice varieties are 35°C and 4 days, respectively. In brown rice tea preparation, Kim et al. (2021) reported enhanced synthesis of reducing sugars and free amino acids that jointly contributed to color and flavor formation when germination was combined with roasting. Similarly, a recent study on the static magnetic field-enhanced germination of brown rice supported the pretreatment's stimulating action on the α-amylase enzyme, thus leading to increased reducing sugar formation (Luo et al., 2022). Hence, a careful combination of germination conditions, that is, temperature, duration, and pH (Table 1), with respect to different rice cultivars could improve the nutritional constituents of germinated brown rice.

1.1.3 | Lipid composition of brown rice

As earlier stated, starch is the most abundant constituent of rice; hence, most studies on rice germination barely pay attention to its lipid component. Rice lipids are primarily composed of triacylglycerol of both saturated and unsaturated fatty acids synthesized and stored in a tiny cell organelle called oleosomes (spherosomes) located in aleurone cells, hulls, and embryos and contribute to the oxidative deterioration of rice flavor (Tortayeva et al., 2014; Xu et al., 2021). Unsaturated fatty acids account for around 75% of the total fatty acids in rice, while the remaining 25% are saturated (Albarracín et al., 2019). The low crude fat content of germinated rice has been attributed to its utilization as an energy source during embryonic development and protein synthesis (Tortayeva et al., 2014). During germination and senescence of the cotyledon, lipid storage bodies are cleaved by lipase to release stored triacylglycerols (Guzmán-Ortiz et al., 2019). The first step in this process is catalyzed by a lipase-hydrolyzing enzyme. Characterizations of germinated brown rice with a large embryo (BLE) and brown rice with a regular embryo (BLN) exhibited palmitic (16:0), oleic (18:1), and linoleic acids (18:2) as the principal fatty acids, accounting for more than 95% of the total fatty acid profile (Choi et al., 2009). In this study, there were no identifiable stearic (18:0) or linolenic acids (18:3). The content of oleic acid, the most abundant fatty acid in both varieties of rice, declined during germination (Table 1), while palmitic and linoleic acids increased (Choi et al., 2009). These findings are in contrast with the observations of Shu et al. (2008), who reported a significant increase in oleic, palmitic, and palmitoleic acids during the early stages of germination but a rapid decline after 72 h. The initial increase in free fatty acids could be attributed to the hydrolytic activity of endogenously stimulated lipases on lipids. These lipolytic enzymes break down stored lipids via some redox reactions into fatty acids and energy (Khan et al., 2017). The produced fatty acids, particularly polyunsaturated ones, are vulnerable to oxidative degradation catalyzed by lipoxygenases, which can result in the formation of chemicals that affect the organoleptic properties of the product, primarily hydroperoxides (Sinha et al., 2020). In contrast to the earlier report of Choi et al. (2009), who did not observe stearic and linoleic acids in brown rice, myristic, palmitic, stearic, linoleic, and linolenic fatty acids constitute the fatty acids reported in brown rice

TABLE 1 Some reported chemical composition of raw brown rice and germinated brown rice.

Reference	Constituent	Cultivar/Varieties	Germination conditions	Levels reported in raw brown rice	Levels reported in germinated brown rice
Charoenthaikij et al. (2009)	Protein	Khao Dawk Mali 105 (*Oryza sativa* L. cv. KDML 105) and RD6 (*Oryza sativa* L. cv. RD6), and glutinous brown rice	Ratio 1:5 grain to steeping buffer solution, pH 6.8 at 35°C for 24, 48, and 72 h	6.74%	5.37%–7.06%
	Reducing sugar			14.98 g/100g	15.48–3130.63 g/100g
	GABA			2.11 mg/100g	8.50–67 mg/100g
Choi et al. (2009)	Saturated fat	Keunnun and Ilpumbyeo	Germinated at 30°C, for 12–60 h and fresh water every 6 h	21.2%–22.55%	24.1%–31.4%
	Unsaturated fat			76.95%–78.8%	67.95%–75.9%
	Total free amino acids			53.96–97.6 mg/100g	31.22–163.56 mg/100g
	GABA			6.27–11.83 mg/100g	5.59–81.25 mg/100g
Liang et al. (2010)	Phytic acid	NR	Germinated till the sprout length was 0.5–1.0 mm	17.5 mg/g	13.1 mg/g
	Calcium			28.6 mg/100 g	25.2 mg/g
	Iron			4.2 mg/100 g	1.4 mg/g
	Zinc			2.6 mg/100 g	1.5 mg/g
Moongngarm and Saetung (2010)	Protein	*Oryza sativa* L., cultivar RD-6	Rough rice was dehusked to brown rice and germinated for 24 h, at 28–30°C, with 90%–95% relative humidity	6.98%	8.98%
	Lipid			1.20%	1.23%
	Ash			1.96%	2.06%
	Carbohydrate			79.2%	77.7%
	Fiber			1.13%	1.22%
	Total sugar			0.91%	1.88%
	Reducing sugar			0.19%	0.81%

(Continues)

TABLE 1 (Continued)

Reference	Constituent	Cultivar/Varieties	Germination conditions	Levels reported in raw brown rice	Levels reported in germinated brown rice
	Total free amino acids			2.11%	3.12%
	Phytic acid			1.32%	1.55%
	Thiamine			0.23 mg/100 g	0.12 mg/100 g
	Niacin			7.66 mg/100 g	4.47 mg/100 g
	Pyridoxine			0.76 mg/100 g	0.66 mg/100 g
	α-Tocopherol			0.93 mg/100 g	0.86 mg/100 g
	γ-Oryzanol			66 mg/100 g	84 mg/100 g
	Total phenolic content			70.3 GAE mg/100g	84.3 GAE mg/100g
Xu et al. (2012)	Moisture	Seven diverse japonica varieties (Doongara, Koshihikari, Langi, Reiziq, Sherpa, Tachiminori, and YRW4) were selected from the Yanco Japonica Diversity Variety set used by rice breeders in Australia. Indica variety (TDK8) was added to widen the diversity further. These 8 varieties consisted of glutinous and non-glutinous genotypes, and they differed in grain type (short, medium, long), milled grain texture)	Brown rice sterilized in 1% NaClO for 10 min, washed, and soaked at 25°C for 12 h. Germinated in biological oxygen demand for 24 h at 30°C, with 65% relative humidity	15.98 g/100g	14.92 g/100g
	Total starch content			79.89 g/100g	72.11 g/100g
	Protein			9.65 g/100g	9.48 g/100g
	Fat			3.05 g/100g	3.14 g/100g
	Reducing sugar			1.08 g/100g	2.55 g/100g
	Ash			1.27 g/100g	1.75 g/100g
	Total free amino acids			0.11 g/100g	0.17 g/100g
	Amylose content of starch			17.39 g/100g	12.13 g/100g

(Continues)

TABLE 1 (Continued)

Reference	Constituent	Cultivar/Varieties	Germination conditions	Levels reported in raw brown rice	Levels reported in germinated brown rice
Cáceres et al. (2014)	GABA	INIAP 14, INIAP 15, and INIAP 17 (coded cv. 14, cv. 15, and cv. 17) and GO39839 (coded cv. GO)	Four Ecuadorian rice cultivars were soaked in NaClO (1:5; w/v) at 28°C for 30 min, soaked at 28°C for 24 h and germinated for 48 and 96 h at 28°C and 34°C.	1.34–8.26 mg/100g	44.63–139.32 mg/100g
Osuji et al. (2019)	Protein	NR	10 varieties of rice germinated at 25–30°C for 2 days.	6.18%–8.91%	6.99%–9.39%
	Lipid			2.9%–5.42%	0.97%–1.94%
	Ash			0.49%–1.95%	0.49%–1.94%
	Carbohydrate			73.77%–80.28%	79.78%–84.84%
	Total phenolic content			57.65–77.84 mg GAE/100 g	103.64–306.65 mg GAE/100g
	ORAC			242.67 mg TE/100g	404.51–1054.68 mg TE/100g
Cáceres et al. (2017)	GABA	Brown rice variety *indica* SLF09	Rice was soaked in NaClO (1:5; w/v) at 28°C for 30 min, soaked at 28°C for 24 h and germinated for 48 and 96 h at 28°C and 34°C.	1.07 mg/100 g	24.33–99.03 mg/100 g
	Total phenolic content			132.53 mg GAE/100 g	176.48–429.34 mg/GAE/100g
	ORAC			494.81 mg TE/100 g	554.85–1283.25 mg TE/100 g
Cáceres et al. (2019)	Moisture	*Oryza sativa* subsp. Indica, var. SLF09	Brown rice soaked in 0.1% NaClO for 30 min and germinated for 48 and 96 h at 30°C	84.57 g/100g	83.33–83.67 g/100g

(Continues)

TABLE 1 (Continued)

Reference	Constituent	Cultivar/Varieties	Germination conditions	Levels reported in raw brown rice	Levels reported in germinated brown rice
	Protein			0.89 g/100g	0.8–0.81 g/100g
	Fat			0.48 g/100g	0.46–0.49 g/100g
	Carbohydrate			13.85 g/100g	14.91–15.24 g/100g
	Ash			0.22 g/100g	0.12–0.16 g/100g
	Energy			64.25 Kcal/100g	68–69.28 Kcal/100g
	γ-Oryzanol			0.16 mg/100g	0.14–0.16 mg/100g
	Total solids			14.97 °Brix	15.27–15.37 °Brix
	pH			6.2	5.77–5.97
	Total phenolic content			9.89 mg GAE/100g	9.81–16.19 mg GAE/100g
	GABA			0.05 mg/100g	0.47–0.74 mg/100g
	ORAC			28.22 µg TE/100g	24.78–49.48 µg TE/100g
	ACE-inhibitory activity			10.73%	25.17%–26.05%
Yodpitak et al. (2019)	Total vitamin E		Germinated at 25–28°C for 12–96 h	11.50–21.11 µg/g	29.24–59.66 µg/g
	γ-oryzanol			40.91–57.27 µg/g	63.21–81.42 µg/g
	Total phenolic content			356–786 µg GAE/g	462.8–1461 µg GAE/g
	DPPH			0.41–0.83 mmol TE/kg	0.46–0.94 mmol TE/kg
	Total simple phenolics			14.33%–35.12%	17.50%– 43.31%
	Total phytosterols			1.32%–4.04%	1.83%–5.68%
	Total triterpenoids			3.83%–5.75%	4.09%–7.98%

Abbreviations: DPPH, 2,2-diphenyl-1-picrylhydrazyl; GABA, γ-aminobutyric acid; NR, not reported; ORAC, oxygen radical absorbance capacity.

according to Albarracín et al. (2019), and the amount differed between brown and rough rice. Aside from the possibility of botanical variations, soaked rice flour had a higher content of oleic acid (45.65 g/100 g fat) and a lower content of myristic acid (0.35 g/100 g fat) (Albarracín et al., 2019)

Moongngarm and Saetung (2010), however, observed no substantial change in the crude fat contents of rough and brown rice after germination. In contrast, other authors have observed a steady drop in fat content in the first 24 h of germination, followed by a considerable increase (Cornejo et al., 2015). The effect of germination on the crude fat content of rice varies depending on the portion of the seed and the rice variety. For instance, Kim et al. (2012) reported that the sprout exhibited a higher increase in crude lipids than the hull. Among the 25 identified metabolites during metabolomic characterization of germinated brown rice (Kim et al., 2020), eight lipid metabolites were identified, which include glycerol, palmitic acid, stearic acid, palmitic acid hydrazide, phosphatidylcholine (PC), phytosphingosine, lysophosphatidylcholines (LPCs), and lysophosphatidylethanolamine (LPEs). The identified LPCs increased in lipid metabolism up to 16 h, but no further rise was found up to 48 h, whereas LPEs, PC, phytosphingosine, and palmitic acid hydrazide increased after imbibition. Glycerol levels declined for up to 12 h during germination, but stearic acid and palmitic acid contents somewhat increased. Another investigation indicated that saturated fatty acids in brown, red, and black rice were significantly elevated, while monounsaturated fatty acids were reduced in all treatments except germinated barrio rice. Red, brown, barrio, and white rice had higher polyunsaturated fatty acid contents after germination. They also observed an increment in palmitic acid, although linoleic, oleic, and stearic acids diminished after germination (Rusydi et al., 2011). An investigation showed an increment in stigmasterol levels of glutinous brown rice, red rice, and brown rice after germination; however, campesterol and sitosterol exhibited no significant alterations (Jung et al., 2013).

1.1.4 | Dietary fiber content of brown rice

Dietary fiber (DF) is described as food macromolecules that are resistant to gastrointestinal digestion by human endogenous enzymes and are mostly constituted of plant cell wall materials such as pectic polysaccharides, cellulose, hemicelluloses, and lignin (Csatári & Kovács, 2022). Studies have shown the positive impacts of germination and other similar biochemical processes on the fiber contents of cereals and pulses. In previous findings (Cácere et al., 2014; Chinma et al., 2015), substantial improvements in soluble dietary fiber content of germinated rice flour compared to ungerminated samples were reported. Ukpong et al. (2022) reported a significant increase in the dietary fiber of brown rice during germination at a rate proportional to the duration and attributed this change to the development of new cell wall constituents. Specifically, brown rice showed a higher comparable increase (49.04%) in dietary fiber after germination than wheat (47.95%) and triticale (34.03%) (Sibian et al., 2017). Considering the nutritional and health benefits of dietary fiber, germinated rice could be utilized as a valuable ingredient in functional food development.

1.2 | Effects of brown rice germination on macronutrient digestibility

Germination is a solvent-free, easy, low-cost, and environmentally friendly, biological process that causes compositional changes that are frequently associated with health benefits due to improved digestibility of macromolecules (e.g., carbohydrate, protein, lipid) (Boukid et al., 2019). The impact of germination on the bioavailability and bioaccessibility of nutrients in brown rice grains has been documented and a significant increase in in vitro protein digestibility measured as amino acid bio-accessibility was reported (Xia et al., 2016). The authors reported a positive correlation between germination time and improved protein digestibility within the first 12 h of germination while additional germination time decreased protein digestibility. In addition, germination improved albumin content while globulin and gliadin content decreased, hence its overall better protein bioavailability. Xia et al. (2016) further observed that the rice proteins have low water solubility, thus rendering them less accessible to digestive enzymes and bile salts during in vitro digestion.

Starches are frequently subjected to physical and chemical modifications to improve several key properties such as solubility, hydrophobicity, and digestibility (Masina et al., 2017). Starch digestibility is an important nutritional parameter in the development of functional rice-based diets containing low and stable postprandial blood glucose response (high amount of slowly digestible and indigestible carbohydrate content) (Toutounji et al., 2019). There are a number of inhibitory factors that influence the degree of starch digestibility in grains, which include, the nature of the plant, plant microstructure, antinutrients, amylose content, and dietary fiber components (Chung et al., 2008; Kaur et al., 2010). Amylase facilitates the hydrolysis of starch, reducing sugars such as glucose and maltose and, to a lesser extent, the non-reducing sugar sucrose, thus increasing digestibility (Benincasa et al., 2019).

Studies have shown significant improvement in starch digestibility in cereals and pulses after germination (Chung et al., 2008; Chung et al., 2012; Panlasigui et al., 1991; Toutounji et al., 2019; Xia et al., 2016; Xu et al., 2012). According to Xia et al. (2016), all germinated brown rice samples had higher average digestible starch levels ranging from 54.61% to 81.56%, with an equivalent drop in resistant starch. Similarly, in cooked brown rice, the concentrations of rapidly digestible starch, slowly digestible starch, and resistant starch were 47.3%, 40.8%, and 11.9%, respectively, but increased to 57.7%, 39.1%, and 3.2%, respectively, upon germination (Chung et al., 2012). The improved starch digestibility during this enzyme-mediated biochemical process has been linked to reduced amylose content, reduced granule size, and elimination of anti-nutrients (Ghavidel & Prakash, 2007; Kaur et al., 2010; Ramadoss et al., 2019).

1.2.1 | Vitamins

The most abundant vitamins in brown rice include vitamin B complex (B1, B2, B3, and B6) and vitamin E, which are resident in the rice bran. The whole milling and polishing process used to convert brown rice to white rice removes over 60% of vitamin B3 (niacin), 80% of vitamin B1 (thiamine), and 90% of vitamin B6 (pyridoxine) (Babu et al., 2009). During rice grain germination, new sprouts synthesize more vitamins (Zilic et al., 2015), thus leading to a significant increase in various B complex vitamins and tocopherols (Kim et al., 2012). Vitamin E and total carotenoid contents of pigmented Philippine rice varieties increased upon germination (Bulatao & Romero, 2014). The niacin and vitamin E contents of germinated brown rice were greater by four times and almost three times higher for pyridoxine and thiamine contents compared to milled rice grains (Kayahara & Tsukahara, 2000). Time and temperature are fundamental factors in enhancing the contents of tocopherol and tocotrienol in germinated brown rice. The tocopherol levels of two germinated brown rice cultivars, Taiwan Japonica and Taichung Indica were significantly higher than the raw samples (Lin et al., 2015). Additionally, Pascual et al. (2013) also reported a higher range of tocotrienol levels of some germinated brown rice varieties in comparison to their counterparts. When rough rice was subjected to combined hydrostatic pressure and germination treatment, all its vitamin E derivatives which include α-tocopherol, α-tocotrienol, γ-tocotrienol, and δ-tocotrienol increased substantially (Kim et al., 2017).

The levels of vitamin E in germinated brown rice did not significantly change after germination for 24 h at 30°C (Moongngarm & Saetung, 2010; Watanabe et al., 2004), which suggests that a long germination period is needed to increase vitamin E. Esa et al. (2011) indicated that tocopherol level increased from an undetectable value to 60 mg/100 g in germinated brown rice for 3 days at 30°C, whereas tocotrienol content remained constant. Thiamine content was also significantly increased in germinated brown rice when germination time was applied for 3 to 4 days at 25°C to 30°C (Trachoo et al., 2006). On the other hand, the values of riboflavin, thiamine, pyridoxine, and niacin contents were not altered or even declined when brown rice was sprouted for only 24 h (Moongngarm & Saetung, 2010; Watanabe et al., 2004). These findings could indicate that vitamin synthesis is only started in the late sprouting periods (Moongngarm & Saetung, 2010; Watanabe et al., 2004;).

1.2.2 | Phytic acid and minerals

Although there are reports that suggest the health benefits of phytic acid, which include being an antioxidant and anti-carcinogenic mainly due to its inositol hexaphosphoric acid component (Adebo et al., 2017; Jyoti et al., 2022), phytic acid is nonetheless considered a major anti-nutritive component in rice since it chelates minerals such as magnesium, iron, calcium, and zinc, and negatively influences protein and starch absorption (Oatway et al., 2001). Previous investigation has established that the reduction of phytic acid content by soaking and germination of rice caused an improvement in mineral bioavailability and protein digestibility (Albarracín et al., 2013). Zn and Fe dialyzability, which is the measure of bioavailability, improved significantly from 9.89% and not-detected levels to 35.97% and 30.36%, respectively, while protein digestibility increased from 74.90% to 86.30% after 48 h of germination at 45°C. It was also observed that phytic acid levels reduced when brown rice was steeped and germinated (Cornejo et al., 2015), and the highest reduction of phytic acid (25%) was observed after 12 and 48 h of germination. In comparison to raw and milled rice, the magnesium level of germinated rice was nearly three times higher (Kayahara & Tsukahara, 2000). It was found that phytic acid reduced from 11.7 to 8.4 mg/g through the steeping stage and further declined during germination (Liang et al., 2008). The same study indicated that the germination process had no significant effect on zinc solubility (Liang et al., 2008). It was observed that iron and zinc bio-accessibility measures about 20% to 30% in sprouted rice (Luo et al., 2014); however, Liang et al. (2008) did not detect a substantial increase in zinc bio-accessibility in germinated brown rice, even though phytate content reduced by 54% as a result of three germination days at 30°C.

1.3 | Effect of germination on chemical composition of brown rice products

There are some attempts to develop novel functional foods from germinated brown rice using the extrusion process. Dried germinated brown rice was used to prepare puffed germinated brown rice using twin-screw extrusion, and the resulting product had higher amounts of inositol, gamma-oryzanol, total dietary fibers, and total ferulic acid than un-puffed white rice (Ohtsubo et al., 2005). They also pointed out that replacing wheat bread with 30% puffed germinated brown rice retains higher free sugar (maltose) and GABA contents compared to normal wheat bread. The cookies containing 10% germinated brown rice recorded higher contents of protein, fat, and ash than the control cookies. Control cookies possessed higher amounts of energy and carbohydrates compared to cookies containing germinated brown rice (Mounika et al., 2017).

Recently, the products of germinated brown rice in Japanese food markets have been on the rise due to their higher levels of GABA and many other nutritional substances in comparison to products of polished rice. A study found that bread prepared from wheat flour substituted with 30% brown rice and 30% germinated brown rice possessed 8.60 and 32.05 mg/100 g of GABA, respectively, compared to the control (Cornejo et al., 2015). On the other hand, germination noticeably enhanced GABA levels in bread, and this influence was significantly observed with germination time extension. For instance, breads prepared from 48-h germinated brown rice had six times greater GABA content than its content in the control bread (Cornejo et al., 2015). It was indicated that GABA accumulation during germination of brown rice is time-dependent (Caceres et al., 2017). It is demonstrated that the germination process elevates the quantity of free amino acids, such as GABA (Veluppillai et al., 2010). Cornejo et al. (2015) reported that some amino acids participate in Maillard reaction throughout baking. In fact, it was observed that GABA was greatly involved in nonenzymatic reactions during baking, causing a significant decrease in its level in wheat bread (Lamberts et al. 2012). Germination activates enzymes such as proteases. Accordingly, in vitro protein digestibility was affected, since it was significantly increased in breads containing germinated brown rice for 12 h; however, increasing germination time led to a substantial reduction in protein digestibility (Zheng et al., 2007). It has been found that germination of brown rice raises albumin and declines globulin and gliadin contents, which help to enhance protein bioavailability (Zheng et al., 2007).

Gluten-free bread chemical composition made from brown rice and soaked brown rice showed no considerable differences, except ash content, which was considerably reduced in the bread made from soaked grains. The reason could be due to the mineral leaching in the soaked water (Cornejo et al., 2015). Bread containing pre-germinated and germinated brown rice had lower phytic acid content. The reason could be associated with the leaching of this component or its degradation by the endogenous enzyme (phytase) during germination (Albarracin et al., 2013). Bread made from germinated and pre-geminated brown rice had significantly lower content of γ-oryzanol; however, extended germination time (24 and 48 h) caused an increase in γ-oryzanol, although the values were still less than the control. The used pre-germinated brown rice and germinated brown rice possessed higher values of γ-oryzanol (11 and 14 mg/100g, respectively) compared to their flours (Cornejo et al., 2015). Thermal degradation during baking and activation of *Saccharomyces cerevisiae* feruloyl esterase throughout fermentation would be the main reasons for γ-oryzanol losses, which resulted in the release of ferulic acid (Coghe et al., 2004). Wheat bread containing 35% malted rice flour was also reported to have significantly higher values of free amino acids and total soluble and insoluble dietary fibers than that of 100% wheat bread (Veluppillai et al., 2010).

Hang rice is a Thai traditional food that is prepared by processes including dehusking, soaking, and steaming. Germinated Hang rice, which was prepared from black waxy rice and white non-waxy rice varieties, had a higher total phenolic content (TPC) than that prepared using the red non-waxy rice variety (Phattayakorn et al., 2016). Nevertheless, non-germinated Hang rice prepared using red non-waxy rice recorded a higher level of TPC compared to germinated grains (Phattayakorn et al., 2016). Hang rice antioxidant abilities were also evaluated through 2,2-diphenyl-1-picrylhydrazyl (DPPH) and ferric ion-reducing antioxidant power (FRAP) assays (Phattayakorn et al., 2016). The results revealed that all the prepared germinated Hang rice from different varieties recorded greater antioxidant capacity than non-germinated rice except that prepared from red non-waxy rice as measured by the DPPH method (Phattayakorn et al., 2016). Accordingly, germinated brown rice can be used as functional food ingredients in several food applications, such as breakfast cereals, noodles, cookies, rice balls, bread, milk, and tea.

1.4 | Nutritional implication of in vitro antioxidant activities of germinated brown rice

Whole rice is naturally endowed with arrays of bioactive polyphenols usually in bound and esterified form inaccessible to digestive enzymes in whole grains. The presence of hydroxyl functional groups in their structural conformation enhances their tendencies to participate in many cellular oxidation–reduction processes, many of which have been linked to mediate several physiological disorders (Rudrapal et al., 2022). These compounds are occasionally lost during the milling process since they are typically concentrated in the outer aleurone layer of the grain along with various metal elements (Abeysekera et al., 2020). Hence, the application of enzyme-mediated bioprocesses such as solid-state fermentation, germination, soaking, or a combination of both have been identified as easily adaptable means of maximizing the recovery of bound polyphenols in rice and other whole grains (Khosravi & Razavi, 2020). Depending on the condition of temperature, time, pH, nature of the substrate, and other operational parameters, germination causes increased activation of the enzymes that eventually cleave bound polyphenols and increase their extractability for in vitro antioxidant activities including DPPH, 2,2'-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) (ABTS), FRAP, Trolox equivalent antioxidant capacity (TEAC) (Mencin et al., 2022).

In a study, aqueous extracts of germinated rough and brown rice with TPC contents of 101.90 and 63.70 mg GAE/g, respectively, exhibited strong DPPH, TEAC, and FRAP activities in that order, while their ethanolic extracts were significant for FRAP (Ahmad & Thuraisingam, 2022). Variations in the antioxidant activities of rice have been attributed to both botanical differences and processing methods including germination. After germination, different varieties of Thai indigenous rice exhibited improved extractable phenolic contents and different antioxidant activities (Summpunn et al., 2022). These antioxidant assays such as DPPH and ABTS evaluate free radical scavenging or neutralizing free radicals, which are highly reactive molecules that can harm cells, and hence play a role in a few diseases, such as cancer, cardiovascular disease, and neurodegenerative disorders. The evaluation of these antioxidant activities offers useful information regarding the possible health advantages of various compounds. The combined effects of 24-h fermentation and lactic acid bacteria bioconversion on brown rice revealed a link between the rice's enhanced antioxidant activities (ABTS, DPPH, FRAP, and pancreatic lipid inhibitions) and ability to reduce obesity when fed to worms (Barathikannan et al., 2023). Similarly, in a multivariate nutritional assessment of a specially developed high-nutrient black rice variety, strong positive Pearson correlations ($R^2 >$ 0.70) between antioxidant activities (DPPH, ABTS, and FRAP) and anti-inflammatory properties were exhibited (Mapoung et al., 2023). Thus, a processing step like germination that increases the amount of rice's extractable polyphenols while maintaining a level of in vitro antioxidant activity might be deemed to be improving the grain's nutritional value and consumers' general well-being.

2 | HEALTH-PROMOTING CHARACTERISTICS OF GERMINATED BROWN RICE AND ITS PRODUCTS

In addition to the marked increase in its nutritional quality, germinated rice is gaining wide acceptance over the past decades, due to its excellent health-promoting characteristics. This is attributed to the sudden increase in the incidence of metabolic-related diseases and the potency of dietary approaches for the management of the diseases (Imam et al., 2013). Many studies have correlated the improved functionality of germinated rice to the increased elaboration of bioactive compounds, during its germination, with excellent antioxidant and nutraceutical properties (Chinma et al., 2015; Kaur et al., 2017; Yodpitak et al., 2019). The compounds include oryzanols, GABA, phenolic compounds, anthocyanins, fiber, and tocopherols and have been shown to have good antioxidant, anti-inflammatory, antidiabetic, anti-cholesterolemic, and anti-hypertensive activities (Imam et al., 2013; Imam et al., 2014; Owolabi et al., 2019; Saki et al., 2017; Wunjuntuk et al., 2015).

2.1 | Elaboration of bioactive compounds during the germination of brown rice grains

The bioactive components of germinated rice vary depending on germination conditions, variety, extraction procedure, and cultural practice during cultivation (Ti et al., 2014). Among these, the effect of germination conditions on the functionality of germinated rice is the most studied. The main operating parameters studied include time, temperature, pre-soaking conditions, and pH. Lin et al. (2015) studied the effect of germination time (24–72 h) and temperature (26–36°C) in the presence or absence of light on the functionality of germinated brown rice. They reported that the germination time of 72 h, temperature of 36°C, and absence of light resulted in an optimum concentration of GABA, γ-oryzanol, dietary fiber, and tocopherol. Table 2 gives a summary of studies that show the changes in the antioxidant properties and bioactive components of rice grain consequent to its germination. An increase in GABA of germinated rice is due to the increase in the decarboxylation of glutamic acid to GABA and carbon dioxide owing to the increased activity of glutamate decarboxylase (Maisont & Narkrugsa, 2010). The pathway

TABLE 2 Trends of bioactive constituents in germinated rice.

Reference	Germination condition	Rice type	Influence of germination
Moongngarm and Saetung (2010)	24 h at 28–30°C	Rough and brown rice	TPC, and γ-oryzanol increased by 19.91%, and 27.27%, respectively in brown rice.
Kim et al. (2012a)	72 h	Rough and brown rice	γ-oryzanol increased by 1.13- and 1.20-fold, respectively, in rough and brown germinated rice.
Kim et al. (2012b)	72 h	Rough rice	GABA increased by 107.24% and γ-oryzanol by 1.13 fold.
Ti et al. (2014)	17–48 h	Brown rice	Germination caused an increase in TPC (63.2%), flavonoid (23.6%), free phenolics (58.10%–87.00%), bound phenolics. (22.50%–44.60%), free flavonoid (51.7%), and bound flavonoid (52.4%).
Kim et al. (2014)	4–6 days	Brown rice	GABA, arabinoxylan, and tocopherol increased by 239.98%, 130.30%, and 56.12%, respectively.
Chinma et al. (2015)	48 h at 30°C	New Nigerian local brown rice	TPC of Jamila, Jeep, Kwandala, and MR219 increased by 70%, 67.62%, 65.25%, and 61.06%, respectively, and FRAP increased by 66.34%, 64.36%, 49.12%, and 8.42%.
Lin et al. (2015)	26–36°C	Brown rice	DPPH, reducing power, Trolox, GABA, and tocopherols increased by 101.31%, 76.67%, 291.06%, 256.59%, and 156.25%, respectively.
Shen et al. (2015)	25 h at 30°C	White, red, and black-pigmented brown rice	TPC in white, red, black-pigmented brown rice increased by 12.80%, 25.70%, and 23.30%, respectively, and flavonoid increased by 13.60%, 9.60%, and 0.90%.
Chung et al. (2016a)	72 h at 30°C	Pigmented and non-pigmented brown rice	DPPH, ABTS, hydroxyl radical scavenging, Fe2+ chelating ability, reducing power, superoxide dismutase activity, anthocyanin, TPC, tocopherol, and tocotrienol increased by 141.19%, 316.68%, 28.35%, 21.29%, 92.00%, 698.24%, 0.00%, 48.09%, 210.44%, and 272.97%, respectively, for non-pigmented rice, and 62.54%, 143.77%, 37.38%, 11.53%, 134.29%, 918.30%, 78.15%, 127.72%, 2107.90%, and 140.75% for pigmented rice.
Jirapa et al. (2016)	12–48 h at 35°C	Paddy rice	TPC, flavonoid, DPPH, and ABTS increased by 2.96-, 7.93-, 3.64-, and 5.52-fold, respectively.
Phattayakorn et al. (2016)	Not stated	Black waxy and white non-waxy brown rice	TPC, FRAP, flavonoid, and DPPH increased by 50.88, 25.99, 143.14, and 66.78, respectively, for black waxy rice, and 35.76%, 155.21%, −51.52%, and 6.51% for white non-waxy rice.
Chaiyasut et al. (2017)	36 h	Brown rice	Anthocyanin, TPC, and tocopherol increased by 77.78%, 11.11%, and 29.03%, respectively.

(Continues)

TABLE 2 (Continued)

Reference	Germination condition	Rice type	Influence of germination
Kaur et al. (2017)	28–30°C	Brown rice	TPC, flavonoid, reduced ascorbate, reducing power, hydroxyl radical scavenging activity, DPPH, and FRAP increased by 112.41%, 47.36%, 383.26%, 72.73%, 93.27%, 108.70%, and 31.13%, respectively.
Abubakar et al. (2018)	Not stated	Malaysian brown and white rice	Scavenging activity increased by 7.88%.
Sangsila et al. (2018)	24–48 h	Pigmented and non-pigmented brown rice	TPC, flavonoid, DPPH, and ABTS increased by 156.24%, 116.22%, 64.82%, and 95.46%, respectively. TPC in white, red, black-pigmented brown rice increased by 13.60%, 9.60%, and 0.9%.

Abbreviations: ABTS, 2, 2'-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid); DPPH, 2,2-diphenyl-1-picrylhydrazyl; FRAP, ferric ion reducing antioxidant power; GABA, γ-aminobutyric acid; TPC, total phenolic content.

is controlled by the regulation of the pH as well as the amount of carbon and nitrogen molecules in the substrate before their introduction into the pathway (Kamjijam et al., 2020). The secretion of GABA is favored by the response of rice grains to stress, induced due to the reduction in oxygen concentration, increase in temperature, darkness, and acidification, during germination (Lin et al., 2015).

During germination, there is a secretion of soluble phenolic compounds, which are present in the endoplasmic reticulum or vacuole of the cell, as well as the insoluble phenolics in the cell wall (Idowu et al., 2019). This is achieved following the polymerization and oxidation of polyphenols by enzymes (Ti et al., 2014). Besides, the increase in phenolics is favored by the breakdown of starch, by amylases, to sugars, which go into different metabolic pathways, such as glycolytic, Kreb, tannin, and pentose phosphate and result in the elaboration of numerous intermediate compounds through the activity of different enzymes (Chung et al., 2016a). Phenolics, collectively referred to as hydroxycinnamates, are synthesized during the germination of rice following the hydroxylation or methylation of phenylalanine-by-phenylalanine ammonia-lyase (Ti et al., 2014). Increased flavonoid synthesis is favored by the germination of rice due to the increased activity of esterases, which function in the conversion of acetyl CoA esters through the phenylpropanoid metabolic pathway (Ti et al., 2014). The synthesis of tocopherols and tocotrienols is associated with the activity of photosynthetic organisms in higher plants (Shen et al., 2015).

2.2 | Production of functional foods from germinated brown rice

Due to the increase in the concentration of bioactive compounds in germinated rice, its utilization to produce functional foods is gaining attention. This is imperative due to the yearning of consumers on the importance of consumption of gluten-free and functional foods (Chinma et al., 2015). Germinated rice-based products have been exploited for their functionality in the last decade in bakery products, breakfast cereals, and beverages. Cornejo et al. (2015) reported a higher level of antioxidants, total phenolic content, and GABA in germinated brown rice-based bread relative to the bread produced from brown and parboiled rice. However, they reported a lower concentration of the compounds in germinated rice-based bread compared to the germinated rice flour, and this was attributed to the sensitivity of the compounds to the high baking temperature. Chaijan and Panpipat (2020) also reported the production of a novel functional drink from germinated Jasmine and new local Thai rice varieties. The main operations involved in the process were mashing (at 45–55°C and 4.5–6.0 pH for 30 min), centrifugation (5000 × *g* for 5 min), filtration, and pasteurization (63°C for 30 min). A high concentration of GABA, flavonoid, and total phenolic content was reported for the drink.

Kim et al. (2012a) evaluated an extruded gluten-free breakfast product from blends of germinated brown and white rice and reported an increasing level of GABA, crude fiber, and ferulic acid with an increasing level of germinated brown rice. In recent times, germinated rice-based drinks have been exploited as carriers of probiotic organisms to improve their functionality. Caceres et al. (2019) formulated a probiotic functional drink from germinated brown rice, and soaked rice. They reported that the germinated brown rice-based drink performed best in terms of GABA and phenolic acid content. Li et al. (2019) also reported the production of a probiotic product from germinated brown rice extract using *Lactobacillus acidophilus* as the probiotic organism.

2.3 | The use of germinated brown rice for the control of free radicals and oxidative stress

The high antioxidant properties of germinated rice are attributable to the elaboration of phenolic compounds following the increased activities of enzymes, such as phenolases, during soaking and germination operations (Owolabi et al., 2019). Phenolic compounds are associated with free radical scavenging and increased enzyme activity (Abubakar et al., 2018). Lin et al. (2015) reported a significantly lower EC_{50} in germinated rice, compared to the non-germinated rice indicating the possibility of germinated rice to protect human tissues from free radical-mediated degenerative complications. Tyagi et al. (2022) also reported an improvement in the antioxidant activity of brown rice, in terms of DPPH, ABTS, and FRAP, following its germination due to the elimination of free radicals and consequent maintenance of internal balance, therefore, resulting in a reduction in oxidative stress. Xia et al. (2016) demonstrated the capability of germinated rice to scavenge DPPH and ABTS radicals by estimating its EC_{50}, the concentration of extract required to inhibit 50% free radicals.

During in vivo antioxidant assessment of black rice (though not brown rice) in hyperglycemic rats, Krisbianto et al. (2016) reported that diet supplemented with black rice anthocyanin extracts had lower glucose levels and insulin resistance and alleviated organs' inflammation and steatosis after 6 weeks of treatment. Chung et al. (2016a) reported an increase in reducing power, radical scavenging activity, ferrous chelating, and superoxide dismutase activities of pigmented and non-pigmented brown rice following their germination. The high antioxidant activity of germinated rice is correlated with the increased synthesis of phenolic compounds during soaking and germination (Kaur et al., 2017). Chaijan and Panpipat (2020) reported a high content of GABA, flavonoid, and total phenolic in a functional drink produced from germinated Jasmine and new local Thai rice varieties. They further reported that the drink had a high angiotensin I-converting enzyme inhibitory activity. Angiotensin I-converting enzyme has been implicated for high blood pressure by causing the constriction of blood vessels (Ng et al., 2013). Caceres et al. (2019) also reported a higher angiotensin I-converting enzyme inhibitory activity in a functional probiotic drink produced from germinated brown rice relative to those produced from brown rice and soaked rice. The potential of germinated brown rice in the reduction of oxidative stress has also been investigated. In a study carried out by Wunjuntuk et al. (2015), the oral injection of carbon tetrachloride-induced male Sprague-Dawley rats with germinated rice extract caused a significant reduction in liver injury, protein putrefaction, and lipid peroxidation. They further reported a higher reduction level of DNA damage and increased glutathione content and antioxidant enzyme, especially glutathione S-transferase, glutathione peroxidase, catalase, and superoxide dismutase, activities in animals treated with germinated brown rice relative to the ones treated with ungerminated brown and white rice. Esa et al. (2011) demonstrated that the feeding of New Zealand male rabbit, induced with 0.5% cholesterol, with germinated brown rice, caused a marked reduction in oxidative stress, following the lowering of malondialdehyde, relative to the test animals fed with white and brown rice. Zamri et al. (2014) evaluated the potency of GABA and acylated steryl glycoside, isolated from germinated brown rice extract, on HepG2 cells incubated with hydrogen peroxide. They reported high hydroxyl radical scavenging of the isolates, and this culminated in the prolonged survival of the cells. Esa et al. (2013) reported a higher level of antioxidant activity, in terms of vitamin E, glutathione peroxidase, and superoxide dismutase, in a group of New Zealand male rabbits treated with aqueous extract from germinated brown rice compared to the extracts from white and brown rice.

2.4 | The use of germinated brown rice for the control of inflammatory-related diseases

The germination of rice increases the concentration of L-dopachrome (by 9.93%), a bioactive compound that has inhibitory action against tyrosinase (Sangsila et al., 2018). Tyrosinase, in the presence of physical and chemical catalysts, triggers the mutagenesis of melanin, the main protective organ of the human skin, and this causes the breakdown of tissues and collagen and the eventual aging and inflammation of the skin (Sangsila et al., 2018). Phenolic compounds, especially bound phenolics, have an antimutagenic tendency and have the potential to reduce colon cancer. Bound phenolics are non-digestible by enzymes in the stomach and small intestine because they are covalently bound to the lignocellulosic component of germinated rice; hence, they serve as substrates for the probiotic population in the large intestine, which in turn confers varying antimutagenic responses (Ti et al., 2014). Kim et al. (2014) reported increased activity of cell wall hydrolases and β-D endoxylanase, which triggers the elaboration of tricin 4-O (threo-β-guaiacylglycerol) ether. Tricin 4-O (threo-β-guaiacylglycerol) ethers are diastereoisomeric flavonolignans and have good antitumor activity due to their ability to induce apoptosis in tumor cells and inhibit the production of nitric oxide (Kim et al., 2014). Owolabi et al. (2019) studied the potency of the extracts (200–1000 µg/mL) from germinated and non-germinated brown rice on the viability of murine macrophage induced with lipopolysaccharide from *Escherichia coli*. The ability of the extracts to inhibit nitric oxide, a measure of cytotoxicity and inflammation, production was also evaluated. At a higher concentration, the extracts from the non-germinated and germinated brown rice did not show any significant difference in their ability to maintain the viability of murine macrophage. However, the extract of germinated brown rice, at lower concentrations, had a higher potency for the inhibition of nitric oxide. The reduction in nitric oxide production is an indication of a reduction in toxicity and inflammation as a result of cell membrane damage, and delay in the development of cancerous cells (Vichit & Saewan, 2016).

2.5 | The use of germinated rice for the control of diabetes and obesity

Fundamentally, sugar is the end product of carbohydrate digestion (Imam et al., 2012). In a healthy individual, the production of prepandial glucose triggers the secretion of more insulin to regulate the excess sugar; however, in a diabetic person, the excess sugar accumulates (Imam et al., 2013). Germination triggers the elaboration of amylolytic enzymes, and this causes a reduction in starch content and an increase in dietary fiber content (Chinma et al., 2015). This results in delayed carbohydrate digestion and consequently, a reduction in propandial glucose levels (Imam et al., 2014). Kongkachuichai et al. (2020) reported the glycemic index of 36 h-germinated parboiled rice, brown rice, and parboiled rice to be 60.58, 66.21, and 83.10, respectively.

They further reported improved serum insulin response, bioactive compounds, and dietary fiber in germinated brown rice compared to brown rice and parboiled rice. In a similar study, Chung et al. (2016b) demonstrated that relative to the ovariectomized Sprague-Dawley rats fed for 8 weeks on a normal diet, the consumption of germinated reddish-brown *Superhongmi* cultivar brown rice caused a significant reduction in body weight, glucose and insulin concentration, and the level of markers associated with bone resorption, while glycogen and 17-β-estradiol levels increased. They attributed the improvement in glucose metabolism of the test animals fed with germinated brown rice to the modulation of adipokine and glucose-regulating enzyme production during germination. The stimulation and secretion of insulin are correlated with the increased availability of phenolic compounds (Lin et al., 2015). Besides, the depressive neuro-transmission of GABA helps in the secretion of insulin from the pancreas (Wu et al., 2013). Cornejo et al. (2015) reported a reduction in the glycemic index of brown rice with increasing germination time (0–48 h). Abubakar et al. (2018) also reported an improvement in the glycemic index and load of Malaysian brown rice following its germination.

According to Usuki et al. (2008), the anti-diabetic property of germinated rice is connected to the increased activity of bioactive lipids, especially acylated steryl glycosides which produce Na^+ and K^+ ATPase and homocysteine-thiolactonase. The anti-obesity effect of germinated brown rice, germinated waxy brown rice, germinated black rice, and germinated waxy black rice on 3T3-L1 murine adipocytes induced with a high-fat diet was evaluated by Ho et al. (2012). They found that the use of germinated brown rice caused the most suppression of obesity-related symptoms, such as body weight, serum triglyceride, total cholesterol, liver, and epididymal adipose tissue lipid, in induced mice. They further reported a significant reduction in mRNA transcriptional factors, including sterol-regulating element-binding protein, and peroxisome proliferator-activated receptors, following the treatment of the test animals with crude extract of germinated brown rice.

2.6 | The use of germinated rice for the control of hypercholesterolemic-related disorders

Cholesterol metabolism is correlated to the concentration of propandial glucose level (Imam et al., 2013). Type-2 diabetes often results from insulin deficiency or insensitivity, and this may cause dyslipidemia, which results in a high concentration of low-density lipoprotein, cholesterol, and triglyceride (Chaiyasut et al., 2017). The results of these are atherosclerosis, cardiovascular diseases, disability, and, in some cases, death. The potential of germinated rice extract in the reduction of cholesterol levels in animal studies has been reported. In a particular study (Imam et al., 2013), the hypocholesterolemic effect of germinated brown rice extract, with an appreciable concentration of GABA, γ-oryzanol, and phytosterol glycoside, was investigated. They reported that the extract of germinated and non-germinated caused a significant reduction in the total cholesterol level of the test animal while white rice extract increased it. Besides, germinated and non-germinated brown rice extracts caused a reduction in low-density lipoprotein levels by 60% and 40%, respectively, while white rice extract increased it by 40%. The triglyceride level of the animals treated with germinated and non-germinated reduced by 30% and 3%, respectively, and increased by 3% in animals treated with white rice. The high-density lipoprotein increased, by 15% and 5%, respectively, in germinated and non-germinated rice-treated animals. However, the level of high-density lipoprotein was reduced by 20% in animals treated with white rice extract. The authors attributed the high concentration of bioactive compounds, in germinated brown rice, to the lowering of total cholesterol, low-density lipoprotein, and triglycerides.

While comparing the effect of germinated brown rice, white rice, and brown rice on hypercholesterolemic New Zealand male rabbits, Esa et al. (2013) reported a higher level of reduction of alanine transferase and aspartate transaminase activities and lipid peroxidation in the animal group fed with germinated brown rice. In a more recent study (Ren et al., 2023), in vivo antihyperlipidemic-reducing potential of germinated brown and black rice diets using blood lipids, lipases, apolipoproteins, and inflammation as measuring indices showed that the treated hyperlipidemia rats exhibited reduced triglycerides, total cholesterol, low-density lipoprotein cholesterol, and apolipoprotein B, and a simultaneous increase in high-density lipoprotein cholesterol, hepatic lipases, apolipoprotein A1, and other serum lipid parameters. The hypocholesterolemic activity of germinated brown rice is associated with bioactive compounds, such as GABA and γ-oryzanol, which cause a reduction in cholesterol and aggregation of platelets (Chaiyasut et al., 2017).

2.7 | The use of germinated rice for the control of cancer and cardiovascular disorders

Saki et al. (2017) reported the efficacy of germinated brown rice extract for the management of colorectal cancer and cardiovascular disorders in Sprague-Dawley rats induced with azoxymethane. They reported a marked reduction of β-catenin, aberrant crypt foci size and number, and high-level non-dysplastic aberrant crypt foci in the azoxymethane-induced rats treated with a crude extract from germinated rice. Imam et al. (2014) reported that the oral injection of germinated brown rice extract in rats caused more reduction in lipid profiles compared to the rats fed with white and brown rice. According to Imam et al. (2014), the mechanism of cardiovascular management using germinated brown rice extract is related to the transcriptional regulation of hepatic lipoprotein, ATP-binding cassette, and murine thymoma viral oncogenes.

In the case of transcriptional regulation, the bioactive components in germinated brown rice extract, such as antioxidants and phytochemicals, have been shown to impact gene expression relevant to lipid metabolism. This could include the overexpression of genes related to good lipoprotein synthesis and secretion (e.g., HDL cholesterol) and downregulation of genes associated with detrimental lipoproteins, as demonstrated in a recent study by Azmi et al. (2023) which showed that germinated brown rice caused a significant reduction in lipid peroxidation and excessive amyloid-β (Aβ) buildup, which are risk factors for Alzheimer and neurodegenerative disease. ATP-binding cassettes, on the other hand, are membrane proteins that carry lipids and cholesterol across cell membranes. They affect cardiovascular health by modulating cellular lipid balance. Antioxidant-rich germinated brown rice extract may promote reverse cholesterol transport, which moves excess cholesterol from peripheral tissues to the liver for elimination, potentially lowering the risk of atherosclerosis and inflammatory alterations. The ethanolic extract of germinated brown rice was found to alleviate the pro-inflammatory alterations caused by high-cholesterol meals in the hippocampus by reducing the expression of the mRNA for cholesterol buildup (Azmi et al., 2022). However, thymoma viral oncogenes are mostly linked to cancer, and their direct relation to cardiovascular health is less evident. However, germinated brown rice has anti-inflammatory and antioxidant qualities that may reduce cancer risk factors indirectly. Murine thymoma viral oncogenes are predominantly connected with cancers, with little direct significance to cardiovascular health. Germinated brown rice, on the other hand, is thought to be a prebiotic candidate with anticancer potential. As a result, a combination of GBR and some lactic acid bacteria, such as *L. acidophilus*, boosted caspase-3 expression while decreasing Bcl-2 expression, indicating the ability to suppress colorectal carcinogenesis via increasing antioxidative capacity and causing apoptosis (Lin et al., 2019). In the same vein, Jeon et al. (2013) studied the inhibition potency of ethyl acetate extract of germinated brown rice on HT-29 cells, known to be associated with colon cancer in humans. They reported a high degree of HT-29 cell inhibition following its treatment with the extract. Li et al. (2019) studied the potential of a combination of germinated brown rice and a probiotic, *L. acidophilus*, in the reduction of colorectal carcinogenesis in rats induced with 1,2-dimethyl hydrazine and dextran sulfate sodium. They reported that 2.5% germinated brown rice extract and *L. acidophilus* caused a significant reduction of preneoplastic aberrant crypt foci, sialomucin-producing aberrant crypt foci, anti-apoptotic B-cell lymphoma-2, and Bax expressions.

3 | TECHNO-FUNCTIONAL PROPERTIES

3.1 | Functional, pasting, and rheological properties of germinated brown rice and its products

Germination confers a wide range of physicochemical changes on brown rice that may subsequently determine its appropriate industrial and domestic applications. Many authors have linked the differences in functional properties of germinated and ungerminated brown rice to several intrinsic biochemical alterations that accompany the process (Chinma et al., 2015; He et al., 2022; Saman et al., 2008; Tortayeva et al., 2014). Some functional properties of cereal-based food materials with technological importance are swelling capacity, solubility, oil and water absorption capacity, foaming capacity and stability, emulsion capacity, bulk density, etc. (Chinma et al., 2015; Wang, Hu et al., 2020).

Swelling behavior is a useful quality parameter that predicts the hydration capacity of rice flour relative to its amylose and amylopectin content during gelatinization. In the work of Li et al. (2020), germinated flours made from brown rice and some other cereals had a lower gelatinization enthalpy than raw flours, as the process caused a significant decrease in apparent amylose content and swelling power. This inverse relationship between swelling factor and amylose content had been confirmed earlier as other cereals like sorghum and millet starches exhibited a higher swelling factor than brown rice (Li et al., 2017). After germination, the author observed increased gelatinization onset and peak temperatures, while the final temperature decreased slightly. Other researchers have attributed the reduced swelling factor after germination to the overall reduction in total starch content due to enzymatic hydrolysis (Ilowefah et al., 2015). The lipids and proteins in flour form a film on the surface of the starch granules, limiting granular swelling, especially in grains rich in protein and lipids. Furthermore, the interaction of starch, lipid, and protein in flour may elevate the melting temperature of gelatinization. As a result of the destruction of protein/lipid connections during germination, a lower gelatinization temperature becomes possible (Li et al., 2020; Wu et al., 2013).

Foaming capacity and stability are other important functional properties of brown rice that have a considerable impact on the physical performance of its product during processing and storage stability. These properties depend on the quantity and quality of protein present and its physicochemical behavior during processing. The foaming capacity and stability of brown rice increased remarkably during fermentation, and these changes were attributed to some novel protein functional properties like improved surface activeness, enhanced solubility, and rapid surface adsorption, developed by fermentation (Ilowefah et al., 2015). Similarly, the increased surface activity and quick surface adsorption in rice and other cereals such as sesame and sorghum following germination can be attributed to the activation of enzymes that break down starch and protein into their lower-molecular-weight compounds. These monomeric units, such as maltose, glucose, amino acids, and free sulfhydryl groups lower the surface tension of water, increase the wettability of the rice surface, and encourage efficient water and nutrient uptake. This biochemical mechanism is critical for the successful germination and early growth of the rice plant (Abah et al., 2020; Di et al., 2022). Hence, germination had the same improved foaming capacity and stability on brown rice (Chinma et al., 2015) and sorghum (Elkhalifa & Bernhardt, 2010). Germination also improved the water absorption capacity of rice flour (Wunthunyarat et al., 2020). Under germination conditions, biopolymers are converted into their monomeric hydrophilic units such as sugars and amino acids that could enhance water interaction (Moongngarm et al., 2014).

The water absorption capacity values reported in the literature for germinated rice (0.88–2.28 g/g) are high enough to support the reconstitution ability and textural integrity of its paste. After germination, the bulk density of rice flour was reportedly reduced (Udensi & Okoronkwo, 2006). The decrease in bulk density during germination has been attributed to the decrease in heaviness and dispersibility of flour particles (Sibian et al., 2017). Chinma et al. (2015) also ascribed the decline in bulk density to biochemical alteration of dietary fiber content during germination. Rice germination enhanced the oil absorption capacity of its flour which has been positively related to protein quality, protein surface hydrophobicity, and ability to retain fat globules (Sibian et al., 2017). During germination, there is a likelihood of partial exposure of hydrophobic sites of amino acids thus assisting in oil retention and emulsion capacity (Singh et al., 2015). The ability of germinated rice flour to retain oil implies that it might be a valuable raw material for gluten-free bakery and confectionery products.

Pasting and rheological properties of food describe the systematic physicochemical modifications that occur in foods in the presence of water and heat (Ocheme et al., 2018). Specifically, rheology measures the flow and deformational behavior of food under stress as a measure of its textural properties. It is a useful tool for characterizing the underlying features of materials in food systems. Germination has been found to alter the pasting and rheological behaviors of rice flour and starch, and these changes have significant impacts on the textural properties, digestibility, and ultimate food application of brown rice. Xu et al. (2012) observed a sharp increase in the viscosity of germinated brown rice just below 70°C and a drop in pasting temperatures of both flour and starch. Enzymatic cleavage of glycosidic linkages during starch hydrolysis makes dissolution and saccharification easy during germination thus resulting in low peak viscosity (Charoenthaikij et al., 2009). In contrast, after 12 h of brown rice germination, there was a modest rise in peak viscosity (Cornejo & Rosell, 2015). Rice proteins have been adjudged as the main source of variations in pasting viscosities of germinated rice starch (GRS) and rice flour (GRF) (Zhu et al., 2010). In GRS, the absence of a protein network and removal of hydrolytic byproducts makes the granules more fragile during gelatinization and hence the low pasting viscosity, whereas the presence of rigid disulfide and other protein network bonds in GRF makes the granules less vulnerable to disintegration (Cornejo & Rosell, 2015). However, an extended period of germination of up to 48 h caused a dramatic reduction in viscosity due to the extensive breakdown of starch granules.

Wang et al. (2020) attributed the reduced, peak, final, breakdown, and set-back viscosities, trough and peak temperatures, observed in temperature-dependent GRS to structural disorientation caused by enzyme-mediated starch granule surface erosion (leaching of amylose and amylopectin degradation), lower relative crystallinity, and unfolding of the double helix structure. Similar observations were reported on rice flour of different varieties germinated at 30°C for 48 h (Chinma et al., 2015). The reduced breakdown viscosity of the starch makes it suitable in high-temperature processed foods. The ability of flour to form a stable and viscous paste after cooking or cooling is represented by its final viscosity (Ayo-Omogie et al., 2021). Hence, the low final viscosity of rice flour after germination implies a reduced amylose content, low retrogradation, and less sticky cooked grain (Chao et al., 2022). In contrast to the previous studies, higher values of these pasting parameters were observed in germinated brown rice flour compared to the control (Moongngarm et al., 2014), possibly due to varying methods of germination and rice varieties. The reducing effect of germination on the setback viscosity of brown rice flour and starch offers the benefits of less retrogradation, syneresis, and improved digestibility (Xu et al., 2012). Germination reduced the gelatinization temperature of both rice flour and starch, with flour slightly higher (67.40°C) than starch (65.85°C) due to lipid interference and possible amylose–lipid complexation thus limiting granule swelling.

Other techno-functional properties of brown rice that have shown variations in response to germination and its conditions are starch granule morphology, crystallinity, and structural features. Morphologically, native rice granules had a uniform surface with no observable modifications, whereas after 35°C germination, the rice granules lost their smoothness and appeared uneven and eroded (Kalita et al., 2017). Brown rice starch granules appeared smaller and less homogenous in size after germination (Xu et al., 2012). Studies have attributed these surface irregularities in the germinated rice granules to the hydrolytic activity of enzymes that accompany germination. Pin holes, medium-sized holes, surface erosion, sponge-like erosion, etc. are some of the identified surface modifications in GRS granules (Wu et al., 2013). The degree of structural organization in a starch polymer is referred to as crystallinity, which is strongly related to the amount of amylopectin, whereas amylose resides in amorphous regions (AL-Ansi et al., 2021). This amorphous region is more sensitive to enzymatic hydrolysis during germination than the crystalline section (Almeida et al., 2019). This is due to the loose arrangement of glucose molecules in the amorphous regions, which allows enzymes to more effectively access and break down glycosidic bonds, releasing sugars that feed the growing plant embryo's energy needs. For instance, germinated brown rice exhibited lower calculated relative crystallinity, while the ungerminated brown rice maintained its typical A-type polymorph, under X-ray diffractometry (XRD) (He et al., 2022). The lower crystallinity in germinated rice flour indicates a higher degree of starch gelatinization, making it easier for digestive enzymes to break down these starches into glucose (do Nascimento et al., 2020). Similarly, the reduced crystallinity makes the flour more susceptible to water absorption and retention (Wunthunyarat et al., 2020), which is a desired feature in baking and other food formulations. These flours are extremely easy to handle due to their low rheological qualities, resulting in softer baked items and a longer shelf life. The reduction in relative crystallinity was proportional to the germination time. Similar observations were recorded for germinated rice, malted rice, and other cereals (Lekjing & Venkatachalam, 2020; Li et al., 2017).

In contrast, relative crystallinity increased in the first 12 h of mung bean germination before declining and germination had no significant effect on the starch crystalline type (Liu et al., 2020). The drop in relative crystallinity during rice germination may be due to enzymatic disruption of starch double-helical structures as a result of damaged polysaccharides (amylose and amylopectin) and subsequent development of imperfect crystallites (Kalita et al., 2017). The infrared vibrational bands between 1047 cm^{-1} and 1022 cm^{-1} are responsive to starch's crystalline and amorphous structures, respectively (Yang & Tao, 2008). The band corresponding to the crystalline area fades during germination, while the amorphous zone grows in intensity thus buttressing the XRD observations of other authors (Kalita et al., 2017; Wang, Xiao et al., 2020). Therefore, from the aforementioned, germination may serve as a natural means to modify the techno-functional properties of rice grains for diverse food applications.

4 | CONCLUSION AND FUTURE PERSPECTIVE

Germinated rice has improved nutritional, antioxidant, anti-inflammatory, anti-diabetic, anti-obesity, anti-cancer, and anti-cardiovascular properties. Germination led to a significant reduction of the major antinutrient, phytic acid, in rice grains, thus, improving mineral bioavailability and protein digestibility. Besides, germination modifies the techno-functional properties of brown rice grains for diverse food applications. Germinated rice and derived products have been identified as valuable functional ingredients for the formulation of novel foods that can mitigate chronic and non-communicable chronic diseases and promote health and wellness due to an increased level of dietary fiber, amino acids, peptides, polyphenols, and other bioactive compounds. Subsequent consumption of products developed from germinated brown rice should also be encouraged for consumption such that the benefits of such products would be derived in humans. Further studies are nevertheless needed to determine the optimum germination conditions of some underutilized rice varieties for improved nutritional quality, health-promoting constituents, and low residual antinutrients for the production of functional rice-based products. There is also the need to investigate the physicochemical, nutritional, and techno-functional changes in some varieties of brown rice following germination because the information is relatively scarce in literature and rice-based products still form the major diet of people in Africa.

AUTHOR CONTRIBUTIONS

Chiemela Enyinnaya Chinma: Conceptualization; project administration; writing—original draft; funding acquisition; data curation; validation; resources. **Olajide Emmanuel Adedeji**: Validation; project administration; writing—original draft; data curation. **Olusola Samuel Jolayemi**: Validation; project administration; data curation. **Vanessa Chinelo Ezeocha**: Writing—original draft; project administration; data curation; validation. **Muna Abdulsalam Ilowefah**: Writing—review and editing; validation; project administration. **Cristina M. Rosell**: Writing—review and editing; project administration; validation. **Janet Adeyinka Adebo**: Writing—review and editing; validation; project administration. **Jonathan D Wilkin**: Validation; writing—review and editing; project administration. **Oluwafemi Ayodeji Adebo**: Project administration; writing—review and editing; data curation; validation.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ORCID

Olusola Samuel Jolayemi https://orcid.org/0000-0003-2072-2468
Janet Adeyinka Adebo https://orcid.org/0000-0003-0044-9126
Jonathan D Wilkin https://orcid.org/0000-0001-8272-6865
Oluwafemi Ayodeji Adebo https://orcid.org/0000-0002-3757-5137

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