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Role of Resistant Starch in Food and Healthcare Industry: A Review

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ABSTRACT

Starches are complex polysaccharides which are notorious to create glucose load in diet. But the advancements in the fields of food chemistry have come up with a fact that there are some starches which can release glucose in controlled manner. They are known as resistant starches. They are basically four types depending upon sources of origin: Type I physical inaccessible starch (RS1), Type II that inhibit the action of enzymes (RS2), Type III retrograded starch (RS3) and Type IV chemically modified starch (RS4). Resistant Starches now a days are used in many sectors of food industry. It has unique physical and chemical properties such as high viscosity, formation of gel and water-binding capacity that make it valuable new food product development. This has enhanced its usage in food industries. The bland flavour and transparency in colour of RS with low water holding property is making them a good encapsulating medium in microencapsulation of probiotics. They are known to have low glycemic index and good impact on bowel health by acting as prebiotic to the gut microflora. Their demand in the food industry is arisen to the extent that normal starches are retrograded to convert them to RS. Impact of dry and wet heat methods of cooking on content of resistant starches in several food products have been established by many studies.

Key words: Cooking methods, Glycemic index, Prebiotics, Resistant starch.

Cereals are among the most consumed and economical sources of carbohydrates (55-75%) and proteins (7-12%) and contribute extensively to energy intake (Vaidya and Sheth, 2011). Especially in South Asian countries, the consumption ratio of cereals to pulses is so high that cereals have become excellent contributors to calories due to the presence of starch. Chemically, these starches are composed of polysaccharides, comprising of many monosaccharides or sugars (glucose) molecules. Structurally, starch is comprised of amylose and amylopectin where amylose is a linear polymer. It has glucose molecules linked by α-D-(1-4) linkage and constitutes about 15% to 20% of starch. Whereas, amylopectin is a larger branched molecule with α-D-(1-4) and α-D-(1-6) linkages and constitutes 80 per cent of starch (Han *et al*., 2003). Recent research has found that not all starches are significant calorie contributors. They can be classified based on the controlled release of glucose.

Classification of starch

Based on enzymatic actions, there are 3 categories of – Rapidly Digestible Starch (RDS), Slowly Digestible Starch (SDS) and Resistant Starch (RS) (Chen *et al.,* 2021).

Rapidly digestible starch (RDS)

The main constituent of RDS is amorphous and dispersed starch. Starchy foods cooked by moist heat like bread and potatoes are some of the common sources of RDS. It takes 20 min of enzymatic digestion to convert it into glucose molecules (Tian and Sun, 2020).

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Slowly digestible starch (SDS)

Unlike RDS, it is digested more slowly. It is inaccessible physically and is an amorphous starch. It is available in granule form as well as in retrograded form in cooked foods. It takes 100 min of enzymatic digestion to convert it into glucose molecules (Noor *et al*., 2021).

Resistant starch (RS)

It is a fraction of starch which is having resistance to *in vitro* hydrolysis by enzymes amylase and pullulanase. It cannot be hydrolyzed after 120 min of incubation. RS are the starches that survive exhaustive digestion by amylolytic enzymes and are the products of degradation of starch that are resilient to digestion in the lower GI tract of human body.

But they are acted upon by the microorganisms of the large intestine, thereby producing short-chain fatty acids. Four types of resistant starches and their structures and their sources were given. RS content in food fluctuates from a fraction up to 20% of product weight and is, to a high extent, relies on the food preparation manner (Brighenti *et al.*, 1998). The types of resistant starches and their properties have been well illustrated by Lockyer and Nugent, 2017). A similar definition of resistant starch was given by Englyst and Hudson in 1996. Resistant starch is found in cereals, seeds, heated starch and starch-containing foods (Charalampopoulos *et* al., 2002). The following method is used to calculate RS from Rapidly digestible starch (RDS) and Slowly digestible starch (SDS) (Sajilata *et al.,* 2006).

$$RS = TS - (RDS + SDS)$$

Classification

Type 1 RS

It is a physical inaccessible starch that cannot be digested because of some physical traits of the seed such as an incomplete milling or intact hull, leaving the grain or seed partly intact resulting in the partial intactness of the grain. It is found in unprocessed whole grains, whole or partially intact seeds and legumes. Under normal cooking operations it remains heat stable. Because of its heat stability, it has been used as a functional ingredient in many processed foods (Sajilata *et al.*, 2006; Malik *et al.,* 2021).

Type 2 RS

It is an ungelatinized starch which is granular in structure and is less susceptible to hydrolysis due to its conformation. This structural compatibility inhibits the action of enzymes of digestion which provide the resistance to RS2 for example, ungelatinized starch. Its sources are raw potatoes, unripe bananas and high amylose corn. Just like RS 1, it has unique property of retaining structure during processing operations. The most common example of RS 2 is high amylose starch in maize (Wepner *et al.,* 1999).

Type 3 RS

It is formed through the process of retrogradation *i.e.* when gelatinized starch is cooled for an extended period. The generation of RS 3 purely depends on of its amylose chains (amount and length), contributing to higher RS content. The degree of retrogradation is influenced by the cycles cooling and heating and the time and temperature of storage which ultimately affect the RS content.

Type 4 RS

It is chemically modified starch formed by esterifying or etherifying due to cross-linking with chemical reagents (Rombo *et* al., 2004). This type has different kind of structure and is not found naturally (Öztürk and Mutlu, 2019); (Fuentes-Zaragoza *et al.*, 2011).

For the current review, studies from various sources viz. Scopus, Publons and Web of Science have been explored and conclusion have been drawn. The paper highlights the use of resistant starch in health care industry food sectors. The study also focusses on effect of cooking methods of increase or decrease in resistant starch content of foods.

Method of estimation of resistant starch (RS)

The method of estimation of resistant starch (RS) using enzymes has been well explained and validated by Mccleary and Monaghan (2002). The following steps are involved: 1. centrifugation of fine powder of cereals after treatment with 80% alcohol followed by 1 ml pepsin in order to eliminate protein 2. Then, to remove digestible starch, 3 ml α amylase is used (30U α amylase in 1 ml tris maleate buffer). After centrifugation, 2 M KOH is used to treat the residues were dispersed along with amyloglucosidase [(6U/ml) Fluka 10115 from *Aspergilus niger*]. After this, glucose is calibrated using glucose oxidase assay method. Lastly, the Resistant Starch (RS) was calculated using the formula given by (Champ, 1992) as glucose x 0.9. Another method for analyzing the RS content was using Megazyme Resistant Starch Assay Kit (Megazyme International Ireland Ltd, Bray, Ireland). Even many methods have been harnessed by many studies to harness the benefits of RS using heat treatment, combined heat treatment and enzyme treatment and chemical treatment (Nissar *et* al., 2017; Deepika *et* al., 2024).

Because of the current scenario of consumers inclination for the better-quality food products having physiological benefits to the body has led to an enhancement in the use of functional ingredients and modern technologies.

Glycemic Index and Resistant Starch

According to Harvard Institute, the glycemic index is a value assigned to foods based on surge in blood glucose levels. The low-glycemic foods have a property of releasing glucose in a slow and steady manner that helps maintain good glucose control (Radha *et al.,* 2024). Nevertheless, the glycemic index of any food is dependent on several factors. They are composition and size of starch molecules, digestibility, and cooking methods employed. The smaller the particle size of the starch molecule more is the glycemic effect. The higher amylopectin content digestion contributes to a greater glycemic effect. On the contrary, the lower the amylose content, lower is the glycemic index. It has been observed that the cooking methods (dry and short time eg. roasting) have a less glycemic effect when compared to foods cooked by long cooking processes including boiling which reduce the particle size and increase the glycemic index. Lifestyle changes play an active role in lowering of glycemic index of the individuals like, including the resistant starch instead of common starches making it a low glycemic index food. Studies have reported that consumption of food items like, porridges from corn and foods with starches that resist digestion always results low postprandial glucose concentrations and concomitant insulin response (Kendall *et al.,* 2010); (Alexander, 2012).

A study done by Blaak *et al.,* (2012) stated that high glycemic diet makes the South Asian populations to be more prone to type-2 Diabetes Mellitus and CVD. The study highlighted the factors like amylose: amylopectin ratio, post-harvest processing (particularly parboiling) and consumer processing (cooking, storage and reheating) leading to changes in the rice in turn affecting the postprandial glycemic responses in the population. In general, the observed glycemic index ranged from 48 to 93, stating rice under high-glycemic foods. The study suggested the relative content of amylose (v. amylopectin), reduction in gelatinization, or the aid in retrogradation can mediate a reduced glycemic load. They concluded that the refrigerated long-grain rice had the high RS content in comparison to the pressure-cooked short-lengthed rice grain cooked in a pressure cooker. Nevertheless, there was no significant difference between the GI of both varieties of rice. The cooking time is directly proportional to the increment in the glycemic index. Moreover, the fluctuation in the blood glucose levels is further influenced by the consumer characteristics like chewing habit, and ethnicity. Hence, the cooking time of rice and choosing high amylose content in rice proves to be beneficial for the diabetic people as it helps in bringing a lower PPG response in the body.

Physiological effects of resistant starch (RS)

Apart from having several benefits in the food industry, promising role of digestion-resistant starches in the prevention and control of chronic human diseases, including obesity, diabetes, colon cancer and potential effects on gut microbiota has well explained by Birt *et al.* (2013) (Table 1). Anti-diabetic and anti-obesity effects of dietary resistant starch and the importance of resistant starch in diet has also been confirmed (Meenu and Xu, 2019). The important physiological effects of RS includes the low postprandial glucose levels and better insulin response, reducing the energy by increasing the rate of lipid metabolism, increasing the adsorption of micronutrients like calcium, helping in maintaining the viability of probiotic bacteria in food processing and consumption and lastly increasing the colonic *Bifidobacteria* and *Lactobacilli*; decreasing pathogenic bacteria exhibiting a potent prebiotic effect on the body (Brown, 2004). The focus has shifted to establish a link between Diabetes and RS content, thus Resistant Starch (RS) are leading consumer interests especially, pre-diabetic and other with metabolic disorders because of the presence of bioactive compounds in them (Moongngarm, 2013). Besides playing an active role in the maintenance of the blood glucose levels and acting as a boon for the diabetic people, it has several other benefits. Some of them are having prebiotic potential, accelerating the onset of satiation, improving colonic health and accelerating the lipid metabolism (Lockyer and Nugent, 2017). According to (Topping and Clifton, 2001) RS helps in the improvement of colonic health as, on breakdown, they produce short chain fatty acids (SCFA), mostly propionate, butyrate, and acetate that help the colonocytes thereby, increasing the colonic blood flow, lowering pH of lumen and helping in the prevention of the development of abnormal colonic cell populations. Additionally, RS has a protective action for gut health by acting as a prebiotic. Prebiotic as defined by Gibson *et al.* (2004) are the non-digestible growth substrate directly beneficial to the good bacteria present in the colon. Effect of RS on microflora of gut has also been revealed in many studies which found that the numbers of *Bifidobacteria* in fecal matter were greater in pigs who were fed with a high amylose corn starch with *Bifidobacterium longum* in comparison to pigs who were fed with a low amylose cornstarch. *In-vitro* utilization of high-amylose maize (Amylomaize) and amylopectin starch granules of starch by bacteria of human colon confirms the prebiotic and symbiotic function of RS (Wang *et al.*, 1999). RS act as a feeding substrate for the good bacteria *viz. Bifidobacteria*. Moreover, the RS exerts other gut health-promoting activities like reducing the fluid loss and halving the recovery time when supplementing with oral rehydration therapy to people suffering from cholera-induced diarrhea. This beneficial action of RS was discovered by Ramakrishna *et al.* (2000). Another crucial physiological effect of RS is on satiety and weight loss (Birt *et al.*, 2013);(Raben *et al.,* 1994); (Alexander, 2012).

The increased market demand of RS is estimated to grow by 6.1 per cent throughout the forecast period 2021-2026.

Increment in resistant starch content

Through several studies done on the resistant starch, it has been found that the variation in resistant starch is on the source level, processing level and storage level (Bede and Zaixiang, 2021). There are several studies accessible on

Table 1: Physiological effects of resistance starch (RS) (Leszczyński, 2004; Chaturvedi *et al*., 2018).

Physiological effects	Health conditions where RS works
Glycemic control and better response to insulin	Diabetes, pre diabetes
Better defecation habits	Large intestinal related illnesses
Low LDL, High HDL	Cardiovascular health and metabolic syndromes
Prebiotics	Colon health
Induction of satiety and reduction in energy intake	Obesity
Improved micronutrient absorption	Enhanced mineral absorption, osteoporosis
Thermogenesis	Obesity, diabetes

cereals, which considers enhancement in the nutritional properties of cereals from farm to folk level. Studies have been done on cereals to discover the physical properties, chemical composition, starch content, etc. that may be useful to mankind. Additionally, studies based on the benefits of cereals in the diet of human beings and at the industrial level have been in full swing. Scientists have been working on the modifications of high glycemic foods especially rice through various techniques such as genetic modification, altering the chemical composition, processing techniques and storage conditions. worked on the lowering of the glycemic index of rice (Guo *et al.*, 2023).

Natural genetic variation has a role to play in it because of the variation caused from the botanical source in starch structure (Birt *et al.*, 2013). The supernumerary genetic variation within botanical sources occurs due to the variation in starch bio-synthesis genes alleles. There is little variation seen in commercial maize varieties in the levels of resistant starch, however a substantial variation is observed in the resistant starch content of exotic germplasm. A variety of treatments like genetic methods (inbreeding of mutants containing genes for high amylose production and the inhibition of starch-branching enzymes), physical treatments (High hydrostatic pressure, extrusion, autoclaving and retrogradation cycles, heat–moisture treatment and annealing), enzymatic treatments (debranching enzymes: pullulanase and iso-amylase), chemical modifications (lintnerization/acid-treated starch, acetylation, phosphorylation, carboxymethylation, oxidation, and hydroxypropylation), γ -irradiation treatment (Co60) and lipid complexation have a role in the increment of the resistant starch content (Dupuis *et al.*, 2014a). Another method suggested is by making use of biotechnology. The genetic engineering approaches play a crucial role in producing starch with increased resistance to digestion by understanding the molecular mechanisms controlling starch structure.

Another way found to enhance the RS content of foods by modifications of processing conditions such as time and temperature applications along with alterations in pH. Has been found to increase RS content (Dupuis *et al.*, 2014b). Genetic methods, physical treatments (autoclaving and retrogradation cycles), enzymatic treatments (pullalanase and isoamylase), chemical modifications (linterization), gamma irradiation, lipid complexation, *etc.* that showed remarkable results in increasing the RS content. The increased RS content suggests a lowered glycemic index in foods. Also, all these technologies are based on increasing the amylose content in starch as higher amylose content implies increased RS content (Ahuja *et al.*, 2013).

Effect of processing and storage conditions on the resistant starch (RS)

Processing affects the resistant starch content of foods as reported in many studies (Table 2). Vaidya and Sheth, (2011) studied the impact of processing techniques and effect of storage of Indian cereal and cereal products on resistant starch content. Effect of processing techniques and storage conditions in cereals specifically, wheat, rice, maize and pearl millet on resistant starch content after roasting, baking, boiling, shallow frying, steaming, and frying was assessed. Sample varieties were of western India, Gujarat. The experiment was performed on cooked products like *Chapatti, Thepla, Rotla, Daliya*, etc. The study concluded that the processing techniques (roasting, baking, and boiling, followed by shallow frying) has a positive impact on the content of RS while steaming and frying decreased the RS content.

In another study conducted in China on the impact of cooling of cooked white rice on resistant starch content and glycemic response increment in RS content was observed (Sonia *et al.*, 2015). The samples were analyzed after cooking, cooking and cooling for 10 hours and 24 hours (at 4°C and then reheating it (test rice II). It was found that the RS content was higher in cooled cooked white rice. Another study done by Nigudkar (2014) on estimation of RS content of selected routinely consumed Indian food preparations concluded that cereals when underwent general moist heat treatment there was an increment in the RS content. On the contrary, on application of dry heat there was decrement in the RS content of a food preparation. A considerable amount of increment in RS content was also seen when stored overnight.

The rate and completeness of fermentation of RS differs as it is dependent on the source and heat treatments used. Consumption of high glycemic index foods is higher in the South Asian populations, thus making them to be more prone to type-II Diabetes Mellitus and CVD. Amylose: amylopectin ratio), post-harvest processing (such as parboiling) and consumer processing (cooking, storage, and reheating) leads to changes in the rice in turn affecting the postprandial glycemic responses in the population. In general, the observed glycemic index ranged from 48 to 93, stating rice under high-glycemic foods. They suggested that a ration of amylose and amylopectin, gelatinization reduction leads to a reduced glycemic impact. They concluded that the refrigerated long-grain rice had the high RS content in comparison to the short-lengthened rice grain cooked in a pressure cooker. But, there was no significant difference between the GI of both varieties of rice. The cooking time is directly proportional to the increment in the glycemic index. Moreover, the fluctuation in the blood glucose levels is further influenced by the consumer characteristics like chewing habit, and ethnicity. Hence, the cooking time of rice and choosing high amylose content in rice will be beneficial for the diabetic people as it will help in bringing a lower PPG response in the body (Blaak *et al.*, 2012).

Noraidah *et al*. (2023) also reported the increment in resistant starch content after addition of high-amylose maize starch (HM) in Chinese steamed bun. There was also reduction in the pasting viscosities and calorific values. This clears that presence of amylose has impact on resistant

Table 2: Effect of processing on Resistance Starch (RS).

Cooking method	Food item	Reason	Reference
Boiling	Beans	Decrease in RS in beans is the catabolism of amylose inhibitors that arises during the boiling.	Wang *et al.* (2010)
	Chickpeas	Increase in RS due to retrogradation of starch that arises after boiling and gelatinization.	
	Rice	Increase in RS due to retrogradation of starch.	Lee and Chang (2004)
Steaming and pressure cooking	Steamed noodles	Increase in RS due to retrogradation.	Dhital *et al.* (2010)
	Common bean and chickpea	Decrease in RS.	Almeida-Costa *et al.* (2006)
Baking	Bread	Increase in RS due to low temperature/ long baking period.	Yadav *et al.* (2011) Buddrick *et al.* (2015)
	Bread by sourdough method	Increase in RS due to low temperature/ long baking period.	Kale *et al.* (2002)
	Whole wheat bread	Increase in RS due to extending the baking time.	Raatz *et al.* (2016) Tahvonen *et al.* (2006)
	Potatoes	Increase in RS due to the use of heat treatment with moisture.	Akerberg *et al.* (1998)
	Chilled potatoes	Increase in RS due to retrogradation of amylose.	
	Barley-wheat	Increase in RS due to high amylose/amylopectin ratio.	
Microwave cooking	Rice and barnyard millet	-	Kanagaraj *et al.* (2019)
	High-carbohydrate foods		Sumardiono *et al.* (2018)
	Indica rice	-	Liu *et al.* (2021)
Extrusion	Green banana flour	Increase in RS due to shorter residence time in extrusion cooking	Sarawong *et al.*, 2014
	Corn starch	-	Adamu, (2001)
Autoclaving	High amylose potato starch	Autoclaving increased the resistant-starch content directly proportional to amylose content.	Berry (1986)
	Corn starch	Increase in RS due to temperature.	Dundar and Gocmen (2013)
	Rice	Increase in RS due to retrogradation of starch.	Ashwar *et al.* (2016)

starch content. Hence, in order to make the resistant starch a functional food, appropriate usage of cooking methods and storage conditions is required (Aruna and Parimalavalli, 2023).

Industrial uses of resistant starch (RS)

With the increase in the consumers awareness towards for better-quality food products and enhancement in popularity of novel food with extended nutritional properties, researchers have started to use the functional properties of RS. They are considering it as one of the fibre components due to its fermentation (partial/complete) in the colon, contributing to various positive impacts on human body, thereby improving the health. It acts as a functional fibre because of its minute particle size and bland taste (Sofi *et al.,* 2017). Thus, this has led to new product development with enhanced acceptability of consumer having greater palatability as compared to those foods made by conventional fibre sources. Additionally, Khatkar *et* al., (2009) during his study on application of cereal starches in food processing, discussed the presence of RS in the Ready-to-eat (RTE) breakfast cereals and the emergence of chemically modified starches in the RS category. Certain grains like maize, sorghum and rice have been considered viable renewable resources for the production of distilled liquors. The study also stated the need for the production of gratifying but less-fattening foods that has led to the development of fat-replacers. The increased resistant starch content of rice will act as a great alternative for high caloric fatty foods in the form of a fat-replacer. There is also an increased need for reducing the plastic packaging that has led to the development of a cereal starch-based plastics known as bioplastics This new trend of packaging has helped in decreasing the costs due to low-use level, compatibility with a range of processes, good flavor release, and friendly labelling. Consequently, Sajilata *et al.* (2006) during a study on resistant starch concluded that RS has unique physical and chemical properties such as swelling and water-binding capacity which is making it valuable in a variety of foods that has led to the increased usage in food industries.

Many studies have well established that repeated heating/cooling of foods can increase in the RS content. indicating that amylose has no direct increase with increase in RS. Many factors including amylose chain lengths, granule size, type of crystalline polymorphs, physical insulation of starch by thick-walled cells, porosity and physical distribution of starch in relation to the dietary fiber components may have influence over it (Yadav *et al*., 2009). The bland flavour and transparency in colour of RS with low water retaining capacity have made them a good encapsulating medium in microencapsulation of probiotics (Homayouni *et al*., 2014). Starch has a variety of industrial applications in concerned with agriculture, food, mining, paper, textiles, oil drilling, bioplastics and (Ellis *et al*., 1998). However, past and current research data claims that the intake of rapidly digested starches is directly proportional to the incidence of chronic diseases. Hence, current researches are focusing on the study of those starches that are resistant to enzymatic digestion (Birt *et al*., 2013). To overcome this problem, starches are retrograded to form Resistant Starch. RS has desirable physicochemical properties such as swelling, viscosity increase, gel formation and water-binding capacity, making it useful in a variety of foods like baked and extruded products.

They also act as functional food ingredients as prebiotics, low calorie foods and in products for oral rehydration therapy and use in products for coeliac, as bulk laxatives (Karunarathna *et al*., 2023). Thus, RS has several technological benefits. Therefore, many industries have fortified their food with RS including yogurt, milk dessert, muffins, ice cream, cheese, cakes, Iranian fermented drink (doogh), bread, corn flakes, battered foods and pasta (Lee Yeo and Seib, 2009) (Homayouni *et al.,* 2014).

CONCLUSION

The review concludes that Resistant Starches are unique in their properties. Many processing methods have been reported to affect content of the resistant starch in food viz. roasting, baking, and boiling, shallow frying, autoclaving and extrusion. From innovative product development to positively impacting the human health in terms of glycemic load and their actions as prebiotics, they have enormous potentials. But still their purified form or the new food products are available at high cost. The paper calls for requirement of more studies in the area of physical conversion of starches to Resistant Starches in common foods of day today life so that health benefits of these can be utilized cost effectively by common man.

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Conflict of interest

The authors declared no potential conflicts of interest.

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