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The Roles of a Native Starch and a Resistant Dextrin in Texture Improvement and Low Glycemic Index of Biscuits

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Abstract: Low-GI biscuits are commonly produced using whole-grain flour, bran, or soluble dietary fibers, giving an undesirable texture. New low-GI biscuits containing dietary fibers and with improved palatability were formulated by substituting 60% of wheat flour (WF) with a native starch (ST) and 15% of WF with a resistant dextrin (RD), a source of dietary fibers. The botanical source of ST was common buckwheat (*Fagopyrum esculentum* Moench). Biscuits were also made with a single substitution by ST or by RD at the same level for comparison. The firmness of the biscuits was increased with the single substitution by RD due to its small average molecular size and high hygroscopicity, while it was decreased with the single substitution by ST. The double substitution by ST and RD not only produced the texture with the lowest firmness and brittleness, but also led to the lowest in vitro starch digestion rate and total starch digestibility. The human trial confirmed that the biscuits with the double substitution had a low GI of 47. The results indicated the additive or synergistic effects of ST and RD on the properties of the biscuits, demonstrating that low-GI biscuits can be produced with a substantial dietary fiber content without jeopardizing their palatability.

Keywords: dietary fibers; common buckwheat; bakery product; textural properties; slowly digestible starch; blood glucose response

Citation: Yu, S.; Dong, K.; Pora, B.L.R.; Hasjim, J. The Roles of a Native Starch and a Resistant Dextrin in Texture Improvement and Low Glycemic Index of Biscuits. *Processes* **2022**, *10*, 2404. https://doi.org/10.3390/pr10112404

Academic Editors: Sanja Podunavac-Kuzmanović, Strahinja Kovačević, Milica Karadžić Banjac and Agnieszka Zgoła-Grześkowiak

Received: 29 September 2022
Accepted: 8 November 2022
Published: 15 November 2022

1. Introduction

Long-term repeated hyperglycemia has been suggested as one of the risk factors for non-communicable chronic diseases, such as diabetes and obesity. Diabetes has become a critical global public health issue due to its high prevalence and high mortality rate [1]. The estimated number of adults with diabetes has reached 537 million in 2021 and the figure is expected to surge to 783 million by 2045, a large proportion of which is contributed by unhealthy lifestyle and obesity [2]. Regulating blood glucose response is evidently pivotal for the prevention and the management of diabetes and obesity. Low-glycemic-index (GI, <55) foods have been reported to improve blood glucose control, alleviate insulin resistance, and lower glycated hemoglobin (HbA1c) [3]. They have been recommended for diabetic and obese patients [4,5].

Digestible starch, a major source of dietary carbohydrates, is one of the main contributors for postprandial glycemic response. However, the digestion rate and the total digestibility of a starch depend on its structure [6,7]. In addition, starch digestibility increases with the degree of gelatinization, and raw ungelatinized starch has been proposed to be a source of slowly digestible starch (SDS) [8,9]. A recent in vitro study reported that common buckwheat (*Fagopyrum esculentum* Moench) starch (ST) could be used as a source of SDS in biscuits [10]. The slow digestion properties of ST can be linked to its high gelatinization temperature and high shear resistance, comparing with those of common wheat (*Triticum aestivum*) starch. Hence, the starch granules of ST are less gelatinized and/or broken after the baking process than those of common wheat starch.

Resistant dextrin (RD) is a type of soluble dietary fibers [11], normally produced from starch through the pyrodextrinization process. It has random glycosidic linkages apart from α-1,4 and α-1,6 linkages found in starch molecules. Amylolytic enzymes in the digestive tract can only hydrolyze α-1,4 and α-1,6 linkages. Therefore, the presence of other glycosidic linkages inhibits the digestion of RD. In the colon, RD can be fermented by gut microflora and has been considered a type of prebiotics [12,13]. The chronic supplementation of RD can increase the postprandial satiety and lower the postprandial glycemic response [14,15]. In addition, it was reported that the GIs of muffins and breads were reduced when wheat flour (WF) was substituted with a mixture of resistant starch (RS), RD, and lentil flour [16]. However, the chemical compositions of these low-GI bakery products and their control counterparts were very different, and there was no comparison with single-ingredient substitution; therefore, the mechanism leading to the low-GI properties of the bakery products was not clear. Furthermore, the textural properties of these low-GI bakery products were not tested.

To date, commercial low-GI bakery products are mostly produced using whole grain or whole-grain flour. Starch granules are trapped inside the cell wall matrices in the whole grain or whole-grain flour, which reduces their digestibility. However, the addition of whole grain or whole-grain flour often results in poor palatability: coarse texture (graininess and grittiness), dry mouth feels, and dark color [10,17]. There were also new developments of high-fiber or low-GI bakery products using high-fiber by-products of cereal processing (such as corn bracts, millet bran, wheat bran, and oat bran) and food processing (such as soy fiber) [18–21], which resulted in less desirable texture and sensory scores. Furthermore, the consumption of excessive dietary fibers, especially leguminous flours and soluble dietary fibers, can cause digestive discomforts [22–24], including abdominal pain, bloating, flatulence, and diarrhea, which may lead to dehydration and malabsorption.

The aim of the present study is to reduce the starch digestibility of biscuits by replacing WF with a native starch and a small amount of RD in order to obtain a low-GI product, while maintaining or improving the palatability comparing with the control biscuits. Based on the findings from the previous in vitro study [10], ST was chosen as the native starch in the present study. The chemical composition of the substituted biscuits was maintained as close as possible to that of the control biscuits. The small amount of RD will also provide enough dietary fibers for nutritional claim (such as a good source of dietary fibers). The absence of whole-grain flour and excessive soluble dietary fibers in the biscuits will not only improve the texture of the biscuits, but also prevent the digestive discomfort associated with them. In addition, biscuits, where WF in the control formula was partially substituted by ST, exhibited a slower starch digestion rate than those made with whole wheat flour [10]. The results of the biscuits where WF was partially substituted by both ST and RD will be compared with those made with single substitutions by ST and by RD in order to understand the impacts of each ingredient. The results from the present study can be useful to improve the nutritional values of bakery products, especially biscuits, while maintaining or improving its palatability.

2. Materials and Methods

2.1. Materials

RD (NUTRIOSE® FM06) and maltitol (SweetPearl®) were provided by Roquette (Lestrem, France). ST was extracted from common buckwheat groats following the method of Yu et al. [10]. The rest of the ingredients for biscuit making were purchased from a local grocery store.

Porcine pancreatin (P7545) and amyloglucosidase (E-AMGDF) were purchased from Sigma-Aldrich, Inc. (St. Louis, MO, USA) and Megazyme International Ltd. (Bray, Ireland), respectively. All chemicals were reagent grade and used as is.

2.2. Biscuit Preparation

Four biscuit formulae were designed to observe the effects of incorporating ST and RD on the textural properties and the starch digestibility of the resulting biscuits. The quantities of all ingredients in the four formulae were kept the same, except for WF, wheat gluten, ST, and RD, as shown in Table 1. In the biscuits made with a single substitution by ST, 60% WF in the control formula was replaced by ST. For the biscuits made with a single substitution by RD, the RD level was adjusted to obtain about 5 g dietary fibers per 100 g biscuits to satisfy the claim of "a good source of dietary fibers". Wheat gluten was added into these two formulae to maintain the similar gluten contents to that of the control biscuits (~9 g/100 g dry biscuits). The starch and fat contents of the formula with the single substitution by RD were slightly lower than those of the control formula as they were replaced by the dietary fibers (enrichment). The formula with a double substitution by ST and RD was the same as that with the single substitution by ST, except that WF was further replaced by RD to obtain about 5 g dietary fibers per 100 g biscuits. In consequence, its protein content was slightly lower than that in the control formula.

Table 1. Formulae and chemical compositions of the control and substituted biscuits.

Formula	Unit	Control	Single Substitution by ST	Single Substitution by RD	Double Substitution by ST and RD
Ingredient					
Wheat flour (WF)	g	180	62	152	37
Starch (ST)	g	-	109	-	109
Resistant dextrin (RD)	g	-	-	25	25
Wheat gluten	g	-	9	3	9
Egg	g	40	40	40	40
Sugar	g	18	18	18	18
Maltitol	g	18	18	18	18
Salt	g	1.5	1.5	1.5	1.5
Butter	g	10	10	10	10
Milk powder	g	10	10	10	10
Baking powder	g	3	3	3	3
Palm oil	g	40	40	40	40
Water	g	22	22	13	21
Total excluding water	g	310.5	310.5	310.5	310.5
Chemical composition					
Moisture	g/100 g	7.8	4.2	3.7	4.6
Ash	g/100 g dry	1.8	2.0	1.9	1.8
Protein	g/100 g dry	8.6	9.2	9.0	7.5
Fat	g/100 g dry	17.3	17.2	15.1	16.3
Total dietary fibers	g/100 g dry	1.3	2.1	5.7	5.3
Starch	g/100 g dry	52.0	52.7	49.6	51.7
Total carbohydrates *	g/100 g dry	72.3	71.7	74.1	74.4
Available carbohydrates *	g/100 g dry	71.0	69.6	68.4	69.2

* Total carbohydrate and available carbohydrate contents were calculated by difference.

The process of biscuit dough making was the same as in Yu et al. [10]. A KitchenAid (5KPM5CWH, Whirlpool Corporation, Benton Harbor, MI, USA) was used for blending and mixing. At the beginning, sugar, maltitol, salt, and eggs were blended together for 10 s. Butter was then combined with the mixture for 20 s, followed by palm oil for 40 s. Afterward, the rest of the ingredients (WF, ST, RD, wheat gluten, baking powder, and milk powder) were blended into the mixture until a uniform dough was formed (60 s). A small amount of water was added to make the dough more workable. The dough was kept in a freezer at −18 °C for an hour before rolling using a desktop dough sheeter (SW-520S, Sinmag Co. Ltd., Wuxi, China) into a sheet of 5 mm thickness. The dough sheet was cut into a round shape with a diameter of 5 cm and baked in an oven with a top temperature of 190 °C and a bottom temperature of 180 °C for 11 to 13 min. The biscuits were hermetically sealed in plastic bags after being cooled to ambient temperature until they were analyzed or consumed by the subjects.

2.3. Textural Properties

The texture of the biscuits was analyzed using a Texture Analyzer (TA-XT Plus, Stable Micro 136 Systems, Godalming, UK) with the three-point bending rig probe (HDP/3PB). The base gap of the two support beams was adjusted to 36 mm, and the travel distance of the probe was 7 mm. The pretest speed and the test speed were 1 mm/s, and the post-test speed was 10 mm/s. Firmness refers to the maximum force that the instrument detected before the biscuit sample was cracked. Distance to break refers to the brittleness of the biscuits based on the distance that the probe had moved (downward) before the biscuit sample was fractured. The average value was obtained from seven separate biscuits.

2.4. In Vitro Starch Digestibility

The in vitro starch digestibility was performed in duplicate following the method of Yu et al. [25]. Biscuit particles containing 50 mg starches were mixed with 7.5 mL sodium acetate buffer (0.2 M, pH 6.0, containing 200 mM $CaCl_2$, 0.49 mM $MgCl_2$, and 0.02% NaN_3) and equilibrated at 37 °C. After adding 0.5 mL enzyme solution (containing 12.5 µL amyloglucosidase and 25 µg pancreatin in sodium acetate buffer), the mixture was stirred at 200 rpm and incubated in a water bath at 37 °C. Aliquots (0.1 mL) were withdrawn at different time intervals (0, 5, 10, 15, 20, 30, 45, 60, 90, 120, 180, 240, and 300 min) and immediately dispersed into 0.9 mL absolute ethanol to terminate the enzyme reaction. The weight of released glucose was determined using the D-Glucose (GOPOD Format) Assay Kit (Megazyme International Ltd., Bray, Ireland), and the percentage of digested starch was calculated as follows:

$$\text{Starch digestibility (\%)} = (\text{weight of released glucose} \times 0.9)/\text{weight of starch in biscuit} \times 100\% \quad (1)$$

where 0.9 is the ratio of the molecular weight of the anhydroglucose monomer unit in starch to that of glucose. The starch digestogram was used to obtain the digestion kinetics following the method Yu et al. [25] with the assumption that the digestion of the starch in the biscuit samples obeys the first-order kinetics at time t, $C(t)$:

$$C(t) = (1 - C_\infty)e^{-kt} + C_\infty \quad (2)$$

where $C(t)$ is the amount of undigested starch at time t, slope k refers to the digestion rate coefficient, and C_∞ is the amount of undigested starch remained at maximum digestibility obtained by extrapolating the digestion time to infinity. Both k and C_∞ were initially estimated by the logarithm of slope (LOS) and then amended by nonlinear least-squares fitting (NLLS) for more accurate values.

2.5. Glycemic Index

The human trial was conducted in Singapore in accordance with the ethical principles outlined in the Declaration of Helsinki [26]. This trial was approved by the Independent Ethics Committee (Reference Number: TP-IRB Ref: IRB 191102).

The recruited subjects were limited to only healthy Chinese men and non-pregnant women. The inclusion criteria were as follows: age between 18 and 60 years old, body mass index (BMI) between 18.5 and 27 kg/m^2, normal fasting serum glucose level, and no known food allergies or intolerances. The subjects were excluded if they failed to meet the inclusion criteria, had a history of chronic diseases (such as type 1 or 2 diabetes, cardiovascular diseases, cancer, and gastrointestinal disorders), had a surgery within the last 3 months prior to the screening process, were suffering from some diseases, or required to take medications that could influence the digestion and the absorption of nutrients or the glucose metabolism (such as steroids and protease inhibitors). The subjects were asked to maintain their regular diets and physical activities throughout the trial, while refraining from smoking before each visit. They were required to fast for 13 h before each test day and were not allowed take any dietary supplements until the end of the test. All subjects signed the written informed consent form prior to the trial. Thirteen subjects completed the trial, and their background information is summarized in Table 2.

Table 2. Background information of the subjects for glycemic index trial.

Number of subjects		13
Gender	Female	30.8%
	Male	69.2%
Age *		40.8 ± 13.9
Height *		1.69 ± 0.09 m
Weight *		61.3 ± 10.8 kg
Body mass index (BMI) *		21.2 ± 2.3
Ethnicity		Chinese (100%)

* Mean ± standard deviation.

The fasting glucose level was determined by a finger prick at each visit. All subjects were asked to consume a solution containing 50 g glucose (dissolved in 250 mL water) on their first visits. After at least a 3-day wash-out period, the subjects were given biscuits containing 50 g available carbohydrates (Table 3) within a time frame of 12 min accompanied by 250 mL water. Blood samples were obtained at 15, 30, 45, 60, 90, 120, and 150 min after the consumption of glucose reference or biscuits, and the blood glucose levels were analyzed using calibrated YSI 2300 Stat Plus Glucose and L-Lactate Analyzer (Yellow Springs, OH, USA). The fasting glucose level was set as zero. The incremental area under the curve (AUC) of the blood glucose response from 0 to 120 min after the consumption of glucose reference or biscuits was determined and used to calculate the GI of the biscuits. The blood glucose response below the fasting line was excluded from the AUC calculation.

Table 3. Serving size of biscuits and nutrition composition per serving size for human trial.

	Biscuits Substituted with ST and RD
Serving size	75.8 g
Total carbohydrates	53.8 g per serving size
Available carbohydrates	50.0 g per serving size
Sugars	5.7 g per serving size
Dietary fibers	3.8 g per serving size
Proteins	5.4 g per serving size
Lipids	11.7 g per serving size
Energy	342 kcal per serving size

2.6. Statistical Analysis

The results were analyzed using RStudio (v1.4.1106, Boston, MA, USA). ANOVA with Tukey's pairwise comparison was used to analyze the textural properties and the in vitro starch digestibility among the four biscuit formulae, whereas Student's t-test was used to analyze the blood glucose responses. These data are presented as means ± standard deviations, except GI, which is presented as means ± standard error of mean (SEM). The significant difference was set at $p < 0.05$.

3. Results and Discussion

3.1. Textural Properties

The firmness of biscuits made with the single substitution by RD was significantly higher than those of the others (Table 4). RD has been added to food products to boost the dietary fiber content or the prebiotic content. It works very well in beverages because of its high transparency and low viscosity. However, it can change the texture of solid food products when it is used for fiber enrichment. RD caused the dough to become sticky and runny, mainly due to its low molecular weight and highly amorphous structure, where the free hydroxyl groups could bind strongly with water molecules (high hygroscopicity) [27], comparing with WF and ST, which contained some crystalline structure. It was not possible to add the same level as water as the control biscuits (Table 1) in order to maintain a workable dough. In addition, water (or steam) is one of the leavening agents for baked foods, and having less water in the dough will lead to less expansion in the structure of the biscuits. As the results, the biscuits had a denser and harder texture than the control biscuits. Firmness reflects the required force to bite the biscuit sample, and thus biscuits with high firmness will pose a difficulty for the population with weak chewing force, such as young children and elderly people.

Table 4. Textural properties of control and substituted biscuits.

Biscuits	Firmness (g)	Distance to Break (mm)
Control	1058 ± 115 [b]	0.12 ± 0.6 [a]
With ST	800 ± 177 [ab]	0.21 ± 0.5 [b]
With RD	1609 ± 388 [c]	0.20 ± 1.6 [b]
With ST and RD	697 ± 121 [a]	0.23 ± 0.5 [c]

Mean ± standard deviation from seven replicates. The values in the same column with different letters are significantly different at $p < 0.05$.

The biscuits made with the single substitution by ST showed slightly lower firmness (but not significantly different) than the control biscuits (Table 4), which agrees with the previous finding [10]. This could be attributed to the higher gelatinization temperature of ST comparing with that of the starch in WF, resulting in less gelatinized starch after biscuit baking. Gelatinized starch can retrograde and form a strong film during storage, which increases the firmness of the biscuits.

It was postulated that the addition of ST could decrease the firmness of the biscuits enriched with RD. Indeed, the biscuits made with the double substitution by ST and RD exhibited the lowest firmness among all formulae (Table 4), suggesting a synergistic effect between ST and RD. For example, RD, being more hygroscopic, might have bound strongly with water molecules, reducing the available water for ST [27], thus further preventing the gelatinization of ST during baking.

Distance to break is a measurement of the brittleness of biscuits, which is an important factor to understand how easy the biscuits can be broken, such as during transportation. Biscuits with high brittleness have a low tendency to deform, and thus their distance to break is small. The control biscuits had the lowest distance to break, whereas the biscuits with the double substitution by ST and RD exhibited the highest distance to break (Table 4). It is known that brittle material has low cohesiveness [28]. Due to its soluble nature, RD could have strengthened the continuous phase in the biscuits, improving the cohesiveness of the biscuit structure. Gluten network can also improve the cohesiveness of a baked product [29]. The presence of gelatinized starch in the control biscuits might have disturbed the gluten network structure and reduced the cohesiveness of the biscuit structure. On the other hand, due to the higher gelatinization temperature, ST was less gelatinized than the starch in WF after baking. Therefore, the gluten could form a more cohesive structure in the biscuits with the single substitution by ST than in the control biscuits. The lowest brittleness of the biscuits with the double substitution by ST and RD indicated the additive or synergistic effects of ST and RD in the texture of the biscuits.

3.2. In Vitro Starch Digestibility

The four biscuit formulae in the present study only differed in the amount of WF, RD, ST, and wheat gluten. The rest of the ingredients in the biscuits were maintained at the same levels. The wheat gluten was added in order to minimize the differences in the chemical compositions among the four formulae, albeit the small differences due to the increased dietary fiber content with RD enrichment. Therefore, any differences observed in their in vitro starch digestibilities were mainly due to the differences in the WF, RD, and ST contents.

All biscuits showed rapid starch digestion at the beginning of the test, whose rate decreased with the digestion time (Figure 1). The digestion rate coefficient (*k*) was obtained from the slope of the digestion curve. The *k* value was the highest for the control biscuits, followed by the biscuits with the single substitution by ST, while the biscuits with the single substitution by RD and those with the double substitution by ST and RD had the lowest *k* values (Table 5). The starch digestions of the control biscuits and the biscuits with the single substitution by ST reached a plateau around 100 and 120 min, respectively, whereas the starch digestions of the biscuits with the single substitution by RD and those with the double substitution by ST and RD reached a plateau at a much later time, around 250 min; however, this was not clear as the in vitro digestion test was stopped at 300 min.

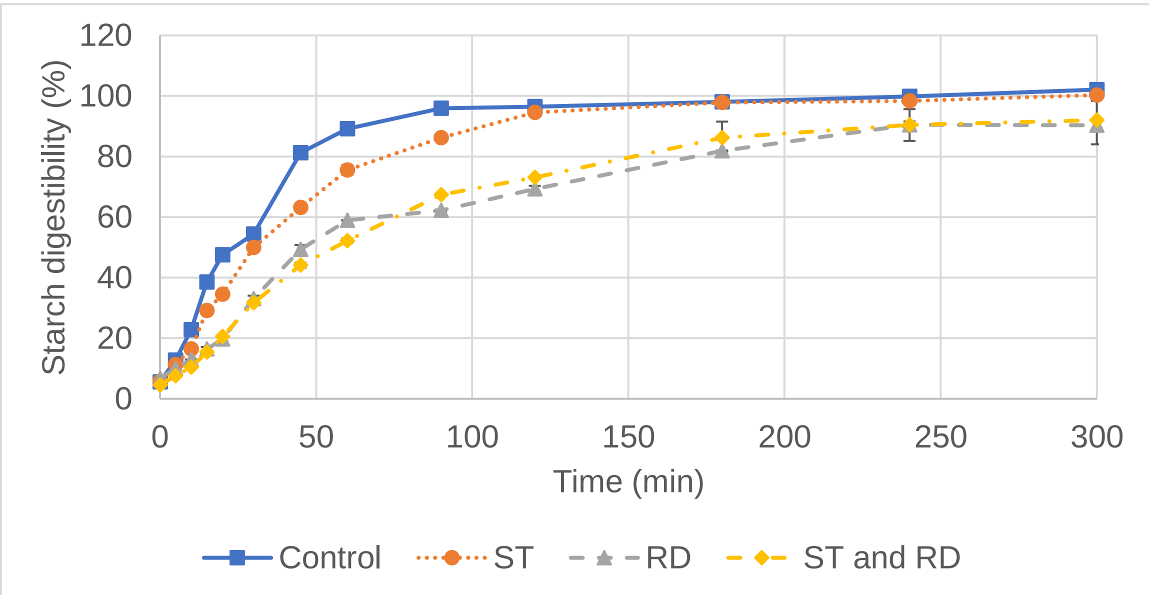

Figure 1. In vitro digestion curves of control and substituted biscuits, averaged from duplicate measurements.

Table 5. In vitro digestibility of control and substituted biscuits.

Biscuits	Digestion Rate Coefficient, *k* (1/min)	Total Undigested Starch, C_∞ (%)
Control	0.0283 ± 0.0001 [a]	-1.44 ± 0.13 [a]
Single substitution by ST	0.0200 ± 0.0002 [b]	-1.09 ± 0.46 [a]
Single substitution by RD	0.0123 ± 0.0001 [c]	7.29 ± 0.76 [b]
Double substitution by ST and RD	0.0119 ± 0.0019 [c]	9.91 ± 0.11 [c]

Mean ± standard deviation from duplicates. The values in the same column with different letters are significantly different at $p < 0.05$.

The total undigested starch (C_∞) is the amount of starch that cannot be digested by the enzymes. It was estimated by extrapolating the digestion curve to time infinity. The results showed that the biscuits with the double substitution by ST and RD had the highest

C_∞ value, followed by those with the single substitution by RD (Table 5), whereas the control biscuits and those with the single substitution by ST showed negative C_∞ values, which essentially means that the starches in these two types of biscuits were almost, if not completely, hydrolyzed by the digestive enzymes. The negative C_∞ values were due to the limitations of the method to analyze real food products. For example, the color of the biscuits could have affected the colorimetric detection of glucose by the D-Glucose (GOPOD Format) Assay Kit. Moreover, it needs to be borne in mind that the estimation of C_∞ values might be less accurate for the biscuits with the single substitution by RD and those with the double substitution by ST and RD because there were only a few data points at the plateau region. However, it was clear from the digestion curves that the single substitution by RD showed a greater reduction in k and a higher C_∞ than the single substitution by ST, and the double substitution by ST and RD displayed the strongest reduction in k and the highest C_∞, indicating the additive or synergistic effects of ST and RD in slowing the starch digestibility of biscuits.

In the previous study [10], it was found that ST had higher gelatinization temperature and was more resistant to shear degradation during heating (lower breakdown viscosity) than common wheat starch; thus, ST might retain more granular structure after baking process. As raw ungelatinized starch was reported to be a good source of SDS [9], retaining the granular structure could lead to lower k or lower total digestibility (higher C_∞) of starch in the biscuits. In addition, the starch granules in WF are known to suffer some level of mechanical damage caused by dry milling process, showing higher susceptibility to enzyme hydrolysis than intact starch granules [30,31]. On the other hand, ST, as any starches isolated by the wet-milling process, had a negligible amount of damaged starch, which might also explain its lower k and higher C_∞.

This mechanism is different from the SDS in buckwheat flour, commonly used to produce low-GI biscuits. The low or slow starch digestibility of common buckwheat flour is likely due to its non-starch components, such as proteins, lipids, dietary fibers, and phenolic compounds, that can retard starch digestion [32–34]. These components were removed during the starch extraction process. The main benefit of using ST instead of whole-grain flour, such as buckwheat flour, is the lack of the coarse, unpleasant texture, resulting from the large particles, especially from the bran particles.

It has never been reported that the addition of RD alone could reduce the in vitro starch digestibility of a food product. The presence of RD in beverages did not seem to affect the hydrolytic activity of the amylolytic enzymes [35], probably because of its low or no viscosity. Therefore, it was surprising to obtain lower in vitro starch digestibility of biscuits with the single substitution by RD. This could be linked to the structure of the biscuits. RD having a small average molecular size and high hygroscopicity produced a dense structure in the biscuits, which not only increased the firmness of the biscuits (Table 4), but also decreased the accessibility of the enzymes to hydrolyze the starch molecules. In addition, it was not possible to add the same amount of water in the dough as the control formula since the dough became sticky and runny with the presence of RD. The limited amount of water in the dough system reduced the degree of gelatinization of the starch in WF after baking, which in turn decreased its digestibility.

Although the double substitution by ST and RD allowed the addition of the same amount of water as the control formula, the majority of the water might be bound by RD due to its high hygroscopicity. As a result, the starches (both ST and the starch in WF) might be less gelatinized after baking than without RD, exhibiting lower in vitro starch digestibility than the control biscuits or those with the single substitution by ST.

3.3. Glycemic Index

Comparing with the glucose reference, the blood glucose response profile after the ingestion of the biscuits with the double substitution by ST and RD displayed a flatter curve (Figure 2). The peak of the blood glucose response appeared earlier for the glucose reference than for the biscuit sample (30 min vs. 45 min, respectively). In addition, the glucose reference showed a larger negative glucose response 150 min after ingestion than the biscuits with the double substitution by ST and RD, indicating that the biscuit sample could delay the feeling of hunger associated with the negative blood glucose level after meal (also known as hyperinsulinemic hypoglycemia). High postprandial hyperglycemia, such as after consuming a high-GI food, stimulates the excess secretion of insulin to rapidly remove the high level of blood glucose to the normal physiological range. However, the removal of the blood insulin is slower than the removal of the blood glucose, which eventually leads to a hypoglycemic state where the blood glucose level is below that at the fasting state. This can be avoided by modulating the postprandial glycemic response, such as by consuming low-GI foods. The GI of the biscuits with the double substitution by ST and RD was 47, which is considered a low-GI food [36], and it was lower than the reported GI values of digestive biscuits, between 55 and 62 [37,38].

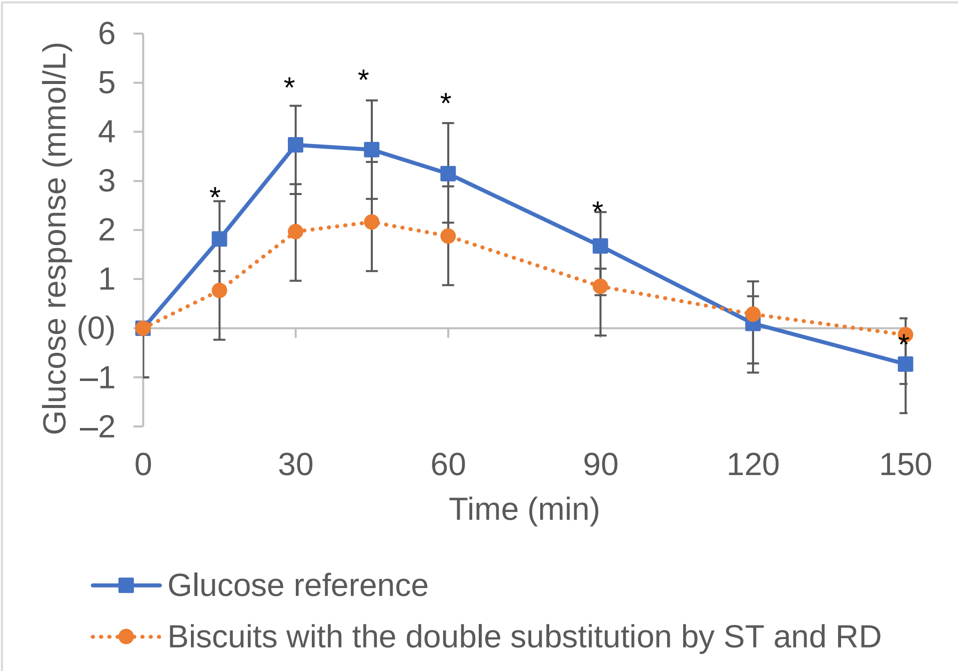

Figure 2. Postprandial blood glucose response curve of the biscuits with the double substitution by ST and RD. Significant difference at $p < 0.05$ between the biscuits and the glucose reference is signified by an asterisk (*).

Many studies reported that RD could lower postprandial glycemic response. However, these studies were either using a mixture of RD with other dietary fibers or food components [16,39] or involving a long feeding time [15,40,41]. When RD was used in a mixture, its individual benefits were not discussed. For the long-term feeding trial, RD mainly altered the hormones, partly due to the production of short-chain fatty acids by gut microflora fermentation (prebiotic effects).

Therefore, this is the first study demonstrating that a small amount of RD (5 g/100 g dry weight) could be used to reduce the starch digestibility and to produce low-GI food products, biscuits in this case, through the formulation with a native starch. RD by itself is a very hygroscopic ingredient, which binds strongly with water molecules, reducing the available water for starch gelatinization during baking. When RD is combined with a starch having high gelatinization temperature, such as ST, it retains more ungelatinized starch inside the biscuits, decreasing the starch digestibility and, in turn, lowering the GI of the biscuits. This allows the production of low-GI biscuits with a good texture and enough dietary fiber content for the claim of "a good source of dietary fibers."

4. Conclusions

ST and RD have additive or synergistic effects on the texture and the starch digestibility of biscuits. When 75% of WF in a biscuit formula was substituted by ST (60%) and RD (15%), the biscuits delivered the texture with the lowest firmness and brittleness and exhibited the slowest in vitro starch digestibility (the lowest k and the highest C_∞ values) among all biscuit formulae studied. The addition of RD also increased the dietary fiber content of the biscuits above 5%, suitable for the claim of "a good source of dietary fibers" in some countries. Although the single substitution by RD exhibited significantly lower k and higher C_∞ values than the control biscuits, it had a negative impact on the texture of the biscuits (i.e., high firmness). This negative impact of RD was cancelled by including ST in the biscuit formula. In addition, the human trial confirmed that the biscuits with the double substitution by ST and RD had a low GI of 47, demonstrating that low-GI biscuits can be produced having a good texture and containing a good amount of dietary fibers by substituting WF with ST and RD. The outcome of the present study can be used to improve the nutritional benefits of biscuits without jeopardizing their palatability, which can be a means to fight pandemic obesity and diabetes.

Author Contributions: Conceptualization and methodology, B.L.R.P. and J.H.; Investigation, S.Y. and K.D.; Writing—original draft preparation, S.Y.; Writing—review and editing, J.H.; Supervision, B.L.R.P. and J.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was internally funded by Roquette Management (Shanghai) Co., Ltd., and Roquette Frères.

Acknowledgments: We appreciate the technical assistance provided by Jingling Tao, Jingjing Yue, Yueping Ding, and Jia Li in this study. We also would like to thank Wei Xia for the assistance with statistical analysis.

Conflicts of Interest: The authors declared no conflict of interest.

Abbreviations

BMI, body mass index; C_∞, total amount of undigested starch; SDS, slowly digestible starch; ST, native starch; GI, glycemic index; k, in vitro digestion rate coefficient, RD, resistant dextrin; RS, resistant starch.

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