Functional profile of apple fiber from processed raw material of snack production

Lyudmila Donchenko[11], *Mariya* Lukyanenko[1], *Natalia* Limareva[2], *Elena* Chebotareva[1], *Ekaterina* Grushina[1], and *Ekaterina* Podpletennaya[1]

[1] Kuban State Agrarian University, Kalinina str., 13, 350044, Krasnodar, Russia
[2] North Caucasus Federal University, Pushkin str., 1, 355017, Stavropol, Russia

Abstract. The rise in socially significant diseases is associated with damage to cellular structures due to exposure to free oxygen radicals, alien substances, and nutrient deficiencies typical in developed countries. In this context, studying secondary apple waste generated during the production of apple snacks is particularly important. In this study, apple waste generated during the production of fruit chips at an existing facility was chosen as the object of research. The calcium pectate method was used to study the composition and fractional distribution of pectins. The mass fraction of crude fiber was determined using the Hennesberg and Stoman method, and the polyphenolic compounds were determined using high-performance liquid chromatography (HPLC). Total antioxidant activity was assessed spectrophotometrically, and the water absorption capacity of the fiber was determined using a total immersion method. This comprehensive study revealed that the total dietary fiber content of the secondary apple raw material samples was 50.7 ± 0.2% of dry matter, of which 15.8 ± 0.1% was soluble. The concentration of polyphenolic compounds reached 270.5 ± 0.1 mg/100 g of dry matter, indicating a high content of antioxidant components. The antioxidant activity of the sample reached 318.4 ± 0.2 mg/100 g, equivalent to 55.6% free radical inhibition. The water absorption capacity of apple fiber was 4.51 ± 0.01 g of water per 1 g of dry matter, demonstrating its significant functionality in hydration and stabilization of food systems.

1 Introduction

The deteriorating environmental situation, and the overall state of the planet's ecology, is becoming an increasingly significant cause of a wide range of diseases in the modern world. Cancer, environmental disorders, and allergic reactions are steadily increasing, as documented in international reports.

The International Agency for Research on Cancer (IARC) analyzed cancer trends for the period 2012-2022. According to the data obtained, the number of cancer cases worldwide increased by 50%—a statistically significant and alarming figure. Along with the increase in new cases, the cancer mortality rate increased to 18%, demonstrating the

[1] Corresponding author: niibiotechn@mail.ru

disease's high fatality rate. One forecast predicts that by 2050, the incidence of cancer could increase to 77%.

Furthermore, over the past thirty years, the incidence of allergic diseases has risen rapidly worldwide. According to the World Health Organization, epidemiological studies show significant variations in the prevalence of allergic diseases across different regions of the world, ranging from 15 to 35%—they now rank third in frequency after cardiovascular diseases and cancer. However, in the context of increasing environmental pressure, allergic diseases may attain the highest prevalence rank in certain global regions, emphasizing their public health significance and requiring a comprehensive approach to diagnosis, treatment, and prevention.

Such projections outline the critical necessity for immediate international and national efforts to develop and implement effective prevention strategies for these diseases.

The potential of functional foods, including probiotics and prebiotics, has been considered as one of the primary avenues for such prevention in recent decades. Their use is based on their ability to modulate the intestinal microbiota and enhance the body's immune response, making them a promising avenue for developing innovative strategies to combat socially significant diseases [1-3].

Apple raw materials are the most readily available industrial source for the production of functional foods and dietary supplements with prebiotic properties [4].

Apple raw materials are characterized by a relatively high content of dietary fiber. Functional foods enriched with dietary fiber help lower the glycemic index of food consumed and stimulate the growth of beneficial intestinal microflora, improving microbiome balance and boosting immunity. They also help slow the rate of nutrient absorption, which helps maintain stable energy levels and prevent sharp fluctuations in blood sugar [5].

Dietary fiber (DF) is divided into soluble (SDF) and insoluble (ISF) depending on its ability to dissolve in water [5].

The prebiotic properties of pectin and its derivatives have been thoroughly researched in a number of studies [5, 6]. In particular, pectin substances have exhibited immunomodulatory and antibacterial activity, inhibited the proliferation of breast cancer cells, and demonstrated antitumor effects.

Pectin and its derivatives have a positive effect on the gastrointestinal tract. They help lower cholesterol levels, slow glucose absorption, delay gastric emptying, and stimulate the growth of beneficial bacteria, acting as next-generation prebiotics [7, 8].

It should be emphasized that SDF has a number of important functional and technological properties. It is hydratable, meaning it expands in volume and retains water. Due to the presence of hydroxyl and carboxyl groups in its molecules, it can form viscous solutions or gels.

Based on research conducted by a number of scientists, the ratio of soluble dietary fiber (SDF) to insoluble dietary fiber (IDF) should be considered when organizing a healthy diet. A 1:2 SDF to IDF ratio is considered optimal. However, an alternative hypothesis exists, which states that the key role in the functional effectiveness of food products is played not so much by the ratio of SDF to IDF, but by their water absorption capacity. Research has shown that apple pomace exhibits high water-holding and water-swelling properties [9]. These properties are due to the presence of polysaccharides such as pectin and hemicellulose, which have a high capacity for water absorption and retention [10].

The nutritional value of apple raw materials is also determined by the high content of polyphenolic compounds, which are characterized by pronounced antioxidant properties [11]. In particular, highly methoxylated pectins exhibit high efficiency in the absorption of quercetin, which significantly enhances the antioxidant activity of food products [12].

These results confirm the important role of apple raw materials in improving nutritional quality and maintaining the body's antioxidant status.

Processed apple raw material in the form of pomace, generated during juice production, is further utilized as a source for pectin manufacture and, to a lesser extent, for dietary fiber production.Complex biochemical transformations of processed apple raw materials occur during the preliminary drying of pomace used for pectin production, as well as throughout the fermentation of apples utilized for juice extraction. Despite their importance for optimizing production processes, these technological stages result in reduced nutritional value of the raw material and, consequently, higher production cost of the finished product.

During this study we examined secondary raw material resources generated by apple chips production, with particular focus on their potential for minimizing the environmental impact of industrial technologies. It should be noted that the processing of apples for snack production involves coring and peeling of the fruit. Mechanical of apple coring and peeling constitutes a standard procedure at most processing enterprises employing specialized machinery and equipment. This processing results in substantial waste generation, accounting for approximately 30-35% of the fruit's initial mass. These wastes include the peel with its adjacent parenchyma layer, as well as seeds and placental tissue.

According to the 2024 analytical report by Verified Market Reports, the global market volume for fruit crisp chips amounts to USD 1.2 bln. According to 2025-2030 forecast, the annual average growth rate of this market segment will reach 6.5%. These figures indicate significant potential for further market expansion that is driven by ever-growing demand for healthy and convenient food products.

One of the fundamental factors determining development trends in the crispy fruit chips market is the sustained growth in demand for functional snacks. Against the backdrop of growing consumer awareness of the importance of balanced nutrition, there is observed an increased interest in products that are featured not only for appealing organoleptic characteristics but also high nutritional value.As an alternative to traditional snacks, fruit chips constitute an innovative solution that effectively satisfies these requirements and meets present healthy lifestyle trends [13].

Another factor influencing market dynamics is the diversification of manufacturers' product lines – modern manufacturers are widely using strategies to expand their range of flavors, offering new products to consumers, and unique packaging solutions, capturing an ever-wider spectrum of target audiences and flexibly adapting to market demands, which contributes to competitiveness and market share expansion.

In light of the above, it seems appropriate and justified to expand the range and increase the production volumes of prebiotic products based on secondary apple raw materials. Particular attention should be paid to secondary raw materials generated during the production of apple crisps. It is a natural raw material that has not undergone significant technological transformations, which makes it particularly promising for the development of innovative prebiotic products.

2 Materials and methods

This study focused on apple by-products generated during chip production at an existing industrial partner facility. The apple varieties studied were those received for processing and grown in the Krasnodar Region of southern Russia: Valentin, Golden Grimes, Grieve Rouge, Golden Winter Parmen, Reinette Lambergsky, and Geneva Early Blaze.

Valentin apple variety. The fruit ripens in the fall. Fruit composition: dry matter – 16.2%, total sugars – 10.9%, titratable acids – 0.57% (fresh weight), ascorbic acid – 9.7 mg/100 g, P-active substances (catechins) – 89 mg/100 g, flavonols – 17 mg/100 g, total phenolic compounds – 450 mg/100 g.

Golden Grimes apple variety. Winter-ripening fruit. Fruit composition: dry matter – 17.3%, sugars – 11.9%, titratable acids – 0.4%, ascorbic acid – 8.7 mg/100 g, P-active substances – 110 mg/100 g.

Grive Rouge apple variety. Autumn-ripening fruit. Fruit composition: dry matter – 15.9%, total sugars – 11.2%, titratable acids – 0.6%, ascorbic acid – 11.2 mg/100 g, P-active substances (catechins) – 81 mg/100 g, flavonols – 15 mg/100 g, total phenolic compounds – 432 mg/100 g.

Parmen Winter Gold apple variety. Fruit ripens in autumn. Chemical composition of the fruit: dry matter – 16.2%, total sugars – 10.9%, titratable acids – 0.57% of fresh weight, ascorbic acid – 9.7 mg/100 g, P-active substances (catechins) – 89 mg/100 g, flavonols – 17 mg/100 g, total phenolic compounds – 450 mg/100 g.

Reinette Lamberg apple variety:. Fruit ripens in autumn. Fruit composition: dry matter – 16.7%, total sugars – 10.6%, titratable acids – 0.54% (fresh weight), ascorbic acid – 8.7 mg/100 g, P-active substances (catechins) – 79 mg/100 g, flavonols – 22 mg/100 g, total phenolic compounds – 650 mg/100 g.

Geneva Early Blaze apple variety. Winter ripening fruit. The chemical composition of the fruit: dry matter – 12.8%, total sugars – 8.9%, titratable acids – 0.53% of fresh weight, ascorbic acid – 8.7 mg/100 g, P-active substances (catechins) – 69 mg/100 g, flavonols – 15 mg/100 g, total phenolic compounds – 430 mg/100 g.

The method for quantitatively determining pectin substances in plant materials is based on extracting pectin from plant materials and converting it into a dissolved state. The study of hydrate pectin and protopectin extracts is based on the calcium pectate method and ethyl alcohol deposition. In addition, the content of carboxyl groups (free and esterified), methoxyl and acetyl groups in the pectin preparations, as well as the degree of esterification, were studied using a conductometric method.

The Hennesberg and Stoman method was used to determine the crude fiber content of the samples. This standard method involves acid and alkali treatment of the product sample. This treatment is followed by washing, drying, weighing the insoluble residue, and determination of mass loss during calcination.

Polyphenolic compounds were determined by high-performance liquid chromatography. Data processing was performed using LCSolution software (Shimadzu, Japan). A Zorbax SB C18 column (55 μm, 150 x 2.1 mm, Agilent, USA) and a Zorbax SB C8 guard column (5 μm, 20 x 2.1 mm, Agilent, USA) were used. The mobile phase consisted of eluent A (acetonitrile) and eluent B (0.04 M KH2PO4, acidified with H3PO4 to pH 2.8). Gradient elution mode: 0-3 min 3% eluent A, 3-4 min 3-5% A, 4-8 min 5% A, 8-15 min 5-20% A, 15-18 min 20% A, 18-25 min 20-40% A, 25-28 min 40% A. Column thermostatting was maintained at 40°C. Mobile phase flow rate was 0.25 ml/min. Sample volume was 1 μl.

The water absorption capacity of plant fiber was determined by the total immersion method: the sample was completely immersed in water, and the dry and saturated masses were measured.

To assess the effect of the resulting product on the proliferation of probiotic microorganisms, a prebiotic index was calculated. The reference probiotic strain line Lactobacillus rhamnosus GG was used in the study. This allowed for a quantitative in vitro study of the prebiotic effect. The prebiotic index is the ratio between the biomass growth of a probiotic strain in a medium containing a prebiotic and the growth in a medium without it. Glucose was used as a control substrate. A prebiotic index value greater than one indicates a stimulating effect of the prebiotic on microbial growth. A value close to one indicates low prebiotic activity of the product being tested.

3 Results and discussion

The first stage of the research examined the pectin content and fractional composition of secondary raw materials generated during the processing of various apple varieties grown in southern Russia into snacks. The results are shown in Figure 1.

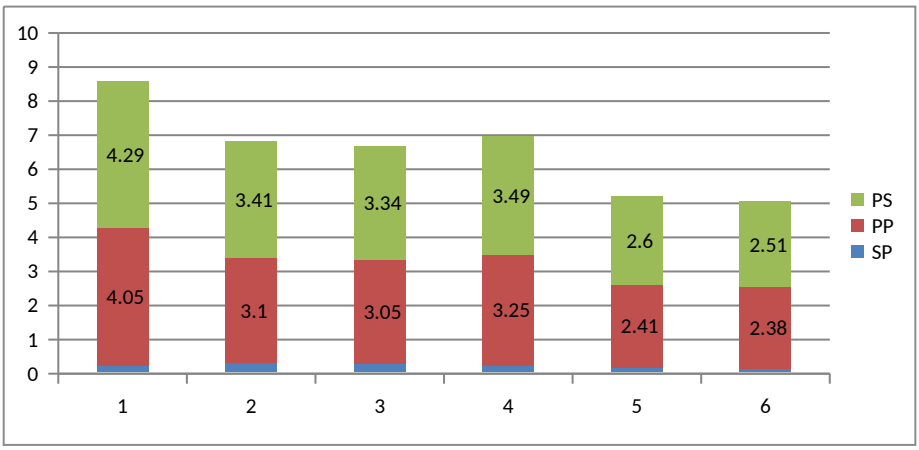

Fig. 1. Content and fractional composition of pectin substances of secondary raw materials formed during the processing of various varieties of apples in the production of snacks, %: 1 – Valentine, 2 – Golden Grimes, 3 – Grive Rouge, 4 – Winter golden Parmen, 5 – Reinet Lambergsky, 6 – Geneva Early blaze.

A study of pectin content in various apple varieties revealed the influence of variety on this parameter. Specifically, the soluble pectin fraction (SP) ranged from 0.16% in the Geneva Early Blaze variety to 0.31% in the Golden Grimes variety. The insoluble pectin fraction (PP) also had a wide range: from 2.38% in the Geneva Early Blaze variety to 4.05% in the Valentin variety. Based on total pectin content (PS), all the studied apple varieties could be divided into three groups. Group 1 includes the Valentin variety featured high content of pectic compounds. Group 2 comprises the Golden Grimes, Grive Rouge, and Winter Gold Parmen varieties with medium pectin substance content. Group 3 is represented by the Renet Lamberg and Early Blaze varieties, that are characterized by relatively low levels of pectic compounds. To determine the functional properties of secondary apple raw materials, it was found that the crude fiber concentration varied between 10.5 and 11.0% of the original material weight, which served as the basis for planning further research into producing a dry product with a high dietary fiber content.

This study aimed to develop a target product with pronounced detoxifying and radioprotective properties characteristic of pectin substances with a high content of free carboxyl groups. To achieve this goal, secondary apple raw materials were subjected to acid-heat treatment: with a 0.1% citric acid solution at a temperature of 70-75°C for 2 hours. After the process, the mixture was dried in a vacuum pulse dryer at a temperature of 35-40°C to a moisture content of 10%.

This processing method allowed for an increase in the content of soluble pectins (SP) in the final product (Table 1).

Table 1. Quantitative and qualitative characteristics of pectin substances in the studied secondary apple raw materials

Indicator	Value
Moisture content, %	10.2 ±0.1
The content of soluble pectin (SP), %	13.7 ±0.4
Protopectin content (PP), %	2.1 ±0.3
Total content of pectin substances (PS), %	15.8 ±0.1
The content of free carboxyl groups, %	3.0 ±0.1
The content of esterified carboxyl groups, %	10.9 ±0.1
Total content of carboxyl groups, %	13.9 ±0.1
Degree of esterification, %	62.0 ±0.2
Polyuronide component, %	57.7 ±0.3
The methoxyl component, %	7.5 ±0.1
The acetyl component, %	0.3 ±0.1
Complexing ability, mg $Pв^{2+}$/ g of pectin	220 ±0.3

Analysis of the provided data revealed a significant increase in the level of soluble pectin compounds (SP) from 1.9–2.0% to 13.7%, indicating the high efficiency of the developed method.

The quantitative content of esterified and free carboxyl groups in pectin substances directly correlates with their degree of esterification and complexing capacity. The studies demonstrated that pectin substances have a high affinity for binding toxic metals, suggesting the pronounced detoxifying activity of the resulting dried apple powder.

It should be particularly emphasized that the complex formation process is influenced by the degree of esterification, which, in turn, determines the linear stability of the macromolecular charge. Furthermore, the type and binding kinetics of cations also play a crucial role in this process. The degree of esterification, 62%, convincingly confirms our hypothesis regarding the achieved effect, demonstrating the validity of our theoretical assumptions and experimental observations.

The next stage of our research was to examine the nutrient profile of dry powder from recycled apple raw materials.

The results of the study are presented in Figure 2.

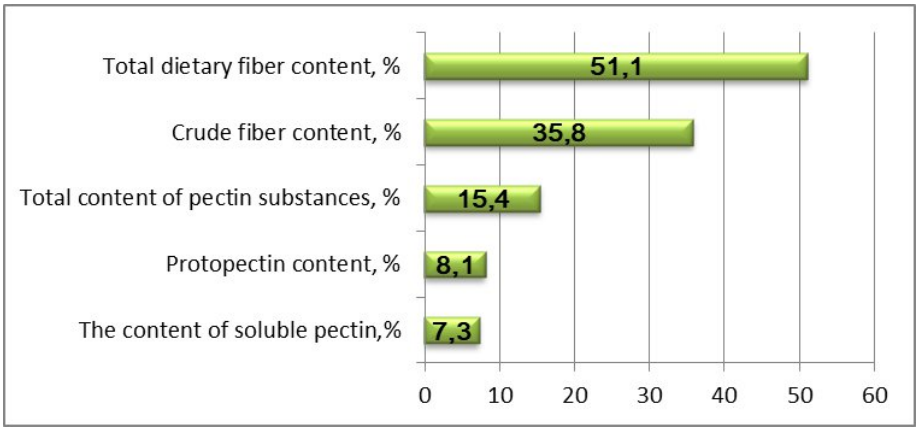

Fig.2. Nutritional profile of the obtained apple fiber by dietary fiber

The presented data show that the powder obtained from the industrial partner's apple by-products contains 51.1% dietary fiber, including 15.4% soluble fiber. These results allow us to consider the resulting product as apple fiber.

Table 2 presents the results of the study of the nutritional and technological potential of the obtained product.

Table 2. Food and technological potential of a dry food product from recycled apple raw materials.

Indicator	Value
Crude fiber content, %	35.8 ±0.2
The content of polyphenolic compounds, мг/100 г	270.5 ±0.3
Water absorption capacity, g per 1 g dry matter	4.5 ±0.5

According to the table, the crude fiber content of this product is 35.8%. This means that the total dietary fiber content is 51.1% on a dry matter basis, of which 15.4% is soluble fiber. As a result, the soluble dietary fiber (SDF) to insoluble fiber (IDF) ratio is 1:3. This aligns with current nutritional recommendations, that refer to the trend toward increased consumption of refined products and decreased intake of fresh vegetables and fruits.

The water absorption characteristics of the studied material demonstrate a high degree of comparability with similar parameters of microcrystalline cellulose (MCC), which is widely used in medical meals and dietary nutrition. MCC, possessing a water absorption capacity within the range of 4–10 g/g, effectively optimizes gastrointestinal tract functions, as confirmed by numerous scientific studies.

This fiber demonstrates antioxidant activity due to available polyphenolic compounds - potent natural antioxidants that neutralize free radicals and prevent oxidative stress. This mechanism is critically important for homeostasis maintenance and various chronic diseases prevention.

The combination of water absorption properties and antioxidant activity renders the studied material promising for its application in therapeutic, preventive, and dietary practices.

Apple fiber's prebiotic capacity is a key property alongside its dietary fiber and polyphenol content as it is demonstrated in Figure 3.

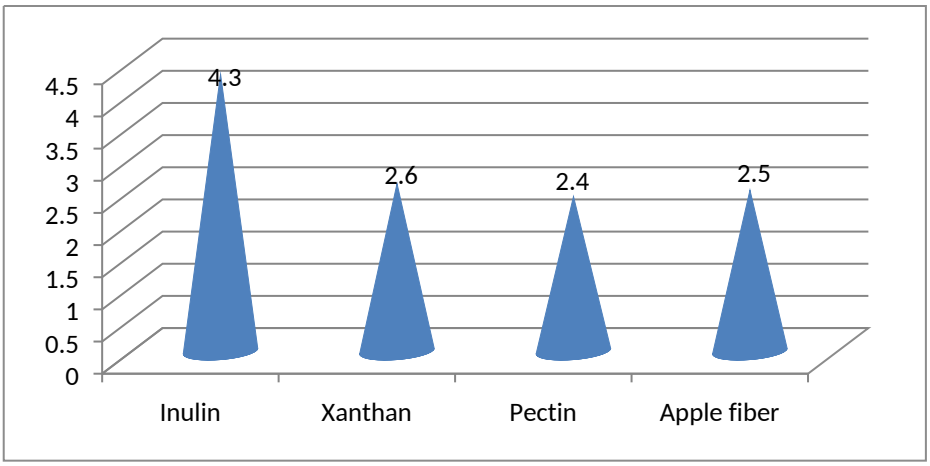

Fig.3. Comparative prebiotic index of hydrocolloids and apple fiber

The data show that the prebiotic index of apple fiber reaches 2.7. This value exceeds the 1.0 threshold, indicating its high capacity to stimulate the proliferation and metabolic activity of beneficial intestinal microflora. The prebiotic index of apple fiber is comparable to that of hydrocolloids but lower than inulin referred to as the benchmark. This property makes apple fiber a promising component for functional food supplements and food products designed to modulate the microbiome and enhance digestive function.

4 Conclusion

The processing of secondary apple raw materials yielded a product with a high concentration of dietary fiber, containing both water-insoluble (35.8%) and water-soluble (15.4%) fractions. Particular attention should be paid to the content of free carboxyl groups in the soluble dietary fiber, primarily represented by pectins, which determines their high ability to complex with toxic cations. The polyuronide component, a biochemical marker of soluble dietary fiber (SDF), enhances the water absorption capacity of apple fiber, demonstrating its pronounced functional properties and potential for use in various food industries.

The polypotent properties of apple fiber are a result of the synergy between polyphenols and pectins. This effect helps modulate inflammatory processes, trigger immune responses, inhibit excessive lipid oxidation, and inhibit malignant cell proliferation. Apple fiber also influences the expression of genes responsible for xenobiotic metabolism. These properties are due to its high polyphenol content (270.5 mg/100 g).

The prebiotic index of fiber (2.7) indicates that it can help stimulate the growth and activity of beneficial intestinal microflora, which allows apple fiber to be considered as a promising component in the creation of functional food supplements aimed at improving microbiota.

Thus, apple fiber obtained from secondary raw materials generated during the production of apple snacks is a promising functional product with polypotent properties, making it a promising target for further research and practical application in the food industry.

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