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FORMATION OF RESISTANT STARCH IN THE PROCESS OF FOOD PREPARATION AND COOLING: APPLIED ASPECTS FOR METABOLIC HEALTH

Summary. *The article reveals the theoretical, physico-chemical, and practical aspects of the formation of resistant starch during the preparation, cooling, and reheating of starch-containing products. It has been established that the formation of resistant starch depends on the starch structure, the ratio of amylose and amylopectin, as well as on the processing conditions. Special attention is paid to retrograde modification, which occurs after heat treatment and subsequent cooling of the product, and is a key factor for the formation of resistant starch type RS3. Data on products that have the greatest potential for the formation of resistant starch are summarized, as well as its importance for metabolic health. Resistant starch helps to reduce the postprandial glycemic response, participates in fermentation in the colon, and may have a beneficial effect on the intestinal microbiota. The article discusses the potential applications of resistant starch in the field of nutrition and food technology. The main limitations were also identified, and directions for future research in this area were outlined.*

Key words: *resistant starch, starch retrogradation, amylose, amylopectin, food cooling, heat treatment of food, metabolic health, postprandial glycemic response, intestinal microbiota, dietary fiber, functional nutrition.*

Relevance of the study. The study is particularly relevant due to the growing prevalence of metabolic disorders worldwide. According to the World

Health Organization, diseases such as diabetes and obesity are becoming more widespread, which focuses on nutritional factors that can affect carbohydrate metabolism, the postprandial glycemic response, and the overall metabolic state of the body. In this situation, it is especially important to find affordable and scientifically proven methods to increase the metabolic value of the daily diet.

The interest in resistant starch in the scientific community is because this starch fraction is not digested in the small intestine and is largely fermented in the large intestine, exhibiting properties similar to dietary fiber. In modern reviews, resistant starch is considered as a part of dietary fiber, and its potential role in reducing the glycemic and insulinemic response after eating, as well as in beneficial effects on the intestinal microbiota, makes it an important object for study in nutrition and medicine.

The importance of this topic lies in the fact that the content of resistant starch can change as a result of common culinary processes such as heating, cooling, and reheating products. This opens up opportunities for practical changes in the physiological properties of food using simple household and technological techniques. The study of the mechanisms of formation of resistant starch during the preparation and cooling of products is necessary to create scientifically sound nutritional recommendations aimed at maintaining metabolic health and preventing disorders of carbohydrate metabolism.

The purpose of the study. The aim of the study is to understand how resistant starch is formed during the preparation and cooling of products, as well as to evaluate its effect on metabolism and the possibility of its use in nutrition.

Materials and research methods. The research is based on open scientific publications, review articles, results of clinical and experimental work, as well as data presented in international regulatory and expert sources on resistant starch. We have studied its structure, conditions of formation and physiological effects.

The methodological basis of the work was the analysis, comparison, generalization, and systematization of scientific data on resistant starch. We classified it, examined the physicochemical mechanisms of its formation, assessed the effect of processing on the content of resistant starch fractions, and determined the importance of resistant starch for carbohydrate metabolism and the intestinal microbiota.

The results of the study. Resistant starch is a part of starch and its breakdown products that are not digested or absorbed in the small intestine of a healthy person. It then enters the colon, where it is fermented by the microbiota. In modern literature, resistant starch is often described as a carbohydrate fraction that is physiologically close to dietary fiber. According to the approach agreed with Codex Alimentarius, resistant starch can be included in dietary fiber if its physiological effect is confirmed [5].

The theoretical significance of resistant starch lies in the fact that its properties depend not only on the botanical origin of the raw material, but also on the structure of the starch itself in the finished product. The main components of starch are amylose and amylopectin. Amylose has a predominantly linear structure, whereas amylopectin is a highly branched polymer. The ratio of these two components affects properties such as crystallinity, accessibility to amylases, and the ability to retrograde. Thus, it is the structure of starch that determines its different digestibility.

In the scientific literature, the most common division of resistant starch is into five types, as shown in Table 1. The first type is physically inaccessible starch, which is contained in intact cellular structures. The second type is associated with native granules with stable crystalline organization. The third type is formed after heat treatment and subsequent cooling during retrogradation. The fourth type includes chemically modified forms of starch. The fifth type is represented by complexes of amylose with lipids, which impede the action of enzymes. This division is important because resistance to digestion does not arise for one reason but because of various structural mechanisms.

Table 1

The main types of resistant starch and the mechanism of their resistance

Type	Entity	Due to which the digestibility decreases	Examples
RS1	Physically inaccessible starch	Starch is shielded by cell walls or protein matrices	Whole grains, legumes
RS2	Native granular starch	Stable crystal structure of granules	Raw potatoes, unripe bananas
RS3	Retrograded starch	Re-ordering of circuits after heating and cooling	Boiled and chilled potatoes, bread, rice
RS4	Modified starch	A change in the chemical structure that reduces the access of enzymes	Esterified and crosslinked starches
RS5	Starch complexes with lipids	Formation of amylose-lipid complexes	It is formed during food processing and in some formulations

Source: the data is summarized from modern reviews and open publications

The process of resistant starch formation is associated with changes in the supramolecular structure of starch during heating and cooling. When heated in the presence of water, gelatinization occurs: starch granules swell, their original crystalline structure collapses, and polymer chains become more mobile (Figure). For some forms, especially for RS2, this means a loss of initial stability. However, it is after gelatinization that favorable conditions are created for the subsequent formation of RS3. When the starch is cooled, the released chains, mainly amylose, begin to re-bind and form more ordered structures.

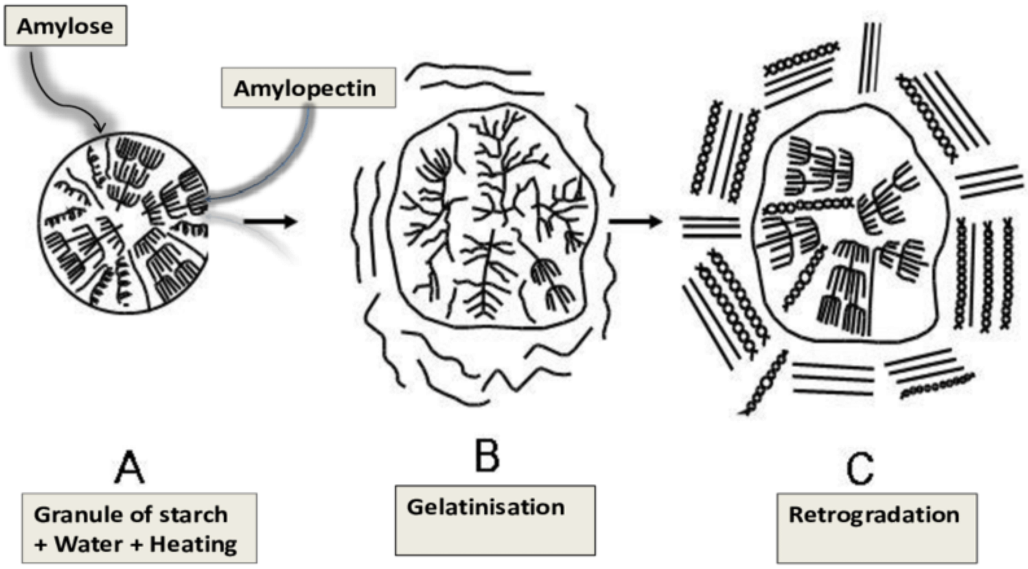

Fig. 1. Diagram of structural changes in starch upon heating in water and subsequent cooling [3]

Retrogradation is a process that occurs when starch gel cools and is characterized by the repeated convergence and ordering of the chains of amylose and amylopectin. As a result, double helices and more stable crystalline regions are formed, which become less accessible to the action of amylases. Cooling after cooking is a key step in the formation of RS3. The intensity of retrogradation depends on several factors: the ratio of amylose to amylopectin, water content, temperature, storage duration, and the number of heating and cooling cycles. High-amylose starches are usually easier to form stable retrograded structures.

In addition to traditional cooling, the formation of resistant starch is influenced by other technological processes. Hydrothermal treatment, autoclaving with subsequent cooling, annealing, and treatment with limited humidity can change the degree of crystallinity, the ability of granules to swell, and the rate of enzymatic hydrolysis. A number of studies have shown that the optimal combination of heating with controlled cooling and humidity makes it possible to purposefully increase the content of resistant starch (RS3). At the same time, excessive heat treatment without subsequent retrogradation, on the contrary, can reduce the proportion of stable fractions [1].

The formation of resistant starch in food depends on several factors: type of feedstock, amylose and amylopectin ratios, water content, heating temperatures, cooling duration, and storage conditions. The cooling process of the already prepared product is particularly important for the formation of resistant starch type RS3. It is during cooling that starch retrogrades – the re-ordering of its polymer chains, which makes them less accessible to digestive enzymes. In addition, the severity of this process is influenced by the cooking method, the duration of storage, and reheating. Studies show that cooling rice, bread, and pasta after cooking can increase the content of resistant starch. However, the final effect always depends on a combination of technological conditions and the properties of the product itself.

The most promising products for producing resistant starch are potatoes, rice, pasta, legumes, bread, and whole-grain products (Table 2). Their value lies either in the initially stable starch fractions present or in the ability to form retrograded starch after cooking and cooling. Potatoes and rice stand out especially, in which the content of resistant starch changes significantly after cooking and subsequent cooling. Legumes are of interest due to the combination of resistant starch, dietary fiber, and protein. In bakery and grain products, the possibility of forming stable starch structures largely depends on the cooking technology and storage conditions.

Table 2

Products with the greatest potential for the formation of resistant starch

Product Group	Why is it promising	What is important for RS education
Potato	After cooking and cooling, it forms RS3	Cooking, subsequent cooling, gentle heating
Rice	It is sensitive to storage conditions and grade	Low storage temperature, sufficient cooling time, variety selection
Pasta products	May increase RS after cooling	Cooking until cooked, cooling, reheating

Legumes	They contain naturally stable starch fractions	Minimal destruction of the structure, cooking and subsequent cooling
Bread and grain products	RS depends on the baking and storage mode	Duration and temperature of baking, cooling, storage
Green bananas	They are the source of native RS2	Minimal recycling

Source: summarized from open reviews and experimental studies

The metabolic properties of resistant starch are determined by the fact that it does not undergo complete breakdown in the small intestine and is less involved in the rapid increase in blood glucose levels after eating. According to the European Register of Approved Food Claims, replacing regular, digestible starches in the diet with resistant starch can help lower blood glucose levels after meals. Clinical studies and reviews also confirm that resistant starch is able to reduce postprandial glycemic and insulinemic responses, although its effect may vary depending on the type, dose, and composition of food [2].

Fermentation of resistant starch in the colon is also important. In modern reviews, this type of starch is described as an energy source for the intestinal microflora, which is processed to produce short-chain fatty acids such as acetate, propionate, and butyrate. These acids, according to scientists, contribute to maintaining the integrity of the intestinal barrier, changing the composition of the microflora, and possibly improving insulin sensitivity. However, it is worth noting that the body's reaction to resistant starch can be different and depends on the initial composition of the microflora and the duration of exposure.

A meta-analysis of clinical studies has revealed that the use of resistant starch leads to improved blood glucose control. This is manifested in a decrease in fasting glucose and fasting insulin levels, as well as a decrease in insulin resistance and increased insulin sensitivity, especially in people with impaired carbohydrate metabolism and overweight. However, it is worth noting that these effects are not universal for all forms of resistant starch and all population groups.

Therefore, it should be considered more as a useful component of the diet, rather than as an independent remedy [4].

The practical application of resistant starch is that it can be used both in cooking and as an ingredient for fortifying finished products. According to reviews on food technology, resistant starch is actively used in the production of bread, pasta, breakfast cereals, snacks and other popular products as an ingredient that increases the fiber content and slows down the rate of glucose release during digestion. Its inclusion in the composition of everyday foods is particularly attractive, which makes it possible to correct the carbohydrate profile of the diet.

An important practical direction is the partial replacement of ordinary flour or digestible starch with resistant starch without significant deterioration in the consumer properties of the product. In a published study conducted on people with type 2 diabetes, it was found that partially replacing food starch with resistant starch reduces postprandial glucose levels and reduces fluctuations in glucose levels after meals. At the same time, there was no noticeable deterioration in the taste of the products. This indicates that resistant starch can be not only a theoretically useful component, but also a practical tool for developing functional products that do not impair their consumer qualities.

In the field of applied nutrition, resistant starch is considered as an effective way to increase the amount of fermentable carbohydrates in the diet without causing a sharp increase in blood glucose levels after eating. However, as noted in scientific reviews, the practical result of using resistant starch depends on its type, dose, method of processing the product and individual tolerance. Therefore, its use is most appropriate in the composition of ordinary dishes and products, where it is possible to achieve a combination of stability of technology, pleasant taste and potential benefits for metabolism.

The main directions of application of resistant starch in the applied field are presented in Table 3.

Table 3

The main applications of resistant starch

Direction	Practical purpose	Confirmed effect
Enrichment of bakery products	Increased fiber content and reduced starch digestibility	In the reviews, it was noted that the glycemic index is decreasing, which means that RS can be added to the bread recipe
Partial replacement of ordinary starch in finished products	Reduction of postprandial glycemia without a drastic change in taste	A clinical study revealed a decrease in glucose levels after meals and a decrease in its fluctuations
Use in functional products	Support for metabolic health and intestinal microbiota	The reviews describe the potential effects that can be achieved through fermentation and the formation of short-chain fatty acids

Source: the data are summarized from open publications

One of the main difficulties in the study of resistant starch is the difference in the results obtained. Scientific reviews emphasize that its effect depends on several factors: the type of resistant starch, dosage, duration of use, product composition, and initial condition of the participants. Because of this, it is not always possible to directly compare data from different studies.

Another important limitation is the lack of a single methodology for all studies. The content of resistant starch in the same product can vary significantly depending on the grade of raw materials, the method of preparation, the conditions of cooling, storage and reheating. This makes it difficult to standardize the results and apply them in nutrition practice.

The prospects for further research include conducting more extensive and standardized clinical work. Special attention will be paid to the study of various types of resistant starch and the assessment of its effects in the composition of everyday foods. It is also necessary to investigate individual reactions to resistant starch, including the role of the intestinal microbiota and metabolic features.

Conclusions. Thus, resistant starch is an important element of the modern diet, which combines the properties of carbohydrates and the beneficial qualities of dietary fiber. Its formation depends not only on the type of feedstock, but also on the conditions of preparation, cooling, storage and reheating of products. Particularly noteworthy is the formation of resistant starch type RS3, which occurs during retrogradation after heat treatment. Studies have shown that foods containing resistant starch can help lower blood glucose levels after meals and have a positive effect on the body's metabolism. However, the degree of these effects depends on the type of resistant starch, the conditions of its formation and the individual characteristics of a person. Resistant starch opens up new horizons for scientific research and is a promising tool for optimizing nutrition.

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