Processing Technologies for Developing Low GI Foods – A Review

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Abstract

This paper reviews the various technologies employed to lower the glycemic index of foods and provides a future outlook for starchy foods. The glycemic index of foods can be reduced by increasing resistant starch or slowly digestible starch. However, information concerning the parameters/settings and mechanisms by which several technologies can be used are limited. Technologies such as microwave, infrared, ultrasonic, autoclaving, and high hydrostatic pressure can facilitate more interactions between food components, thereby resulting in the formation of various types of resistant starch or slowly digestible starch. Based on the findings of this paper, the use of microwave technology to produce resistant starch has been sufficiently reported in comparison to the other technologies. Given the research done in the last two decades regarding other technologies, there is a need for more research work on optimizing the parameters or processing conditions for thermal and non-thermal technologies in order to produce low GI starch and starchy foods. There is limited work done on combination treatments that can effectively develop low GI foods. The data provided for glycemic index and starch digestibility kinetics is mostly from in vitro studies.

Keywords: digestibility; in vitro; in vivo; resistant starch

1 Introduction

There has been increasing attention on food processing technologies application in developing food products that can be classified as low GI foods.[1] The current production trends are towards using emerging technologies in the food industry to make processes more efficient, less energy-intensive, and more environmentally friendly. The food processing technologies applied to starchy foods/grains result in a wide range of nutritional properties based on the starch fractions present. The combination of high moisture levels and high temperatures or high pressure and mechanical energy has been reported to convert nearly all slowly digestible starch (SDS) and rapidly digestible starch (RDS).[2]

Rapidly digestible starch promotes metabolic syndrome, and this will influence insulin resistance, obesity, and type 2 diabetes.[3] The benefit of slowly digestible starch (SDS) is a moderate impact on the GI. Resistant starch (RS) within a calorie-controlled diet is beneficial in protecting against metabolic syndrome and colon cancer.[3] Therefore, careful consideration of processing parameters and complementary approaches can be used to observe structural modifications to starch during food processing to increase RS and SDS.

Comprehensive studies have described the potentially deleterious effects of increased carbohydrate intake on the glycemic response but limited work has focused on optimizing the conditions for various technologies to effectively lower the GI of starch and starchy foods. Thus, the application of different technologies in modifying starchy foods should be investigated in greater detail. Most thermal technologies result in gelatinization and retrograded starch while others have been reported to promote more hydrogen bonds of starch chains without necessarily destroying the starch crystalline structure and increase crystallinity. The varying changes in starch structure are because of the processing parameters and mechanism of the technology adopted.

The digestibility of these modified starches/starchy foods can be investigated using both in vitro and in vivo studies. It is important to note that few human studies have been done comparing the physiological effects of starch-based products with specific SDS/RS contents and showing a strong link between in vitro starch digestibility and postprandial plasma glucose and insulin responses. It is important to note that few human studies have been done comparing the physiological effects of starch-based products with specific SDS/RS contents and showing a strong link between in vitro starch digestibility and postprandial plasma glucose and insulin responses. The innovative goal of this review was to determine the relationships between technology parameters involved in starch modification and the digestibility thereof. The findings from this review will improve our understanding of the impact of food processing parameters on developing low GI foods and ultimately impacting on human health.

Structural changes to starch have been reported to be one of the approaches adopted in reducing the glycemic index of food. Pellegrini et al.[4] highlighted that food design strategies such as modifying starch structure or introducing enzyme inhibitors are among the several practical approaches to lower the glycemic index of foods. Technology can have an impact in promoting commercial production of low GI foods. The true efficacy of most technologies in terms of commercialization in developing low GI foods remains to be established. The transition from lab- and pilot-scale equipment to industrial-scale equipment concerning the development of low GI foods has not been reported much. Even though new commercial RS starches have been introduced on the market using different preparation technologies, there is still need for large scale industrial operations.[5]

2 Technologies

Technologies can be thermal or non-thermal and are further discussed in the next section. Thermal technologies discussed include infrared, microwave, and extrusion while the non-thermal technologies discussed include ultrasonication (US), and high hydrostatic pressure (HHP). These technologies have become more popular in the food industry and have been used to develop food and food ingredients. Different technologies can be used to produce RS and SDS resulting in low GI food stuffs

2.1 Infrared Energy

IR heating utilizes radiative and conductive heat transfer mechanisms to generate and transfer heat. The radiation heating occurs at the surface and conductive heating occurs inside the food.[6] Mapengo et al.[7] suggested that during infrared heating starch molecules will have less molecular spaces due to increased hydrogen bonding and that contributed towards reducing the glycemic index of starch. The multiplicity of these hydrogen bonds between starch molecules (amylose-amylose, amylose-amylopectin, and amylopectin-amylopectin side chains) restrains the movement of the starch chains.

There is limited research that has been done on the application of infrared technology to reduce the glycemic index of starch/starchy foods. The majority of work reported on the impact of infrared heating on the nutritional properties of food focused mainly on making grains/seeds more rapidly digestible. The infrared treatment has been reported to result in partial gelatinization which improves starch digestibility and palatability and reduces the cooking time without significantly affecting other nutrients (essential minerals and proteins) present in grains.[8] According to the Food & Drug Administration reports, minerals present in foods are not affected by technologies that employ radiation. However, the macro- and micronutrients stability in food is dependent on specific infrared processing parameters. High infrared power can promote Maillard reactions and protein denaturation thereby reducing the bioavailability of essential amino acids. Research has shown that the effects of radiation on the content of vitamins are still inconclusive although some factors such as the dosage and controlled conditions of process such as temperature and presence of oxygen can influence the stability of vitamins.

The increased starch digestibility could be as a result of prolonged infrared treatment (from 60 to 180 s) or use of high infrared power (130—170 °C) and moisture content between 20% and 40%. From **Table** 1, infrared technology yielded estimated glycemic index, RS and SDS values between 67% and 70%, 15–27%, and 3–36% respectively. These values can be manipulated by the processing conditions such as treatment power, period, and other combination treatments incorporated. It is also important to note that factors such as starch source and amylose to amylopectin ratio also account for the varying digestibility properties. Starch granules are classified into A, B, and C due to their different molecular arrangements in the granules and this seems to correlate with the rate of digestibility. In A-type crystalline starch, glucose helixes are packed densely whereas B-type crystalline starch is packed less dense, leaving room for water molecules in between the branches and these water molecules reduce the rate of starch digestibility. Also starches with lower amylose content will have higher glycemic indexes. This is because starch granules with high amylose content result in high levels of retrogradation (RS3) while starch granules with high amylopectin content (waxy starches) have a low retrogradation susceptibility.

While Arce-Arce et al.[9] used the same moisture content as Mapengo et al.,[7] their RS content was lower than that of Mapengo et al.[7] This could have been as a result of the varying treatment period and infrared power used by the authors. Arce-Arce et al.[9] used 900 W for ~200 s while Mapengo et al.[7] used 1000 W for 1–3 h and perhaps the increased power and treatment time by Mapengo et al.[7] promoted more in more starch chain interactions and amylose-lipid complexes. The interaction between amylose and lipids is facilitated by temperature and the use of 1000 W for a prolonged time facilitated increased molecular vibrations to potentially provide more free amylose chain for interaction between amylose and lipids to form amylose-lipid complexes.

Pan et al.[10] mentioned the main drawbacks of adopting infrared technology in the food industry as the lack of understanding of IR heating fundamentals required to replace existing conventional processing equipment. However, based on the findings reported in Table 1, it is also important to highlight that the parameters or conditions/settings for infrared heating systems are crucial when adopting the technology to develop low GI food products. Increase in surface temperature and high moisture content promoted more RDS for infrared treated grains.[8, 11] Shogren[12] reported that the corn starch with low moisture content (<30%) required high temperatures (>100 °C) to destroy the starch crystalline structure. Therefore, the increased RDS in high moisture system could be as a result of starch crystalline structure disruption. The use of high infrared power (>900 W) increases mobility of starch polymer chains and there is

Table 1. Various conditions of infrared treatment and the impact on the nutritional properties various starch and starchy foods.

Food type	Particle size	Thickness layer	Conditions				Combination treatment	In vivo/in vitro starch digestibility assay	Reported findings				RDS	References
			Moisture [%]	Surface temperature [°C]	Power [W]	Time [min]			RS type	eGI	RS [%]	SDS [%]		
Sorghum whole grains	N/A	ND	ND	ND	1000	1–2	ND	In vitro	ND	ND	ND	ND	6.8 increase	[17]
Barley grains	ND	ND	41	140	ND	ND	ND	In vitro	ND	ND	ND	3	48	[11]
Maize grains	ND	ND	20	130		3	ND	In vitro	ND	ND	ND	ND	7.1–7.7 increase	[8]
Bean seeds	ND	ND	25	ND	900	3.5	ND	In vitro	RS5; RS3	ND	15	ND	ND	[9]
Maize starch	ND	~2 mm	25	110	1000	60–120	1.5% stearic acid	In vitro	RS5; RS3	70	26	36	38	[7]
Maize meal	ND	2 mm	25	110	1000	60–120	1.5% stearic acid	In vitro	RS5; RS3	~67	27	22	51	[13]

ND indicates no data available.

no guarantee that the surface temperature will remain below the gelatinization temperature of starch.

It is important to note that combination treatments (such as the addition of other components such as lipids, phenolics, or proteins) by Mapengo and Emmambux,[13] Li et al.,[14], Mapengo et al.,[7] and Chen et al.[15] promoted more RS yield. The use of lipid addition coupled with infrared HMT facilitates more amylose-lipid complex formation. Mapengo's et al.[7] results suggested that infrared energy resulted in the increased movement of starch polymer chains, thus causing stronger and enhanced hydrogen bonding between starch chains. These enhanced hydrogen bonds resulted in the formation of slowly digestible and resistant starch. The SDS and RS formed is responsible for the reduced eGI observed by the authors. This eGI is however not an exact accurate value as it was obtained via in vitro studies. Ferrer-Mairal et al.[16] reported that both in vitro result trend was similar to the in vivo studies results but also mentioned that all the obtained GI was higher in in vitro method than in vivo studies with human subjects. This suggests that in vitro starch digestibility assays are not a true representation of what happens within the human gut. However, there are no reported in vivo studies involving infrared treated food stuffs. Most of the published work lacks data relating to the quantities of starch fractions or the processing parameters of infrared treatment such as the particle size, sample thickness, and moisture content. These parameters could explain the properties of the food stuffs obtained by the various researchers using infrared technology.

2.2 Microwave Heating

Microwave energy heats by two primary mechanisms, dipolar rotation, and ionic conduction of polar molecules. The component most responsible for heating is water due to its dielectric properties. The two mechanisms by microwave heating allows the energy to be deposited directly within the material through molecular interaction with the electromagnetic fields of components in food, therefore not relying on transfer of heat into the food.[18]

From **Table** 2, a moisture content between 30% and 90%, microwave power between 300 and 1000 W, and a treatment period of 0.5–10min has been shown to increase the amount of RS for various starchy foods. The high moisture and microwave power combination promotes starch gelatinization and retrogradation upon cooling. Li et al.[19] and Cañas et al.[20] reported an increase in RS and SDS in rice starch and pasta after microwave cooking combined with cold storage for a period of about 24 h. Cold storage promotes amylose recrystallization after gelatinization thereby resulting in resistant starch type 3.[21] Microwave heating has been reported to decrease the branching degree of amylopectin, resulting in the retrogradation of linear chains, and further promoting the formation of RS in the cooling process.[22] The high-frequency microwave electric fields can lead to micro-movements of amylopectin side chains thereby resulting in molecular chain breakage.[23] These molecular chain breakages are however not definitive as to whether its covalent or hydrogen bonds. Thus in depth work in terms of starch fine molecular structure by size exclusion chromatography could be helpful.

However, several researchers (Table 2) have also reported an increase in starch digestibility after microwave treatment which is contradictory to the reported findings above. Similarly Emami et al.[24] reported contradictory results, that is microwave treatment promoted more rapidly digestible starch formation and increased starch digestibility. Regardless of using a moisture content (≤30%) work that reported an increase in starch digestibility used a treatment period of over 10 min (Table 2). This suggests that extended microwave treatment promotes gelatinization and leads to a greater degree of starch degradation by more fully destroying the

Table 2. Various conditions of microwave treatment and the impact on the nutritional properties of various starch and starchy foods.

Starch/Food type	Time [min]	Moisture [%]	Power [W]	Other treatments	Starch digestibility assay	RS type	RS	SDS	eGI	References
Rice starch	3	80	8 W per gram	Cold storage	In vitro	RS 3	32	41	ND	[19]
The fresh and dry pasta	0.5–1	90	1000	Cold storage	Amylolysis assay	RS3	ND	ND	ND	[20]
Proso millet starch	10	80	500		In vitro	RS3	11–18	ND	ND	[26]
Potato starch	1.7	60	300		In vivo using mice	RS3	27	Reduced post prandial	ND	[14]
Lotus seeds	Until gelatinized	70	8 W g^{-1}		In vitro	RS3	30	32	77	[22]
Maize flour	4	30	400		None	RS5	ND	ND	ND	[27]
Rice grains	15	50	600	Cold storage	In vitro	RS3	11–19	55–59	ND	[25]
Maize and wheat starch	2.5	ND	300–600		In vitro	No significant change observed				[28]
Hulless barley grains treated and milled into	180	45	300–700		In vitro	Increased starch digestibility				[24]
Pound cake	5	ND	240		In vitro	RS3	4.6		59	[29]
Rice starch	60	20	270–1350		In vitro	Did not show significant effects on the extent of digestibility				[30]
Moth Bean	15	50	ND		In vitro	Digestibility of moth bean cultivars was increased by 88–90% over the control				[31]

ND indicates no data available.

starch crystalline structure thus making enzyme easier accessible to the alpha 1–4 glycosidic bonds.[25] It is clear that the microwave technology can be used to produce rapidly digestible starch or resistant starch depending on the conditions set.

There is growing interest in the addition of lipids to starch and starchy foods to increase the formation of amylose-lipid complexes (RS5). Similarly, to infrared technology, combination treatments could be effective in developing low GI foods using microwave technology.

2.3 Extrusion

According to Fellows,[32] extrusion technology involves mixing, shearing, kneading, cooking, compressing, and forcing a molten material, under high pressure, through a narrow die. This process results in the structural changes of food components via protein denaturation, starch gelatinisation/depolymerization, and crosslinking/bonding between components. These changes are responsible for the nutritional properties of extruded food and food ingredients. Extrusion technology's versatility makes it convenient to develop nutritionally value-added products with a combination of different raw materials. However, like microwave and infrared heating, the production of low GI foods using extrusion cooking depends on the processing parameters. There is limited numeric data on the starch fractions and in vitro starch digestibility kinetics on extruded starch/starchy foods (Table 1).

As highlighted in **Table** 3, different studies have shown conflicting trends on the various extrusion conditions (moisture content, screw speed) and the effects of those parameters on starch digestibility. While Koa et al.[33] reported that high moisture promoted retrograded starch formation in extrudates, the reduction in RS as the processing moisture decreased was in agreement with a previous study that reported a decrease in RS on a higher mechanical degradation the increase in RDS may be due to higher mechanical shear exhibited by lower processing moisture which provided a higher mechanical rupture on the plant cell wall. The mechanical shear also increases the degree of depolymerization and breaking of 1, 6, and alpha 1,4 bond thereby exposing the glycosidic bonds. All this would create a larger surface area between starch and digestive enzymes and also an increase in gelatinization of the starch.[34] Extrusion processing of legume flour resulted in more rapid starch digestion at low incorporation, with slower digestion due to water limiting gelatinization at higher incorporation rates.[35] However, Šárka et al.[36] showed that the higher temperature caused a slight increase in resistant starch content perhaps as a result of increased retrogradation. Adeleye et al.[37] supported the contradictory findings that extrusion temperatures (i.e., 100 °C vs 140 °C) had no significant effect on starch digestion kinetics. These variations could be as a result of the structural or morphological differences between the starches used by the researchers. Šárka et al.[36] worked on cereal starch while Adeleye et al.[37] worked on legume starches.

The combination of treatments when applying extrusion technology in the production of low GI foods has become increasingly familiar (Table 3). Ye et al.[38] reported that enzymatic treatment of extruded starch with β-amylolysis (the hydrolysis of the α-1,4-glucan linkages using beta amylase) reduces crystalline-to-amorphous ratio regions, which increases the level of resistant starch, thereby slowing down digestion. The authors suggested that β-amylase (an *exo*-hydrolase) specifically cleaves the α-1,4 glycosidic linkages between two glucose monomers, moving inwards from the non-reducing ends of the starch chains and impedes starch hydrolysis since the hydrolysis stops when the number of glucose units is between two and three units from the branch point (α-1,6 glycosidic linkages).[38]

Table 3. Various conditions of extrusion and how they impact the nutritional properties of various starch and starchy foods.

Starch/Food type	Conditions			Starch digestibility analysis done	eGI	RDS	RS	SDS	Overall findings	References
	Screw speed [rpm]	Moisture [%]	Die zones temp [°C]							
Potato snacks with red lentil and chickpea flour	30	25–35	80	In vitro	ND	ND	ND	ND	Processed snacks digested much more rapidly than raw flours. 10% pulse incorporation resulted in decreased starch digestion rate compared to 0% incorporation, with 80% showing further decrease	[35]
Rice starch	37	30–50	50–95	In vitro	ND	14	78	9	Hydrolysis of in vitro starch digestion study was reduced for extruded samples treated with β-amylase, which was attributed to an increase in resistant starch (RS) after β-amylase treatment	[38]
Cassava and soy flour porridge	200	12	60–140	In vitro	83	54	43	3	Addition of 20% grape pomace significantly ($p < 0.001$) increased the SDS of cassava-soy porridge	[44]
Red sorghum (genotype Maxi) and brown barley (genotype ND19119)	150–300	25–40	140–133	In vitro	52	ND	ND	ND	Extrudates digested more than the non-extrudates; the sorghum-barley blend, extruding at moisture above 30% was possibly high; moisture extrusion that probably enhanced starch retrogradation and resistant starch type 3 (RS3)	[33]

Phenolic compounds bind to the active and secondary sites of digestive enzymes, therefore making them inactive. The in vitro starch digestibility of barley-based extrudates from fruit and vegetable by-products was also reported to have been decreased by increasing level of both tomato and grape pomace.[39] An animal study by Zhang et al.[40] also revealed that the oral intake of Norton GSE (containing grape pomace extract) (400 mg kg^{-1}) significantly reduced postprandial blood glucose by 30.9% in the streptozocin-treated male C57BL/6 J mice following starch challenge. Šárka et al.[36] also reported that the addition of soluble fiber in the extrusion premix resulted in an increase in resistant starch. These authors attributed the reduced rate of starch digestion to reduced lower viscosity of the melt because of low-molecular weight of Nutriose (Mw 4400 Da) that was added. Extrusion cooking combined with a moderate level of protein or fiber protein has also been reported to yield mid-range GI products that could be suitable for diabetics or others desiring to control blood glucose response.[41] White rice is considered a high glycemic index (GI) food and extruded reformed rice has been reported to be a lower GI product.[41] De Pilli et al.[42] also reported that extrusion cooking promoted amylose-lipid complexes' formation. Wang et al.[43] also explored the possibility of starch-lipid-protein complexes, which could also have potential health benefits. Overall extrusion generally promotes the formation of RDS but it is a very convenient way to combine with other ingredients to make low GI: extrudes.

2.4 Autoclaving

There is very little reported on the use of autoclaving to reduce the digestibility of starch. Autoclaving involves subjecting material in a high-pressure chamber to a gradual temperature. However, Dundar and Gocmen[47] and Hickman et al.[48] have reported that autoclaving temperature (145 °C) followed by long storing time (72 h) showed beneficial impacts on RS formation. Autoclave technology reduces the glycemic index of starch by altering the starch structure. During autoclaving, the formation of resistant starch is dependant on moisture (**Table** 4). A low moisture content does not promote complete gelatinization hence there will be minimal retrogradation, while high moisture content would increase the inter-molecular spaces between starch molecules. The increased intermolecular spaces reduces intermolecular hydrogen bonding between amylose chains and this will result in increase the susceptibility of starch to enzymes and hence increase glycemic index. Hickman et al.[48] used a combination of autoclave and beta-amylolysis to modulate the digestibility of normal corn starch and wheat starch. The increase of RS was observed and associated with enhanced branch density. This finding corresponds with the conclusions of Ye et al.[38] who worked on the extrusion of rice starch coupled with β-amylase treatment discussed earlier.

2.5 Other Emerging Thermal Technologies

There is a growing interest in radio frequency, plasma, and ohmic heating application in the food industry. However, there is very limited work that has been done with regards to their impact on starch digestibility of starch. Radiofrequency involves dielectric heating that involves the interaction between an alternating electromagnetic field and the dipoles and ionic charges contained within a food product that enables the volumetric heating of the product.[52] Due to this principle that is similar to microwave heating, radiofrequency has been reported to alter the structure and reduced the crystallinity of the starch.[53] This indirectly suggests that radiofrequency treatment potentially increases starch digestibility.

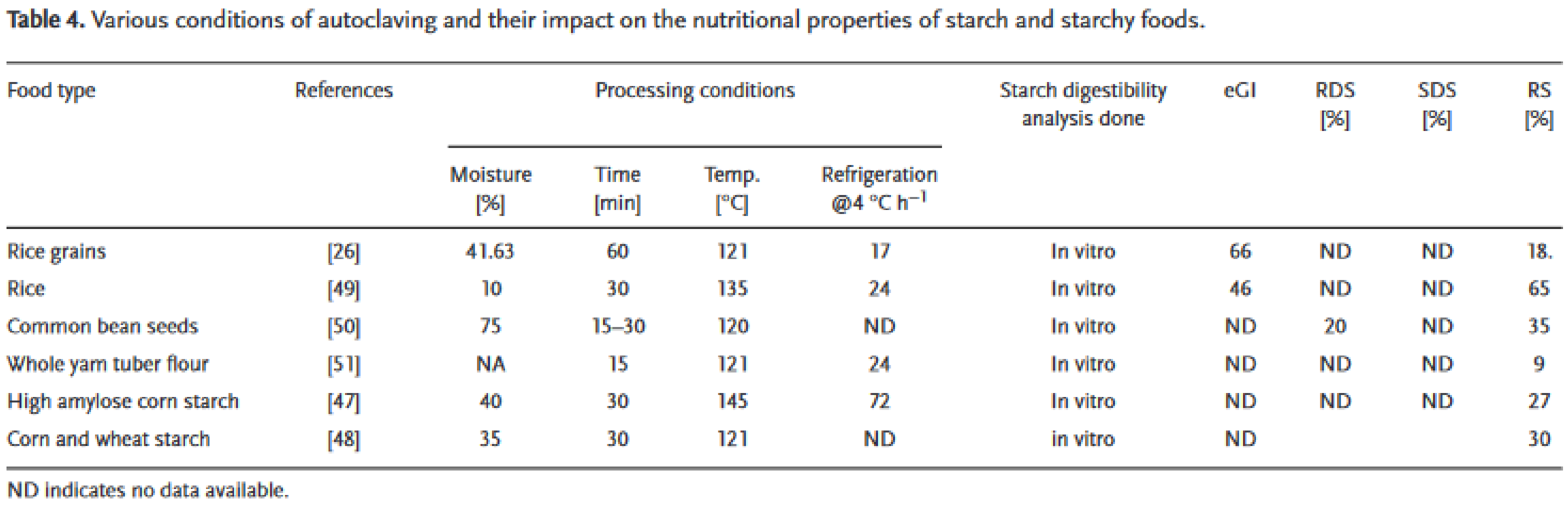


Table 4. Various conditions of autoclaving and their impact on the nutritional properties of starch and starchy foods.

Food type	References	Processing conditions				Starch digestibility analysis done	eGI	RDS [%]	SDS [%]	RS [%]
		Moisture [%]	Time [min]	Temp. [°C]	Refrigeration @4 °C h^{-1}					
Rice grains	[26]	41.63	60	121	17	In vitro	66	ND	ND	18.
Rice	[49]	10	30	135	24	In vitro	46	ND	ND	65
Common bean seeds	[50]	75	15–30	120	ND	In vitro	ND	20	ND	35
Whole yam tuber flour	[51]	NA	15	121	24	In vitro	ND	ND	ND	9
High amylose corn starch	[47]	40	30	145	72	In vitro	ND	ND	ND	27
Corn and wheat starch	[48]	35	30	121	ND	in vitro	ND			30

ND indicates no data available.

Ohmic heating (OH) is based on the principle that most food products have the ability to resist to the passage of an electrical current.[54] Heating occurs when an alternating electrical current is passed through a food resulting in the internal generation of heat due to the food's electrical resistance. The OH process could be improved by applying the electrical energy in three descending power steps: using the first step with high power input (in this study, 2–6 kW for 15 s), followed by 1 kW for 10 s, and 0.3 kW for 1–30 min, Bender et al.[55] reported that ohmic heating reduced the starch digestibility of bread.

Plasma is known as the fourth state of matter which consists of electrons, ions, free radicals, atoms in free and excited state, and large number of unionized neutral molecules.[56] Cold plasma technology has drawn more attention in recent times as it is chemical free, nontoxic, environmental friendly.[57] Thirumdas et al.[58] reported a decrease in starch hydrolysis from 91% to 87% for 60 W–10 min samples while working with plasma treated starch. The decrease in degree of starch hydrolysis could have been due to cross linking of starch molecular chains caused by the plasma treatment.[58] Gao et al.[57] worked on combining plasma treatment and addition of phenolic compounds and reported that plasma-modified Tartary buckwheat starch formed non-inclusive complex with quercetin which increased RS from 20% to ∼44%. These authors suggested that the method of plasma treatment led to smaller fragments of starch, which increased the possibility of binding between starch and polyphenols.

Gao et al.[59] reported that cold plasma treatment increased RDS to 48% as compared to the native starch (17%). These results were contradictory to the increase in RS reported by other researchers. Gao et al.[59] suggested that the increase in RDS could be from the destroyed surface and interior starch granular structure. Plasma treated starch was reported to have a very low viscosity and Gao et al.[59] suggested that the lower viscosity could facilize the mix of enzymes with substrate thus increasing the rate of starch hydrolysis. Other authors highlighted that plasma treatment could lead to a different extent of starch depolymerization which can form abundant end products such as maltose, maltotriose, and maltotetrose, thus leading to an increase in hydrolysis after plasma treatment.[60]

2.6 Non-Thermal Technologies

2.6.1 High-Pressure Processing

High pressure processing (HPP) is a non-thermal emerging technology that subjects a product to high pressures (up to 1000 MPa) for a controlled time and temperature. HPP affects only non-covalent bonds and can cause serious structural damage to biological macromolecules.[61] High-pressure processing (HPP), an emerging technology, can be used to promote gelatinization of starch granules.[62] According to Hu et al.[63] an immediate retrogradation process after HHP-assisted starch gelatination occurred, which accounted for decreased digestibility. Since HHP promotes starch non-thermal gelatinization, this makes it useful as a potential preparation method for resistant starch via retrogradation.[64, 65] Contradictory findings were reported by Linsberger-Martin et al.[66] while working with quinoa and amaranth starches. Linsberger-Martin et al.[66] reported significantly increased RS content for quinoa starch at pressures respectively above 350 MPa but a decreased RS content for HHP-treated amaranth starch compared to its native amaranth starch. These differences could have been as a result of the small starch granule size of amaranth compared to quinoa.

Table 5. Various conditions of high hydrostatic pressure treatment and the impact on the nutritional properties of starch and starchy foods.

Starch/Food type	References	Conditions				Starch digestibility analyses done	eGI	SDS	RS	General findings
		Temp [°C]	Moisture [%]	Pressure [MPa]	Time [min]					
Potato starch	[69]	21	33	600	10	In vitro	ND	ND	ND	Slower rate of glucose release which decreased proportionally with HMT
Brown rice (*Oryza sativa* L.)	[65]	37	ND	100–500	10	In vitro	ND	ND	3.2	Reduced digestible starch content at high pressure; increased digestible starch and reduced resistant starch with HHP in germinated seeds
Fresh ripe mangoes (*Mangifera indica* L. cv. Tommy Atkins)	[70]	25	ND	592	3	In vivo	ND	ND	ND	A significantly higher proportion of subjects showed a low GI following the consumption of HHP-MP compared to unprocessed-MP
Atemoya puree	[71]	25	ND	600	15 min	In vivo	49.8	ND	ND	The delayed increase in postprandial blood glucose levels, decrease the peak value of postprandial blood glucose by 76.1%, and significantly decrease the GI of AP to 49.8 in the experimental group compared to 65.4 in the control group

ND indicates no data available.

Another study done by Papathanasiou et al.[67] showed that HHP technology favors starch gelatinization and the formation of RS3 in potato and maize starches. Guo et al.[68] reported the formation of lotus seed amylose-fatty acid complexes during HHP but also highlighted that the formation of complexes decreased with an increase in high hydrostatic pressure from 500 to 600 MPa, suggesting that the lotus seed amylose was decomposed into short glucan chains. Guo et al.[68] also mentioned that the Raman spectra and in vitro digestion results showed that the content of both single helical amylose-fatty acid complexes and double-helical retrograded amylose were responsible for the reduced digestibility of the complex matrix (**Table** 5).

2.6.2 Ultrasonic Treatment

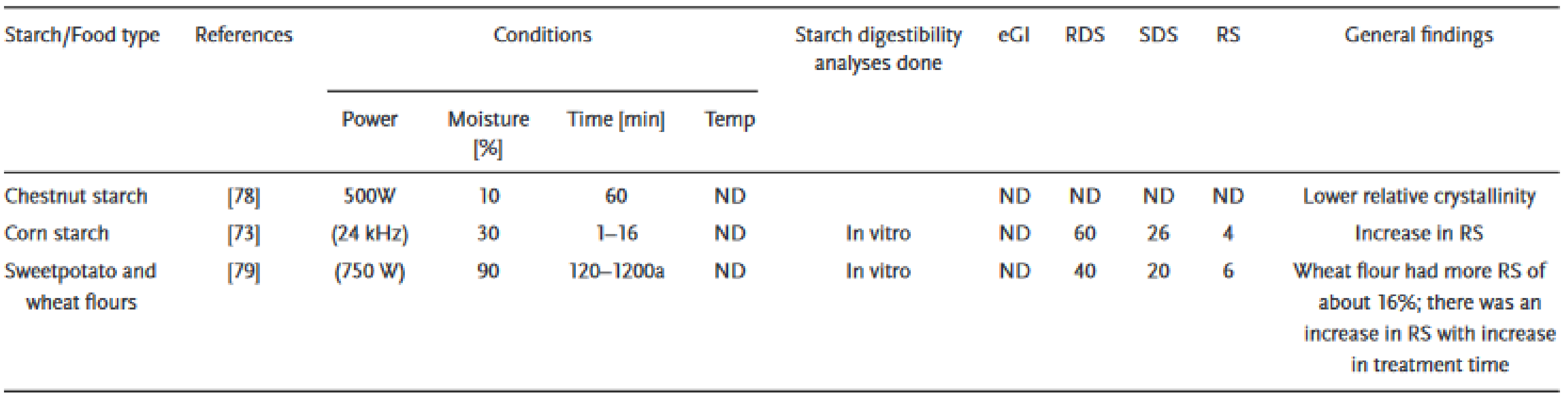
As a green, non-thermal, and innovative technology, ultrasonication generates acoustic cavitation in an aqueous medium, developing physical forces that affect the starch chemistry and functionality.[72] Flores-Silva et al.[73] reported that the resistant starch content increased from 2.1% to 4.0%, while the rapidly digestible starch fraction showed an increase from 42.9% to 60% and this was attributed to the formation of short-chained amylose molecules by effects of ultrasonic cavitation. Ning et al.[74] also found out that ultrasonic treatment disrupted the organized crystalline structure that facilitated enzyme access to the starchy matrix, thereby increasing rapidly digestible starch. According to Flores-Silva et al.,[73] the increased resistant starch content was attributed to the compact rearrangement of the double-helix structures in the starch granules limiting the hydrolysis rate by amylolytic enzymes, leading to a slower degradation of amylopectin chains. Ultrasonic waves, therefore, enhance the rearrangement of the internal granule structure. Ultrasonic waves increase the interactions between amylose – amylose and this promotes a more compact structure, due to the regular arrangement in the crystalline region. These changes in the molecular structure of starch reduces the susceptibility of starch to enzymatic hydrolysis.[75]

Liu et al.[76] investigated the effect of ultrasonication in the formation of RS and reported that low power ultrasound was beneficial to the formation of amylose-lipid complexes. After treating the starch-lauric acid suspension with ultrasound for 5 min, using a 20 kHz ultrasonic processor, Liu et al.[76] reported that low power density (240 W cm^{-2}) ultrasound contributed to RS formation. However, the high power density (560 W cm^{-2}) ultrasound was suggested to destroy the structure of the formed amylose-lipid complex.[76] The destruction of the structure of amylose-lipid complexes could be as a result of ultrasound waves disrupting the inter-helix interactions between amylose and lipids.[77] It is however difficult to compare findings from different studies as researchers are using different units (**Table** 6) to highlight the output power. Even with the power density it is difficult to deduce the power output without the dimensions of the probe.

2.7 Enzyme Technology

Enzymes are biological molecules with a definite structural organization that influence their catalytic function.[80] Currently enzymes are being employed in industrial biotechnology for numerous purposes for the production of novel and sustainable food products. Enzymatic starch modification is to design a starch with a new structure, in which the molecular mass, branch chain length distribution, and amylose/amylopectin ratio can be changed by enzyme reactions, when the enzymes react with gelatinized starch.[81] The use of enzyme is often coupled or combined with other technologies such as autoclaving (**Table** 7). This is because for RS formation there is need for a cyclic heating-cooling treatment or its combination with a previous enzymatic debranching step. There are a number of enzymes that can be used alone

Table 6. Various conditions of ultrasonic treatment and the impact on the nutritional properties of starch and starchy foods.



Starch/Food type	References	Conditions				Starch digestibility analyses done	eGI	RDS	SDS	RS	General findings
		Power	Moisture [%]	Time [min]	Temp						
Chestnut starch	[78]	500W	10	60	ND		ND	ND	ND	ND	Lower relative crystallinity
Corn starch	[73]	(24 kHz)	30	1–16	ND	In vitro	ND	60	26	4	Increase in RS
Sweetpotato and wheat flours	[79]	(750 W)	90	120–1200a	ND	In vitro	ND	40	20	6	Wheat flour had more RS of about 16%; there was an increase in RS with increase in treatment time

ND indicates no data available.

Table 7. Various conditions of enzymatic treatment and the impact on the nutritional properties of starch and starchy foods.

Starch/Food type	Conditions				Pretreatment/ post treatment Gelatinization	Starch digestibility analyses done	eGI	RDS	SDS	RS	References
	Enyzme used	Slurry db%	Time [min]	Hydrolysis time							
Wheat starch starch	Pullulanase(20 ASPU per g NS)	90	30	2 h	Autoclaving	In vitro	35	ND	ND	ND	[82]
Waxy maize starch	amylo-(1,4→1,6)-transglycosylase (20 or 1000 U g^{-1})	90	30	2–20 h	Jet cooking	In vitro	ND	69	27	4	[87]
Corn starch	4-α-glucanotransferase (10 U g^{-1})	90	30	4 h	Water bath	In vitro	ND	60–77	11–18	11–23	[83]
Oat starch	0.1 mg% β-amylase and 40 µL of transglucosidase	80	30	20 min	Autoclaving	In vitro	ND	ND	ND	49	[84]

ND indicates no data available.

or in combination with other enzymes to promote debranching and the formation of RS 3 and RS5.

Arp et al.[82] reported that the most influencing factor for resistant starch formation was the application of the pullulanase-debranching step previous to the cyclic treatment (autoclaving and cooling). This step wise process increased starch retrogradation. Jiang et al.[83] reported that the use 4-α-Glucanotransferase (member of the α-amylase super-family, and also known as amylomaltase) was effective in promoting the formation of RS. This was because of the enzyme's multiple action modes (disproportionation, cyclization, coupling, and hydrolysis) reducing the molecular weight and a great number of short ($DP < 13$) and long ($DP > 30$) chains through cleaving and reorganization of starch molecules. This enzyme then rearranged the starch chains to produce a partial crystalline lamella with reduced surface area for starch digestion.[83]

Using combination enzymes has been reported to increase the number of α-(1,6)-glycosidic bonds, crystallized amylose regions, and amylose-lipid complexes in starch. This is due to the formation of short linear chains and trimming of external chains of amylopectin molecules which enhances the amylose–amylose/amylose-lipid interactions which when subjected to gelatinization-cooling process results in enhanced RS3 and RS5 crystallites respectively.[84] Therefore, the development of enzymatic processes for designing a novel slowly digestible starch can potentially contribute towards controlling postprandial hyperglycemia.

New enzyme technologies are rapidly developing isomalto-oligosaccharides (IMO). These technologies include the fusion of different transferase enzymes, enzymes bound to living cells, simultaneous saccharification and transglucosylation approaches, different enzyme combinations, recombinant designer enzymes.[85] Isomalto-oligosaccharides are linear α-(1-6) linked oligosaccharides with isomaltotriose as the representative trisaccharide[86] and have been reported to reduce the glycemic response. In humans, IMO are partially digestible but the digestibility of specific components of commercial IMO preparations remains unknown.[86]

2.8 Concluding Remarks

As much as several technologies have been shown to be effective in developing low GI foods, there is less documentation in terms of the optimal parameters with substantial data on the starch fractions and eGI values obtained. This review showed the combination techniques such as phenolics/lipids addition and processing technologies promote more RS and SDS and exhibit more promising potentials in the development of low GI foods. Thermal technologies led to increased RS because of retrogradation and new crystallites formation while others led to increased RDS due to the destruction of the starch and increased exposure of the glycosidic bonds. However, these technologies still require a proper design to develop low GI from pilot to industrial scale. There is need to understand the right set of parameters that promote effective utilization of new emerging technologies to develop low GI foods. Microwave, infrared, and extrusion technologies are extensively reported on however other technologies such as ohmic and cold plasma show promising future trends although there is limited literature reporting their application in developing low GI foods. Also, it is important to note that the varying in vitro methods of determining starch digestibility contribute to the inconsistent data in cross comparison. More research is needed to design standard methods for comparison as well as prove or demonstrate the effectiveness of certain technologies. In vitro results do not always reflect actual in vivo responses since they do not account for mastication, gastric emptying, and glucose removal rate. There is need for in vivo studies and more rapid methods of analyses.

By contrast there were limited studies involving in vivo studies to confirm the in vitro findings and this information is important in the modulation of postprandial glycemia to contribute towards the prevention of metabolic diseases.

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Conflict of Interest

The authors declare no conflict of interest.

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