Creation of new polymer composite bioplastics to produce disposable tableware based on starch

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Abstract. The article discusses the creation of new polymer-starch compositions based on starch extracted from nongraded wheat grains, hydrolyzed sugar beet pulp and polyethylene glycol. The main points of agricultural waste disposal are discussed with the aim of obtaining products with new properties, safe for the environment and biodegradable. Prototypes have a uniform distribution of particles in the matrix, provide enough tensile strength and elongation under tension. A study on the selection of the mass ratio of the components revealed the optimal concentration of the components. The temperature of exposure to the composition to obtain biodegradable material is 105 °C. It was shown that the tensile strength of samples of the polymer composition decreases with an increase in the rotational speed of the screw to 150 min⁻¹ and a temperature above 130°C. Speed below 110 min⁻¹ lead to an increase in strength. The obtained experimental material opens prospects for further research with respect to improving the properties of these biocomposites based on starch and sugar beet pulp by modifying starch and searching for compositions with starch, using reinforcements (both organic and inorganic) and processing conditions.

1. Introduction

Today, there is a shift towards a circular economy in which energy, resource management, production and consumption patterns need to be revised due to the growing population of developed countries, excessive consumption of plastics and their negative impact on the environment. In the context of the global crisis caused by the excessive and indispensable sustainable use of synthetic polymer raw materials, we need to overestimate the production of goods, paying more attention to food packaging, which consumes less energy and continues its life cycle, being biodegradable [1, 2].

Based on the need to rely on stable raw materials, depend less on fossil resources and reduce carbon emissions, biomaterials and bioplastics as substitutes for conventional petroleum-based plastics have become the focus of attention of many materials scientists, architects and industrial designers [3]. In response to environmental problems caused by the dumping of petroleum-based plastics as waste in the oceans, research and development of new biocomposites is underway [4].

Biopolymer-based plastic products have two main advantages: they save fossil resources using renewable biomass and provide an urgently needed carbon neutrality potential. In addition, bioplastics are biodegradable [5].

Thus, this justifies scientific research regarding the improvement of the properties of these starch-based biocomposites by modifying starch and searching for starch compositions, using reinforcements (both organic and inorganic) and processing conditions.
2. Formulation of the problem

The problems of recycling plastics is a serious global environmental hazard. Considering that some plastics (especially thermosetting) are not recyclable, the industry faces additional problems of high energy consumption and difficulties caused by pollution and reinforcing fibers [6]. In 2018, only in the black soil part of Russia 28.9 million tons of plastic waste was generated (11.8% of all 245.7 million tons of household waste) with a very small volume of about 1.7 million tons extracted during disposal for recycling (5.7% of the total volume of plastic waste). Remaining 27.3 million tons (about 16.4% of the total volume of household waste) went to landfills. The category of containers and packaging made up the larger part of the total volume of household waste. This is logical, as these products are mostly disposable. Thus, new developments in the plastics industry are aimed at the search for new renewable materials with properties comparable to their plastics counterparts [7].

Great efforts are being made to create and improve this new generation of “green plastics” using renewable resources as basic materials. In addition, they can significantly reduce environmental impacts than conventional polymers, such as energy consumption and the greenhouse effect [8]. According to Wang, 2017, 0.8-3.2 tons of CO$_2$ per ton of plastic can be saved using starch-based biopolymers [9]. The advantages of starch to produce biopolymers include its biodegradability, renewability, a good oxygen barrier in the dry state, widespread and low cost. In this regard, starch remains a promising source in the production of thermoplastic biodegradable polymers.

3. Materials and methods

Objects of research are new compositions based on starch from substandard wheat grains, sugar beet pulp and polyethylene glycol 1500 M.

Mixed compositions of biodegradable material based on starch of substandard wheat grains and sugar beet pulp powder were obtained on a Brabender mixer at $T = 105 \, ^\circ \text{C}$ for 15 minutes. Test samples pressed at room temperature with a thickness of $200 \pm 10 \, \mu\text{m}$ were kept in a thermostat at $T = 65 \, ^\circ \text{C}$. Compliance of the material with GOST (State All-Union standard) R 57432-2017 “Packaging. Envelopes from biodegradable material. General technical conditions” was obtained by instrumental methods specified in the standard.

When testing biodegradable material, the following indicators were evaluated: vapor permeability, tensile strength, water absorption, density of laboratory samples, biodegradation.

The development of the component composition of hydromodules to obtain biodegradable material was carried out by selecting the ratios of polyethylene glycol 1500 M based on mathematical modeling to the other components [10], the extrusion temperature and the rotational speed of the screw with stirring were set based on the viscosity of the mixture to obtain a sample with desired properties.

4. Results and Discussion

To obtain a thermoplastic mixture, starch and powder of sugar beet pulp were mixed in a container with a mixer with a plasticizer and organic acid in ratios 30/60/10. Additionally, the amount of polyethylene glycol 1500 M (PEG) was selected upon application. The resulting mass was placed in a water bath for polymerization.

Analysis of temperature changes during polymerization revealed that an increase in temperature leads to an improvement in their strength and deformation characteristics. Figure 1 shows the tensile strength of the test samples.

The tensile strength of samples of the polymer composition decreases with an increase in the rotational speed of the screw to $150 \, \text{min}^{-1}$ and a temperature above $1300 \, ^\circ \text{C}$. Speed below $110 \, \text{min}^{-1}$ lead to an increase in strength. The greatest strength was possessed by sample 3, and strengths of 3–7 were stronger than 4 MPa. All of them were obtained at a temperature exceeding $1000 \, ^\circ \text{C}$ and a rotation frequency of not more than $100 \, \text{min}^{-1}$. The concentration of introduced polyethylene glycol at this indicator has the least impact.
Figure 1. The tensile strength of the samples of the polymer composition: 1 – t=100°C, PEG =1,0%, N=80 min \(^{-1}\); 2 – t=105°C, PEG =0,5%, N= 60 min \(^{-1}\); 3 – t=105°C, PEG =1,5%, N= 60 min \(^{-1}\); 4 – t=105°C, PEG =0,5%, N = 100 min \(^{-1}\); 5 – t=105°C, PEG =1,5%, N = 100 min \(^{-1}\); 6 – t=110°C, PEG =0,2%, N = 80 min \(^{-1}\); 7 – t=110°C, PEG =1,0%, N = 80 min \(^{-1}\); 8 – t=110°C, PEG =2,5%, N = 80 min \(^{-1}\); 9 – t=110°C, PEG =1,0%, N = 55 min \(^{-1}\); 10 – t=110°C, PEG =1,0%, N = 104 min \(^{-1}\); 11 – t=115°C, PEG =0,5%, N = 60 min \(^{-1}\); 12 – t=115°C, PEG =1,5%, N = 60 min \(^{-1}\); 13 – t=115°C, PEG =1,5%, N = 100 min \(^{-1}\); 14 – t=115°C, PEG =1,5%, N = 100 min \(^{-1}\); 15 – t=120°C, PEG =1,0%, N = 80 min \(^{-1}\).

Figure 2. Elongation at break of samples of the polymer composition: 1 – t=001°C, PEG =1,0%, N=80 min \(^{-1}\); 2 – t=105°C, PEG =0,5%, N= 60 min \(^{-1}\); 3 – t=105°C, PEG =1,5%, N = 60 min \(^{-1}\); 4 – t=105°C, PEG =0,5%, N = 100 min \(^{-1}\); 5 – t=105°C, PEG =1,5%, N = 100 min \(^{-1}\); 6 – t=110°C, PEG =0,2%, N = 80 min \(^{-1}\); 7 – t=110°C, PEG =1,0%, N = 80 min \(^{-1}\); 8 – t=110°C, PEG =2,5%, N = 80 min \(^{-1}\); 9 – t=110°C, PEG =1,0%, N = 55 min \(^{-1}\); 10 – t=110°C, PEG =1,0%, N = 104 min \(^{-1}\); 11 – t=115°C, PEG =0,5%, N = 60 min \(^{-1}\); 12 – t=115°C, PEG =1,5%, N = 60 min \(^{-1}\); 13 – t=115°C, PEG =1,5%, N = 100 min \(^{-1}\); 14 – t=115°C, PEG =1,5%, N = 100 min \(^{-1}\); 15 – t=120°C, PEG =1,0%, N = 80 min \(^{-1}\).
Figure 2 shows the elongation at break of samples of the polymer composition. Samples 3-5 had a more significant indicator. According to the values of the deformation-strength characteristics, sample 5 was selected, having the ratio in the composition: starch hydromodule, crushed sugar beet pulp and polyethylene glycol 1500 M 50: 50: 1.5; processing temperature of 105 °C and a mixing frequency of the components of 100 min-1.

According to the results of studies of the physicomechanical properties of laboratory sample 5 of biodegradable material from starch of substandard wheat grains in a composition with powdered sugar beet pulp, ultimate strengths were established (Table 1).

The density is 1.17 g/cm³, the tensile strength in the longitudinal direction is 19 MPa, the transverse strength is 15 MPa and the elongation at break is 6%. The material is not suitable for vacuum packaging: vapor permeability was 150 g/m² day, water absorption at room temperature - 22%.

Table 1. Physico-mechanical properties of a biodegradable composite film of granules of thermoplastic starch, sugar beet pulp and polyethylene glycol

| Polymer properties                        | Value   | Unit          | Standard                  |
|------------------------------------------|---------|---------------|----------------------------|
| Density                                  | 1.17    | g/cm³         | ISO 1183                   |
| Water absorption, 23 °C, absorption.     | 22      | %             | ASTM                       |
| Tensile strength.                        |         |               |                            |
| • in the longitudinal direction          | 19      | MPa (kg/cm²)  | По ГОСТ 14236              |
| • in the transverse direction            | 15      |               |                            |
| Elongation at break                      | 6       | %             |                            |
| Vapor permeability                       | 150     | g/m² day      | По ГОСТ 21472              |

The obtained laboratory sample of biodegradable material from starch of substandard wheat grains in a composition with powdered sugar beet pulp has properties for forming disposable tableware and shipping containers and rigid packaging.

Sample 5 of biodegradable material obtained in laboratory conditions can withstand ambient temperatures up to 600 °C, humidity 75%; contact with alkalis and acids is not permissible during operation of the products (Table 2). Moderate susceptibility to oil and water. The destruction of the material begins when it enters the environment with natural microorganisms.

Table 2. Indicators of resistance to external influences

| Name of indicator                          | Biodegradable material from wheat starch and beet pulp | The value of GOST R 57432—2017 |
|-------------------------------------------|------------------------------------------------------|--------------------------------|
| Temperature, °C                           | 60                                                   | 60                             |
| Humidity, %                               | 75                                                   | Up to 75                       |
| Chemical resistance                       | Do not allow contact with alkalis, acids.             | Moderate susceptibility to oils and water. |
| Biological resistance                     | Contact with natural microorganisms is not allowed   |                                |

In accordance with the technical characteristics, the obtained laboratory sample of the polymer is biodegradable, can withstand elevated temperatures, and is safe in accordance with GOST R 57432—2017 (Table 3).
Table 3. Specifications

| Name of indicator          | Biodegradable material from wheat starch and beet pulp.                                                                 |
|----------------------------|---------------------------------------------------------------------------------------------------------------|
| Softening point            | 60 °C                                                                                                         |
| Processing temperature     | 130-210 °C                                                                                                    |
| Degree of biodegradation   | Fully degrades in the presence of moisture both by aerobic and anaerobic mechanisms in 45 days                  |
| Heat resistance            | 70 °C                                                                                                         |
| Burning behavior           | Burns without soot, the smell of burning paper, ash remains after combustion.                                      |

The degree of decomposition of the biopolymer was determined visually every 5 days when the sample was placed on the soil, with a moisture content of 60% (Figure 3). Within 45 days, complete degradation of the proposed material was observed.

![Figure 3](image-url)

**Figure 3.** Biodegradation stages in the presence of moisture under the influence of a standardized substance with a given microorganism content of Bacillus Subtilis.

For compliance with GOST R 57432-2017, prototypes of the biopolymer do not emit toxic substances into the environment at room temperature and do not have a harmful effect on the human body through direct contact. Samples of biodegradable material are not explosive; when exposed to open flame, they ignite without explosion and burn with a smoky flame to form an ash residue and release non-toxic products.

5. Conclusion
The component composition of the biopolymer based on starch of non-graded wheat grains, hydrolyzed sugar beet pulp and PEG is created. It is biodegradable and designed for the manufacture of disposable tableware and packaging. The temperature of exposure to the composition to obtain a biodegradable material of 105 ° C has been optimized. Parameters providing maximum strength at elongation of 20% are proposed.

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