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Review

Resistant starch as functional ingredient: A review

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ABSTRACT

Dietary starches are important sources of energy for many human societies and it is clear that they can also make quite specific contributions to health. Resistant starch has received much attention for both its potential health benefits (similar to soluble fibre) and functional properties. Resistant starch positively influences the functioning of the digestive tract, microbial flora, the blood cholesterol level, the glycemic index and assists in the control of diabetes. Apart from the potential health benefits of resistant starch, another positive advantage is its lower impact on the sensory properties of food compared with traditional sources of fibre, as whole grains, fruits or bran. Among its desirable physicochemical properties are its swelling capacity, viscosity, gel formation and water-binding capacity, which make it useful in a variety of foods. In this review, we discuss different types of resistant starch, food sources, and potential health benefits and food applications of resistant starch.

Contents

1. Introduction

The increase in consumer demand for high quality food products has led to a growth in the use of new technologies and ingredients. Several factors influence changes in consumer demand, including: health concerns (cholesterol, cancer, obesity, etc.), changes in demographic characteristics (ethnics, population ageing, etc.) (Pérez-Alvarez, 2008a), the need for convenience, changes in distribution systems and price. As a result of these changes, interest in new products, particularly convenience oriented products prepared using new technologies (Fuentes-Zaragoza et al.,

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2009,2010), high pressures, etc., has dramatically increased in recent years. The food industry offers quality and convenience to a wide spectrum of consumers including single households, working couples, the ageing population, and others (Pérez-Alvarez, 2008b; Fagan & Gormley, 2005). To develop these types of products, one must evaluate consumer perceptions, the most important quality aspects being that they taste good, appear healthy and have nutritional value (Garcia-Segovia, Andres-Bello, & Martinez-Monzo, 2007). Also Pérez-Alvarez (2008b), describe that any functional food must be safety, healthy and tasty.

The greater awareness on the part of consumers of the relationship between a nutritious diet and health and well-being has been one of the reasons for the increase in popularity of novel food with good nutritional properties (Pérez-Alvarez, 2008b; Sanz, Salvador, & Fiszman, 2008a).

Actually, considerable importance is given to functional foods, which, in principle, apart from their basic nutritional functions, provide physiological benefits and/or reduce the risk of chronic diseases. Functional foods either contain (or add) a component with a positive health effect or eliminate a component with a negative one. One of the added components could be resistant starch (RS) (Mikulíková, Masár, & Kraic, 2008), which is widely used as a functional ingredient, especially in foods containing high dietary fibre levels.

These foods are used to prevent several pathologies such colon cancer, diabetes or obesity. Obesity is a complex condition, with serious social and psychological dimensions, that affects virtually all age and socioeconomic groups (Trasande et al., 2009) and which threatens to overwhelm both developed and developing countries (Kelaher et al., 2008). WHO projections indicate that globally in 2005 approximately 1.6 billion adults (age 15+) were overweight, 400 million adults were obese and, at least, 20 million children under the age of 5 years were overweight. WHO further projects that by 2015, approximately 2.3 billion adults will be overweight and more than 700 million will be obese (Viuda-Martos et al., 2010). Once considered a problem only in high-income countries, overweight and obesity are now dramatically on the rise in low- and middle-income countries, particularly in urban settings (WHO, 2006; Jokela et al., 2009). It is therefore critical to identify which changes in food choices will be the most effective in reducing obesity. Energy dilution of the diet with fruits, vegetable, and whole grains is considered a possible way to fight obesity (Pérez-Alvarez, Fernández-López, & Sayas-Barberá, 2003), since all of them contain high amounts of fibre and water that dilute the metabolizable energy content per volume of food (Keenan et al., 2006).

There is general consensus among public health authorities and nutritionists that the inclusion of fibre in the human diet provides health benefits (Férnandez-López et al., 2007). That benefit message has reached consumers, and many meat product companies, for example, have responded by launching products fortified with fibre (Fernandez-Ginés, Fernández-López, Sayas-Barberá, & Pérez-Alvarez, 2005; Pérez-Alvarez, 2008a). Many studies have found that people on diets high in fibre have reduced risks of certain diseases such as cancer, coronary heart disease, obesity and possibly diabetes (Canovas & Pérez-Alvarez, 2006). Some health benefits linked to fibre consumption are well established (e.g. promoting a regular bowel habit) and others are slowly becoming more firmly established (Buttriss & Stokes, 2008; Viuda-Martos et al., 2010).

Some recommendations have been made for general carbohydrate consumption by FAO and WHO: the Acceptable Macronutrient Distribution Range (AMDR) for carbohydrates is 55–75% of energy intake, and the Adequate Intake (AI) for total fibre is 38 g for men and 25 g for women; added sugars should be limited to 10% of the total energy intake (FAO/WHO Expert Consultation, 2002). However, FAO and WHO recommendations are based on reducing the risk of coronary heart disease and other diseases, and do not consider total low digestible carbohydrates (LDC) consumption (fibre, resistant starches, and sugar alcohols) nor recommend an upper limit for LDC intake based on potential gastrointestinal effects (Grabitske & Slavin, 2008).

Dietary fibre (DF) can be defined from different points of views, including legal, technological, chemical, nutritional and functional. Hipsley defined fibre in 1953 (Buttriss & Stokes, 2008) but, dietary fibre is not an entity, but a collective term for a complex mixture of substances with different chemical and physical properties, which exert different types of physiological effects. Dietary fibre was first defined as non-digestible components of plants that make up the plant cell wall: cellulose, hemicelluloses (both non-starch polysaccharides) and lignin. The Commission of The European Communities (2008) defines ‘fibre’ as carbohydrate polymers with three or more monomeric units, which are neither digested nor absorbed in the small intestine.

In 2001, the Institute of Medicine’s Panel on the Definition of Dietary Fibre provided an updated definition of dietary fibre and defined total fibre as the sum of dietary fibre and functional fibre. They defined dietary fibre as “non-digestible carbohydrates and lignin that are intrinsic and intact in plants”, where non-digestible means not digested or absorbed in the human small intestine, and functional fibre as “isolated, non-digestible carbohydrates that have beneficial physiological effects in humans” (Mermelstein, 2009).

The Codex Alimentarius Commission’s Committee on Nutrition and Foods for Special Dietary Uses, adopted a new definition of dietary fibre for inclusion in the Guidelines on Nutrition and Health Claims. The committee defined dietary fibre as “carbohydrate polymers with 10 or more monomeric units, which are not hydrolyzed by the endogenous enzymes in the small intestine of humans”. The committee also allowed local authorities to decide whether to include or exclude polymers with 3–9 monomeric units (Mermelstein, 2009).

In the early development of the NSP determination, a fraction of starch was identified that could not be hydrolyzed without prior chemical dispersion. This starch fraction, identified subsequently as retrograded starch, was termed resistant starch (Englyst & Englyst, 2005). Thus, there are many components, such as resistant starches and the oligosaccharides, which, by their indigestible nature, could be considered to contribute to the total amount of dietary fibre in the diet. Dietary fibre can be classified according to its origin (vegetal, animal...), and also according its solubility (Table 1).

2. Resistant starch definition

Starch is the major source of carbohydrate in the human diet (Ratnayake & Jackson, 2008). It occurs in many plant tissues as granules, usually between 1 and 100 μm in diameter, depending upon the plant source. Chemically, starches are polysaccharides composed of α-D-glucopyranosyl units linked together with α-D-(1–4) and/or α-D-(1–6) linkages, and are comprised of two molecular types: amylose, the straight chain polyglucan comprised of approximately 1000, α-D-(1–4) linked glucoses; and amylopectin, the branched glucan, comprised of approximately 4000 glucose units with branches occurring as α-D-(1–6) linkages (Sharma, Yadav, & Ritika, 2008; Haralampu, 2000).

Two crystalline structures of starch have been identified (an ‘A’ and ‘B’ type), which contain differing proportions of amylopectin. A-type starches are found in cereals, while B-type starches are found in tubers and amylose-rich starches. A third type called ‘C-type’ appears to be a mixture of both A and B forms and is found

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Table 1

Types of dietary fibre, its description and principal sources. *Sources*: Dutta et al. (2009), Mermelstein (2009), Sharma et al. (2008), Lunn and Buttriss (2007), Charalampopoulos et al. (2002), Tharanathan (2002), and Quesada and Pérez-ALvarez (2006).

Origin	Chemical component	Description	Sources
Plant	material	IDF[a]	Cellulose
	Polysaccharides comprising up to 10,000 closely packed glucose units, arranged linearly, making cellulose very insoluble and resistant to digestion by human enzymes	Principal component of the cell walls of most plants Forms about 25% of the fibre in grains and fruit and about a third in vegetables and nuts Much of the fibre in cereal bran is cellulose	
	Hemicellulose	Polysaccharides containing sugars other than glucose Associated with cellulose in cell walls and present in both water soluble and insoluble forms	Forms about a third of the fibre in vegetables, fruits, legumes and nuts The main dietary sources are cereal grains
	Lignin	Three-dimensional network of coupled monomers of a varied 4-hydroxyphenylpropanoid type	Foods with a woody component, for example celery, and the outer layers of cereal grains
	Resistant Starch	Polysaccharides composed of linear α-1,4-D-glucan, essentially derived from retrograded Amylose fraction	Whole grains, legumes, E.A. cooked and chilled pasta, potatoes, rice and unripe bananas
SDF[b]	β-Glucans	Unbranched polysaccharides composed of (1–4) and (1–3) linked β-D-glucopyranosyl units in varying proportions	Major component of cell wall material in oats and barley, only present in small amounts in wheat
	Pectin	Polysaccharides comprising galacturonic acid and a variety of sugars; soluble in hot water and forms gels on cooling	Found in cell walls and intracellular tissue of fruits and vegetables Fruits contain the most, but pectins also represent 15–20% of the fibre in vegetables, legumes and nuts Sugar beet and potatoes are sources
	Gums	Hydrocolloids derived from plant exudates	Plant exudates (gum arabic and tragacanth), seeds (guar and locust beans) and seaweed extracts (agar, carageenans, alginates)
	Mucilages	Present in the cells of the outer layers of seeds of the plantain family	Psyllium (*Plantago ovata*)
	Oligosaccharides	Polysaccharide consisting of 3–15 monosaccharide units	Pulses, onions, Jerusalem artichokes, garlic, etc.
Animals	Chitosan	Linear polysaccharide consisting of (1,4)-linked 2-amino-deoxy-b-D-glucan, deacetylated derivative of chitin	Mainly obtained from crustacean shells, is the second most abundant natural polymer in nature after cellulose
Synthetic	Resistant maltodextrins	Typically produced by purposeful rearrangement of starch or hydrolyzed starch to convert a portion of the normal alpha-1,4-glucose linkages to random 1,2- , 1,3- and 1,4-alpha or beta linkages	

[a] IDF: insoluble dietary fibres.

[b] SDF: soluble dietary fibres.

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in legumes. In general, digestible starches are broken down (hydrolyzed) by the enzymes a-amylases, glucoamylase and sucrase–isomaltase in the small intestine to yield free glucose that is then absorbed (Nugent, 2005). However, not all starch in the diet is digested and absorbed in the small intestine (Ratnayake & Jackson, 2008).

Resistant starch refers to the portion of starch and starch products that resist digestion as they pass through the gastrointestinal tract. RS is an extremely broad and diverse range of materials and a number of different types exist (RS1–4). At present, these are mostly defined according to physical and chemical characteristics (Nugent, 2005).

Resistant starch is the fraction of starch which is not hydrolyzed to D-glucose in the small intestine within 120 min of being consumed, but which is fermented in the colon. Many studies have shown that RS is a linear molecule of α-1,4-D-glucan, essentially derived from the retrograded Amylose fraction, and has a relatively low molecular weight (1.2×10^5 Da) (Tharanathan, 2002).

Resistant starch may not be digested for four reasons:

(i) This compact molecular structure limits the accessibility of digestive enzymes, various amylases, and explains the resistant nature of raw starch granules (Haralampu, 2000). The starch may not be physically bioaccessible to the digestive enzymes such as in grains, seeds or tubers.
(ii) The starch granules themselves are structured in a way which prevents the digestive enzymes from breaking them down (e.g. raw potatoes, unripe bananas and high-amylose maize starch) (Nugent, 2005).
(iii) Starch granules are disrupted by heating in an excess of water in a process commonly known as gelatinization, which renders the molecules fully accessible to digestive enzymes. Some sort of hydrated cooking operation is typical in the preparation of starchy foods for consumption, rendering the starch rapidly digestible (Haralampu, 2000). However, if these starch gels are then cooled, they form starch crystals that are resistant to enzymes digestion. This form of 'retrograded' starch is found in small quantities (approximately 5%) in foods such as "corn-flakes" or cooked and cooled potatoes, as used in a potato salad.
(iv) Selected starches that have been chemically modified by etherisation, esterisation or cross-bonding, cannot be broken down by digestive enzymes (Lunn & Buttriss, 2007).

The physical properties of resistant starch, particularly its low water-holding capacity, make it a functional ingredient that provides good handling and improves texture in the final product (Baixauli, Salvador, Martinez-Cervera, & Fiszman, 2008). By careful control of the processing conditions employed, for example, the moisture content, pH, temperature, duration of heating, repeated heating–cooling cycles, etc., the content of RS may reach as much as 30%. RS is shown to improve eating qualities because of its increased expansion, enhanced crispiness, and reduced oil "pick up" in deep-fat-fried foods, contrary to the traditional dietary fibre, which imparts a gritty texture and strong flavor (Tharanathan, 2002).

In comparison with traditional fibres, such as whole grains, bran or fruit fibres (Pérez-Alvarez, 2008a), RS possesses the advantage of affecting the sensory properties of the final products less, which is very positive for consumer acceptability. Resistant starch provides many technological properties, such as better appearance, texture, and mouthfeel than conventional fibres (Charalampopoulos, Wang, Pandiella, & Webb, 2002). A wide range of foods has been enriched with RS including bread, cakes, muffins, pasta and battered foods (Sanz, Salvador, & Fiszman, 2008b).

3. Resistant starch as a component of dietary fibre

The above description of dietary fibre refers especially to non-starch polysaccharides, resistant oligosaccharides and analogous carbohydrates. It also includes resistant starch (Sharma et al., 2008).

Traditionally, in the UK, the definition of dietary fibre includes only non-starch polysaccharides and lignin, and does not include RS (Sharma et al., 2008). However, currently, naturally occurring resistant starch (such as found in whole grains, legumes, cooked and chilled pasta, potatoes and rice, unripe bananas) is considered dietary fibre, while resistant starches added to foods for health benefits are classified as functional fibre under the AACC (American Association of Cereal Chemists, 2000) and NAS (National Academy of Sciences, 2002) definition (Sajilata, Singhal, & Kulkarni, 2006).

The increased awareness of consumers concerning the relationship between food, lifestyle and health has been one of the reasons for the popularity of food rich in fibre, so resistant starch (RS) has gained importance as a new source of dietary fibre (Sanz et al., 2008b). The general behavior of RS is physiologically similar to that of soluble, fermentable fibre, like guar gum. The most common results include increased fecal bulk and lower colonic pH (Slavin, Stewart, Timm, & Hospattankar, 2009). Additional observations suggest that resistant starch, such as soluble fibre, has a positive impact on colonic health by increasing the crypt cell production rate, or decreasing colonic epithelial atrophy in comparison with non-fibre diets. There are indications that resistant starch, like guar, a soluble fibre, influences tumorigenesis, and reduces serum cholesterol and triglycerides. Overall, since resistant starch behaves physiologically as a fibre, it should be retained in the total dietary fibre assay (Haralampu, 2000). The recent increased interest in RS is related to its effects in the gastrointestinal tract, which in many ways are similar to these of dietary fibre. Like soluble fibre, RS is a substrate for the colonic microbiota, forming metabolites including short-chain fatty acids (SCFA), i.e. mainly acetic, propionic and butyric acid. Butyric acid is largely metabolised by the colonocyte, and is the most import energy source for the cell (Elmstahl, 2002). RS consumption has also been related to reduce postprandial glycemic and insulinemic responses, which may have beneficial implications in the management of diabetes (Tharanathan & Mahadevamma, 2003). Therefore, there is wide justification for assuming that RS behaves physiologically like fibre (Sajilata et al., 2006).

RS is not a cell wall component but is nutritionally more similar to NSP than to digestible starch. Of late, RS has been considered a new ingredient for creating fibre-rich foods, although one of the problems of including RS is that it does not have all the properties of soluble and insoluble fibre together (Sharma et al., 2008).

Several studies have attempted to quantify the dietary intake of resistant starch in different populations. Worldwide, the dietary intake of resistant starch varies considerably. It is estimated that resistant starch intake in developing countries with high-starch consumption rates ranges from approximately 30–40 g/day (Baghurst, Baghurst, & Record, 2001). Intakes in the EU are thought to be from 3 to 6 g/day (Dyssler & Hoffmann, 1994), and 5–7 g/day in Australia (Baghurst et al., 2001). It should be noted that intakes of resistant starch in Australia are likely to be higher than in Europe, because of the commercial availability of top-selling breads, baked goods and cereals that contain ingredients high in resistant starch. Australia's Commonwealth Scientific and Industrial Research Organization (CSIRO) has recommended that the total intake of resistant starch should be around 20 g a day based on a study by Baghurst et al. (2001) for good health. However, compared with current resistant starch intake rates in the UK population and elsewhere, to achieve

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intakes at this level would require substantial dietary changes and, indeed, may only be reached by the consumption of foods containing resistant starches as a food ingredient, rather than in the natural form. However, resistant starch could make a valuable contribution to dietary fibre intakes, as it is fermented slowly in the large bowel and is therefore tolerated better than other soluble fibres (Lunn & Buttriss, 2007).

4. Types of resistant starch

Resistant starch has been classified into four general subtypes called RS1–RS4. Table 2 outlines a summary of the different types of resistant starch, their resistance to digestion in the small intestine and food sources of each type of RS (Lunn & Buttriss, 2007).

The natural types of RS are frequently destroyed when processed. The manufacture of resistant starch usually involves partial acid hydrolysis and hydrothermal treatments, heating, retrogradation, extrusion cooking, chemical modification and repolymerisation (Charalampopoulos et al., 2002).

The four distinct classes of RS in foods are: (1) RS1 – physically inaccessible starch, which is entrapped within whole or partly milled grains or seeds; (2) RS2 – some types of raw starch granules (such as banana and potato) and high-amylose (high-amylose corn) starches; (3) RS3 – retrograded starch (either processed from unmodified starch or resulting from food processing applications); (4) RS4 – starches that are chemically modified to obtain resistance to enzymatic digestion (such as some starch ethers, starch esters, and cross-linked starches) (Ratnayake & Jackson, 2008; Sanz, Salvador, Baixauli, & Fiszman, 2009).

RS1 and RS2 represent residues of starch forms, which are digested very slowly and incompletely in the small intestine. RS1 is the term given to RS where the starch is physically inaccessible to digestion, e.g. due to the presence of intact cell walls in grains, seeds or tubers (Hernández, Emaldi, & Tovar, 2008). RS1 is heat stable in most normal cooking operations, which enables its use as an ingredient in a wide variety of conventional foods (Sajilata, Singhal, & Kulkarni, 2006). RS2 are native, uncooked granules of starch, such as raw potato or banana starches, whose crystallinity makes them poorly susceptible to hydrolysis (Hernández et al., 2008). RS2 describes native starch granules that are protected from digestion by the conformation or structure of the starch granule. This compact structure limits the accessibility of digestive enzymes, various amylases, and accounts for the resistant nature of RS2 such as, ungelatinized starch. In the diet, raw starch is consumed in foods like banana (Sajilata et al., 2006). A particular type of RS2 is unique as it retains its structure and resistance even during the processing and preparation of many foods; this RS2 is called high-amylose maize starch (Wepner, Berghofer, Miesenberger, & Tiefenbacher, 1999).

RS3 refers to non-granular starch-derived materials that resist digestion. RS3 forms are generally formed during the retrogradation of starch granules (Wepner et al., 1999). RS3 are retrograded starches, which may be formed in cooked foods that are kept at low or room temperature (Hernández et al., 2008). Most moist-heated foods therefore contain some RS3 (Sajilata et al., 2006). RS3 is of particular interest, because of its thermal stability. This allows it to be stable in most normal cooking operations, and enables its use as an ingredient in a wide variety of conventional foods (Haralampu, 2000). Food processing, which involve heat and moisture, in most cases destroys RS1 and RS2 but may form RS3 (Faraj, Vasanthan, & Hoover, 2004). RS3 has shown a higher water-holding capacity than granular starch (Sanz et al., 2008a). Some examples of RS3 are cooked and cooled potatoes and "corn-flakes" (Wepner et al., 1999).

About 80–90% of the glucose produced by the enzymic hydrolysis of standard starch is metabolized in the human body. Most studies have indicated that 30–70% of RS is degraded to short-chain fatty acids in the colon by bacterial amylases, while the balance of the RS escapes even colonic fermentation and gets excreted in the feces. The overall digestibility of RS depends on the category and source of RS consumed. Of the total amount of RS3 present in corn and wheat, about 84% and 65%, respectively, are degraded by bacterial fermentation in the colon. Similarly, 89% RS2 from raw potato and 96% RS2 from green banana is degraded by bacterial fermentation in the colon. The degradation of RS is also affected by various food processing conditions under which RS is generated. The digestibility of RS was also found to vary per individual. This variability may be attributed to individual differences regarding enzymic responses (Sharma et al., 2008).

Retrograded amylose is responsible for the generation of resistant starch RS3. According to this, the prolonged intake of an amylose-rich diet improves fasting triglyceride and cholesterol levels more than a corresponding amylopectin-rich diet (Mikulíková et al., 2008).

In addition to the three main types of RS, chemically-modified starch has been defined as RS type 4, similar to resistant oligosaccharides and polydextrose (Wepner et al., 1999). RS4 describes a group of starches that have been chemically modified and include starches which have been etherised, esterified or cross-bonded with chemicals in such a manner as to decrease their digestibility. RS4 may be further subdivided into four subcategories according to their solubility in water and the experimental methods by which they can be analyzed (Nugent, 2005).

RS4 can be produced by chemical modifications, such as conversion, substitution, or cross-linking, which can prevent its digestion

Table 2

Types of resistant starch, their resistance to digestion in small intestine and food sources. *Sources*: Bird et al. (2008), Sharma et al. (2008), Rajman et al. (2007), Lunn and Buttriss (2007), Sajilata et al. (2006), and Nugent, 2005.

Type of starch	Description	Digestion in small intestine	Resistance reduced by	Food sources
RS1	Physically inaccessible to digestion by entrapment in a non-digestible matrix	Slow rate; partial degree Totally digested If properly milled	Milling, chewing	Whole or partly milled grains and seeds, legumes, pasta
RS2	Ungelatinized resistant granules with type B crystallinity, slowly hydrolyzed by α-amylase	Very slow rate; little degree Totally digested when freshly cooked	Food processing and cooking	Raw potatoes, green bananas, some legumes, high-amylose starches
RS3	Retrograded starch formed when starch-containing foods are cooked and cooled	Slow rate; partial degree Reversible digestion: digestibility improved by reheating	Processing conditions	Cooked and cooled potatoes, bread, corn flakes, food products with prolonged and/or repeated moist heat treatment
RS4	Selected chemically-modified resistant starches and industrially processed food ingredients	As a result of chemical modification, can resist hydrolysis	Less susceptible to digestibility *in vitro*	Some fibre: drinks, foods in which modified starches have been used (certain breads and cakes)

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by blocking enzyme access and forming atypical linkages such as α(1 → 4) and α(1 → 6) linkages (Kim et al., 2008; Sajilata et al., 2006).

Different sources of RS2 and RS3 of different origins and with different percentages of RS are available as commercial ingredients in the European market to be included in food. As RS4 is made up of chemically-modified starches, with a far higher number of modifications than the usual chemically-modified starches authorized in Europe, it is a novel food not yet approved by the European Union. However, RS4 is authorized in Japan (Sanz et al., 2008b; Lunn & Buttriss, 2007).

In addition to the structural factors mentioned above whereby the chemical structure of starch can influence the amount of RS present, other factors intrinsic to starchy foods can affect α-amylase activity and therefore starch breakdown. These include the formation of amylose–lipid complexes, the presence of native α-amylase inhibitors and also non-starch polysaccharides, all of which can directly affect a-amylase activity. Extrinsic additives, e.g. phosphorus, may also bind to starch, making it more or less susceptible to degradation. In addition, physiological factors can affect the amount of RS in a food. Increased chewing decreases particle size (smaller particles being more easily digested in the gut), while intra-individual variations in transit time and biological factors (e.g. menstrual cycle) also affect the digestibility of starch. At present, it is not known how RS4 is affected by digestion in vivo (Nugent, 2005).

From a commercial point of view, there are resistant starch products derived from high-amylose corn starch, including Hi-maize® whole grain corn flour (RS1 and RS2), Hi-maize®260 corn starch (RS2), and Novelose®330 (RS3) resistant starch.

Recently, Mermelstein (2009) reported that there is a fifth type of soluble polysaccharide called “resistant maltodextrins”. They are derived from starch that is processed to purposefully rearrange starch molecules to render them soluble and resistant to digestion. Two commercial resistant maltodextrins are Nutriose® and Fibresol®2.

5. Food sources of resistant starch

Starch, which is the major dietary source of carbohydrates, is the most abundant storage polysaccharide in plants, and occurs as granules in the chloroplast of green leaves and the amyloplast of seeds, pulses, and tubers (Sajilata et al., 2006). Resistant starch is naturally found in cereal grains, seeds and in heated starch or starch-containing foods (Charalampopoulos et al., 2002).

Factors that determine whether starch is resistant to digestion include the physical form of grains or seeds in which starch is located, particularly if these are whole or partially disrupted, size and type of starch granules, associations between starch and other dietary components, and cooking and food processing, especially cooking and cooling (Slavin, 2004). The digestibility of starch in rice and wheat is increased by milling to flour (Sajilata et al., 2006).

As a food ingredient, RS has a lower calorific (8 kJ/g) value compared with fully digestible starch (15 kJ/g); however, it can be incorporated into a wide range of mainstream food products such as baked products without affecting the processing properties or the overall appearance and taste of the product (Rochfort & Panozzo, 2007).

Unripe banana is considered the RS-richest non-processed food. Several studies have suggested that consumption of unripe bananas confers beneficial effects for human health, a fact often associated with its high resistant starch (RS) content, which ranges between 47% and 57%. Recently, the preparation of unripe banana flour was described, with 73.4% total starch content, 17.5% RS content and a dietary fibre level of 14.5%. Although banana represents an alternative source of indigestible carbohydrates, mainly RS and dietary fibre, it is important to keep in mind that, when the unripe fruit is cooked, its native RS is rendered digestible (Rodríguez, Islas, Agama, Tovar, & Bello, 2008).

As a percentage of total starch, potato starch has the highest RS concentration and corn starch has the lowest. Raw potato starch contain 75% RS as a percentage of Total Starch (TS). Starches from tubers such as potatoes tend to exhibit B-type crystallinity patterns that are highly resistant to digestion. Amylomaize contains mostly amylose, which has been shown to lower not only digestibility but also blood insulin and glucose values in humans (Bednar et al., 2001).

Whole grains are rich sources of fermentable carbohydrates including dietary fibre, resistant starch and oligosaccharides (Slavin, 2004). Fibre provided by the whole grain includes a substantial resistant starch component, as well as varying amounts of soluble and fermentable fibres, depending on the whole grain source (Lunn & Buttriss, 2007).

RS concentrations are low for the flour group as a whole. Cereal flours display an A-type crystalline pattern, which is more readily hydrolyzed than raw cereals that are not as highly processed as flours. Therefore, cereal flours contain more RDS and SDS than RS. The nutrient profile of cereal grains and their corresponding flours vary considerably. Grain flours are made up primarily of two components: protein and starch. Cereal grains, in contrast, contain the pericarp, aleurone layers and germ portions of the grain that provide lipid and fibre, Cereal grains are processed and milled to flours, thereby altering the chemical composition of the flour compared with the cereal grain. The RS concentrations are five times higher in the cereal grains than in the flours (Bednar et al., 2001).

Prepared grain products contain moderate levels of RS (mean 9.6% as a percentage of TS). Starch in foods like spaghetti is more slowly digested because of the densely packed starch in the food (Bednar et al., 2001).

Legumes are known for their high content of both soluble and insoluble dietary fibre. Pulse grains are high in RS and retain their functionality even after cooking (Rochfort & Panozzo, 2007). Legume starches have higher amylose levels than cereal and pseudocereal starches (Mikulíková et al., 2008). Legumes has high TDF and RS concentrations (mean 36.5% and 24.7%, respectively). RS concentrations generally constituted the highest proportion of the starch fractions of legumes. Leguminous starches display a C-type pattern of crystallinity. This type of starch is more resistant to hydrolysis than that with an A-type crystallinity pattern and helps explain why legumes have high amounts of RS. Another possible reason for the higher RS concentrations in legumes could be the relationship between starch and protein. When red kidney beans are preincubated with pepsin, there is an increase in their susceptibility to amylolytic attack (Bednar et al., 2001).

Cooked legumes are prone to retrograde more quickly, thereby lowering the process of digestion. Processed legumes contain significant amount of RS3. The digestibility of legume starch is much lower than that of cereal starch. The higher content of amylose in legumes, which probably leads to a higher RS content, may account for their low digestibility. High-amylose cereal starch has been shown to be digested at a significantly lower rate (Tharanathan & Mahadevamma, 2003).

There is a very high diversity of the content of resistant starch in seeds of leguminous plants (from 80% to only a few percent). Nevertheless, is very important influence processing on part resistant starch. Hydrothermal processing can cause an increase or reduction in the fraction of resistant starch (depending on the parameters of processing and varieties of legumes) (Giczewska & Borowska, 2003).

6. Beneficial physiological effects of resistant starch

RS has received much attention for both its potential health benefits and functional properties (Sajilata et al., 2006). Resistant starch is one of the most abundant dietary sources of non-digestible carbohydrates (Nugent, 2005) and could be as important as NSP (non-starch polysaccharides) in promoting large bowel health and preventing bowel inflammatory diseases (IBD) and colorectal cancer (CRC) (Topping, Anthony, & Bird, 2003) but has a smaller impact on lipid and glucose metabolism (Nugent, 2005).

A number of physiological effects have been ascribed to RS, which have been proved to be beneficial for health (Sajilata et al., 2006) and are listed in Table 3. The physiological properties of resistant starch (and hence the potential health benefit) can vary widely depending on the study design and differences in the source, type and dose of resistant starch consumed (Buttriss & Stokes, 2008; Nugent, 2005). It is possible that modern processing and food consumption practices have led to lower RS consumption, which could contribute to the rise in serious large bowel disease in affluent countries. This offers opportunities for the development of new cereal cultivars and starch-based ingredients for food products that can improve public health. These products can also be applied clinically (Topping et al., 2003).

RS acts largely through its large bowel bacterial fermentation products which are, in adults, short-chain fatty acids (SCFA) (Topping et al., 2008) but interest is increasing in its prebiotic potential. There is also increasing interest in using RS to lower the energy value and available carbohydrate content of foods. RS can also be used to enhance the fibre content of foods and is under investigation regarding its potential to accelerate the onset of satiation and to lower the glycemic response The potential of RS to enhance colonic health, and to act as a vehicle to increase the total dietary fibre content of foodstuffs, particularly those which are low in energy and/or in total carbohydrate content (Nugent, 2005).

6.1. Prevention of colonic cancer

There is evidence that butyrate may reduce the risk of malignant changes in cells. Population studies in the cecum of rats fed RS preparations have shown that increase in fecal bulking and lower fecal pH, as well as greater production of SCFA, are associated with the decreased incidence of colon cancer, which have been suggested to resemble the effects of soluble dietary fibre (Ferguson, Tasman-Jones, Englyst, & Harris, 2000; Tharanathan & Mahadevamma, 2003).

Dietary fibre and resistant starch, as they ferment in the large bowel, produce high levels of butyric acid or its salts (Sharma et al., 2008) as *in vitro* experiments with human fecal inocula have shown (Sajilata et al., 2006). Champ, Langkilde, and Brovns (2003) also demonstrated a specific role for resistant starch in the stimulation of bacteria able to produce butyric acid.

As butyrate is one of the main energy substrates for large intestinal epithelial cells and inhibits the malignant transformation of such cells *in vitro*; this makes easily fermentable RS fractions especially interesting in preventing colonic cancer (Asp & Bjorck, 1992). As observed in the various studies, the butyrates can have an inhibitory effect on the growth and proliferation of tumor cells *in vitro* by arresting one of the phase of cell cycle (G1) (Sharma et al., 2008).

Bingham, Day, and Luben (2003) showed that in populations with a low to average intake of dietary fibre, the doubling of dietary fibre intake could reduce the risk of colorectal cancer by up to 40%. In contrast, there was no relationship between dietary NSP and large bowel cancer (Sharma et al., 2006).

However, when RS was combined with an insoluble dietary fibre, such as wheat bran, much higher SCFA levels, in particular of butyrate was observed in the feces (Leu, Hu, & Young, 2002). In rats, when RS was combined with a soluble fibre as Psyllium (*Plantago ovata*), the site of RS fermentation was pushed more distally. As the distal colon is the site where most tumors arise, it may be of additional benefit for cancer protection if fermentation is further enhanced within the distal colon. Psyllium (*Plantago ovata*) may be a good candidate to spare and deliver starch to the distal colon (Morita, Kasaoka, Hase, & Kiriyama, 1999).

More recently, Liu and Xu (2008) showed that RS dose-dependently suppressed the formation of colonic aberrant crypt foci (ACF) only when it was present during the promotion phase to a genotoxic carcinogen in the middle and distal colon, suggesting that administration of RS may retard growth and/or the development of neoplastic lesions in the colon. Therefore, colon tumorigenesis may be highly sensitive to dietary intervention. Adults with preneoplastic lesions in their colon may therefore benefit from dietary RS. This suggests the usefulness of RS as a preventive agent for individuals at high risk for colon cancer development (Liu & Xu, 2008).

6.2. Hypoglycemic effects

The GI of starchy foods may depend upon various factors such as the amylose/amylopectin ratio, the native environment of the starch granule, gelatinization of starch, water content and baking temperature of the processed foods. Thus, the factors affecting the GI values are in accordance with those of RS formation. With glucose as reference, reported GI values range from about 10 for starch from legumes to close to 100 in certain potato or rice products and breakfast cereals (Sharma et al., 2008). Thus foods containing RS reduce the rate of digestion. The slow digestion of RS has implications for its use in controlled glucose release applications (Sajilata et al., 2006) and therefore, a lowered insulin response and greater access to the use of stored fat can be expected (Nugent, 2005). This is clearly important for diabetes and has led to major changes in dietary recommendations for diabetics (Cummings, Edmond, & Magee, 2004).

The metabolism of RS occurs 5–7 h after consumption, in contrast to normally cooked starch, which is digested almost immediately. Digestion over a 5–7 h period reduces postprandial glycemia and insulinemia and has the potential for increasing the period of satiety (Raben et al., 1994; Reader, Johnson, Hollander, & Franz, 1997).

There have been a number of studies on the effects of different forms and doses of RS on glucose and insulin responses but the data are contradictory (Sharma et al., 2008). In a study on humans, Reader et al. (1997) reported that the consumption of RS3 resulted in lower serum glucose and insulin levels than obtained with other

Table 3
Physiological effects of resistant starch. *Sources*: Grabitske and Slavin (2009), Sharma et al. (2008), Scholz-Ahrens et al. (2007), Brouns et al. (2002), and Nugent (2005).

Protective effect	Potential physiological effects
Diabetes	Control of glycemic and insulinemic responses
Colorectar cancer, ulcerative colitis, inflammatory bowel disease, diverticulitis and constipation	Improved bowel health
Cardiovascular disease, lipid metabolism syndrome, cholesterol and triglycerides	Improved blood lipid profile
Colonic health	Prebiotic and culture protagonist
Obesity	Increased satiety and reduced energy intake
Osteoporosis, enhanced calcium absorption	Increased micronutrient absorption

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carbohydrates. The study also showed that food containing RS decreased postprandial blood glucose and might play a role in providing improved metabolic control in type II diabetes. From a human study, using a commercial RS3 ingredient (CrystaLean®), the maximum blood glucose level was found to be significantly lower than that of other carbohydrates (simple sugars, oligosaccharides, and common starch). Higher glycemic index values have been reported in humans consuming potatoes and cornflakes – foods that contain significant amounts of retrograded starch (Truwell, 1992). In general, positive effects were usually observed shortly (within the first 2–8 h) after heavy meal (Higgins, 2004).

An RS3-containing bar decreased postprandial blood glucose and could play a role in providing improved metabolic control in type II diabetes (non-insulin dependent) (Sajilata et al., 2006). RS must contribute at least 14% of total starch intake in order to confer any benefits to glycemic or insulinaemic responses (Behall & Hallfrisch, 2002; Brown, Storlien, & Brown, 2003; Higgins, 2004). More recently, a study showed that RS reduces levels of glucose-dependent insulinotropic polypeptide m-RNA along the jejunum and ileum in both normal and type 2 diabetes rats (Shimada, Mochizuki, & Goda, 2008).

Chemically-modified starches (RS4) have also been found to generate different glucose responses. The effect of two test meals containing 1–2% acetylated potato starch and beta cyclodextrin enriched potato starch (2–3%), respectively, was studied in humans and only the latter was found to lower body glucose levels. This may be due to the more distal absorption of beta cyclodextrin in the intestine or to delayed gastric emptying (Roben, Andersen, & Karberg, 1997).

As RS has a low glycemic response, adding it as an ingredient to foods will help lower the overall GL value of the food (particularly if it is replacing existing readily absorbed forms of carbohydrate). RS is likely to become an increasingly attractive ingredient to many food manufacturers (particularly those of breads and cakes or similar products which traditionally may have had higher GI values) (Nugent, 2005).

6.3. Resistant starch as a prebiotic

Prebiotics are non-digestible food ingredients that beneficially affect the host by selectively stimulating the growth and/or activity of one or more bacteria (probiotics) in the gastrointestinal tract and thereby exert a health-promoting effect (Scholz-Ahrens et al., 2007; Roberfroid, 2000). Typical of prebiotics are inulin and oligofructose, both naturally present in a number of fruits and vegetables (*e.g.* bananas, chicory, Jerusalem artichokes, onions, garlic and leeks, and wheat), and other resistant oligosaccharides such as inulin-type fructans (Buttriss & Stokes, 2008).

Various experimental studies on pigs and humans have revealed a time-dependent shift in fecal and large bowel SCFA profiles, suggesting the possible interaction of RS with the ingested bacteria (Topping et al., 2003).

RS has also been suggested for use in probiotic compositions to promote the growth of such beneficial microorganisms as bifidobacterium (Brown et al., 1996). Since RS almost entirely passes through the small intestine, it can behave as a growth substrate for probiotic microorganisms (Sajilata et al., 2006).

6.4. Hypocholesterolemic effects

RS appears to particularly affect lipid metabolism, as seen from studies in rats, where reductions in a number of measures of lipid metabolism have been observed. These include total lipids, total cholesterol, low density lipoproteins (LDL), high density lipoproteins (HDL), very low density lipoproteins (VLDL), intermediate density lipoproteins (IDL), triglycerides and triglyceride-rich lipoproteins (Nugent, 2005). Hypocholesterolemic effects of RS have been widely demonstrated. In rats, RS diets (25% raw potato) markedly raised the cecal size and the cecal pool of short-chain fatty acids (SCFA), as well as SCFA absorption and lowered plasma cholesterol and triglyceride levels. Also, there was a lower concentration of cholesterol in all lipoprotein fractions, especially the HDL1 and a decreased concentration of triglycerides in the triglyceride-rich lipoprotein fraction (Sajilata et al., 2006).

The results of feeding trials on rats using RS from Adzuki bean starch (AS) and Tebou bean starch (TS) suggested that AS and TS has a serum cholesterol-lowering function due to enhanced levels of hepatic SR-B1 (scavenger receptor class B1) and cholesterol 7alpha-hydroxylase mRNA (Han et al., 2003).

The bean starches lowered the levels of serum total cholesterol and VLDL + IDL + LDL cholesterol, increased the cecal concentration of short-chain fatty acids (in particular the butyric acid concentration), and increased fecal neutral sterol excretion. From studies on hamsters fed diets containing cassava starch extrudated with 9.9% oat fibre or cassava starch extruded with 9.7% RS, hypocholesterolemic properties of both were demonstrated suggesting their potential for use in foods to improve cardiovascular health (Martinez-Flores, Chang, Martinez-Bustos, & Sgarbierid, 2004).

According to several studies, RS ingestion may decrease the serum cholesterol level in rats fed a cholesterol-free diet (De-Deckere, Kloots, & Van-Amelsvoort, 1993; Hashimoto et al., 2006).

Some earlier studies in humans reported the beneficial effect of RS on fasting plasma triglyceride and cholesterol levels. However, some other studies indicate that RS consumption does not affect the measures of total cholesterol in humans. Therefore it is evident that more research is needed to help us better understand the effects of RS on lipid metabolism in humans (Nugent, 2005).

6.5. Inhibition of fat accumulation

A number of authors have examined the potential of RS to modify fat oxidation (Nugent, 2005) and various studies (Nugent, 2005; Sharma et al., 2008) have examined its potential as satiety agent and also an ingredient by weight management (Mikušová, Šturdík, Mošovská, Brindzová, & Mikulajová, 2009), although the results are still not conclusive. It is proposed that eating a diet rich in RS may increase the mobilization and use of fat stores as a direct result of a reduction in insulin secretion (Tapsell, 2004). Studies to date in humans would indicate that diets rich in RS do not affect total energy expenditure, carbohydrate oxidation or fat oxidation (Ranganathan et al., 1994; Tagliabue et al., 1995; Howe, Rumpler, & Behall, 1996; Raben et al., 1997). In another study on human volunteers, breads rich in RS imparted greater satiety than white breads between 70 and 120 min after eating (De Roos, Heijnen, & De Graff, 1995). Anderson, Catherine, and Woodend (2002) reported that high-RS meals caused less satiety than low-RS meals 1-h post ingestion. Higgins et al. (2004) examined the relationship between the RS content of a meal and postprandial fat oxidation, finding that replacing 5.4% of total dietary carbohydrates with RS could significantly increase postprandial lipid oxidation and probably reduce fat accumulation in the long term.

Keenan et al. (2006) reported that the use of resistant starch in the diet as a bioactive functional food component is a natural, endogenous way to increase gut hormones that are effective in reducing energy intake, so may be an effective natural approach to the treatment of obesity.

6.6. Other beneficial physiological effects of RS

6.6.1. Reduction of gall stone formation

Digestible starch contributes to gall stone formation through a greater secretion of insulin, and insulin in turn leads to the stimulation of cholesterol synthesis, so RS reduces the incidence of gallstones. Gallstones are less frequent in southern India where whole grains are consumed rather than flour, as in northern India. The dietary intake of RS is 2- to 4-fold lower in the United States, Europe, and Australia, compared with populations consuming high-starch diets, such as in India and China, which may be reflected in the difference in the number of gallstone cases in the latter countries (Sajilata et al., 2006).

6.6.2. Absorption of minerals

Resistant starch enhance the ileal absorption of a number of minerals in rats and humans. Lopez et al. (2001) and Younes et al. (1995) reported an increased absorption of calcium, magnesium, zinc, iron and copper in rats fed RS-rich diets. In humans, these effects appear to be limited to calcium (Trinidad, Wolever, & Thompson, 1996; Coudray et al., 1997). RS could have a positive effect on intestinal calcium and iron absorption. A study to compare the apparent intestinal absorption of calcium, phosphorus, iron, and zinc in the presence of either resistant or digestible starch showed that a meal containing 16.4% RS resulted in a greater apparent absorption of calcium and iron compared with completely digestible starch (Morais, Feste, Miller, & Lifichitz, 1996).

7. Food applications of resistant starch

Resistant starch has a great interest to product developers and nutritionists for two reasons, the first being the above-mentioned potential physiological benefits and the second the unique functional properties, yielding high quality products not attainable otherwise with traditional insoluble fibres (Yue & Waring, 1998; Baixauli et al., 2008).

Historically, fibre-containing foods have been coarser, denser and sometimes less palatable than refined, processed foods. The use of resistant starches as food ingredients typically does not change the taste or significantly change the texture, but may improve sensory properties compared with many of the traditionally used fibres, such as brans and gums (Sajilata et al., 2006).

RS has desirable physicochemical properties (Fausto, Kacchi, & Mehta, 1997) such as swelling, viscosity increase, gel formation and water-binding capacity, making it useful in a variety of foods. RS has a small particle size, white appearance, bland flavor and also provides good handling in processing and crispness, expansion, and improved texture in the final product (Sajilata et al., 2006). Its low water-holding capacity, make it a functional ingredient that provides good handling and provides and improves texture in the final product (Yue & Waring, 1998).

RS shows improved crispness and expansion in certain products and better mouthfeel, color, and flavor than can be obtained with some traditional, insoluble fibres (Sajilata et al., 2006). This greatly increases the likelihood that consumers will accept these foods and hence increase their dietary fibre intake (Buttriss & Stokes, 2008).

These properties make it possible to use most resistant starches to replace flour on a 1-for-1 basis without significantly affecting dough handling or rheology. RS not only fortifies fibre but also imparts special characteristics not otherwise attainable in high-fibre foods (Tharanathan & Mahadevamma, 2003). Some of the functional properties and advantages of commercial sources of RS2 and RS3 (Nugent, 2005) are shown in Table 4.

They may also be used to provide fibre in some commercially available low-carbohydrate foods marketed for those following low-carbohydrate dieting regimens (Nugent, 2005). There are also potential uses in fermented foods, such as dry-cured sausages.

The processing conditions can affect the resistant content of starch by influencing its gelatinisation and retrogradation (Thompson, 2000). Augustin, Sanguansri, and Htoon (2008) describe that it is possible to make a physically functional RS ingredient by the application of physical processes to starch suspension. Technically, it is possible to increase the RS content in foods by modifying the processing conditions such as pH, heating temperature and time, number of heating and cooling cycles, freezing, and drying (Sajilata et al., 2006). The substitution of 3% milk solids in yoghurts (12% total solids) with heated, sheared and microfluidised starch suspensions increased the viscosity and decreased syneresis of yoghurts but the incorporation of starch that had only been heated and sheared without microfluidisation did not.

Unlike natural sources of RS (*e.g.* legumes, potatoes, bananas), commercially manufactured resistant starches are not affected by processing and storage conditions. For example, the amount of RS2 in green bananas decreases with increasing ripeness, while a commercial form of RS2, Hi-maize, does not present these difficulties (Nugent, 2005).

The food manufacture may be thought of as enhancement of the proportion of the starch that test as RS. The reason for including an ingredient high in RS is to combine physical functionality, processing stability and nutritional functionality. The physical functionality of RS is required for the physical characteristics of the food, such as texture, water-holding capacity. The processing stability of RS is important in order to preserve the nutritional functionality of the RS-containing ingredients. The nutritional functionality of the RS-containing ingredients can involve both resistance to digestion in the small intestine and resistance to fermentation in the colon. Eventually, we should be able to produce starch materials with the desired rate and extent of digestion (in terms of mean population responses) and (for any RS that might be present) a desired rate of hydrolysis and fermentation in the colon.

In any starch material, the constituent molecules will have a range of susceptibility to amylolytic activity *in vitro*. For a starch or starch-containing ingredient, it is possible to alter this range by judicious selection of processing conditions to increase the proportion of RS. The starch material will also have a range of thermal stabilities before and after processing, which may or may not reflect the range of susceptibility to hydrolysis (Thompson, 2000).

The industrial applications of RS mainly involve the preparation of moisture-free food products (Yue & Waring, 1998). Bakery products such as bread, muffins, and breakfast cereals can be prepared by using RS as a source of fibre. The amount of RS used to replace flour depends on the particular starch being used, the application,

Table 4

Functional properties and advantages of commercial sources of RS2 and RS3. *Sources*: Sharma et al. (2008), Augustin, Sanguansri, and Htoon (2008), Sajilata et al. (2006), and Nugent (2005).

Natural sources
Bland in flavor
White in color
High gelatinization temperature
Fine particle size (which causes less interference with texture)
Useful in products for coeliacs as bulk laxatives and in products for oral rehydration therapy
Allow the formation of low-bulk high-fibre products with improved texture, appearance, and mouth feel (such as better organoleptic qualities) compared with traditional high-fibre products
Increase coating crispness of products
Increase bowl life of breakfast cereals
Functional food ingredients
Lowering the calorific value of foods
Lower water properties than traditional fibre products
Good extrusion and film-forming qualities

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the desired fibre level, and, in some cases, the desired structure–function claims.

The incorporation of RS in baked products, pasta products and beverages imparts improved textural properties and health benefits (Premavalli, Roopa, & Bawa, 2006). A panel rated 40% TDF RS loaf cakes as best for flavor, grittiness moisture perception, and tenderness 24 h after baking. Based on an evaluation by a trained sensory panel of toasted waffles for initial crispness, crispness after 3 min, moistness and overall texture, RS waffle showed greater crispness than control or traditional fibre. RS can improve expansion in extruded cereals and snacks. RS may also be used in thickened, opaque health beverages in which insoluble fibre is desired. Insoluble fibres generally require suspension and add opacity to beverages. Compared with insoluble fibres, RS imparts a less gritty mouth feel and masks flavors less (Sajilata et al., 2006). Bread containing 40% TDF RS had greater loaf volume and better cell structure compared with traditional fibres tested (Baghurst, Baghurst, & Record, 1996).

Hydrolyzed starches (those which retain their granular structure and essentially behave like unmodified starches in undergoing gelatinization on heating), which are also referred to as thin boiling starches, are also a form of RS. The advantage of this starch is the high concentration, which can be used as a paste of low viscosity, and its ability to set as a firm gel (Seib & Kyungsoo, 1999). Cross-linked starches of RS4 type, based on maize, tapioca and potato, have been useful in formulations needing pulpy texture, smoothness, flowability, low pH storage, and high temperature storage (Sajilata & Singhal, 2005).

Baixauli, Salvador, Martinez-Cervera, and Fiszman (2008) studied the instrumental texture characteristics of muffins with added resistant starch and noted that its addition produced a softer texture: the samples were less hard, elastic and cohesive, reflecting a more tender structure; these effects were more evident at higher concentrations of resistant starch.

Arimi, Duggan, O'Riordan, O'Sullivan, and Lyng (2008) have successfully replaced most or all of the fat in imitation cheese with resistant starch without adversely affecting meltability or hardness and conferring the well-established benefit of resistant starch as a functional fibre. In addition, low-fat, starch-containing imitation cheese has been demonstrated to have the potential to expand during microwave heating. Since this type of imitation cheese expands on microwave heating, it can be presented as a stand-alone snack, pre-expanded or as a home expansion product.

8. New sources of production

There is considerable opportunity for future developments, especially for tailor-made starch derivatives with multiple modifications, although the problem of obtaining legislative approval for the use of novel starch derivatives in processed food formulations is still under debate. Nevertheless, it can be predicted that new ventures in starch modifications and their diverse applications will continue to be of great interest in applied research (Rudrapatnam & Tharanathan, 2005).

More recent innovation has seen the development of insoluble, resistant maltodextrins with a functionality similar to that of resistant starches (Buttriss & Stokes, 2008).

Chemically-modified starch derivatives, for example, phosphorylated starches, which are also non-digestible, have been categorized as RS, similar to polydextrose or resistant oligosaccharides (Rudrapatnam & Tharanathan, 2005). Esterification of native starch using citric acid resulted in chemically-modified starch with an RS content that depended on the degree of esterification. The production of this modified starch is relatively simple, and good results regarding the RS content can be achieved independent of the source of starch so that a range of RS-products can be produced, suitable for various foods. The results show that the RS content in toast bread could be increased by approximately 3%, when 7.5% citrate starch is added, compared to non-fortified bread (Wepner et al., 1999). The use of citric acid for esterification seems to be evident as it rated as nutritionally harmless compared to other substances used for starch derivatisation (Jyothi, Moorthy, Sreekumar, & Rajasekharan, 2007).

Powdered preparations enriched in resistant starch (RS) have been obtained from native and lintnerized (prolonged acid treatment) banana starches by consecutive autoclaving/cooling treatments. The autoclaved samples had a higher RS content than their parental counterparts, but the chemical modification (lintnerization process) allowed development of higher RS proportions (19%, dry matter basis). These RS-enriched products appear suitable for the formulation of functional foods (Aparicio-Saguilán et al., 2005).

Bello-Pérez, González-Soto, Sánchez-Rivero, Gutiérrez-Meraza, and Vargas-Torres (2006) reported that extrusion can be used to elaborate products with a higher RS content that their native counterparts. The native starches of unripe banana and mango had a purity higher than 90%, with a 37% amylose content in banana starch and 27.5% in mango starch. No effect was observed in RS formation, which was 5.7% for banana starch (with more amylose) and 9.7% for mango starch.

Reaction conditions were optimized to increase the content of resistant starch in adlay starch using esterification with glutaric acid, and the physicochemical properties of the prepared glutarate starches were investigated. Glutarate starches with lower crystallinity than raw starch had a similar RS content before and after heating with excess water. This glutarate starch could be used to enhance the textural properties and health benefits of low-moisture products, such as crackers and cookies, due to its low solubility and digestibility and heat stability (Kim et al., 2008).

Wheat bran starch isolated from commercial wheat brans using a wet-milling process was shown to have unique properties compared to commercial wheat endosperm starch. Starch recovery was 90% and the starch fraction contained a low level of protein (0.15%). The more resistant starch content and lower retrogradation rate are properties that present an opportunity to make wheat bran starch a new functional ingredient for the food industry (Xie, Cui, Li, & Tsao, 2008).

9. Conclusion

Fibre consumption has been reduced significantly in western society and is far below the recommended level. The main reason has been the change in life style, which has promoted a significant reduction in fruit, vegetables and legume consumption. With the aim of increasing fibre intake in the diet, many fibre-enriched foods have been developed. Resistant starch (RS) is a recently recognized source of fibre and is classified as a fibre component with partial or complete fermentation in the colon, producing various beneficial effects on health. RS also offers an exciting new potential as a food ingredient. As a functional fibre, its fine particles and bland taste make the formulation of a number of food products possible with better consumer acceptability and greater palatability than those made with traditional fibres. Technically, it is possible to increase the RS content in foods by modifying the processing conditions such as pH, heating temperature and time, the number of heating and cooling cycles, freezing, and drying. RS shows improved crispness and expansion in certain products, which have better mouthfeel, color and flavor than products produced with traditional insoluble fibres.

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