
PERFORMANCE PROPERTIES AND BIODEGRADATION OF BIOPLASTIC FILM MATERIALS

Krykhovets Oleksandra

DOI <https://doi.org/10.30525/978-9934-26-714-7-25>

INTRODUCTION

Polymer film materials have become virtually indispensable to the modern packaging industry due to their combination of functionality, processability, and cost-effectiveness¹. Along with their undeniable technological advantages, the intensive use of synthetic polymers has led to one of the most pressing environmental problems of our time. According to estimates by international organizations, global plastic production already exceeds 400 million metric tons annually, with the packaging industry remaining the largest consumer of these materials. A distinctive feature of packaging materials is their extremely short “servicelife”: most products are used only once, after which they become waste². As a result, packaging generates the largest stream of plastic waste among all areas of polymer use and is one of the key sources of anthropogenic pressure on the environment.

Despite continuous improvements in sorting and recycling systems, most plastic waste is still not being recycled. Significant amounts of packaging end up in municipal solid waste landfills or directly in the natural environment, where traditional polymers can persist for decades or even centuries. The high chemical stability of polyethylene, polypropylene, polyethylene terephthalate, and other synthetic polymers – which is an advantage during use – becomes one of the main causes of their accumulation in natural ecosystems once their life cycle ends. As a result, plastic waste pollutes soil, surface water, and marine waters, negatively impacts biodiversity, and places an additional burden on waste management systems³.

¹ Geyer R., Jambeck J. R., Law K. L. Production, use, and fate of all plastics ever made. *Science Advances*. 2017. Vol. 3. № 7. Art. e1700782. DOI: 10.1126/sciadv.1700782

² Letcher T. M. *Plastic Waste and Recycling: Environmental Impact, Societal Issues, Prevention, and Solutions*. London : Academic Press, 2020. 686 p. DOI: 10.1016/C2018-0-01939-8

³ Plastic Industry 2026. *ReportLinker*. URL: <https://www.reportlinker.com/market-report/Plastic/6347/Plastic>

The problem of microplastic formation is of particular concern. Under the influence of solar radiation, mechanical abrasion, temperature fluctuations, and other environmental factors, polymeric materials gradually break down into small particles that circulate in natural ecosystems for a long time⁴. Unlike biological decomposition, this type of degradation does not result in the complete mineralization of the polymer but merely leads to its fragmentation. Microplastics accumulate in water bodies, bottom sediments, soils, and living organisms, becoming part of food chains. Recent studies indicate their presence in drinking water, atmospheric air, seafood, and other food products, leading to increased concern about potential risks to human health.

An additional environmental concern is the presence of functional additives in polymer materials that provide the necessary technological properties of the packaging. These include plasticizers, stabilizers, antioxidants, dyes, flame retardants, and other auxiliary components. As polymers age or degrade, some of these substances may migrate into the environment or come into direct contact with food products. That is why modern safety assessments of packaging materials encompass not only an analysis of the polymer matrix but also an investigation of the behavior of functional additives throughout the entire life cycle of the packaging.

The problem of plastic waste is viewed today not only as an environmental issue, but also as an economic and resource-related one. The loss of materials following the single-use of packaging is accompanied by significant expenditures of natural resources, energy, and financial resources invested in the production of polymer products. In this regard, modern environmental policy is increasingly focused on the principles of the circular economy, which aim to minimize waste generation, reuse materials, recycle them, and gradually reduce the use of fossil-based raw materials. The implementation of these principles has become one of the key priorities of the European Green Deal, which aims to reduce the use of virgin polymers and promote the adoption of alternative, environmentally safe materials⁵. Alongside improvements in recycling technologies, one of the most important areas of development in modern materials science is the creation of new biopolymer materials capable of providing the necessary performance characteristics during use and minimizing the negative impact on the environment at the end of a product's life cycle⁶. The use of bioplastics is

⁴ Fredi G., Dorigato A. Recycling of bioplastic waste : A review. *Advanced Industrial and Engineering Polymer Research*. 2021. Vol. 4. № 3. P. 159–177. DOI: 10.1016/j.aiepr.2021.06.006

⁵ The European Green Deal / European Commission. URL: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

⁶ Niaounakis M. Recycling of biopolymers – the patent perspective. *European Polymer Journal*. 2019. Vol. 114. P. 464–475. DOI: 10.1016/j.eurpolymj.2019.02.027

a promising approach, as they combine the potential to reduce dependence on fossil-based raw materials with the potential to minimize the negative impact of packaging waste on the environment. In recent years, biopolymer packaging materials have become one of the most dynamic areas of research in the fields of materials science, food technology, and polymer chemistry, as evidenced by a significant number of review articles published in highly ranked international journals.

At the same time, the term “bioplastic” is often interpreted in different ways. In scientific literature, bioplastics are defined as polymeric materials that meet at least one of two criteria: they are made entirely or partially from renewable biological raw materials, or they are capable of biodegrading under appropriate conditions. Thus, bio-based and biodegradable are not synonymous terms. A material may be synthesized from plant-based raw materials but not decompose in the natural environment, or conversely, be produced from petrochemical raw materials yet completely biodegrade under the action of microorganisms.

According to the current classification, bioplastics are divided into three main groups. The first group includes bio-based and biodegradable polymers, the most common of which are polylactic acid (PLA), polyhydroxyalkanoates (PHA), thermoplastic starch (TPS), cellulose-based materials, and polybutylene succinate (PBS). The second group consists of biodegradable polymers of petrochemical origin, primarily polybutyrate-adipate-terephthalate (PBAT) and polycaprolactone (PCL). The third group includes bio-based but non-biodegradable materials, such as bioPE, bioPET, and bioPP, which help reduce the use of fossil-based raw materials but behave similarly to traditional polyolefins at the end of their useful life. This classification is important for selecting the optimal disposal strategy and assessing the environmental performance of a specific packaging material⁷.

Despite significant progress in the development of biopolymer materials, their share of global plastics production remains relatively small for now. The main factors hindering the large-scale adoption of bioplastics include high production costs, dependence on the cost of biological feedstocks, the difficulty of scaling up certain synthesis technologies, and insufficient mechanical and barrier properties compared to traditional polymer materials. At the same time, most analytical forecasts indicate steady growth in the global bioplastics market, driven by stricter environmental requirements, advances in biosynthesis technologies, and increasing demand for environmentally friendly

⁷ European Bioplastics. Bioplastics: Facts and Figures. URL: https://docs.european-bioplastics.org/publications/EUBP_Facts_and_figures.pdf

packaging. Despite significant progress in the development of biopolymer materials, the key prerequisite for their widespread adoption remains ensuring a set of performance characteristics that are on par with those of traditional polymers. Packaging film must not only meet environmental requirements but also effectively fulfill its primary function – ensuring that product quality is maintained throughout the entire period of transportation, sale, and consumption. That is why modern research on bioplastics is increasingly focused on a comprehensive assessment of the materials' functional properties. Unlike traditional polymers, most bioplastics are characterized by a more complex structural organization and a significantly stronger dependence of their properties on operating conditions. While polyethylene or polypropylene films exhibit relatively stable characteristics across a wide range of temperatures and humidity levels, biopolymer materials can significantly alter their behavior when exposed to moisture, temperature fluctuations, or prolonged contact with food products. It is precisely this characteristic that necessitates a comprehensive study of performance characteristics as early as the material development stage, since the environmental benefits do not compensate for the loss of packaging functionality⁸.

Among the wide range of biopolymer materials, composite systems based on starch have attracted particular attention from researchers in recent years. Combining starch with other polymers, particularly polyvinyl alcohol (PVA), holds promise for the development of environmentally safe film materials, as it allows for the combination of the good performance characteristics of synthetic polymers with the high biodegradability of natural polysaccharides. Recent review studies note that PVA/starch composites are among the most intensively studied materials for food packaging due to the high compatibility of their components, the possibility of structural modification, and a wide range of functional properties⁹.

Polyvinyl alcohol is one of the few synthetic polymers that combine high film-forming ability, water solubility, biocompatibility, and the potential for biodegradation under appropriate conditions. Due to the large number of hydroxyl groups, PVA molecules easily form a dense network of intermolecular hydrogen bonds, which ensures good adhesion between polymer chains and high compatibility with natural polysaccharides, proteins, nanofillers, and functional additives. One of the key advantages of PVA is its high barrier properties against oxygen and other gases under conditions of low relative humidity. For food

⁸ Ashter S. A. Introduction to Bioplastics Engineering. 1st ed. Oxford : William Andrew, 2016. 320 p.

⁹ Chi H., Xu K., Wu X., Chen S. Preparation and characterization of biodegradable heat-seal packaging films based on corn starch and poly(vinyl alcohol). *Journal of Polymers and the Environment*. 2012. Vol. 20. № 3. P. 810–816. DOI: 10.1007/s10924-012-0438-2

packaging, this characteristic is of fundamental importance, since it is precisely oxygen permeation that often determines the rate of fat oxidation, color change, loss of aroma, and a shortened shelf life of products. In addition, polyvinyl alcohol forms transparent, smooth, and uniform films that are highly printable, ensure high-quality application of informational labeling, and meet the modern aesthetic requirements of the packaging industry. As a result, materials based on it are being actively researched not only as traditional packaging films but also as a basis for active and smart packaging.

Along with its numerous advantages, polyvinyl alcohol also has certain limitations, the main one being its high hygroscopicity. That is why current research is primarily focused on improving the moisture resistance of PVA through chemical cross-linking of the polymer matrix, the use of nanofillers, the incorporation of hydrophobic components, or the creation of multicomponent polymer composites. The most effective approach is considered to be the combination of PVA with natural biopolymers, which allows for simultaneously improving the material's performance characteristics and enhancing its environmental friendliness.

The compatibility of PVA and starch is largely due to the ability to form a well-developed system of hydrogen bonds between their molecules. This ensures the formation of a homogeneous polymer matrix, improves mechanical properties, promotes the uniform distribution of plasticizers and functional additives, and creates the conditions for effective modification of the material's properties. Recent reviews emphasize that it is precisely the intermolecular interaction between PVA and starch that is one of the key factors determining the physical and mechanical properties, gas permeability, transparency, and stability of composite films¹⁰.

Another equally important characteristic of composite materials based on PVA and starch is their enhanced biodegradability. Starch is readily utilized by microorganisms as a carbon source, which promotes the gradual breakdown of the polymer matrix and facilitates the subsequent degradation of PVA. At the same time, the rate of this process is determined not only by the ratio of components but also by the degree of polymer crystallinity, the presence of cross-linking agents, film thickness, temperature, humidity, and the composition of microbial communities. Thus, the biodegradation of composite materials is a complex, multifactorial process that requires comprehensive experimental study¹¹.

¹⁰ Mao L., Imam S. H., Gordon S., Cinelli P., Chiellini E. Extruded cornstarch-glycerol-polyvinyl alcohol blends: mechanical properties, morphology, and biodegradability. *Journal of Polymers and the Environment*. 2000. Vol. 8. № 4. P. 205–211. DOI: 10.1023/A:1015201928153

¹¹ Westlake J. R., Tran M. W., Jiang Y., Zhang X., Burrows A. D., Xie M. Biodegradable biopolymers for active packaging: demand, development and directions. *Sustainable Food Technology*. 2023. Vol. 1. № 1. P. 50–72. DOI: 10.1039/D2FB00004K

In light of this, composite films based on polyvinyl alcohol and starch are currently considered one of the most promising platforms for creating a new generation of environmentally safe packaging. At the same time, the effectiveness of their practical application is determined not by individual characteristics, but by a balanced combination of mechanical strength, barrier properties, stability during use, and the ability to undergo controlled biodegradation after the product's end-of-life. That is why a comprehensive study of the performance characteristics and biodegradation of such materials is one of the priority areas of modern materials science and packaging technologies

The aim of this study is to investigate the performance characteristics and biodegradability of bioplastic packaging films, which will allow for an objective assessment of their practical suitability as an alternative to traditional polymeric materials and determine the prospects for their widespread adoption in modern packaging technologies.

1. Materials and Methods

To produce the experimental bioplastic films, polyvinyl alcohol (Polyviol G 04/140) was used as the main film-forming polymer, along with water-soluble corn starch, glycerin (FS 42-2202-84) as a plasticizer, and sodium tetraborate ($\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$, analytical grade) as a cross-linking agent and functional additive. The polymer composition was prepared in an aqueous medium. Polyvinyl alcohol was dissolved in water under continuous stirring while simultaneously heating until the granules were completely dissolved and a homogeneous, transparent solution was formed. Afterward, cornstarch was added to the system and gelatinized at a temperature of 358–363 K until a homogeneous polymer matrix formed. The resulting composition was cooled, and glycerin and sodium tetraborate were added. Glycerin was used to increase the elasticity and reduce the brittleness of the films, while sodium tetraborate provided partial cross-linking of the polymer network through the formation of additional intermolecular bonds between the hydroxyl groups of PVA and starch, which helped stabilize the composition's structure.

The film samples were prepared by solution casting. The polymer composition was evenly applied to a horizontal glass substrate and dried at room temperature until the solvent had completely evaporated.

Before conducting physical and mechanical tests, all samples were conditioned under laboratory conditions to stabilize their moisture content and geometric parameters. Film thickness was determined using an IZV-2 thickness gauge. For each sample, measurements were taken at a minimum of five different points, after which the arithmetic mean of the thickness was calculated. Multi-point thickness measurement allowed for possible heterogeneity in the polymer

composition to be accounted for and increased the reliability of subsequent mechanical and barrier tests.

The mechanical properties of the bioplastic films were determined in accordance with the requirements of DSTU EN ISO 8067:2018¹². Rectangular strips 15 mm wide were cut from each sample to ensure uniform testing conditions. Prior to testing, the samples were conditioned at a temperature of $(23 \pm 2)^\circ\text{C}$ and a relative humidity of $(50 \pm 5)\%$ for at least 48 hours. The tests were conducted on a universal tensile testing machine with an initial distance between the grips of 50 mm. During tensile testing, the maximum tensile load, tensile strength, and relative elongation at break were determined.

The tensile strength σ (MPa) is calculated using the following formula:

$$\sigma = \frac{P}{S},$$

where: σ – tensile strength, MPa;

P – maximum tensile force, N;

S – initial cross-sectional area, mm^2 .

The relative elongation at break (ε , %) was determined using the formula:

$$\varepsilon = \Delta l / l_0,$$

where: $\Delta l = l - l_0$;

l – length of the specimen at the moment of break, mm;

l_0 – initial length of the specimen, mm.

For each composition, at least five samples were analyzed, after which the mean value and standard deviation were determined.

The chemical structure of the bioplastic films was analyzed using Fourier transform infrared (FTIR) spectroscopy. The spectra were recorded on a Spectrum Two FT-IR spectrometer (PerkinElmer, USA) in the wavenumber range of $4000\text{--}400\text{ cm}^{-1}$.

Water absorption was determined in accordance with the requirements of ISO 62:2008¹³. The samples were first dried to a constant mass, then completely immersed in distilled water at a temperature of 293 K. At specified time intervals, the samples were removed, excess water was blotted from the surface with filter paper, and the samples were weighed on an analytical balance. The

¹² DSTU EN ISO 8067:2018. Materialy politmerni porysti elastychni. Metod vyznachennia mitsnosti pid chas rozdyrannia [Flexible cellular polymeric materials – Determination of tear strength (EN ISO 8067:2018, IDT; ISO 8067:2018, IDT)]. Kyiv, 2018.

¹³ International Organization for Standardization (ISO). ISO 62:2008. Plastics – Determination of water absorption. Geneva : ISO, 2008.

study was continued until equilibrium mass was reached or the film lost its integrity.

Water absorption (Wt, %) was determined using the following formula:

$$Wt (\%) = \frac{m_t - m_0}{m_0} \times 100\%,$$

where m_0 is the mass of the sample before the experiment began, and m_t is the mass after soaking in water for a time t . The results obtained were used to evaluate the moisture resistance and stability of the polymer structure. The methodology complies with the requirements of ISO 62 for determining the water absorption of polymeric materials.

The biodegradability of the films was evaluated using the soil burial test¹⁴. Samples measuring 15×100 mm were placed in mesh polymer containers and buried in a soil mixture of chernozem and loam to a depth of approximately 2 cm. Soil moisture was maintained at 40–50%, and the tests were conducted at a temperature of 293 K.

At set time intervals, the samples were removed, cleaned of soil residues, dried to a constant mass, and weighed. The degree of biodegradation was determined based on mass loss:

$$\text{Biodegradation (\%)} = \frac{m_t - m_0}{m_0} \times 100\%,$$

where m_0 is the mass of the sample before the experiment began and m_t is the mass after exposure in the soil.

In addition to changes in mass, morphological changes on the surface, the appearance of cracks, color changes, and loss of mechanical integrity were assessed, which allowed for a comprehensive characterization of the biodegradation process.

2. Results and Discussion

For this study, we selected film materials that are commercially used to manufacture flexible food packaging in retail chains in Ukraine (samples № 1, № 2, and № 3). These bioplastic films are marketed as starch-based biodegradable materials. We produced experimental films containing starch, the water-soluble polymer polyvinyl alcohol, glycerin as a plasticizer, and

¹⁴ International Organization for Standardization (ISO). ISO 20200:2023. Plastics – Determination of the degree of disintegration of plastic materials under simulated composting conditions. Geneva : ISO, 2023.

sodium tetraborate as a functional additive (samples № 4, № 5, № 6), similar to the previous study¹⁵. The experimental films were prepared by casting from a solution. During the drying process, the samples formed with a fairly uniform structure and stable thickness across the entire surface. After the completion of the structure-forming processes and the complete removal of moisture, the films easily separated from the glass substrate, indicating their integrity, sufficient mechanical stability, and suitability for further physicochemical studies. To stabilize the film structure, the samples were held for 7 days at 293 K (sample 4), for 60 min at 393 K (sample 5), and for 1 hour at 423 K (sample 6) (Table 1).

Table 1

Composition and average thickness of films

№ samples	Composition of films samples, % by mass				Stabilisation temperature, K	Film thickness, mm
	Starch	PVA	Glycerole	Na ₂ B ₄ O ₇		
1	–	–		–	293	0,0150
2	–	–		–	293	0,0161
3	–	–		–	293	0,0172
4	10	40	40	10	293	0,0735
5	10	40	40	10	393	0,0661
6	10	40	40	10	4 232	0,0621

The mechanical properties of the resulting film materials were evaluated using a universal tensile testing machine. During the testing, two main parameters were determined: the tensile strength and the elongation of the samples under tension. The results of the tensile strength tests for commercial films and experimental films containing starch, PVA, borax, and glycerin are shown in Fig. 1. The test results indicate that the tensile strength values for commercial film materials differ only slightly from one another. Higher tensile strength values were observed for the experimental films. This is explained by the fact that the experimental samples have greater thickness and, consequently, a larger cross-sectional area, and are therefore capable of withstanding a greater load before failure. Heat treatment of the experimental films increases their tensile strength.

At the same time, tensile strength alone is not always a sufficiently objective indicator of the strength of film materials, since it depends to a large

¹⁵ Krykhovets O., Slobodyanyk V. Preparation and characteristics of films based on polyvinyl alcohol and starch for environmentally friendly packaging. *Advances in Science and Technology*. 2025. Vol. 162. P. 101–108. DOI: 10.4028/p-eR3mdB

extent on the geometric parameters of the sample, primarily its thickness and width. Therefore, the primary characteristic of film strength is considered to be the stress at break, which takes into account the cross-sectional area of the material. This parameter allows for a more accurate assessment of the material's actual strength, regardless of the dimensions of a specific specimen. Tensile stress is defined as the ratio of the tensile load acting on the specimen at the moment of failure to the cross-sectional area of the film. The tensile strength of the biofilms is shown in Fig. 2. For the three types of commercial biofilms, the tensile strength values differ only slightly. The experimental biofilms, stabilized at 393 K and 433 K, are stronger than the thermally untreated ones.

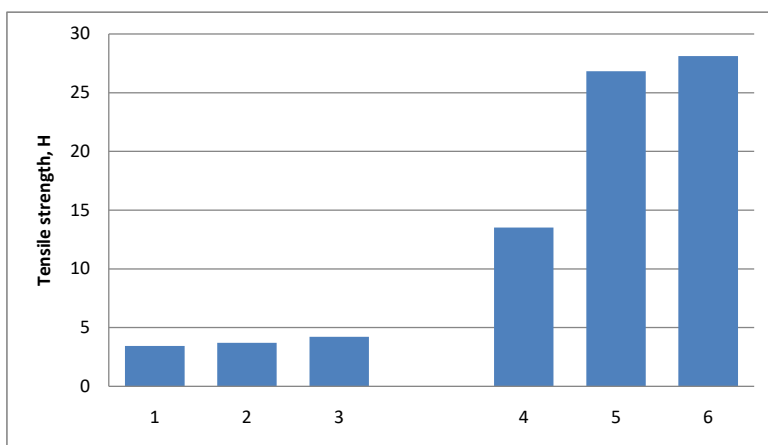


Fig. 1. Tensile strength of bioplastic films: 1, 2, 3 – industrial bioplastic films; 4, 5, 6 – experimental bioplastic films (sample numbers and composition according to Table 1)

The value of relative elongation at break characterizes the ability of a film material to deform under tensile loading until failure and allows for an assessment of the elasticity, flexibility, and deformability of the films under study. Fig. 3 shows the variation in relative elongation at break for the film materials under study. Analysis of the results shows that the trend in this parameter differs from that observed for tensile strength. While the strengthening of the polymer structure was the primary factor affecting tensile stress, the material's ability to retain its elasticity during deformation plays a more significant role in determining relative elongation at break.

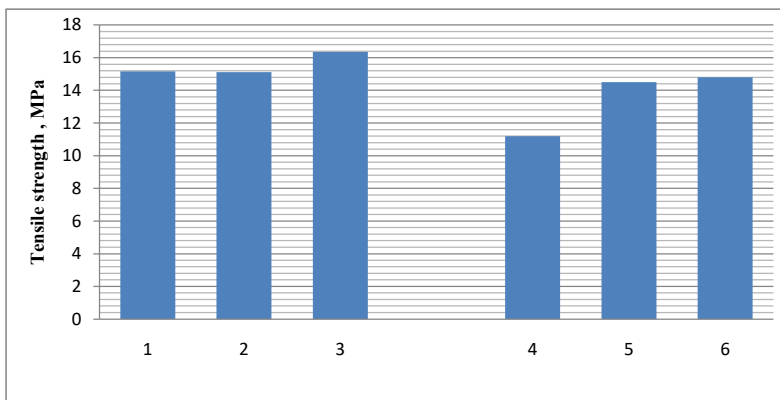


Fig. 2. Tensile strength at break of bioplastic films: 1, 2, 3 – commercial bioplastic films; 4, 5, 6 – experimental bioplastic films

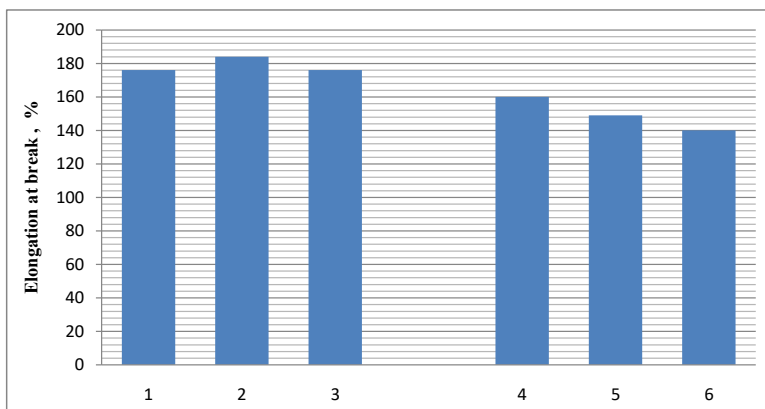


Fig. 3. Variation in relative elongation at break of bioplastic films: 1, 2, 3 – commercial bioplastic films; 4, 5, 6 – experimental bioplastic films

The results of the mechanical tests conducted – specifically, the determination of tensile strength, tensile deformation characteristics, and the calculation of tensile stress at break – demonstrate the potential of experimental film materials based on polyvinyl alcohol, cornstarch, glycerin, and borax for use in the packaging industry. Thanks to their combination of sufficient strength, elasticity, and environmental friendliness, such materials can be considered a potential alternative to traditional polymer packaging films, particularly for

food packaging, as well as for encapsulating or providing a protective coating for fresh fruits and vegetables. Of particular importance is the fact that an increase in tear strength and tensile stress at break was observed for the thermally stabilized films. This indicates improved cross-linking of the polymer matrix.

The spectra of the studied film materials, obtained in the wavenumber range from 400 to 4 000 cm^{-1} , are shown in Figs. 4 and 5. The FTIR spectra of commercial bioplastic films confirm that the films under study are composites based on thermoplastic starch modified with polymer additives (Fig. 4).

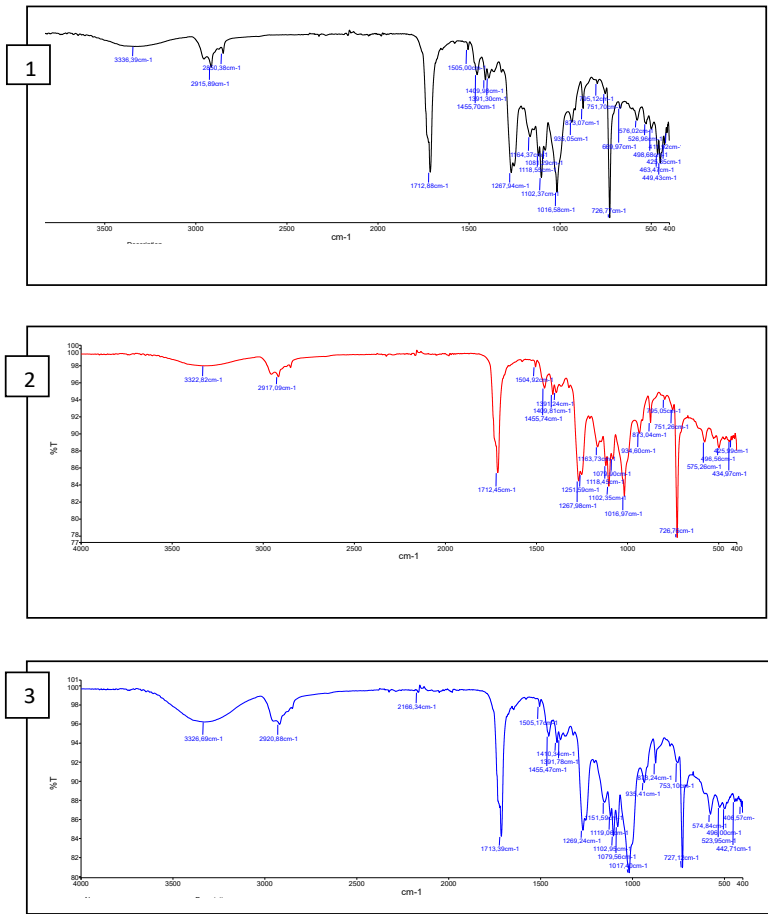


Fig. 4. Spectra of industrial bioplastic films
(1 – Sample № 1; 2 – Sample № 2; 3 – Sample № 3)

The FTIR spectrum of Sample № 2 most closely matches the spectral profile of moderately modified starch. This may indicate that primarily simple plasticizers, such as glycerin or sorbitol, were used to form this material, and that the amount of foreign polymeric components was minimal. The FTIR spectrum of sample № 3 is characterized by the highest intensity of absorption bands in the 1 100–900 cm^{-1} region compared to the other samples studied. This may indicate an increased content of the polysaccharide phase, specifically amylopectin, in the material's structure.

The results of the infrared spectroscopy analysis of the experimental biofilms showed that the main characteristic absorption bands in the spectra of samples 4, 5, and 6 correspond to the spectral features of polyvinyl alcohol and starch. This indicates that PVA remains the main structure-forming component of the studied films. The presence of borax and heat treatment contribute to better cross-linking of the polymer matrix.

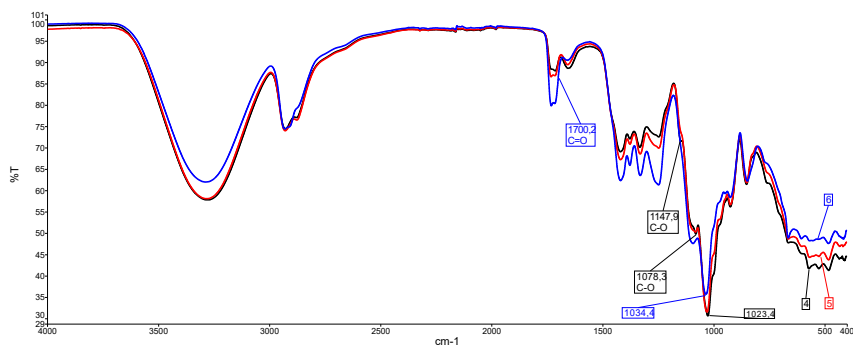


Fig. 5. Spectra of polyvinyl alcohol- and starch-based films (4 000–400 cm^{-1} range)

Studying the disintegration and biodegradation of film materials is an essential step in assessing their environmental suitability and involves the following stages.

1. Characterization of the chemical composition of the bioplastic under study.

According to the results of IR spectroscopy, films № 1, № 2, and № 3 are made from starch. The filler content in these materials is negligible. IR spectroscopy revealed the use of thermoplastic and modified starch for the production of durable packaging materials. The experimental film materials were formulated using polyvinyl alcohol – a water-soluble synthetic polymer that is widely used in various fields, particularly in medicine, and can also be

used as an approved food additive. Due to its water solubility, film-forming ability, and relative safety for living organisms, polyvinyl alcohol was selected as the main component of the polymer matrix. Glycerin, which has no harmful effects on living organisms, was added to the composition as a plasticizer. Starch, a naturally occurring polymer and a renewable resource, was also incorporated into the film materials. Starch is capable of decomposing through enzymatic processes or under composting conditions, which enhances the environmental sustainability of the resulting films. The minerals present in the film materials under study generally do not have a significant harmful effect on living organisms when found in low concentrations.

2. Material Characteristics.

Industrial-grade film materials are uniform in thickness and color. The high physical, chemical, and performance characteristics of these films, combined with the material's thinness, make them an economically viable packaging solution.

The experimental films were characterized by a virtually transparent structure, sufficient softness, elasticity, and uniformity. These properties indicate good compatibility of the main components of the composition and the system's ability to form a uniform film material. In terms of their physicochemical and performance characteristics, the experimental composite film materials – which, in addition to polyvinyl alcohol, contain starch, borax, and glycerin – may hold promise for eco-friendly packaging. These films retain a homogeneous structure, have a uniform thickness across the entire surface, and demonstrate sufficiently high tensile strength and elongation capacity. The combination of a synthetic polymer and a natural polymer component in the composition not only improves the material's properties but also reduces its production cost. In addition, the inclusion of starch enhances the films' environmental appeal, as it increases the proportion of renewable raw materials and potentially promotes the material's biodegradability.

3. Study of swelling and dissolution processes.

In the initial stage of assessing the environmental impact of bioplastic film materials, a study was conducted on their interaction with an aqueous environment. The solubility of the film samples was tested in distilled water at room temperature. This approach allowed for the evaluation of the materials' behavior under standard conditions without the influence of additional impurities, salts, or aggressive chemical agents. The temperature of the aqueous medium during the experiment was 293 K.

Figure 6 presents the results of the experimental study, which show the change in mass of the film materials after immersion in water at room temperature. For film samples № 1, № 2, and № 3, there was virtually no increase in mass during

the first few minutes of full contact with water. Weighing the samples after 1 day, 2 days, and 3 days in water revealed a slight increase in the mass of the films. For samples № 1 and № 2, a 10% increase in mass per day was recorded. Sample № 3 showed virtually no change in mass (a 5% increase).

When fully immersed in water at room temperature, the samples of experimental film materials – composed of PVA, starch, borax, and glycerin – exhibit a pronounced swelling process.

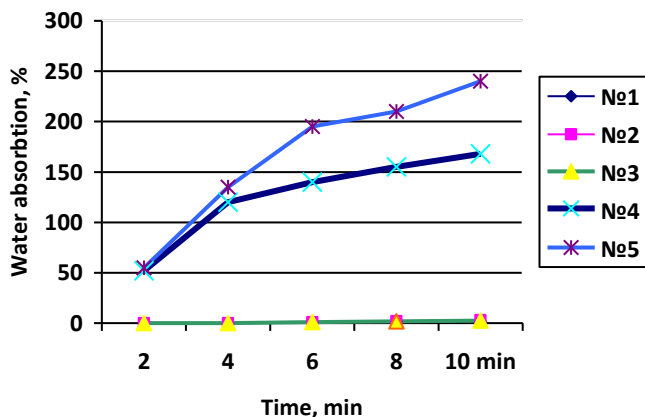


Fig. 6. Dependence of moisture content in films on water absorption time

This is accompanied by a significant increase in the mass of the film material, indicating active water absorption by the polymer matrix and deformation of the film (Fig. 7). This increase in mass indicates a higher ability of these films to adsorb and retain water compared to the other materials studied. This is likely due to the presence of hydrophilic components in the composition, specifically polyvinyl alcohol, starch, and glycerin, which contain functional groups capable of interacting with water molecules.



Fig. 7. Swelling of experimental films № 4 and № 5

4. Biodegradation of polyvinyl alcohol-based films.

To study the biodegradation of film materials, strips of commercial films (Nos. 1, 2, and 3) and experimentally produced films (Nos. 4, 5, and 6) were placed in special bags made of a material designed for polymer composting. The size of the holes in these bags was approximately 2 mm², which ensured contact between the film samples and the soil environment and microorganisms, while also allowing for the retrieval of any remaining material after the experiment was completed.

The bags containing the film samples were then placed in containers filled with a 5–6 cm layer of soil (a mixture of chernozem and clay loam) freshly collected from a suburban plot. The samples were then covered with an additional layer of soil at least 2 cm thick. This arrangement simulated the conditions under which the film material would be present in the soil and ensured its contact with moisture, air, and the soil microbiota. The layout of the samples in the soil is shown in Fig. 8.



Fig. 8. Containers with soil and biofilms

As early as 48 hours after the start of the study, it was found that samples № 1, № 2, and № 3 showed virtually no noticeable deformation. Samples № 4, № 5, and № 6 lost their original shape. This indicates the active onset of swelling, softening, and partial structural degradation of the film material under the influence of moisture and the soil environment. During the first three days in the soil environment, an increase in the mass of the film samples was observed, which was due to moisture absorption. For samples № 1, № 2, and № 3, the increase in mass was up to 10%. For samples № 4, № 5, and № 6, the level of water absorption in the soil reached 200–213% after just one day, and rose to 250–279% after two days.

After 48 hours of the soil burial test, samples № 1, № 2, and № 3 showed virtually no change in appearance. Film materials № 4, № 5, and № 6 underwent noticeable deformation, and their surface also changed (Fig. 9). The appearance

of pores, microcracks, and defects was observed, which increased over time. Such changes indicate a breach in the integrity of the polymer matrix and the development of material disintegration processes.

After two weeks of exposure to the soil environment, the mass of the samples remained unchanged for industrial films, while a decrease in mass was observed for the experimental film materials. During the soil burial test for films containing the synthetic polymer polyvinyl alcohol, the natural polymer cornstarch, borax, and glycerin, an increase in soil microflora activity was observed.

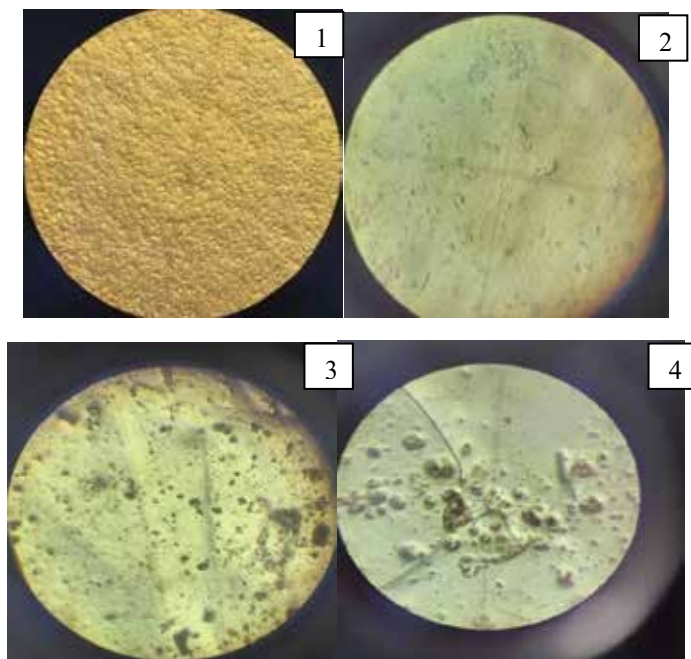


Fig. 9. Changes in the surface structure of films 5 and 6:
1, 2 – before the soil burial test; 3, 4 – 13 days after the soil burial test

It is soil microorganisms that play a key role in the breakdown of the biomaterial's organic matrix and participate in its biodegradation processes. During the experiment, the initially colorless experimental biofilms gradually took on various hues, including gray, greenish, and pink. Such color changes may indicate the formation, development, and spread of microbial colonies on the surface of the film material.

After eight weeks in a moist soil environment, the samples of industrial films underwent partial degradation: they lost their strength, and localized changes were visually observable. However, no disintegration or biodegradation of the starch-based industrial materials occurred during the experiment. According to the results of the eight-week soil burial test, the level of biodegradation of the experimental biofilms under study reached 90%. This indicates the high degradability of the resulting film materials in a soil environment and confirms their potential as environmentally friendly packaging materials.

Since the final stage of the life cycle of packaging materials is their disposal, one of the key tasks of modern materials science is the development of polymer composites capable of controlled biodegradation. The inclusion of biopolymer components in the polymer matrix helps increase the biodegradability of film materials and accelerate their degradation after the end of their service life. In particular, N. N. Nasir and S. A. Othman found that the addition of starch significantly increases the rate of biodegradation of polymer films¹⁶, while M. C. Alvarado demonstrated a similar effect when using nanocellulose as a functional filler¹⁷. Our results are consistent with recent studies of composite films based on starch and polyvinyl alcohol and confirm that biopolymer components not only improve the material's environmental performance but also ensure its effective degradation in the soil environment.

A study by O. Fedoryshyn et al. (2024)¹⁸ of experimental and industrial films based on potato starch revealed increased microbiological activity on the surface of the materials after exposure to soil, indicating their capacity for effective biodegradation. Similar patterns were observed by V. Lebedev et al. (2022)¹⁹, who confirmed that the addition of starch to a polymer composition accelerates the biodegradation of film materials without a significant loss of their functional properties during use.

CONCLUSIONS

Current research on bioplastic films is increasingly focused on a comprehensive assessment of their performance characteristics and end-of-life options to ensure

¹⁶ Nasir N. N., Othman S. A. The physical and mechanical properties of corn-based bioplastic films with different starch and glycerol content. *Journal of Physical Science*. 2021. Vol. 32. № 3. P. 89–101. DOI: 10.21315/jps2021.32.3.7

¹⁷ Alvarado M. C. Recent progress in polyvinyl alcohol (PVA)/nanocellulose composite films for packaging applications : A comprehensive review of the impact on physico-mechanical properties. *Food Bioengineering*. 2024. Vol. 3. № 2. P. 189–209. DOI: 10.1002/fbe2.12086

¹⁸ Fedoryshyn O., Chervetsova V., Yaremkevych O., Skril Y., Khomyak S., Kohut F. A. Physico-chemical and microbiological characterization of starch-based biodegradable films. *Chemistry & Chemical Technology*. 2024. Vol. 18. № 3. P. 417–425. DOI: 10.23939/chcht18.03.417

¹⁹ Lebedev V., Miroshnichenko D., Bilets D., Mysiak V. Investigation of hybrid modification of eco-friendly polymers by humic substances. *Solid State Phenomena*. 2022. Vol. 334. P. 154–161. DOI: 10.4028/p-gv30w7

a high level of functionality without compromising environmental benefits. An investigation of the mechanical properties of industrial packaging films used as flexible food packaging in retail stores, as well as experimental bioplastic films based on starch, polyvinyl alcohol, glycerin, and borax revealed approximately the same tensile strength values for all six bioplastic film samples. Industrial film samples are thinner and therefore their use is resource-efficient. The elongation at break for the films studied ranges from 136% to 184%, indicating sufficient elasticity of the materials.

The experimental films are moisture-sensitive, unlike commercial samples. Stabilizing the experimental film materials at temperatures of 393 K and 423 K helps strengthen the biomaterial.

The results obtained indicate that the use of sodium tetraborate as a cross-linking agent is an effective method for modifying compositions based on polyvinyl alcohol, cornstarch, and glycerin. Such modification enhances the chemical resistance, strength, and operational stability of the film materials without compromising their biodegradability. This paves the way for the application of the developed materials in both the packaging industry and the agricultural sector, where there is a growing need for environmentally safe polymeric materials.

Composite films based on polyvinyl alcohol and starch have significant potential for use in the production of biodegradable packaging materials, providing the necessary level of performance characteristics and enabling more environmentally sound waste management after the end of their useful life.

SUMMARY

The growing accumulation of plastic waste and increasing environmental requirements have intensified the search for sustainable alternatives to conventional petroleum-based packaging materials. Bioplastic film materials based on renewable polymers represent a promising solution because they combine reduced environmental impact with the potential for biodegradation after use. This study investigated composite films prepared from polyvinyl alcohol, corn starch, glycerol, and sodium tetraborate to evaluate their functional performance and biodegradation behaviour. The films were characterized by determining their thickness, tensile properties, water absorption, surface wettability, chemical structure using FTIR spectroscopy, and biodegradability under soil conditions. The incorporation of sodium tetraborate promoted the formation of a more stable polymer network, resulting in improved mechanical strength, enhanced chemical stability, and greater durability during service. At the same time, starch in the polymer matrix accelerated biodegradation while maintaining the functional properties required for packaging applications.

The obtained results demonstrate that optimizing the composition of PVA-starch composites enables a balance between mechanical performance, water resistance, and biodegradability, which is essential for sustainable packaging materials. The developed films exhibit considerable potential for use as environmentally friendly packaging materials and may also be applied in agricultural applications requiring controlled biodegradation.

Bibliography

1. Geyer R., Jambeck J. R., Law K. L. Production, use, and fate of all plastics ever made. *Science Advances*. 2017. Vol. 3. № 7. Art. e1700782. DOI: 10.1126/sciadv.1700782
2. Letcher T. M. Plastic Waste and Recycling: Environmental Impact, Societal Issues, Prevention, and Solutions. London : Academic Press, 2020. 686 p. DOI: 10.1016/C2018-0-01939-8
3. Plastic Industry 2026. *ReportLinker*. URL: <https://www.reportlinker.com/market-report/Plastic/6347/Plastic> (дата звернення: 28.07.2026).
4. Fredi G., Dorigato A. Recycling of bioplastic waste : A review. *Advanced Industrial and Engineering Polymer Research*. 2021. Vol. 4. № 3. P. 159–177. DOI: 10.1016/j.aiepr.2021.06.006
5. The European Green Deal / European Commission. URL: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en (дата звернення: 28.07.2026).
6. Niaounakis M. Recycling of biopolymers – the patent perspective. *European Polymer Journal*. 2019. Vol. 114. P. 464–475. DOI: 10.1016/j.eurpolymj.2019.02.027
7. European Bioplastics. *Bioplastics: Facts and Figures*. URL: https://docs.european-bioplastics.org/publications/EUBP_Facts_and_figures.pdf (дата звернення: 28.07.2026).
8. Ashter S alcohol blends: mechanical properties, morphology, and biodegradability. *Journal of Polymers and the Environment*. 2000. Vol. 8. № 4. P. 205–211. DOI: 10.1023/A:1015201928153
9. Westlake J. R., Tran M. W., Jiang Y., Zhang X., Burrows A. D., Xie M. Biodegradable biopolymers for active packaging: demand, development and directions. *Sustainable Food Technology*. 2023. Vol. 1. № 1. P. 50–72. DOI: 10.1039/D2FB00004K
10. DSTU EN ISO 8067:2018. *Materialy politmerni porysti elastychni. Metod vyznachennia mitsnosti pid chas rozdyrannia* [Flexible cellular polymeric materials – Determination of tear strength (EN ISO 8067:2018, IDT; ISO 8067:2018, IDT)]. Kyiv, 2018.

11. International Organization for Standardization (ISO). ISO 62:2008. *Plastics – Determination of water absorption*. Geneva : ISO, 2008.
12. International Organization for Standardization (ISO). ISO 20200:2023. *Plastics – Determination of the degree of disintegration of plastic materials under simulated composting conditions*. Geneva : ISO, 2023.
13. Krykhovets O., Slobodyanyk V. Preparation and characteristics of films based on polyvinyl alcohol and starch for environmentally friendly packaging. *Advances in Science and Technology*. 2025. Vol. 162. P. 101–108. DOI: 10.4028/p-eR3mdB
14. Nasir N. N., Othman S. A. The physical and mechanical properties of corn-based bioplastic films with different starch and glycerol content. *Journal of Physical Science*. 2021. Vol. 32. № 3. P. 89–101. DOI: 10.21315/jps2021.32.3.7
15. Alvarado M. C. Recent progress in polyvinyl alcohol (PVA)/nanocellulose composite films for packaging applications: A comprehensive review of the impact on physico-mechanical properties. *Food Bioengineering*. 2024. Vol. 3. № 2. P. 189–209. DOI: 10.1002/fbe2.12086
16. Fedoryshyn O., Chervetsova V., Yaremkevych O., Skril Y., Khomyak S., Kohut F. A. Physico-chemical and microbiological characterization of starch-based biodegradable films. *Chemistry & Chemical Technology*. 2024. Vol. 18. № 3. P. 417–425. DOI: 10.23939/chcht18.03.417
17. Lebedev V., Miroshnichenko D., Bilets D., Mysiak V. Investigation of hybrid modification of eco-friendly polymers by humic substances. *Solid State Phenomena*. 2022. Vol. 334. P. 154–161. DOI: 10.4028/p-gv30w7

Information about the author:

Krykhovets Oleksandra,

Candidate of Chemical Sciences,

Associate Professor at the Department of Multimedia Technology

Lviv Polytechnic National University

12, Bandery Street, Lviv, Ukraine