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Improving the nutritional and nutraceutical properties of wheat and other cereals

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Introduction

With more consumers moving away from traditional cereal-based foods due to concerns about health impacts, including wheat intolerance, the sector must develop next-generation nutritionally-enhanced cereal products to maximise market potential. This collection examines key research into the nutritional components of cereals and their role in preventing chronic diseases. The book is organised into two parts.

Part 1 focuses on the nutritional properties of cereals, with chapters covering aspects such as the nutritional value of starch, antioxidants and lipids in wheat. The first part of the book also addresses how cereal grains can prevent type 2 diabetes and cancer. Part 2 examines developing nutritionally enhanced cereal products. Chapters focus on areas such as understanding the genetics of the nutritional properties of cereals and optimising the effects of processing these properties. Chapters also discuss wheat flour fortification and human help, as well as reviewing the key steps in nutritional enhancement of cereal-based products, specifically emmer, einkorn spelt, sorghum and millet.

Part 1 Nutritional properties of cereals

The first part of the book opens with a chapter on advances in understanding the nutritional value of starch in wheat. Chapter 1 begins by providing an overview of wheat starch structure, focusing specifically on elements such as amylose and amylopectin. The chapter then goes on to discuss A-, B- and C-type wheat starch granules, before highlighting the role of wheat starch in food. It also examines the digestibility of diverse wheat starches, and highlights interactions of starch and other biomolecules such as proteins, lipids, and non-starch polysaccharides. The chapter concludes by emphasising the importance of rapidly digestible and slowly digestible starch in animal and human health.

Moving on from Chapter 1, Chapter 2 focuses on the nutritional value of antioxidants in wheat. The chapter provides a discussion of phytochemical antioxidants in wheat and how these can be extracted. It assesses the methods of analyses for phytochemical antioxidants in wheat grain, such as the analysis of total phenolic, anthocyanins, flavonoids, condensed tannins and carotenoid content. The chapter also discusses the analysis of phenolic compounds, carotenoids and tocochromanols in wheat grains. It then goes on to review the nutritional value of phytochemical antioxidants in wheat, focusing specifically on the effect of these compounds on the nutritional value of wheat food.

Chapter 3 addresses the nutritional value of lipids in wheat. Lipids are a small component in the wheat grain composition (2-4%) and roughly, two thirds

(66%) of them are contained in the germ, 15% are in the bran and particularly in the aleuronic layer, whereas about 20% are distributed in the endosperm, partly within the starch granules. They include a variety of different structural types, i.e. carboxylic acids (or fatty acids); mono, di and triacylglycerols (triglycerides or neutral fats); phospholipids; glycolipids; waxes; terpenes; steroids and alkylresorcinols. This chapter reviews the importance of lipids in wheat kernels and their significance in wheat technology and products. It also addresses the significance of wheat lipids and associated substances in human nutrition. A discussion on the wheat germ and how this wheat germ can be used to produce wheat oil is also included.

Moving on from the nutritional value of various compounds in wheat grains, Chapter 4 focuses on how dietary fibres can prevent the development of Type 2 diabetes mellitus. Dietary fibres are a heterogenous group of food compounds. The physicochemical properties of dietary fibres determine their effects on gastrointestinal and metabolic health, including effect on gastrointestinal transit, glycaemic response, microbial composition and fermentative capacity. Most fibre rich foods contain insoluble, prebiotic and viscous fibres in varying ratios. The chapter begins by discussing underlying mechanisms of action of insoluble fibres. It then goes on to discuss the various dietary fibre intervention studies, specifically focusing on prebiotic fibres and soluble viscous fibres. The chapter concludes by highlighting the importance of consuming high levels dietary fibre and whole grains and their positive impact on metabolic health.

The final chapter of Part 1 examines fibre-associated wheat lignans and colorectal cancer prevention. Wheat, as a staple food, is largely consumed worldwide. In addition to nutritional values, whole grain including fibre-enriched wheat bran has been reported to provide many nutraceuticals such as wheat lignans. Chapter 5 reviews recent epidemiological and animal data on wheat lignans and their role in colorectal cancer prevention. It covers aspects of the lignan structure, biosynthesis, analysis, metabolism and potential health benefits with emphasis on anti-proliferative, antioxidant, anti-inflammation, antiestrogenic and cell cycle arrest mechanisms.

Part 2 Developing nutritionally-enhanced cereal products

Part 2 begins with an overview of the advances in understanding the genetics of the nutritional properties of cereals, specifically focusing on maize and oat proteins. Maize, after rice and wheat, is the most important cereal crop and is globally produced for food and feed. Similar to maize, oats are one of the six major cereal grains grown worldwide, with its production largely focused in the cooler parts of the world. Chapter 6 covers the genetics of maize and oat nutritional properties and the progress that has been made in terms of quality and the importance of these grains as macro- and micro-nutrients in humans. The chapter concludes by emphasising the importance of the biofortification of staple grains to help meet the nutritional demands of global populations.

Chapter 7 discusses developments in fractionation methods to improve extraction of aleurone from wheat grain. In wheat grain, the aleurone layer is located between the peripheral tissues and the starchy endosperm and is rich in soluble proteins, minerals, lipids, vitamins and micronutrients and contains several compounds with antioxidant activity. However, during grain fractionation it is mainly recovered in bran fractions, generally used to feed animals or for energy production. These last few years, the cereal scientist community and companies have developed research and new processing technologies (mainly protected with patents) to exploit its potential more deeply. This was mainly based on an enhanced knowledge of its composition and properties facilitated by a better monitoring of its behaviour along milling, de-branning and further isolation. The chapter summarises main strategies for aleurone layer isolation and pinpoints how its cell walls or cellular content may be of interest to obtain. It also highlights potential drawbacks, the synergistic effect of different compounds, question of bioavailability and possible future trends.

The next chapter focuses on wheat flour fortification and human health. Chapter 8 begins by providing a definition of wheat flour fortification and why its important to fortify wheat flour. It then goes on to discuss the status of wheat flour fortification worldwide and highlights the countries that currently mandate the process, allow voluntary fortification and have standards for wheat flour fortification. The chapter also examines how the impact of wheat flour fortification is measured in terms of human health and provides examples of health outcomes associated with the process. Additional considerations when assessing the health impact of wheat flour fortification are also included, such as the lack of a control group, the challenges of using birth defects registry data, selecting an outcome indicator that is only responsive to the nutrients added through fortification and allowing sufficient amount of time before measuring such outcomes. A section on health impact results observed from wheat flour fortification studies is also provided.

Chapter 9 addresses developing hulled wheat-based cereal products with enhanced nutritional properties, specifically emmer, einkorn and spelt. Hulled wheats have low yields but are suitable for organic and low-input agriculture under marginal or high-stress conditions. However, data on the composition of hulled wheats, often also called ‘ancient wheats’ is still scarce, especially on bioactive components such as vitamins. The chapter begins by discussing protein content and composition in hulled wheats compared to common and durum wheat as well as examining immunogenic and allergenic proteins in hulled wheats. Sections on starch and dietary fibre in hulled wheats are also provided, followed by an analysis of the various antioxidants and micronutrients that can be found as well. The chapter also provides case studies on yellow pigments in einkorn, before concluding with an overview of how hulled wheats have potential in terms of processing healthy and nutritious foods.

Moving on from Chapter 9, Chapter 10 focuses on the nutritional and nutraceutical properties of sorghum. Sorghum is a globally grown cereal. Many sorghum varieties contain high levels of polyphenolic compounds with potential health benefits. With a growing interest in using diet as a preventative measure against chronic diseases, the benefits of sorghum need to be examined. The chapter discusses current research on sorghum and its bioactive compounds, particularly the diversity of polyphenolic compounds present in sorghum. The effects of the phenolic compounds against cancer, their anti-inflammatory properties, anti-obesity effects and effects on gut microbiome are discussed. The chapter also discusses anti-nutritional effects of sorghum polyphenols as well as the effects of processing on bioactive compounds and bioavailability.

Chapter 11 concentrates on developing millet-based cereals products with enhanced nutritional properties. There is a growing awareness today about climate change and its expected ravaging effects on agricultural productivity, food production and ultimately, food and nutrition security. Against this backdrop, drought-tolerant hardy crops are gaining importance as significant sources of food and nutrition especially in the most vulnerable parts of the world mainly in sub-Saharan Africa and Asia. In this regard, the millets, which are major cereal staples in many parts of Africa and Asia are of importance for food and nutrition security in these regions. Millets are processed into various foods using traditional processing methods such as fermentation and malting and modern technologies such as extrusion cooking. This chapter focuses on how these processing methods can enhance the nutritional properties of millet-based foods. The simple practice of compositing millets with other plant foodstuffs for enhanced nutritional quality of millet-based foods is also explored.

Chapter 1

Advances in understanding the nutritional value of starch in wheat

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1 Introduction

Starch is the major component in cereal grains; however, less attention has been given to its contribution to the health benefits of whole-grain foods (Luo and Zhang, 2018). Native starches are insoluble, semi-crystalline granules, and consist of two glucose homopolymers namely, amylose and amylopectin. They are highly variable in structure and functionality between and within plant species, growth conditions, and environment. Variability can also be observed in granule size, shape, amylose content, amylopectin chain length, distribution, and how amylose and amylopectin molecules are arranged into crystalline and amorphous regions within granules. The functional properties of starch, such as swelling, gelatinization retrogradation, pasting, and susceptibility to enzymatic digestion, are very important for food processing and human nutrition (Copeland et al., 2009; Wang et al., 2011).

Digestibility and glucose release are two main physiological properties of starch in terms of nutritional prospectives (Lehmann and Robin, 2007). Nutritionally important starch fractions are divided into rapidly digestible starch (RDS), slowly

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digestible starch (SDS), and resistant starch (RS) based on the rate and degree of digestive enzymes hydrolysis (Englyst et al., 1992). Digestion and absorption of starch in the human body vary depending upon composition. Some starches are digested slowly and help in maintaining blood glucose levels and providing extended energy supply (Brennan et al., 2008; Woolnough et al., 2008). RDS can induce a rapid increase in blood glucose and insulin level and will cause a series of health complications (Jacobs and Gallaher, 2004; Lehmann and Robin, 2007). In contrast, SDS is digested slowly in the small intestine and it will have a lower glycemic response, which will help in controlling and preventing hyperglycemia-related diseases (Zhang and Hamaker, 2009). RS is not digested and absorbed in the small intestine, but it is fermented in the colon (Hoover and Zhou, 2003; Sajilata et al., 2006). The nutritional quality of different starch fractions can be described by the Glycemic index (GI) and it is a term used to describe the levels of postprandial glucose rise in blood as compared to a reference food or glucose (Jenkins et al., 1981). High glycemic index (GI>70) foods have rapid fluctuations in blood glucose levels (Ludwig et al., 1999) and long-term consumption of high-GI foods could lead to different complications such as the imbalance of glucose homeostasis and insulin resistance that are associated with several metabolic diseases such as obesity and type 2 diabetes (Lerer-Metzger et al., 1996).

This chapter aims to provide a nutritional overview of the wheat starch structure, function, digestibility of diverse wheat starches, and highlight interactions of starch and other biomolecules such as proteins, lipids, and non-starch polysaccharides.

2 Wheat starch structure

Wheat (*Triticum aestivum* L.) is an important food source for about 35% of the global population (Zhang et al., 2013). Starch is the main storage carbohydrate in wheat and comprises about 60–75% of grain and 70–80% of flour. It plays an important role in human nutrition as it contributes to >50% of caloric intake in the Western world and up to 90% in developing countries (Wang et al., 2015).

Wheat starch is made up of two polymers namely amylose and amylopectin. Amylose is a primarily linear polymer of (l→4)-linked α-D-glucopyranosyl units with some minor branching, whereas amylopectin is a high-molecular-weight-branched polymer synthesized through α (l→4) and α (l→6) linkages that create branch points (Wang et al., 2014).

2.1 Amylose

Amylose is a left-handed single helix structure with a relative molecular weight of about $1 \times 10^5 \sim 1 \times 10^6$ g/mol and the degree of polymerization of about 300–5000 (Buléon et al., 1998). Approximately 20% of the weight of wheat amylose is complexed with lysophospholipids (90% pure) (Seib, 1994). Amylose content varies for wheat starch granules with different granular sizes. The A-type granules have 4–10% higher amylose content than the B-type granules (Peng et al., 1999; Shinde et al., 2003; Geera et al., 2006; Ao and Jane, 2007; Liu et al., 2007). It could be due to the lower relative crystallinity of A-type granules compared to smaller B-type granules (Ao and Jane, 2007), as the amylose in the starch granules mainly remains in the amorphous lamellae. However, no significant differences in the amylose contents of A-type and B-type granules for certain wheat varieties have also been reported (Salman et al., 2009). In food systems, amylose molecules are largely responsible for the gelling and film-forming properties of cooked starch (Yoo and Jane, 2002; Chung et al., 2008). Amylose has a high tendency to retrograde and produce tough gels and strong films (Pérez and Bertoft, 2010 as cited in Hizukuri et al., 1970). Molecular weight (Mw) of amylose is reported to range from 1.88×10^5 (Mukerjea and Robyt, 2010) to 3.90×10^6 g/mol (Ong et al., 1994) using different wheat starches and measurement techniques. The starch molecules within A-type wheat starch granules seem to possess more of the longer chains (degree of polymerization (DP) > 25), and fewer of the short chains (DP <12) than B-type wheat starch granules (Liu et al., 2007).

2.2 Amylopectin

Wheat amylopectin has a cluster structure with a large number of branching structures on its molecular chains. Its relative molecular weight is about $1 \times 10^7 \sim 5 \times 10^8$ g/mol and its DP is more than 10^7 (Tester et al., 2004; Whistler and Daniel, 1984). But recent studies indicated that High Performance Size Exclusion Chromatography (HP-SEC) underestimates the size of amylopectin due to the shearing of that polysaccharide (Cave et al., 2009). The amylopectin molecules are associated with the crystallinity, gelatinization, and swelling of starch (Yoo and Jane, 2002; Chung et al., 2008). Amylopectin, dispersed in water, is more stable and produces soft gels and weak films (Pérez and Bertoft, 2010 as cited in Hizukuri et al., 1970).

3 Granules of wheat starch

Native starch occurs as semi-crystalline granules (Fig. 1) and has a very complex hierarchical structure. The starch granules are composed of an amorphous bulk core area surrounded by concentric semi-crystalline growth rings alternating with amorphous growth rings (Wang et al., 2015). The amorphous core contains amylose and amylopectin chains disordered at the reducing end (Wang and Copeland, 2012).

Starch is synthesized as discrete granules of varying sizes in amyloplasts. Different sizes and shapes of starch granules build up during the development

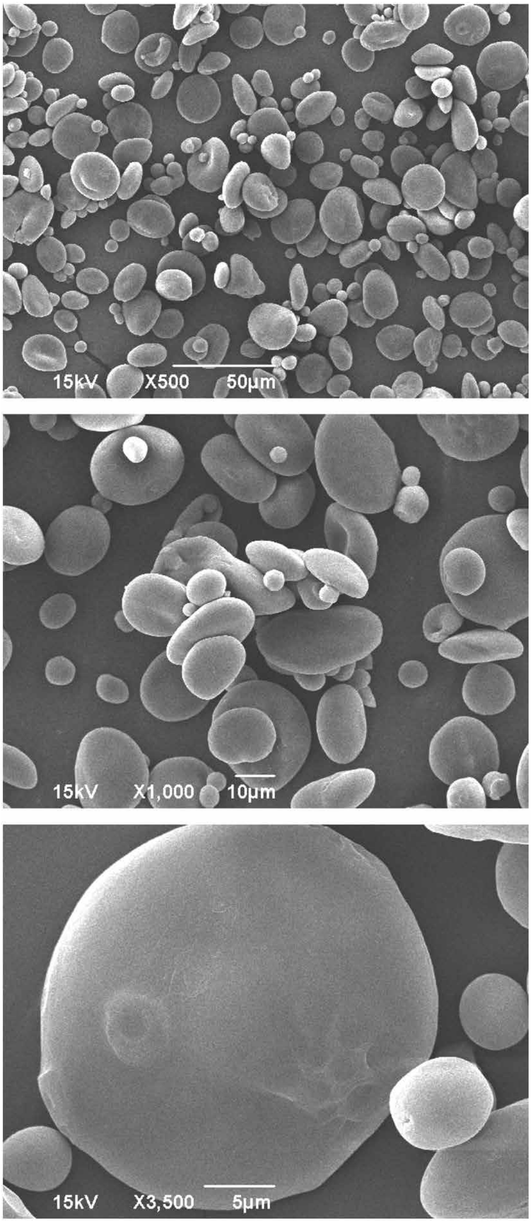

Figure 1 Scanning electron microscopy (SEM) images of wheat starch granules shown at X500, X1000, and X3500 magnification. (This material is based on work supported by the National Science Foundation under Grant Nos. 0619098, 0821655, 0923354, and 1229417. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation).

of grain. The starch granule distribution of different wheat starches is shown in Table 1. Wheat starch has a trimodal distribution of starch and consists of 3 different types of starch granules large (A), intermediate (B), and small (C) granules (Bancel et al., 2010; Cao et al., 2015).

3.1 A type granules

The A-type starch granules are disk or lenticular in shape with a diameter of >10 μm (Vermeylen et al., 2005; Ao and Jane, 2007; Kim and Huber, 2008; Wang et al., 2014). These granules contribute to more than 70% total weight of the starch in wheat (Bechtel et al., 1990; Peng et al., 1999; Shinde et al., 2003). A-type granules have higher gelatinization enthalpy, amylose content, pasting parameters such as peak, trough, breakdown, final and setback viscosities, and lower gelatinization onset and peak temperatures compared to B type granules (Sahlström et al., 2003; Geera et al., 2006; Soh et al., 2006; Kim and Huber, 2010; Yin et al., 2012). They also contain more amylose and less lipid than B-granules (Maningat et al., 2009; Tao et al., 2016). The proportions of A- and B-starch granules differ among genotypes by weight, volume, and number (Raeker et al., 1998; Li et al., 2001).

3.2 B-type granules

B-type starch granules are spherical or polygonal in shape and measure less than 10 μm in diameter (Vermeylen et al., 2005; Ao and Jane, 2007; Kim and Huber, 2008; Wang et al., 2014). Although they make up <30% of total starch weight, B-type granules comprise up to 90% of granules in number (Raeker et al., 1998). B-starch granule volume variation was wider in bread wheat, suggesting possibilities of genetic manipulation of the granule size distribution (Stoddard, 1999).

The B-granules occupied volumes in the range of 28.5–56.2% for hard red winter and hard red spring wheat (Park et al., 2009). The volume percentages of A- and B-type starch granules were 52.7–65.5% and 34.5–47.3% in seven Chinese wheat cultivars (Dai et al., 2009). In several studies, environmental stress such as temperature (Liu et al., 2011), water deficit (Dai et al., 2009; Zhang et al., 2010), nutrient supplementation (Ni et al., 2012; Li et al., 2013), and light intensity (Li et al., 2010) significantly changed starch granule size distribution and amylose content in wheat. B-type granules have lower gelatinization enthalpy, higher lipid-complexed amylose content higher swelling power, and broader gelatinization ranges compared to A-type granules (Sahlström et al., 2003; Geera et al., 2006; Soh et al., 2006; Kim and Huber, 2010; Yin et al., 2012). The proportion of B-granules is of particular importance in the commercial production of wheat starch because these granules owing to their smaller size are difficult to purify and recover than A-granules (Wei et al., 2010; Yu et al., 2015).

Table 1 Granule size distribution of wheat starches (Singh et al., 2008, 2009, 2010; Shevkani et al., 2011; Blazek and Copeland, 2008; Li et al., 2013; Kaur et al., 2016; Wilson et al., 2008 as cited in Shevkani et al., 2017).

Wheat species	Hard/Soft wheat	Type of granules	Distribution	% of A granules	% of B granules	% of C granules
Common			Trimodal	71.4–79.1	12.1–19.7	7.6–9.4
			Trimodal	45.6–73.2	14.0–37.0	10.5–17.5
			Trimodal	63.7–68.9	20.2–22.3	10.8–14.9
			Trimodal	71.4–79.1	12.1–19.7	7.6–9.4
			Bimodal	57.6	42.4	
	Hard		Bimodal	75.4	14.6	
	Soft		Bimodal	75.0	25.1	
	Hard	A	Bimodal	92.3	7.7	
	Soft	A	Bimodal	91.0	9.0	
	Hard	B	Bimodal	13.3	86.7	
	Soft	B	Bimodal	12.5	87.5	
Durum			Trimodal	69.9–85.4	9.4–20.1	4.7–10.0
Spelt			Trimodal	37.7–71.6	25.8–55.0	2.4–6.8

3.3 C type granules

C-granules are roughly spherical or oval and irregular or cuboidal in shape and exhibited an average size of 2–3 micrometers. However, B- and C-granules were sometimes considered together as small B-granules (Bancel et al., 2010; Cao et al., 2015).

A wide variation in granule size distribution exists amongst starches from different wheat type and cultivars/varieties (Table 1). The starches from hard wheat varieties were observed to contain a higher proportion of B-granules and a lower of A-granules than soft wheat (Li et al., 2008; Edwards et al., 2010; Singh et al., 2016). Normal and waxy starches have both A- and B-granules; however, these differed in relative granule size distribution and morphology. The starch from normal wheat contained more B-granules (Zhang et al., 2013), while that from waxy cultivars/varieties showed more spherical disc-like granule morphology (Zhou et al., 2014).

4 Role of wheat starch in food

Wheat starch has a significant role in food systems. Wheat starch can affect the appearance, texture, cooking characteristics, and eating quality of different foods. It can act as a tenderizer in cakes, doughnuts, cookies, and cheese analogs. It is also incorporated into batters, ice creams, soups, gravies to provide adhesion, structure, moisture control, and/or thickening (Maningat et al., 2009).

Wheat starch gelatinizes at 5–10°C below that of corn, rice, potato, and tapioca starches. The low gelatinization temperature of wheat starch results in rapid cooking in microwaveable soups, sauces, and gravies, but it has been reported that wheat starch generally has a lower paste viscosity compared with other commercial starches (Ral et al., 2008).

The wheat starch plays a significant role in bread making. It acts as a filler, provides extra sugars for fermentation. The sugars are provided by the degradation of damaged starch through amylase action (Glennie et al., 1987). Wheat starch provides a surface suitable for a strong union with the gluten adhesive and dilutes the gluten to a consistency desirable for dough processing during dough mixing (Hoseney et al., 1971; Hoseney, 1994). During baking, starch granules in the bread dough gelatinize, become flexible, and elongate as the gas cell walls expand, but the granules do not disintegrate (Lagrain et al., 2008). When granules swell, they also exude amylose that pools in the center of swollen granules, between granules, and at the starch-gluten interface (Hug-Iten et al., 2003). The crumb structure in fresh bread is set during cooling further by the gelling and crystallization processes of the pooled amylose and the stiffening of the swollen granules. Storage of bread over a period of time causes undesirable textural changes and loss of flavor. In bread staling, the crust becomes 'leathery' as moisture migrates from crumb to crust.

However, in some products such as noodles and pasta, retrogradation is promoted to improve textural and sensory properties as increased firmness, and reduced stickiness are desirable in such products. Additionally, retrogradation was also considered desirable in terms of the nutritional significance as retrograded starches were digested slowly and less completely than unretrograded starches, resulting in unstable postprandial blood glucose levels. Starch influenced cooking characteristics, appearance, and texture of cooked noodles (Ross et al., 1997; Zhao and Seib, 2005).

Wheat starch has been identified as an attractive choice to produce edible and/or biodegradable films due to low cost, high availability, renewability, and biodegradability (Lu et al., 2009).

5 Digestibility of wheat starch

Starch digestibility has gained substantial interest concerning the increasing incidence of non-communicable diseases (Wang et al., 2015). Nutritionally, starch can be categorized into 3 categories: rapidly digestible starch (RDS), slowly digestible starch (SDS), and resistant starch (RS) (Table 2).

5.1 Rapidly digestible starch

The starch that is digested rapidly or the amount of glucose release after 20 minutes (Englyst et al., 1992) in the upper gut causes a rapid elevation of glucose into the bloodstream. RDS can trigger physiological responses that over time are associated with increased risks for diabetes, cardiovascular disease, and cancer (Brand-Miller, 2003). It can produce large fluctuations in postprandial glycemia, which induces oxidative stress that may be a health concern (Monnier et al., 2006).

The postprandial physiological response was investigated to the ingestion of RDS in healthy subjects and type 2 diabetics (Ells et al., 2005, Seal et al., 2003). Significantly greater and more rapid changes in blood glucose and insulin were observed after the consumption of RDS compared to SDS. RDS differ from SDS in their ability to stimulate the secretion of gut incretin hormones. Glucagon-like peptide-1 (GLP-1) and glucose-dependent insulinotropic polypeptide (GIP) increased in the late postprandial phase (180–300 min) after SDS consumption. This could indicate beneficial effects of SDS in the late postprandial phase (Wachters-Hagedoorn et al., 2006).

Table 2 Nutritional classification of starch (Englyst et al., 1992).

Starch type	Starch structure	Digestion rate in the small intestine	Digestion timeline/place	Examples
RDS	Amorphous	Rapid	Within 20 minutes, the mouth, and small intestine	Freshly cooked starch, white bread
SDS	Amorphous/crystalline	Slow	20–120 minutes, small intestine	Most cereal starches
RS	Depending on the type mainly crystalline	Resistant	>120 minutes The main action in the colon	
RS1	Depending on the type	Resistant		Partially milled grain
RS2	Depending on the type	Resistant		Raw potato and banana starch
RS3	Depending on the type	Resistant		Cooled cooked potato
RS4	Depending on the type	Resistant		Cross-linking starch

*RDS – Rapidly Digestible Starch, SDS – Slowly digestible starch, RS – Resistant starch.

5.2 Slowly digestible starch

The amount of glucose released between 20 and 120 minutes, after hydrolysis of starch in the small intestine are called slowly digestible starches (SDS) (Englyst et al., 1992). SDS has a medium to low GI and thus reduces the glycemic load of a food product compared to rapidly digestible starch with a high GI (Ells et al., 2005; Englyst et al., 2003). Jenkins et al. (2002) stated that low GI diets are associated with decreased risk of diabetes and cardiovascular diseases. In addition, positive associations were found between dietary GI and risk of colon and breast cancer.

A few studies investigated the postprandial physiological responses to the ingestion of RDS and SDS in healthy subjects and type 2 diabetics (Ells et al., 2005 Seal et al., 2003). A reduction of potential risk factors for metabolic syndrome by the exchange of RDS by SDS was proposed (Ells et al., 2005). In obese, insulin-resistant subjects, Harbis et al. (2004) showed that the intake of slowly available glucose resulted in an improved metabolic profile, particularly in lower postprandial insulinemia, lower levels of circulating triacylglycerols and apolipoproteins B-100 and B-48 in the triacylglycerol-rich lipoproteins. Also, rapidly and slowly digestible starches differ in their ability to stimulate the secretion of gut incretin hormones. Glucagon-like peptide-1 (GLP-1) and glucose-dependent insulinotropic polypeptide (GIP) increased in the late postprandial phase (180–300 min) after SDS consumption. This could indicate beneficial effects of SDS in the late postprandial phase, for example, related to glucose homeostasis and energy storage (Wachters-Hagedoorn et al., 2006).

Epidemiological studies suggest that reduced postprandial glucose peaks, reduced episodes of hypoglycemia, improved lipid response, lower concentration of glycosylated hemoglobin and fructosamine, and greater insulin sensitivity are beneficial for diabetes management (Wolever et al., 2003). Slowly digestible starch intake results in a beneficial metabolic response for these conditions and is recommended for the prevention and management of diabetes (Axelsen et al., 1999; Ells et al., 2005; Seal et al., 2003). It was shown that SDS-containing foods at breakfast improved carbohydrate metabolism and reduced insulin requirement of insulin-treated type 2 diabetic patients (Golay et al., 1992).

Studies to date on the health benefits of SDS are limited. Furthermore, most studies do not make a precise distinction between starch fractions. The potential health benefits of SDS are linked to stable glucose metabolism, diabetes management, mental performance, and satiety.

6 Resistant starch

The portion of starch and starch products that resist digestion as they pass through the gastrointestinal tract are called resistant starch (Nugent, 2005). It

Table 3 Resistant starch content of wheat and wheat-based products

Wheat type or wheat product	Resistant starch content	Reference
Wheat grain	13.6*	(Lunn and Buttriss, 2007)
Wheat flour	1.7*	(Lunn and Buttriss, 2007)
White bread	1.9*	(Lunn and Buttriss, 2007)
Whole wheat cereal, flaked	1.0**	(Murphy et al., 2008)
Crackers, wheat thin	0.4**	(Murphy et al., 2008)
Whole wheat bread	1.0**	(Murphy et al., 2008)
Wheat rolls	0.1**	(Murphy et al., 2008)
Wheat germ bread	0.1**	(Murphy et al., 2008)
High fiber white bread	0.9**	(Murphy et al., 2008)

*-Grams per 100 g of dry matter.
**-Grams per 100 g of food.

is also defined as the fraction of starch that is not hydrolyzed to its monomeric units, D-glucose in the small intestine within 2 hours of being consumed but can be fermented in the colon, which does not lead to a significant increase in blood glucose concentration after consumption (Goni et al., 1997; Yamada et al., 2005). Resistant starch intake ranges approximately 30–40 g/day (Baghurst et al., 2001), from 3 g/day to 6 g/day (Dyssler and Hoffmann, 1994), and 5–7 g/day (Baghurst et al., 2001) in developing countries, the European Union, and Australia, respectively. Resistant starch content of wheat and wheat based products are shown in (Table 3).

Most of the studies have shown that resistant starch is a linear molecule of α-1,4-D-glucan derived from the retrograded amylose fraction and it has a relatively low molecular weight (1.2×10^5) (Tharanathan, 2002).

The reason for the resistance of digestion in the small intestine can depend upon several factors. Mostly, the starch granules are not accessible to digestive enzymes such as amylases due to the compact molecular structure (Haralampu, 2000). The resistance of starch to digestion is influenced by the nature of the association between starch polymers, with higher amylose levels in the starch being associated with slower digestibility rates.

Based on the structures contributing to the enzymatic resistance, RS can be categorized into five different types. These are discussed in the following sections.

6.1 Resistant Starch-1 (RS1)

The content of different types of resistant starch in wheat and wheat products are shown in Table 4. RS1 is the physically protected form of the starch found in whole grains, seeds, or tubers and physically inaccessible to digestion, due to the presence of intact cell walls in grains, seeds, or tubers (Hernández et al.,

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