Resistant Starch Content in Foods Commonly Consumed in the United States: A Narrative Review

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ABSTRACT
Resistant starch (RS; types 1 to 5) cannot be digested in the small intestine and thus enters the colon intact, with some types capable of being fermented by gut microbes. As a fiber, types 1, 2, 3, and 5 are found naturally in foods, while types 2, 3, and 4 can be added to foods as a functional ingredient. This narrative review identifies RS content in whole foods commonly consumed in the United States. Scientific databases (n=3) were searched by two independent researchers. Ninety-four peer-reviewed articles published between 1982 and September 2018 were selected in which the RS was quantified and the food preparation method before analysis was suitable for consumption. The RS from each food item was adjusted for moisture if the RS value was provided as percent dry weight. Each food item was entered into a database according to food category, where the weighted mean±weighted standard deviation was calculated. The range of RS values and overall sample size for each food category were identified. Breads, breakfast cereals, snack foods, bananas and plantains, grains, pasta, rice, legumes, and potatoes contain RS. Foods that have been cooked then chilled have higher RS than cooked foods. Foods with higher amylose concentrations have higher RS than native varieties. The data from this database will serve as a resource for health practitioners to educate and support patients and clients interested in increasing their intake of RS-rich foods and for researchers to formulate dietary interventions with RS foods and examine associated health outcomes.
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DIETARY FIBER CONSISTS OF MANY TYPES OF NONdigestible plant components that have been found to reduce the risk of cardiovascular disease, cancer, and obesity while promoting gut health and immune function.[1] Despite the health-related properties associated with adequate dietary fiber intake, US consumption patterns are substantially lower than the current recommendations of 25 g for females and 38 g for males, or 14 g per 1,000 calories daily.[2,3] The Institute of Medicine defines dietary fiber as nondigestible carbohydrate and lignin intrinsic and intact in plants, as well as those nondigestible carbohydrates that are isolated and provide a physiological benefit.[3] Resistant starch (RS) is a type of fiber that can be categorized as being intrinsic to starchy plants or isolated to function as an ingredient.

RS is the component of starch that is not hydrolyzed by digestive enzymes and enters the large intestine intact, with some types undergoing fermentation by resident microbiota. Because of the digestive properties of RS it is considered an insoluble fiber. Five types of RS have been classified (RS1, RS2, RS3, RS4, and RS5) based on the nature and properties of the RS granule. RS1 includes granules that are resistant, as a result of physical inaccessibility, to digestive enzymes because of the physical nature of the food. RS1 is found in seeds, legumes, and cereals that are partially milled (eg, whole grains), in which the granule is trapped in the cell wall or matrix. RS2 granules are resistant because of a tightly packed amylose structure that forms a crystallized molecule. RS2 is found in raw potatoes and green bananas, as well as legumes and high-amylose corn. RS2 is resistant to digestion because of its native granule conformation. RS3 is formed when the starch granules are gelatinized and then cooled and causes the starch to crystalize, which is known as retrogradation. RS4 is a chemically modified RS that is not naturally occurring in foods, but can be added as a functional ingredient to improve the dietary fiber content in foods. RS5 is heat-stable and formed when lipids bind to amylose in the starch granule to prevent expansion of the granule, which is necessary for digestive enzyme hydrolysis.[4]

Foods with naturally occurring RS include potatoes, cereals, whole grains, beans, legumes, rice, and bananas—many of which are staple foods in the United States. The RS in these foods can be altered because of several factors, including variety, preparation or cooking method, storage temperature and duration, and serving temperature.[5] For example, higher amylose to amylopectin ratio within the starch granule can compact under certain conditions to become resistant to hydrolysis. RS concentrations can also be influenced by the environment, natural selection, and mutations.[4] These inconsistencies, along with the methodology used to quantify RS in foods, make it challenging to identify the amount of RS in foods.

RS can be measured using the integrated dietary fiber methods utilizing chromatography (AOAC 2011.25, 2009.01), enzymatic-gravimetric methods (AOAC 991.43, 985.29), and a specific RS method (AOAC 2002.02); however, the amount of RS quantified by these methods varies, and poses a challenge for labeling and understanding actual dietary RS intake.[6] Estimation of RS in foods was initially proposed by Englyst and colleagues,[7,8] who recognized RS fractions in both plant foods (in vitro) and human ileostomy effluent samples (in vivo). In vitro analysis can be either direct or indirect. The amount of RS quantified is dependent on several factors, such as sample preparation, sample pretreatment, enzymes used, and incubation conditions.[9] The Englyst method indirectly analyzes RS, where the total RS is estimated to be the difference between total starch and sum of rapidly and slowly digested starch.[7] Modifications to this indirect method include reduction of sample particle size and change in incubation temperature to 37°C, which established a preliminary basis towards quantification of RS in a food sample and further enabled the estimation of different types of RS.[10]

Berry[11] was one of the first to modify the indirect procedure proposed by Englyst and colleagues[7,8] to measure RS directly. Modifications proposed by Berry included omitting the initial heating step to 100°C, changes in α-amylase and pullulanase ratio to starch, and a KOH-dependent solubilization procedure. Subsequent changes to both Berry and Englyst procedures by Goni and colleagues,[12] Muir and O'Dea,[13] and Akerberg and colleagues[14] aimed to replicate the actions in the human digestive tract. Predominant changes in methodology included sample pretreatment (chewed vs milled vs homogenized), enzyme variations (sample treatment with pepsin, replacing pullulanase with amyloglucosidase), and the pH at incubation (5.0 vs 5.2 vs 6.9).

More recently, McCleary and Monaghan[15] reported that omitting the sample treatment with pepsin, inclusion of amyloglucosidase at an incubation pH of 6.0, and a shaking tube experiment resulted in replicating in vivo conditions. A commercially available kit based on this methodology (AOAC 2002.02) is commonly used to determine RS in foods and is available through Megazyme.[16] This kit accurately measures total RS, which is the sum of RS1, RS2, and RS3; however, it is not a reliable measure of RS4 because of underestimation.[9,16] There are currently no reported methods to estimate RS5 in foods.

Numerous health benefits of RS have been observed in a variety of populations. The resident gut microbiota ferment primarily RS2 and RS3 in the distal bowel to produce short-chain fatty acids (butyrate, propionate, and acetate), which decreases fecal pH.[17] Other gastrointestinal benefits from RS intake include increased fecal wet weight,[17] mild laxation, defecation ease, and frequency.[18] Because some types of RS can be fermented by gut bacteria, RS may be considered a prebiotic.[19,20] To classify RS as a prebiotic, more evidence that RS selectively increases the abundance of gut bacteria and provides benefit to the host is needed. Studies have shown that RS2 improves *Ruminococcus bromii* and *Eubacterium rectale*[21] and increases the *Bifidobacteria* genus in middle-aged and elderly adults, while improving dysbiosis from *Proteobacteria* in the elderly adults.[22] Another study found that a 2-week supplementation of 66 g RS2/day in adults with reduced insulin sensitivity increased the ratio of Firmicutes to Bacteroidetes,[23] suggesting that RS2 can alter the gut microbiome in populations with metabolic dysfunction. RS also reduces gastric emptying to promote feelings of satiety[24] and lowers energy intake at a subsequent meal.[25]

Consistent data have shown that RS lowers postprandial glycemia and insulinemia[26,27]; improves insulin sensitivity[28-30]; and reduces inflammation,[31] postprandial fat oxidation,[32] and both serum and low-density lipoprotein cholesterol.[33] A recent review summarized the body of evidence from animal and human trials, specifically noting that the most consistent benefit was related to postprandial blood glucose management and improvements in insulin sensitivity.[34] Additional publications have examined the role of RS in digestive health and cardiometabolic risk factors.[23,31,35]

Many of the health benefits of RS result from RS consumed as a functional fiber in adequate amounts (≥15 g/day)[26,29] with either acute administration[36] or over time (≥4 to 12 weeks).[28,37] However, with appropriate meal planning, this level of RS can be achieved through foods with naturally occurring RS. In fact, RS has been attributed to improved health in populations consuming a non-Western diet, such as an African diet rich in corn meal.[38] Many RS-containing foods are rich in fiber and can contribute to the total US dietary fiber intake and benefit overall health. The mean RS intakes in the United States have been estimated to be 4.9 g/day (range=2.8 to 7.9 g/day).[39] However, the intake data were calculated from 155 individual foods, where only approximately 57% of the foods reported were analyzed using methods that best mimic human digestion.[39] Over the past several years, the number of foods analyzed for RS has expanded considerably as a result of a commercially available RS analysis kit utilizing a method that simulates RS digestion. Therefore, the purpose of this narrative review was to create a database using data from peer-reviewed journal articles that quantified the RS content in foods commonly consumed in the United States. In addition, differences in variety, preparation, storage, and processing of RS content in food will be described. The creation of this database is important because it will allow health practitioners and researchers to identify foods containing RS and examine how consuming these foods contributes to health outcomes. The benefits of

RESEARCH SNAPSHOT

Research Question: What are the foods consumed in the United States that contain resistant starch (RS) and how much RS do they contain?

Key Findings: In this narrative review, foods containing RS were identified, which include breads, cereals, cakes and muffins, chips and snacks, cookies and crackers, bananas and plantains, grains, noodles and pasta, rice, legumes, potatoes, and hazelnuts. Barley, potatoes, and rice with higher amylose concentrations have more RS then lower amylose varieties, and foods cooked then chilled have higher RS than foods cooked without chilling.

RS related to insulin sensitivity have been reported when adequate amounts (approximately ≥15 g/day)[29] are consumed from RS administered as a functional ingredient, not foods with naturally occurring RS. Additional research is needed to identify the amount and duration of RS found naturally in foods to produce health outcomes. By utilizing the database, 15 g of RS from food can be achieved in free-living individuals with appropriate meal planning.

METHODS

Three databases (PubMed, Scopus, and Science Direct) were utilized to identify peer-reviewed articles published between 1982 and September 2018 that analyzed the amount of RS in foods commonly consumed in the United States for this narrative review. The search terms *resistant starch*, *English language*, *and food** were used to identify references. References were included if the RS analysis was conducted in a laboratory either inside or outside of the United States, but the foods were commonly consumed in the United States. Excluded terms included *human**, *animal**, and *clinical trial**. Exclusion criteria included the use of RS from flours or starches, isolated raw starch, or uncooked foods unsuitable for consumption (eg, raw potatoes and raw cassava). However, raw bananas and plantains and raw oats were included. References that used specific methods not commonly used by consumers before food consumption (eg, adding an acid, enzymes such as pullanase, extrusion of raw material to create an ingredient, or other process) were also excluded. Autoclaved foods were included because this is a technique used in the canning process. Foods that were cooked or milled incompletely were excluded. Foods cultivated to produce a mutant of the native food as a means to alter the nutritional or RS content were also excluded, except for barley, rice, and potatoes, as they were identified as low- or high-amylose varieties. The references meeting inclusion criteria were hand selected by two independent researchers according to the title and abstract, followed by reviewing the full text. In this review, data were pooled from all of the studies that analyzed RS using both in vivo and in vitro methods. Any references that reported either heating the sample before enzyme hydrolysis or an incubation temperature of 100°C were omitted, as it has been reported that this method estimated only RS3 and not RS1 or RS2.[9]

The references presented the RS data in one of two ways: percent dry weight (g RS/100 g dry weight) or as a whole food with the moisture included (g RS/100 g whole food). Both data types were included in the database. However, because the objective of this review is to provide RS content in whole foods, the percent RS in dry weight was adjusted to include moisture content. Moisture was either measured and provided in the article or identified by the US Department of Agriculture FoodData Central database[40] from the most similar food item. The pooled data were compiled in an Excel (Microsoft) database, then summarized in the Table according to food category.

Statistical Analysis

The raw data added to the Excel database included percent RS based on dry weight (g RS/100 g dry weight)±standard deviation (SD), percent RS in the whole food (g RS/100 g whole food)±SD, the number of samples analyzed in each reference, the percent moisture either as provided in the reference or as identified in the US Department of Agriculture FoodData Central database.[40] Using the raw data, calculations were employed to adjust for moisture content if percent dry weight was given in the reference, as well as the individual weighted means for each item followed by the overall weighted mean±weighted SD.

When only percent RS by dry weight was given, the formula (1−% moisture)*% dry weight RS was used to adjust for moisture, which provided RS content in the whole food. Due to some references measuring RS in several samples, the weighted mean was calculated for each food item. The weighted mean was determined by multiplying the number of RS samples analyzed in the reference by the whole food RS content (with moisture). Then the overall weighted mean was calculated by summing the individual weighted means and dividing by the total number of samples from all references in the food category. Next, the weighted SD was calculated for each individual food item by multiplying the sample size by the mean RS content in the whole food minus the overall weighted mean squared. The individual weighted SD was summed and divided by the total sample size minus 1, then the square root of this value was calculated to obtain the overall weighted SD. The overall weighted mean of whole food RS and overall weighted SD for each food category are reported in the Table. In addition, the ranges (minimum to maximum) of weighted means in each food category are listed in the Table. Also, the total number of samples in each food category is provided. Note that some references analyzing RS in more than one sample list the mean without the SD. However, the SD for each food item was not necessary to calculate the overall weighted SD. Some references listed a mean RS value without noting the sample size in which a value of 1 was given in the Table. RS values that were >200% of the mean were removed from the database to control for potential outliers.

RESULTS

The Table provides the overall weighted mean±weighted SD, range (minimum to maximum for each food item), and the total sample size of naturally occurring RS concentrations in the whole food for each food item from 94 articles. All foods requiring percent moisture values from the FoodData Central database were available except baked corn tortillas, where the measured value from a reference was used.[63] The number of individual food samples included in each food category include 145 bananas and plantains,[13,41-46] 446 breads,[8,10,46-80] 37 breakfast cereals,[10,14,50,79,81,82] 222 ready-to-eat cereals,[8,10,12-15,41,45,47,49-52,74,75,79,81,83,84] 11 cakes and muffins,[51,54,85] 18 chips and snacks,[47] 50 cookies and crackers,[47,49-52,85] 103 cooked grains,[10,50,74,76,79,82,84,86-89] 765 legumes,[10,15,45,50-52,69,75,76,79,90-109] 98 noodles and pasta,[10,14,41,47,50,52,74,76,78,81,82,110-112] 6 hazelnut,[113] 311 potatoes,[10,13,14,41,45,50,52,76,80,81,114-122] and 170 rice.[5,14,41,50,52,81,84,123-127] The foods with the highest mean RS content included uncooked or raw foods, such as uncooked rolled oats (7.7 g/100 g), uncooked rolled milled oats (6.5 g/100 g), ripe raw plantains (5.1 g/100 g), and unripe raw plantains (5.0 g/100 g). Of the cooked foods, high-amylose potatoes that were cooked then chilled for 2 days (6.4 g/100 g); butter or lima beans (6.4 g/100 g); potato salad (5.2 g/100 g); yellow potatoes that have been cooked, chilled, then reheated (5.1 g/100g); corn tortillas that have been

Table. Naturally occurring resistant starch in whole foods commonly consumed in the United States, extracted from peer-reviewed articles published from 1982 to September 2018

	g RS[a] per 100 g Food[b]		
Food	**Weighted mean±weighted SD[cd]**	**Range[e]**	**n[f]**
Bananas and plantains			
Banana, unripe, cooking type, raw[41,42]	2.8±0.1	2.3-2.9	42
Banana, ripe, cooking type, raw[42,43]	1.8±0.1	1.0-2.0	42
Banana, cooked[13,44]	0.0±0.0	0.0-0.3	11
Banana, cooked and cooled[44]	2.0	NA[g]	NA
Banana, cooked, cooled and reheated[44]	1.4	NA	NA
Plantain, unripe, raw[42,45]	5.0±1.1	4.2-7.0	18
Plantain, ripe, raw[42,46]	5.1±13.6	1.7-11.4	15
Plantain, cooked[44-46]	2.6±1.3	0.0-3.5	10
Plantain, cooked and cooled[44]	3.2	NA	NA
Plantain, cooked, cooled and reheated[44]	1.2	NA	NA
Plantain, cooked, unripe chips[46]	0.0	NA	3
Bread			
Bagel, plain[47]	0.7	NA	2
Barley, commercial variety[48]	1.0±0.3	0.7-1.3	4
Barley, high β-glucan[48]	0.9±0.2	0.8-1.1	2
Barley, low β-glucan[48]	0.9±0.2	0.8-1.1	2
Barley, low amylose[48]	0.4±0.0	0.3-0.4	2
Barley, high amylose[48]	1.6±0.4	1.3-1.9	2
Breadsticks, white wheat[47]	0.4	NA	2
Brioche[49]	1.1	NA	NA
Biscuit, oatmeal[50]	0.9	NA	NA
Biscuit, spelt[51]	0.5	NA	3
Biscuit, unspecified type, store bought[52]	1.1	NA	4
Biscuit, wheat, whole grain[51]	0.5	NA	3
Ciabatta, plain[53]	0.5	NA	NA
Corn bread[54]	0.5	NA	NA
Croissant, store bought[53]	0.3	NA	NA
Crumpet[47,53]	0.7±0.5	0.1-1.0	3
Croutons, store bought[47]	1.4	NA	2
English muffin, white, store bought[47,53]	0.7±0.5	0.1-1.0	3
Focaccia[47]	1.2	NA	2
French baguette, white, long and thin[49,53]	1.0±0.6	0.4-1.4	3
Gluten-free bread[55,56]	0.9±0.3	0.5-1.2	15
Mixed-grain bread[47,57-59]	2.6±4.9	1.5-4.4	23
Naan[53]	0.2	NA	NA
Oatmeal bread[47]	1.2	NA	2
Pastry shell, store bought, baked[47]	0.5±0.1	0.4-0.5	4
Pita bread, wheat, store bought[47]	0.5	NA	2
Pita bread, white, store bought[47,53]	0.5±0.4	0.1-0.7	3

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Table. Naturally occurring resistant starch in whole foods commonly consumed in the United States, extracted from peer-reviewed articles published from 1982 to September 2018 (*continued*)

	g RS[a] per 100 g Food[b]		
Food	**Weighted mean±weighted SD[cd]**	**Range[e]**	**n[f]**
Pizza crust, baked[47,60]	0.9±0.9	0.4-2.0	3
Potato dumpling[60]	0.4	NA	NA
Pumpernickel bread[47,53]	0.9±0.5	0.4-0.9	3
Rye bread[50,57]	3.0±0.2	2.9-3.2	3
Scones, white with fruit[53]	0.1	NA	NA
Sourdough bread, spelt[51]	0.7±0.0	0.6-0.7	6
Sourdough bread, wheat[61,62]	3.3±3.1	0.7-5.0	10
Sourdough bread, whole wheat[51]	0.7±0.0	0.7-0.7	6
Spelt bread[51,61]	0.8±0.0	0.8-0.8	11
Tortilla, corn, store bought[h] [47]	0.8	NA	2
Tortilla, corn, freshly baked[h] [63-71]	2.6±0.6	1.8-4.0	33
Tortilla, corn, stored 4°C, 24 h[h] [65-69]	3.3±0.8	2.1-4.7	24
Tortilla, corn, stored 4°C, 48 h[h] [65-69]	3.6±0.7	2.5-5.0	24
Tortilla, corn, stored 4°C, 72 h[h] [65-69]	3.9±0.6	2.9-5.1	24
Tortilla, corn, stored 4°C, 96 h[h] [65]	4.5±0.5	4.0-5.1	9
Tortilla, corn, stored 4°C, 7 d[h] [68]	4.6	NA	18
Tortilla, corn, stored 4°C, 14 d[h] [68]	4.7	NA	18
Tortilla, corn, stored 25°C[h] [67]	3.6±0.3	3.2-4.0	18
Tortilla, corn, hard shell[47,69]	2.7±1.2	0.9-3.9	5
Tortilla, flour, store bought[47,53]	0.2±0.2	0.0-0.4	5
Waffles, multigrain, toasted[47]	0.5	NA	2
Waffles, plain, toasted[47]	0.6	NA	2
Wheat-germ bread[53]	0.1	NA	NA
White bread, added fiber[72]	1.7±0.2	1.4-1.9	12
White bread[8,10,46,47,50-53,57-62,72-79]	1.0±0.9	0.0-3.9	85
White bread, baked 120°C to 150°C for 3 to 4 h[61]	1.1±0.0	1.1-1.1	8
White bread baked 120°C to 150°C for 12 to 20 h[80]	2.2±0.5	1.9-2.5	2
White bread, crusty or toasted[53,60]	1.9±2.4	0.2-3.6	2
Whole-wheat bread[10,47,50,53,77,79]	1.7±1.2	0.3-2.9	14
Breakfast cereal			
Oats, unknown type, cooked[10,50]	1.0±1.2	0.1-1.8	2
Oats, flaked, cooked[81]	0.3	NA	6
Oats, rolled, uncooked[82]	7.7	NA	NA
Oats, rolled, milled, and uncooked[82]	6.5	NA	NA
Rice, cooked[14,79,81]	1.0±0.6	1.2-1.6	18
Semolina, cooked[81]	4.8	NA	6
Wheat, cooked[79]	0.4	NA	3
Breakfast cereal, ready to eat			
Corn, flaked[8,10,12-15,41,45,47,49,51,52,74,75,79,83,84]	4.0±1.8	1.0-6.3	165
Corn, puffed[47]	1.4	NA	2

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Table. Naturally occurring resistant starch in whole foods commonly consumed in the United States, extracted from peer-reviewed articles published from 1982 to September 2018 (*continued*)

	g RS[a] per 100 g Food[b]		
Food	**Weighted mean±weighted SD[cd]**	**Range[e]**	**n[f]**
Corn, square[47]	1.3	NA	2
Granola[47]	0.1	NA	2
Multigrain, flaked[47]	0.0	NA	2
Multigrain, baked[47]	0.8	NA	2
Oat, bran[47,50]	0.5±0.4	0.3-0.7	3
Oat, flaked[14,79]	0.6±0.5	0.3-0.7	9
Oat, square[47]	0.9±0.3	0.6-1.2	4
Rice, flaked or crisped[10,45,47,49,50]	1.4±0.8	0.0-2.5	11
Rice, square[47]	4.2	NA	2
Wheat bran, flaked[47,50]	0.8±0.2	0.7-1.1	3
Wheat, puffed[50,81]	1.9±1.9	1.2-6.2	7
Wheat, shredded[10,47,50]	1.0±0.7	0.0-1.6	4
Wheat, square[47]	1.4	NA	2
Wheat, whole, flaked[47]	1.0	NA	2
Cakes and muffins			
Cake, apple crumble[54]	0.2	NA	NA
Cake, plain, white[85]	1.8	NA	NA
Cake, unspecified type[54]	0.4	NA	NA
Muffins, plain[85]	1.0	NA	NA
Muffins, spelt[51]	0.4	NA	3
Muffins, unspecified type[54]	1.0	NA	NA
Muffins, wheat[51]	0.6	NA	3
Chips and snacks (store bought)			
Cheese puffs[47]	0.2	NA	2
Chips, corn, low fat[47]	0.7	NA	2
Chips, corn[47]	0.8	NA	2
Chips, multigrain[47]	0.9	NA	2
Corn puffs, fried[47]	0.9	NA	2
Granola bar, oats and honey[47]	0.2	NA	2
Popcorn cakes[47]	0.3	NA	2
Pretzels[47]	1.0	NA	2
Rice cakes[47]	0.2	NA	2
Cookies and crackers (store bought unless specified)			
Biscuit, tea or sugar[47,50,52]	1.1±0.5	0.1-1.4	7
Cone, ice cream[47]	0.3	NA	2
Cone, sugar, old fashioned[47]	0.5	NA	2
Cookies, ginger snaps[47]	0.4	NA	2
Cookies, oatmeal[47]	0.2	NA	2
Cookies, plain, laboratory prepared[85]	0.8	NA	NA
Cookies, spelt, laboratory prepared[51]	0.2	NA	3

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Table. Naturally occurring resistant starch in whole foods commonly consumed in the United States, extracted from peer-reviewed articles published from 1982 to September 2018 (*continued*)

	g RS[a] per 100 g Food[b]		
Food	**Weighted mean±weighted SD[cd]**	**Range[e]**	**n[f]**
Cookies, vanilla wafers[47]	0.2	NA	2
Cookies, wheat, laboratory prepared[51]	0.3	NA	3
Crackers, club[47]	0.4	NA	2
Crackers, graham[47]	0.3	NA	2
Crackers, multigrain[47]	1.0±0.6	0.5-1.5	4
Crackers, melba type[47]	1.2±0.3	0.9-1.5	4
Crackers, rice crunch[47]	0.4	NA	2
Crackers, rye crisp (store bought and laboratory prepared)[47,50]	2.0±2.0	0.9-4.3	3
Crackers, saltine type[47]	0.6±0.1	0.5-0.6	4
Crackers, unspecified type[49]	1.7	NA	NA
Crackers, wheat, shredded[47]	1.2	NA	2
Crackers, wheat, thin[47]	0.4	NA	2
Grains, cooked			
Barley, native[10,50,74,84,86]	3.4±0.8	1.7-4.2	24
Barley, high amylose[86]	3.5±0.3	3.1-3.8	18
Barley, low amylose, waxy[86]	0.3±0.0	0.3-0.3	18
Corn, hominy grits[82]	1.3	NA	NA
Corn, meal[76,79,82]	0.8±0.2	0.7-1.0	7
Corn, tamale[87]	1.3±0.4	0.9-1.6	6
Groats, buckwheat[88,89]	0.9±0.2	0.8-1.8	25
Millet[10,79]	1.0±0.5	0.8-1.6	4
Legumes			
Cooked			
Butter or lima bean[15,50]	6.4±1.8	1.2-7.1	10
Black bean[69,90-93]	2.7±1.7	1.2-5.3	12
Chickpea[45,50,52,76,90,93-99]	2.1±1.0	0.8-4.1	67
Fava bean[92]	0.7	NA	NA
Great Northern bean[92,93]	1.2±0.4	0.8-1.6	3
Kidney bean[15,50,51,79,93,100]	3.8±1.4	0.8-4.7	50
Kidney, white bean[50,92]	3.6±3.2	1.4-8.3	4
Lentils[10,50,52,76,79,94,95,98,101-104]	2.0±16.9	0.5-3.2	232
Lentil, gram dhal[105]	1.6±0.4	1.2-2.2	4
Mung bean[45,99,106]	1.2±0.3	0.6-1.5	20
Navy bean[92,95]	1.6±0.2	1.6-1.9	4
Peas[10,50,75,76,79,95,98,100,103]	1.9±0.9	0.9-6.3	40
Pinto or common brown bean[50,52,91,93,95,97,98,107]	2.0±0.3	1.4-2.4	27
Pinto, refried bean[90]	0.8	NA	4
Red, small bean[93]	1.4	NA	NA
White bean[52,84,93,103,108]	2.2±1.5	1.4-2.6	24

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Table. Naturally occurring resistant starch in whole foods commonly consumed in the United States, extracted from peer-reviewed articles published from 1982 to September 2018 (*continued*)

	g RS[a] per 100 g Food[b]		
Food	**Weighted mean±weighted SD[cd]**	**Range[e]**	**n[f]**
Cooked and stored for 24 to 96 h			
Black[69,91]	4.7±2.0	2.3-7.3	21
Pinto or common brown[52,91,107]	2.7±1.6	2.0-8.4	43
Cooked, chilled, and reheated			
Lentils[102,109]	1.6±0.2	1.5-3.0	198
Noodles and pasta			
Noodles, egg, cooked[47]	0.2±0.2	0.0-0.4	4
Noodles, rice, cooked[47]	0.6±0.1	0.5-0.6	4
Pasta, corn, cooked[41]	0.1	NA	8
Pasta, cooked[10,14,47,50,52,74,76,81,82]	1.5±0.8	0.2-2.9	34
Pasta, cooked then chilled[10,76]	1.0±0.2	0.8-1.4	5
Pasta, durum wheat, cooked[41,78,110-112]	1.2±1.2	0.2-3.2	23
Pasta, durum wheat, cooked then chilled 3 to 5 d[111]	3.4±0.0	3.4-3.5	12
Pasta, mixed grain, cooked[41]	0.5	NA	6
Pasta, whole wheat, cooked[47]	0.2	NA	2
Other			
Hazelnuts[113]	1.4±0.1	1.3-1.4	6
Potatoes[i]			
Boiled, baked, or microwaved			
Potato, unknown variety[10,13,14,41,45,50,52,76,80,81,114-119]	0.7±0.5	0.1-2.0	74
Potato, high-amylose variety[118]	4.6	NA	3
Potato, red variety[120,121]	1.7±1.3	0.7-3.8	16
Potato, russet[121]	3.1±0.5	2.6-3.5	6
Potato, sweet variety[45,50,80]	0.5±0.5	0.3-2.1	15
Potato, yellow variety[120,121]	1.4±1.3	0.3-3.5	16
Cooked then chilled			
Potato, unknown variety[10,13,14,80,114-116,118,119]	1.3±0.6	0.3-2.4	47
Potato, high-amylose variety[118]	6.4±0.2	6.0-6.8	6
Potato, red variety[120,121]	2.0±1.7	1.1-4.8	13
Potato, russet[121]	4.3±0.5	3.8-4.7	6
Potato, salad[81,115]	5.2±1.9	1.0-5.9	7
Potato, sweet variety[80]	0.4±0.0	0.4-0.4	2
Potato, yellow variety[120,121]	2.5±3.8	0.6-5.4	16
Cooked then frozen			
Potato, unknown variety[117]	0.4±0.0	0.4-0.4	2
Cooked, chilled then reheated			
Potato, unknown variety[115,116]	1.6±0.7	0.4-2.2	11
Potato, red variety[121]	3.2±0.7	2.6-3.8	6
Potato, russet[121]	3.9±0.3	3.6-4.2	6
Potato, yellow variety[121]	5.1±2.3	2.2-4.3	6

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Table. Naturally occurring resistant starch in whole foods commonly consumed in the United States, extracted from peer-reviewed articles published from 1982 to September 2018 (*continued*)

Food	g RS[a] per 100 g Food[b]		
	Weighted mean±weighted SD[cd]	Range[e]	n[f]
Fried			
Potato, unknown variety[80,81,114,115]	3.8±1.9	0.2-5.5	15
Potato, sweet variety[80]	0.3±0.0	0.3-0.3	2
Fried then frozen			
Potato, unknown variety[122]	2.9±0.6	2.3-3.8	12
Other			
Potato, chips[50,52,114,115]	3.1±0.7	1.4-4.5	11
Potato, instant[10,50,81,114,115]	1.4±1.1	0.2-2.4	13
Rice			
Steamed, boiled, or pressure cooked			
Brown[50]	0.1±0.0	0.0-0.1	5
White, long grain[5,14,50,52,81,84,123-125]	1.4±1.0	0.0-3.7	46
White, medium grain[5,41]	0.2±0.1	0.1-0.5	18
White, short grain[5,123,124]	0.3±0.2	0.0-0.6	20
White, high amylose[126,127]	0.8±0.1	0.7-0.9	18
White, intermediate amylose[126,127]	0.5±0.0	0.5-0.6	9
White, low amylose[124,126,127]	0.2±0.1	0.1-0.4	11
Cooked then chilled			
White, long grain[5,125]	0.9±0.8	0.4-2.6	13
White, medium grain[5]	0.6±0.3	0.3-0.9	6
White, short grain[5]	0.4±0.3	0.2-0.8	6
Stir-fried			
White, long grain[124]	2.2	—	2
White, short grain[124]	1.4±0.1	1.4-1.4	4
Stir-fried then chilled			
White, long grain[124]	4.5±0.8	3.9-5.2	4
White, short grain[124]	3.7±1.0	2.5-5.0	8

[a]RS=resistant starch.
[b]RS value in whole food with moisture included. For references providing RS values on a dry weight basis, the formula (1−% moisture)*% dry weight RS value was used to calculate RS in the whole food. Moisture content was either measured and provided in the reference or obtained from the US Department of Agriculture FoodData Central database (www.fdc.nal.usda.gov)[40] using the most similar food item.
[c]SD=standard deviation.
[d]First, the weighted mean RS was calculated for each food item by multiplying the mean RS in the whole food (with moisture) by the number of samples analyzed in the reference. Next, the individual weighted means were summed and divided by the total of samples from all references in the food category to obtain the overall weighted mean. Then, the weighted SD was calculated by the individual food item by multiplying the sample size by the mean RS of each whole food (with moisture) minus the overall weighted mean squared. Next, the individual weighted SD were summed and divided by the total sample size minus 1. Lastly, the square root of this value provided the overall weighted SD. The weighted SD is not provided if the SD was not reported in the reference, even if more than one sample was analyzed.
[e]Minimum to maximum weighted mean RS values in each food item category with more than 1 mean RS value.
[f]Total number of samples analyzed for each food item.
[g]NA=not available.
[h]Baked corn tortilla moisture content was not available in the FoodData Central database,[40] therefore, the measured moisture from Rohlfing and colleagues[63] was used.
[i]Analyzed without skin.

stored at 4°C for 14 (4.7 g/100 g) and 7 (4.6 g/100 g) days, respectively; and cooked high amylose potatoes (4.6 g/100 g). The foods with the lowest mean RS content include multi-grain flaked store-bought cereal (0.0 g/100 g), cooked bananas (0.0 g/100 g), and cooked unripe plantain crisps (0.0 g/100 g), fruit scones (0.1 g/100 g), wheat-germ bread (0.1 g/100 g), store-bought granola (0.1 g/100 g), cooked corn pasta (0.1 g/100 g), and cooked brown rice (0.1 g/100 g).

DISCUSSION

RS is found in many starch-containing foods, such as breads, grains, pasta, cereals, beans and legumes, potatoes, and rice. Over the last several years, an increase in the quantitative analysis of RS in foods resulted from the development of a commercially available assay that indirectly measures RS. A complete database showing the RS content of whole foods has not been developed because the commercially available assay was used widely by the scientific community. In addition, the prior reference providing RS content in foods included RS values on a dry weight basis,[39] which would not be accurate in whole foods, where moisture is included. Therefore, a database was developed based on data from peer-reviewed publications that analyzed the RS content in whole foods that are consumed by individuals in the United States.

The database has the potential to assist registered dietitian nutritionists, researchers, the food industry, and consumers in several ways. First, the database could be a resource for registered dietitian nutritionists to assist client and patient efforts to incorporate naturally occurring RS foods into their diets. Next, the database could be used as a resource for practitioners and researchers to support the development of well-controlled dietary intervention studies that may examine the appropriate amount of naturally derived RS from foods needed to achieve a specific health outcome. Studies have indicated that adequate amounts of RS (approximately ≥15 g/day)[128] can improve postprandial glucose[26,36] and insulin sensitivity, especially among adults with insulin resistance,[29,129] and modulate the gut microbiome,[130] which may improve gastrointestinal health. However, many of these studies used RS as a functional ingredient either alone or added to a specific food (eg, muffin or cookie) instead of foods with naturally occurring RS. Next, food-manufacturing companies can utilize the database to formulate new products that contain naturally occurring RS-containing foods. Lastly, the database can also be used as a resource for consumers who are interested in adding RS foods to their diet.

Variation in RS Content in Foods

The variation in RS content within and between each food item category can be influenced by many factors. Breeding techniques can increase the amylose to amylopectin ratio of the starch granule to allow for RS formation during the cooling process.[4] According to the database, high-amylose grains have more than 10 times, boiled high-amylose potatoes have more than 4 times, and high-amylose cooked white rice has more than 4 times the amount of RS than low-amylose varieties.

Varietal differences among the same food also contain different amounts of RS.[4] For example, according to the database, russet potatoes have a higher mean RS (4.3 g/100 g) than yellow (2.5 g/100 g) and red (2.0 g/100 g) potatoes that were cooked and then chilled. Butter or lima beans (6.4 g/100 g), kidney beans (3.8 g/100 g), and white kidney beans (3.6 g/100 g) had the highest mean amount of RS, while fava beans (0.7 g/100 g), refried pinto beans (0.7 g/100 g), Great Northern beans (1.2 g/100 g), and mung beans (1.2 g/100 g) had the lowest amount of mean RS among the cooked legumes.

The preparation methods and storage conditions can change the RS content of food. Heat and moisture improve the gelatinization properties of the starch granule, which upon cooling allows the linear amylose chains to pack tightly and resist digestive enzymes, a process called retrogradation.[9] Cooking and then chilling of bananas and plantains, pasta, stir-fried rice, black and pinto beans, and potatoes increase the RS content. However, reheating after chilling reduces the RS content in bananas and plantains, legumes, and potatoes. In fact, cooking bananas eliminates all RS. Storage temperature and duration also influence RS formation in some foods, such as corn tortillas. Freshly baked corn tortillas have the lowest RS content compared to corn tortillas stored at 4°C, in which the RS content increases with time. The maximum RS formation in corn tortillas occurs when stored at 4°C for 3 to 5 days. Another example includes durum wheat pasta, where chilling the cooked pasta for 3 to 5 days increases the RS by almost three times compared to the freshly cooked pasta. Baking temperature and duration of the baking process also influence RS formation in breads. White wheat bread baked at a lower temperature (120°C) for longer duration (20 hours) contained 2.2 g/100 g RS compared to 1.1 g/100 g RS when bread is baked a higher baking temperature (150°C) for shorter duration (3 hours) (specific data not shown in the Table).[61,80]

Finally, the type of analytical methods used to quantify the amount of RS can vary across the same food. The differences in analytical methods used pose challenges in adequately quantifying RS, especially when RS is to be included as a component of dietary fiber declarations. For example, AOAC methods 2011.25 and 991.43 yield distinctly different fiber values for some RS sources.[131] These analytical challenges can create confusion for consumers seeking to add sources of RS to their diet, especially when RS is incorporated into the dietary fiber quantity on the Nutrition Facts label.

RS as Functional Ingredient

Enrichment of processed foods with RS can improve RS intake beyond the consumption of naturally occurring RS foods. Adding RS as a functional ingredient, specifically RS2 and RS3, to foods can improve the nutritional profile and retain sensory appeal without significant changes in texture or shelf life.[132-135] Apart from being bland in flavor and having a neutral white color, commercial sources of RS2 and RS3 have a high gelatinization temperature, finer particle size, and are less susceptible to changes during processing and storage than RS found naturally in foods.[135] These properties can improve texture, provide better mouthfeel, color, and food flavor, thereby increasing the consumer acceptability of foods with added RS.[135] For these reasons, enriching foods with RS2 or RS3 as a functional ingredient may be more advantageous than foods with naturally occurring RS because the commercial RS retains resistance under processing and cooking conditions.[136] For example, heating potatoes in water increases the solubility of the RS2 starch granule to improve digestibility and reduce resistance, thus lowering RS content. However, RS as a functional ingredient incorporated into pasta will retain its resistance when cooked in water.

RS Food Claims Based on Clinical Trials

The US Food and Drug Administration (FDA) has now recognized some types of RS, specifically high amylose starch containing RS2, as dietary fibers for Nutrition Facts and

Supplement Facts labeling.[137] In addition, the US FDA authorized a qualified health claim for high-amylose maize RS and reduction of risk of type 2 diabetes. Additional requirements for foods bearing the claim are described in FDA Letter of Enforcement Discretion: Docket # FDA-2015-Q-2352.[138] The FDA will exercise enforcement discretion for the following qualified health claim statements: "High-amylose maize resistant starch may reduce the risk of Type 2 diabetes. FDA has concluded that there is limited scientific evidence for this claim."[138] "High-amylose maize resistant starch, a type of fiber, may reduce the risk of Type 2 diabetes. FDA has concluded that there is limited scientific evidence for this claim."[138]

The clinical science for this qualified health claim is based on improved insulin sensitivity in healthy or at-risk individuals after consuming high-amylose maize RS.[29,30,37,129,139,140] The European Food Safety Authority has also authorized a health claim that describes the benefit of RS on postprandial blood glucose concentrations.[137]

Several strengths and limitations of this review must be mentioned. The strengths include identifying RS in foods that were analyzed in samples appropriate for human consumption. For example, raw foods (except bananas, plantains, and oats) or starches were not included, as they are not suitable for consumption, although some individuals add RS flour to foods as a functional ingredient. However, this review did not include these type of flours because they are manufactured and not present naturally in foods. In addition, three databases were searched by hand to include as many peer-reviewed articles quantifying RS in foods as possible. The database adjusted the RS value to include moisture if given as percent dry weight basis, which is more representative of RS in whole foods. A weighted sampling method was used to provide more weight for values with higher sampling representation compared to lower, which improves the validity of the data.

A few limitations must also be noted. The method of RS analysis highlights one major limitation. There is an ever-present gap between in vitro and in vivo analysis regardless of the methods used to quantify RS. Englyst and colleagues,[7,8] and many others who adapted the Englyst procedure, based their RS analysis on a broad assumption of homogenization or milling food showing similar properties as those of chewing. However, chewing is very individualized and cannot be controlled to replicate a milled or homogenized product. Estimation of newly identified RS, such as RS4, deviates from methods utilized to estimate RS2 and RS3. The changes range from significant decrease in initial incubation times to a cold KOH treatment in order to solubilize RS4.[141] It is clear that RS estimation is a constantly evolving process and any comparisons of RS values by different analytical methods are bound to reflect some amount of over- or underestimation. Also, a method to quantify RS5 has not been described. Another limitation was the adjustment of moisture when RS was provided on a percent dry weight basis. If the moisture was not measured and given in the reference, a food database was utilized to identify the moisture content in a similar food item. In addition, environmental and natural genetic differences influence starch digestibility and are inherently difficult to control.[4] Processing, cooking, and storing methods can change the properties of the starch granule to allow for more or less resistance. Future research attempting to standardize RS quantification is needed to be more accurate in assessing RS content in foods. Lastly, only peer-reviewed articles estimating RS in foods were included. Private or food companies conducting an independent RS analysis in foods were excluded, which limited the comprehensiveness of the database.

CONCLUSIONS

RS is found naturally in both processed and whole starchy foods, including breads, cereals, bananas and plantains, grains, noodles and pasta, potatoes, rice, and legumes. According to the database, raw foods, including oats and plantains, had the highest RS content. Among cooked foods, potatoes and grains (barley and rice) bred to have a higher amylose to amylopectin ratio have higher amounts of RS than those with a lower amylose to amylopectin ratio. Potatoes and grains that are cooked and then chilled have more RS than if boiled or heated, where the chilling process promotes the retrogradation of the starch granule to make it less digestible. The duration of storage also increases RS in some foods, such as corn tortillas, durum wheat pasta, and black and pinto beans. Foods with the lowest RS include multigrain flaked cereal, cooked bananas, cooked unripe plantain chips, fruit scones, wheat-germ bread, store-bought granola, cooked corn pasta, and cooked brown rice.

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STATEMENT OF POTENTIAL CONFLICT OF INTEREST

M. L. Stewart is an employee of Ingredion Incorporated; however, the perspectives provided by the author are her own, and do not necessarily reflect the perspectives of her employer. No potential conflict of interest was reported by the remaining authors.

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AUTHOR CONTRIBUTIONS

M. A. Patterson developed the idea. M. A. Patterson and M. Maiya identified and extracted the peer-reviewed articles meeting inclusion criteria. M. A. Patterson and M. Maiya developed and contributed to the database. M. A. Patterson, M. Maiya, and M. L. Stewart wrote the initial manuscript, revised and commented on all versions, and approved the final version of the manuscript.