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REVIEW

A review on the effects of resistant starch on the postprandial glycaemic response and the influence of processing conditions on the formation of resistant starch

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Abstract

In a world of rapidly changing food habits and stressful lifestyles it is more and more recognized that a healthy digestive system is essential for overall quality of life. This recognition has led to the development of foods that are designed to contribute to a healthy digestive system and indirectly to the maintenance of general well-being. For this reason, there is an immediate growing interest in the field of gut health related to the consumption of resistant starch. In this review article, the effects of resistant starch on the postprandial glycaemic response and the influence of processing conditions on the formation of resistant starch were discussed. The use of resistant starch for lowering blood glucose has promising implications for people with diabetes since, for this subpopulation, controlling blood glucose concentrations is a beneficial trait. Besides, the processing method reported in this article showed mixed trends in resistant starch formation.

1. Introduction

The latest Malaysian National Health and Morbidity Survey (NHMS) reports have defined non-communicable diseases (NCDs) as medical conditions which are non-contagious or non-transmissible from one person to another (Ministry of Health Malaysia, 2015). A total of 73% of deaths have been estimated caused by NCDs alone in Malaysia, with cardiovascular diseases being the biggest contributor that includes heart attacks and strokes. There are approximately 35% of deaths occur in Malaysian individuals aged below 60 years, who had at least one NCD risk factor such as diabetes, obesity, high blood pressure, or high blood cholesterol (Ministry of Health Malaysia, 2015). The statistics have also ranked diabetes, obesity, hypertension, tobacco use, and hypercholesterolemia as the biggest contributors to premature deaths (Rampal *et al.,* 2008).

Priority is focused on decreasing the global burden of NCDs as it is important for sustainable development (WHO, 2016). The phenomenon of NCDs burden is triggered by four behavioural risk factors that are extensive aspects of economic transformation, rapid urbanization and modernized lifestyles. There are at least 5.7 million (18.3%) Malaysian adults aged 18 years old and above who are suffering from diabetes mellitus (DM) (Ministry of Health Malaysia, 2015). Statistically, there is presumably one undiagnosed individual behind every diagnosed diabetic patient, as the majority of newly reported cases are coming from those who have been unconsciously suffering from DM (Cheisson *et al.,* 2018). One alternative to cope with the rising prevalence of DM is to develop food with a reduced glycemic index (GI) (Zhu and Jia, 2019; Haini *et al.,* 2021). GI relates to the blood glucose-raising ability of digestible carbohydrates. It is defined as the incremental area under the blood glucose curve (iAUC) of a 50 g carbohydrate portion of a test food, expressed as a percentage of response when compared to 50 g carbohydrate of a reference food taken by the same subject (Jenkins *et al.,* 1981). Food carbohydrate that is slowly metabolized belongs to low GI foods (GI < 55), whereas food carbohydrate with intermediate digestibility pattern has a medium GI (GI < 70) (Zhu and Jia, 2019). Food carbohydrate that is rapidly digested is found in high GI foods (GI > 70). High-GI diets have been associated with a range of metabolic diseases and health conditions, typically diabetes and obesity (Zhu and Li, 2019).

Over the years, previous studies have shown the ability of low GI foods to improve blood glucose control for patients with diabetes (Ojo *et al.,* 2018), aid in weight

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management (Zafar *et al.,* 2019) and reduce the risks of cardiovascular diseases (Clar *et al.,* 2017). Studies also reported that the consumption of low GI foods has the ability to increase satiety, reduce appetite, delay hunger, and reduce excessive energy intake in adults (Stewart *et al.,* 2018). In regard to the dissatisfaction with the high costs and potentially hazardous side effects of treatment drugs, the potential of using functional food for preventive measures is currently ongoing (Maziarz *et al.,* 2017). Lowering the GI of food would therefore serve better alternative in aiding and managing general health programs (Cassidy *et al.,* 2018). One of the functional ingredients that can be used in lowering the GI of food is known as resistant starch (Shukri *et al.* 2017).

2. Resistant starch

Carbohydrates are the mainstay of the human diet all over the world. Carbohydrates are present in a variety of foods and drinks where they primarily serve as a source of fuel to energize the body. They are also used as a primary source of energy by components of biological systems such as the brain, blood, and nervous system. Furthermore, when some forms of carbohydrates are ingested, this essential nutrient offers a variety of health benefits as well as possible disease defence (Fuentes-Zaragoza *et al.,* 2010). Numerous studies have been conducted to recognize and classify different types of carbohydrates, especially those that provide additional benefits beyond energy. Carbohydrates are classified in a broad variety of ways, from simple sugars to complex sugars, which include the type of sugar, the number of sugar units, and the type of bond for further classification. Simple sugar, two or more sugars connected by glycosidic bonds are called dioligo-, or polysaccharides. Starch and glycogen are examples of polysaccharides. Polysaccharides can also be classified as complex carbohydrates, whereas monosaccharides and disaccharides are examples of simple carbohydrates (Amaral *et al.,* 2016).

Dietary fibre, which is the leading carbohydrate under research over the years, is one ultimate example of complex carbohydrates (Hasmadi *et al.,* 2021). Carbohydrates account for 50% or more of a standard Asian diet, making them the most common nutrient available for daily consumption. When it comes to carbohydrates that are quickly digested, such as simple carbohydrates, there is a worrying condition as it increases the risk of developing health problems like diabetes mellitus and coronary heart disease (Liu, 2002). In this regard, dietary fibre has therefore been long recognized for its potential to enhance various aspects of human health. Daily recommendations on increased dietary fibre intake and regular intake of simple carbohydrates have been made throughout the past decades, however, carbohydrate consumption has been increasing whereas dietary fibre consumption has been decreasing until now (Guo *et al.,* 2021). As a result, nutritional advancements are being confronted to improve total dietary fibre intake as well as excessive intake of carbohydrate-rich foods that are often overlooked.

Out of all carbohydrate types, resistant starch (RS) has been extensively researched for its physiological benefit as dietary fibre (Guo *et al.,* 2021). Though resistant starch was only recently discovered as one of the dietary fibre constituents, it has been considered an essential ingredient in functional food as the scientific findings gather about the structure, uses, function, and biological effects (Hasmadi *et al.,* 2020; Kaimal *et al.,* 2021). The word "resistant starch" was coined in 1982 to characterize the portion of starch that is not enzymatically metabolized by human digestive enzymes either in the mouth or the small intestine (Englyst *et al.,* 1982). RS, therefore, passes into the colon undigested, showing its ability as a prebiotic component. This also refers to non-digestible carbohydrates that are not metabolized by human digestive enzymes which are occupied by the bacterial microflora in the lower digestive tract. To date, there are five classifications of RS which have been categorized based on their respective mechanism of digestive resistance (Homayouni *et al.,* 2014).

Resistant starch type 1 (RS1), which can be obtained from tubers, milled seeds, and grains, is often referred to as physically inaccessible starch in the literature. A physical barrier, normally a cell wall, prevents enzymes from coming into contact with the starch granules. RS1 is also thermally stable, giving its manufacturing advantages to food innovators and product developers (Ashwar *et al.,* 2016). Resistant starch type 2 (RS2) is best defined as raw or natural starch, where the starch has not been thermally processed and retains the starch granules. This type of RS2 is mostly found in raw bananas, where its naturally crystalline starch structure restricts enzymatic digestion (Ashwar *et al.,* 2016).

RS type 3 (RS3), on the other hand, has undergone some sort of processing condition that causes the starch granules to recrystallize or retrograde. This is normally accomplished by hydrothermal processes that cause starch gelatinization, followed by cooling that assists the starch to crystallize into its resistant form. Unlike RS1 and RS2, RS3 is of special interest to the food industry because it has the ability to form during the manufacturing and processing of food (Raigond *et al.,* 2015). For example, RS3 is present in a cooked starch component like cooked potato or other starchy food

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products including baked bread, rice and pastry foods that have been through heating and cooling cycle.

The next one is resistant starch type 4 (RS4), a term for starch that has been chemically engineered to make it less digestible. Ethylation, esterification, and cross-linking are examples of such modifications, which frequently result in starch with a higher degree of alteration than that of the typical chemically modified starches. As a consequence, RS4 is regarded as a novel food but it has not been validated by the European Union for use within Europe, even though it has now been legally authorized for use in Japan (Ashwar *et al.,* 2016).

The last one is RS type 5 (RS5), the only type of RS which has been recently reported in the literature for the past three to four years. A part of the amylose starch fraction that has been configured with lipids to form a complex helical structure is named RS5 (Dupuis *et al.,* 2014). In regard to the recent addition of RS5 into the category, it is likely that ongoing research in food innovation will lead to the discovery of novel forms of RS in the future. Eventually, the RS content in foods is varied and appears to be very dependent upon multiple factors which comprise the processing and storage conditions applied.

3. Resistant starch as a functional ingredient

Functional foods fundamentally have been defined as natural and/or modified components with physiological value beyond basic nutrition, which aid in the improvement of human health (Henry, 2010). Functional ingredients can be food additives used to fortify foods or nutritional components naturally present in food. These definitions are loosely accepted because in Malaysia the terms have no legal definition. Notwithstanding that in Malaysia, functional foods are reported to be purchased for health issues such as weight loss, cholesterol reduction, and digestive health (Kasim *et al.,* 2018).

Functional foods span a wide range of foods and beverages. Examples of functional foods or ingredients are salmon, green vegetables, cereals, bread, garlic, onion, vitamins, calcium, and yoghurt. RS is also a functional ingredient (Fuentes-Zaragoza *et al.,* 2010) that is naturally present or incorporated into products to make functional foods. Commercial companies have developed functional foods with dietary fibre, but more specific products are being formulated with RS or RS as an additive (Aigster *et al.,* 2011). Many research studies have successfully used RS as a functional ingredient to evaluate physiological efficacy and health benefits such as lower cholesterol or improved lipid profile, modulation of glycemic and insulin response, and improved bowel health (Fuentes-Zaragoza *et al.,* 2010); although the term 'functional ingredient' might not always be used.

Interestingly, the use of RS has been quite explored in the production of bakery products. In Hedayati *et al.* (2018), the substitution of RS (Hi-Maize 260, 20%) into sponge cake formulation has been well accepted by consumers. It had been reported that cakes enriched with RS had lower hardness and porosity than the control. The study also agreed with Majzoobi *et al.* (2014) that the addition of RS (Karen Nutrilife, 20%) improved the hardness and viscoelasticity of sponge cake as opposed to control, suggesting that RS could be applied in producing sponge cake at a maximum level 20% without causing undesirable effects on the sensory properties. On the contrary, Bilgiçli and Levent (2013) reported that compositing RS (C*ActiStar, 15%) reduced the volume index and firmness of cake samples which could have been due to differences in the cake formulation used.

Other than cake, resistant starch is also used in muffin making. According to Sharma *et al.* (2016), muffins consisting of 10% gelatinized-retrograded starch had improved texture compared to those added with or without extruded starch. Maziarz *et al.* (2013) incorporated RS (Hi-Maize 260, 4.73%) into the muffins and resulting in enhanced textural and higher overall likeability score than the control. Both findings are in agreement with Baixauli *et al.* (2008) that RS contributed to softer-texture muffins as the effects were seen evident at the highest amount of RS (20%). Sanz *et al.* (2008), on the other hand, reported that muffins containing RS type 3 (Novelose 330 and C*Actistar) had greater viscoelasticity, height and volume than those muffins containing RS type 2 (Hi-Maize and Novelose 240), noting the differences were dependent on the type of RS. The appearance of RS can range from coarse to fine powder that is white in colour. RS has a bland taste, which makes it desirable as a food additive. Other desirable traits that are present in types of RS are small particle size, low water-holding capacity, viscosity, solubility, gel formation, light texture, and high gelatinization temperatures. One or more of these traits allow for the successful incorporation of RS into a food product while still maintaining a fairly palatable food product, although other sensory attributes such as grittiness, chewiness, and cohesiveness have been affected by the addition of RS to muffins (Baixauli *et al.,* 2008). Baixauli and associates (2008) noticed an increase in grittiness, sweetness, and overall increase in moisture as RS increased, while springiness, chewiness, and cohesiveness decreased as RS increased.

In the production of biscuits, Laguna *et al.* (2011)

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and Laguna *et al.* (2013) reported that the substitution of resistant starch (Hi-Maize, 20 – 60%) increased the breaking strength, crumbliness and dough resistance. Biscuits prepared with 20% RS had been similarly acceptable to that of control while biscuits containing 40 – 60% RS had lower sensory scores. In Sharma *et al.* (2016), cookies made with gelatinized-retrograded starch (10%) had paler colour, and higher spread ratio and were generally acceptable compared to extruded starch cookies. Yeo and Seib (2009) incorporated different types of RS in cookie formulation and found that the use of cross-linked resistant starch phosphate (50%) produced cookies with better shape and textural properties.

Efforts to enrich low-fibre foods with dietary fibre have encountered setbacks due to sensory issues. Bread, muffins, and crackers are foods commonly fortified with whole-grain dietary fibre. However, sensory evaluation of the appearance or colour, taste, and feel of high-fibre fortified foods has been somewhat unfavourable. For example, fibre-fortified bread has been summarized to have a dark colour, reduced loaf volume, poor mouthfeel, and flavour-masking properties (Sajilata *et al.,* 2006). Bread formulated to be functional foods can replace part of rapidly digestible flour with RS to improve sensory concerns. Sanz *et al.* (2009) replaced 15% of wheat flour with four different types of RS (2 type RS2, 2 type RS3) for the final RS g (%) of muffin product to be between 8.3 g (1.55% RS) and 12.5 g (1.76) as compared to the wheat control 0.65g (0.031% RS).

Due to the desirable physicochemical characteristics of RS, it improves sensory properties in baked goods compared to control baked goods (Maziarz *et al.,* 2013), and in some cases, the addition of RS can improve sensory properties above other dietary fibres. This allows RS to be used to increase dietary fibre in foods not typically viewed to be good sources of dietary fibre, as in the case of Maziarz *et al.* (2013) who also tested the use of RS in a meat entrée chicken curry, for sensory evaluation. However, RS is more commonly incorporated into baked goods to modify texture and act as a crisping agent (Sajilata *et al.,* 2006). With the increase of RS and its use as a functional ingredient, understanding the physicochemical dynamics of RS when incorporated into food products is not only good for the improvement of human health but also has monetary importance for the food industry. Table 1 summarizes the applications of resistant starch in bakery products.

4. Effects of resistant starch on postprandial glycaemic response

Discussions and recommended strategies for controlling glucose and insulin responses through diet are commonly associated with metabolic syndromes such

Table 1. Resistant starch as a functional ingredient in bakery products

Food Product	Type of RS	References	Effect of resistant starch
Sponge cake	Hi-Maize 260, 20%	Hedayati *et al.* (2018)	Cakes enriched with RS had lower hardness and porosity than the control
Sponge cake	Karen Nutrilife, 20%	Majzoobi *et al.* (2014)	Improved the hardness and viscoelasticity of sponge cake
Cake	C*ActiStar, 15%	Bilgiçli and Levent (2013)	Reduced the volume index and firmness of the cake
Muffin	10% gelatinized-retrograded starch	Sharma *et al.* (2016)	Improved texture compared to those added with or without extruded starch
Muffin	Hi-Maize 260, 4.73%	Maziarz *et al.* (2013)	Enhanced textural and higher overall likeability score than the control
Muffin	Hi-Maize 260	Baixauli *et al.* (2008)	RS contributed to softer-texture muffin
Muffin	RS type 3 (Novelose 330 and C*Actistar); RS type 2 (Hi-Maize and Novelose 240)	Sanz *et al.* (2008)	Muffins containing RS had greater viscoelasticity, height and volume than those muffins containing RS type 2 (Hi-Maize and Novelose 240)
Biscuit	Hi-Maize, 20 – 60%	Laguna *et al.* (2011) and Laguna *et al.* (2013)	Increased the breaking strength, crumbliness, and dough resistance
Cookies	Gelatinized-retrograded starch (10%)	Sharma *et al.* (2016)	Cookies made with gelatinized-retrograded starch (10%) had paler colour, higher spread ratio and were generally acceptable compared to extruded starch cookies.
Cookies	Cross-linked resistant starch phosphate	Yeo and Seib (2009)	Cookies with better shape and textural properties.
Muffin	Hi-Maize 260	Baixauli *et al.* (2008)	Increase in grittiness, sweetness, and an overall increase in moisture as RS increased, while springiness, chewiness, and cohesiveness decreased as RS increased.

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as diabetes mellitus. An extensive study has been conducted implicating RS as a dietary agent that can be used to control postprandial glucose and insulin (Guo *et al.,* 2021). Furthermore, because RS has been shown to reduce glycemic response by impaired glucose bioavailability, it can also lower the insulin surge. Postprandial glucose and insulin response after a carbohydrate dietary intervention are conventionally studied within a 2-to-8-hr period. Likewise, with experimental feeding of RS, however, RS feeding studies can have prolonged study periods to assess if RS has a second meal effect or other overlapping interactions.

The main dietary source of blood glucose comes from carbohydrates (e.g., starch), which according to the Department of Agriculture's 2010 Dietary Guidelines for Americans, should be 45 to 65% of daily calories (USDA, 2010). Therefore, deductively starches are a major contributor to the glycemic response and thus are categorized by their digestibility with respect to glycemic response: rapidly digestible starch (RDS), slowly digestible starch (SDS) and resistant starch (RS). RDS is not known for physiological benefits other than when the quick release of glucose is needed, such as in cases of hypoglycemia. Otherwise, large doses of rapidly available glucose can have drawbacks, especially for prolonged periods of time. Diets with low glycemic foods have established their benefit in reducing the risk of developing diabetes (Salmerón, Ascherio, Rimm *et al.,* 1997; Salmerón, Manson, Stampfer *et al.,* 1997 and cardiovascular disease (Nestel *et al.,* 2021) in long-term prospective cohort studies. Such observations have led to the sustained investigation of foods and dietary components with a lower glycemic index.

Whereas, both SDS and RS are being investigated for physiological benefits akin to dietary fibre. Though SDS and RS are dietary fibres, each with specific physiochemical properties that respond differently to enzymatic hydrolysis of glucose into the bloodstream (Miao *et al.,* 2015; Bede and Zaixiang, 2021). With respect to RS digestion and absorption of glucose, the source, structure, preparation, and concentration of starches are important variables to consider. Ratios of amylose and amylopectin influence digestive resistance and thus alter the glycemic response. Depending on the amylose: amylopectin structure, hydrolysis to monomeric glucose in digestion can be enzymatically hindered. Starches with higher amylose content have higher digestion resistance than starches high in amylopectin. This is the induction for the ideology that RS lowers postprandial glucose as well as insulinemic response, which has been shown in selected human studies (Xiong *et al.,* 2021).

In general, foods that have larger proportions of RS will be digested at a much slower rate due to a combination of their physical or chemical properties when compared to a similar food that is largely made up of either readily digestible starch (RDS) or slowly digestible starch (SDS) (Wong and Louie, 2017). Therefore, foods with higher contents of RS, including those enriched with added RS, have the potential to contribute fewer kilojoules compared with their more digestible counterparts. The influence of this altered digestion can be determined in human and animal subjects through the measurement of blood glucose levels for the glycaemic index, GI, along with subsequent insulin responses (Zaman and Sarbini, 2016).

Food products enriched with RS, therefore, have the potential to become part of treatment programs for the management of diabetes mellitus and obesity. A number of mammalian studies have confirmed these benefits although the mechanism is not completely understood but appears to depend on how the RS itself is integrated into the food system. MacNeil *et al.* (2013) provided human subjects suffering from type 2 diabetes with bagels made from wheat flour supplemented with varying levels of RS2 flour. When the RS2 flour replaced a portion of the wheat flour, it lowered levels of both postprandial glucose and insulin. However, when the RS2 was added in addition to the wheat flour, the differences in glucose and insulin levels were not observed. This indicates that the GI-lowering effect of RS is only effective when RS replaces RDS as opposed to being added in conjunction with RDS.

Behall *et al.* (1988) fed 25 people (12 women, 13 men) 2 cracker meals in a crossover design. The two meals were comprised of either a cracker with 70% amylose and 30% amylopectin or 30% amylose and 70% amylopectin. The cracker recipe was the same for each type of cracker only varying by the different type of starch. Crackers were administered to give a dose of 1-gram carbohydrate and 0.33gram fat/kg body weight. The goal was to observe if the different chemical structures of starch due to different amylopectin and amylose ratios had an effect on glycemic responses. Insulin was also measured. Six blood samples over a period of 180 mins were used for evaluation. The sum insulin response above fasting measurements was significantly different between test meals but the same was not true for glucose measurements above fasting. However, the high amylose cracker obtained a lower glucose peak at 30 min and lower insulin responses at 30 and 60 min when compared with the high amylopectin cracker (Behall *et al.,* 1988). When glucose response was summed, there was no difference between treatments. This study noticed a stable glucose response and lower

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insulin response after a high amylose meal. Being one of the earlier RS human feeding studies they surmised that these results suggested a benefit to carbohydrate-sensitive or diabetic individuals.

Meanwhile, Bodinham *et al.* (2010) conducted a study where they incorporated RS supplements into a flavoured mousse fed to twenty healthy males. The study was an acute randomized, single-blind crossover design where the subjects participated in two separate test days scheduled a week apart. The supplements were either an RS product comprised of 60% RS and 40% RDS or a placebo comprised of 100% RDS. The supplemented mousse was administered to the subjects with a standardized breakfast and lunch. This study also tested satiety by separately consuming an ad libitum pasta dinner at the end of the dietary intervention until subjects felt full. The results from this study were similar to Behall *et al.* (1988) with respect to glucose and insulin response. They observed no change overall in postprandial glucose concentrations between treatments, but a significantly lower insulin response was observed with the RS-supplemented meal when compared to the placebo-supplemented meal (Bodinham *et al.,* 2010).

Bodinham *et al.* (2010) study differed from the Behall *et al.* (1988) study because instead of one test meal per day, Bodinham *et al.* (2010) served two test meals per day. Bodinham *et al.* (2010) also supplemented standard meals with their test product, instead of only the test product being served as a meal. Generally, it is believed RS lowers postprandial glucose as well as an insulinemic response; however, overall, both studies reported no change in glucose response. Nonetheless, other human feeding studies have reported lower glucose coupled with a lower insulin response (Raben *et al.,* 1994; Hoebler *et al.,* 1998).

Luhovyy *et al.* (2014) came to similar conclusions in a study with high amylose maize starch which was incorporated into cookies. Behall and Hallfrisch (2002) exposed twenty-five human subjects to bread with varying amounts of amylose and measured both glycaemic and insulin responses. They found that bread containing at least 50% amylose produced significantly lower blood glucose levels and insulin responses in comparison to bread that had lower amylose contents. These observations were attributed to the presence and formation of RS from the packing and crystallizing of the straight-chained amylose during the bread-making process.

There is also evidence to suggest that RS has an impact on the regulation of the gut hormones glucagon-like peptide-1 (GLP-1) and peptide YY (PYY). GLP-1 is secreted by the L-cells of the intestine, thereby stimulating insulin production whilst also inhibiting the secretion of glucagon. Comparatively, PYY has been linked to insulin secretion (Wong and Louie, 2017) and also plays a major role in acting synergistically with leptin to promote satiety through the central nervous system (Maziarz *et al.,* 2017). Zhou *et al.* (2008) saw increased levels of both PYY and GLP-1 in rats that were fed with RS2 diet and improved glucose tolerance in rats that had induced diabetes. Hoffmann Sardá *et al.* (2016) conducted a similar study with humans and observed increased levels of PYY, and additionally, decreased levels of ghrelin.

The GI lowering ability of RS is further demonstrated by the work of Srikaeo and Sangkhiaw (2014) who manufactured amylose-enriched rice noodles. The GI of the noodles was measured using both *in vivo* and *in vitro* methods, finding that as the GI decreased, both the amylose and RS contents increased. This enabled the authors to produce a rice noodle that could be classified as low GI (<55) from a product that is traditionally high GI. The improved nutritional functionality, however, was at the cost of a loss of texture and tensile strength within the noodle microstructure. Increased RS content in foods having a detrimental effect on the sensory properties of the product is a common issue and presents itself as one of the primary challenges in this research area. Despite this, however, there is a significant body of contradictory results in this field and additional work is justified to establish links (Wong and Louie, 2017) more clearly.

There is a wealth of publications on the effects of RS on glycemic and insulin responses. These studies assess glucose and insulin response with food products composed mainly of starch and/or where portions of food constituents have been substituted with RS (Hoebler *et al.,* 1998). Observed differences in glucose or insulin response after ingestion of RS have led to conflicting reports. Many researchers have reported a decrease in postprandial glycemic or insulin response while others have reported no observed difference. Major differences have been found in glucose response when consumption of an RS meal was only compared with control. For example, the use of raw potato starch against pregelatinized potato starch (Raben *et al.,* 1994) and RS bread against white bread (Hasjim *et al.,* 2010) expressed noticeable differences between treatment and control.

5. Effects of processing methods on the formation of resistant starch

5.1 Boiling

Boiling as in the cooking method can increase and

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decrease the resistant starch content depending on the type of food. In Wang *et al.* (2010), while the resistant starch amount of boiled beans decreased, boiled chickpeas' resistant starch amount increased. The reason for the decrease in resistant starch content in beans is the catabolism of amylose inhibitors that arises during the boiling whereby the increase in resistant starch content in chickpeas is explained by the retrogradation of starch that arises after boiling and gelatinization (Wang *et al.,* 2010).

Similarly, Kutoš *et al.* (2003), Pujola *et al.* (2007) and Fabbri *et al.* (2016) also achieved similar results in their study using the beans. A cooling period for cooked legumes is suggested to maximize the amount of RS consumed by diet (Fabbri *et al.,* 2016). Boiling lentils significantly increased the resistant starch content from 15.6–43.2 g/kg dry matter in the raw lentils to 37.3–50.9 g/kg dry matter in the cooked lentils due to retrogradation of starch after gelatinization (Wang *et al.,* 2009), showing that boiling decreases the resistant starch content of potatoes from 6.9 to 1.2%, whereas cooling after boiling increases such content by 4.6%.

According to Sagum and Arcot (2000), the resistant starch amount in rice, especially rice that contains low and intermediate levels of amylose, is reduced by boiling due to the absence of higher amounts of the linear component of the starch. Rashmi and Urooj (2003) reported that pressure cooking and steaming methods produced rice with a higher resistance amount as compared to boiling and straining methods. Moreover, Lee and Chang (2004) studied the effect of heat treatments on *in vitro* starch digestibility of rice, with different levels of amylose. They found that boiling increased 0.23 - 3.66% of resistant starch in the rice.

5.2 Steaming and pressure cooking

Steaming helps the formation of resistant starch. According to Dhital *et al.* (2010), steaming noodles increased both the moisture content and the amount of resistant starch. The resistant starch amount isolated from steamed beans was found to be higher than the amount isolated from raw beans. Similarly, the directly measured resistant starch amount in traditional high-pressure steamed beans was higher than in the raw beans. It is suggested that retrogradation is the main reason for failure in digestion (Tovar and Melito, 1996). In a study in which common bean and chickpea were cooked in a domestic pressure cooker for 20 and 40 mins, respectively, and peas and lentils cooked at atmospheric pressure, cooked legumes had lower resistant-starch content than the raw ones (Almeida-Costa *et al.,* 2006). The unstandardized methodology for the obtained data about resistant starch could cause different results in each study.

5.3 Baking

Baking increases the resistant-starch content of bread. A low temperature/long baking period is more effective in resistant starch formation. The resistant starch content of bread baked at 120°C for 24 hrs was found to be 4.2% higher than bread baked at 200°C and 150°C for 35 mins and 12 hrs respectively. In the same study, when the baking time was extended from 15 to 45 mins, bread baked for 45 mins had 49% more resistant starch content than that bread baked for 15 mins. In starch gels that contain high moisture, such as bread, the crystallization of amylose can cause to generate resistant starch that can occur between glass transition temperature and melting temperature. Hence, in the condition of low temperature/long baking period, the temperature of bread may reach around 100°C and stay for a long period, which can cause propagation and crystallinity, leading to the generation of more resistant starch in bread (Yadav, 2011).

A recent study by Buddrick *et al.* (2015) analyzed that the fermentation time, temperature and the inclusion of palm oil into wholemeal bread formulations had a significant effect on the formation of resistant-starch content in all the bread, whereas fermentation time and the temperature had no significant effect. Additionally, because of the increased organic acid content of the sourdough fermentation process, it is shown that sourdough fermentation of rye bread had a greater impact on resistant starch formation than bulk fermentation of wheat and wheat blend bread.

Extending the baking time of whole-wheat bread from 15 to 35 mins also increases resistant-starch content from 17.98 to 45.6% (Kale *et al.,* 2002). Similarly, the resistant-starch content of wheat bread and rye bread also increased with prolonged baking periods (Rabe and Sievert, 1992). A low temperature/long baking period increases resistant starch formation by extending the activity time of endogenous enzymes. The traditional baking method breaks a-D-(1-6) glycosidic bonds of amylopectin, which causes the formation of short-chain (Yadav, 2011).

Raatz *et al.* (2016) compared the RS content of potatoes by two different cooking methods (baking and boiling) and service temperatures (hot: 65°C, chilled: 4°C, and reheated: 4°C for 6 days and reheated to 65°C) and found that baked potatoes have more resistant starch content than boiled ones. The use of heat treatment with moisture, shown to increase resistant starch formation with the cooking method baking, may explain the difference that was observed with baking vs boiling of

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the potatoes. Regardless of the cooking method, chilled potatoes have a more resistant starch content than hot or reheated potatoes. These results can be explained by the R3 content of chilled potatoes may be increased by retrogradation of amylose (Tahvonen *et al.,* 2006). Akerberg *et al.* (1998) also reported that the increase in resistant-starch content during the processing of food is related to a high amylose/amylopectin ratio. Traditional baking (200°C/45 mins) of a mixture of barley-wheat flour with different levels of amylose resulted in the mixture with high amylose (44% amylose), gaining more resistant starch than other mixtures.

5.4 Microwave cooking

Microwave increases the digestibility of tuber starch with physicochemical and structural modifications. Microwave cooking of legumes like chickpeas and beans transforms insoluble polysaccharides into soluble fractions (Marconi *et al.,* 2000). Microwave cooking is generally considered to reduce the resistant starch amount but depending on the processing conditions, changes in compact structure and physical conditions may result in an increase in RS2. For instance, cooking with low microwave energy followed by cooling increased the resistant starch content of Canna edulis Ker tuber (Zhang *et al.,* 2009).

5.5 Extrusion

Extrusion cooking is a process including high temperature, pressure and plucking which causes changes in the physicochemical and structural features of the flour. The effects of extrusion cooking on the resistant-starch content of foods are conflicting. While some studies showed a reduction in the resistant-starch content (Sarawong *et al.,* 2014; Gonzalez-Soto *et al.,* 2006), other studies showed the contrary (Adamu, 2001).

Extrusion cooking caused a significant decrease in the resistant-starch content of green banana flour compared to native flour (91.5-98.1% reduction). Although green banana native starch granules have very high amounts of resistant starch, thermal processing may cause a loss of resistant starch (Sarawong *et al.,* 2014). In a study in which extrusion cooking with banana, mango and cornflour is performed, the amount of resistant starch of all flour types decreased, whereas the largest decrease was found to be in banana flour. A shorter residence time in extrusion cooking may result in less opportunity for linear amylose chains to associate at the higher screw speed, which causes a reduction of resistant starch content.

In contrast, a longer residence time in extrusion cooking may give rise to more opportunities for amylose chain association. Therefore, the conditions in extrusion cooking play an important role in the preparation of products that contain resistant starch, due to its effect on their functional and physicochemical features (Gonzalez-Soto *et al.,* 2006). On the contrary, the cooling process after extrusion cooking increased the RS3 content of food. After cooling at 4°C for 24 hrs, RS3 arise from corn starch in a twin-screw extruder at 150°C and 180 rpm screw speed (Adamu, 2001).

5.6 Autoclaving

Autoclaving increases the resistant-starch content directly proportional to amylose content. While autoclaving high amylose potato starch increases resistant starch formation, autoclaving of high amylopectin starch does not increase such formation (Berry, 1986). Apart from the amylose content, the temperature is another important factor in the formation of resistant-starch content during autoclave cooking. Corn starch, which was autoclaved at 145°C, was significantly higher than the corn starch samples autoclaved at 140°C (Dundar and Gocmen, 2013).

By dual autoclaving-retrogradation treatment of rice varieties, the resistant starch content of the rice was extremely higher (30.31-38.65%) than native starches (4.42-10.94%). There is a two-step process in the production of RS by autoclaving-retrogradation. The autoclaving step gelatinization of hydrated starch takes place when amylose chains are leached out from the granules as random coils. The cooling step retrogradation of starch takes place when the linear flexible amylose chains recrystallize and form tightly packed double helices stabilized by hydrogen bonds, which are resistant to enzymatic hydrolysis (Ashwar *et al.,* 2016).

6. Conclusion

The applications of resistant starch in the development of food products showed a promising impact in stabilizing blood glucose concentration. During processing, the starch molecules undergo several physical modifications depending upon the type of starch and the severity of the conditions applied, leading to the formation of resistant starch. Moreover, cooking conditions such as baking, autoclaving and steaming and pressure cooking increased the formation of resistant starch whereas boiling, extrusion and microwaving demonstrated mixed trends.

Conflict of interest

The authors declare no conflict of interest.

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