

Article

A Concept of New Generation Films for Haylage Production Which Meets the Condition of the Closed-Loop Material Cycle

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Abstract

The recycling rate of silage and stretch films is low. The low degree of recycling of polymer films used in agriculture results from the high contamination of films and technological problems in their processing. Material recycling of haylage preservation films is conditioned by the possibility of their effective and cost-effective cleaning. Thus, the study focuses on designing a new generation material for wrapping hay-silage bales that meet the closed-loop material cycle condition while at the same time guaranteeing the desired operating conditions. The developed new generation silage films made it possible to achieve 100% recycling, while this indicator for traditional films did not exceed 50%. The concept is based on the notion of circular economy. The study compared four types of film—one that is commonly used for feed preservation and three types of new generation film. The nanosilver-containing film and the film containing a microbiological additive of zinc provided a high quality of silage and, due to the low contamination, facilitated the recycling of the burdensome waste. The 8% microcellulose film had too little viscosity, which was why it did not cut off the atmospheric air penetration into the bale. Hence, the biodegradable film with the addition of microcellulose does not comply with the technological regime for feed preservation.

Keywords: new generation of silage films; agricultural plastic waste; silage films recycling; closed-loop material cycle; circular economy



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1. Introduction

1.1. Polymer Films in Silage Production—The Idea of Closed-Loop Material Cycle

The concept of circular economy (CE) is seen as the operationalization of a widely discussed notion of sustainable development [1,2]. Other trends that also operationalize sustainable development are the concepts of green economy [3] and green growth [4]. The CE concept involves redesigning processes and materials to implement more sustainable economic models. Nature is based on the principles of a closed loop, without wastage. On the other hand, human interference in the environment through economic processes causes nature to overflow with waste, including plastics that are particularly burdensome to nature. The time necessary for nature to deal with the onerous waste can be long, and the results of the process are unexpected and difficult for humanity to accept [5].

The annual polymer film consumption in agriculture is 6.1 MT [6]. It is expected to increase by 5.94% in 2022–2027 [7]. The global consumption of films in silage production—low density polyethylene (LDPE)—in 2021 is estimated at more than 22 million tons, and the projected upward trend in the coming years is 3% per year [8]. The use of different types of films allows food production to be increased without increasing the area of agricultural land. In addition, technologies that make use of films reduce crop losses and prevent wastage. Increasing consumption of films is also a form of response from the agricultural sector to the changing climate, accompanied by increased pest attacks and an increasingly burdensome problem of weed infestation of crops. The use of films is both economically efficient and more efficient than other smart farming technologies.

The trend of increasing consumption of agricultural films will be stimulated by the increasing use of biodegradable films. However, not in all cases does the use of biodegradable film give a positive environmental effect. Using material that can be fully recycled can be more effective. In silage production, this condition is met by a film with nanosilver and a film containing a microbiological additive of zinc. Silage, bacteria, and fungi residues do not stick to these types of film. These films are easy to clean at relatively low cost. The cleaning of polymer waste enables its recycling.

Stretch silage film contaminated with organic residues is expensive to process, and effective recovery of the material is only about 50% of its mass. The authors were guided by the idea of optimizing the management of waste from polymer materials after silaging feeds in cylindrical bales. The aim of the study was to develop an easily cleaned material, allowing for the recycling of the burdensome waste, i.e., used silage film. The paper presents original results of tests that produced an easily recycled film for wrapping bales. Work on novelty materials for feed preservation films refers to the idea of optimizing the use of resources raised by the concept of a circular economy (CE).

The designed study aimed to address specific research gaps related to the lack of low-cost silage films that are widely recyclable while simultaneously meeting the requirements of the technological regime. The specific objectives of the presented study, which also represent its innovative aspects, were as follows:

- To increase the recyclability of used silage films (ideally up to 100%).
- To extend the storage period of haylage by designing a film with high oxygen barrier properties.

1.2. Conceptual Framework

The small amount of impurities on the film and the ease of cleaning are factors that predispose the waste material to recycling instead of disposal in landfills or incineration. Therefore, the main purpose of the study was to evaluate the new generation of stretch films produced with the addition of biocomposites, which are used for the production of haylage in cylindrical bales. The research resulted in three types of new generation film: a film with nanosilver, a film with a microbiological additive based on zinc, and a microcellulose film (to assess biodegradability and reduce the consumption of synthetic polymers).

2. Plastics in Agriculture—A Global Problem

2.1. Use of Plastic Films in Agriculture

The global production of plastics in 2020 is estimated at 367 million tons [9]. The production of plastics in Europe (2019) was approximately 57.9 million tons, and consumption was 50.7 million tons [10]. It is estimated that the agricultural sector accounts for approximately 2% of the annual consumption of global plastic production [11]. In the EU, the share of agriculture in the use of plastic products is almost twice as high (Figure 1).

The issue of plastic waste on a global scale cannot be precisely assessed due to the lack of relevant data.

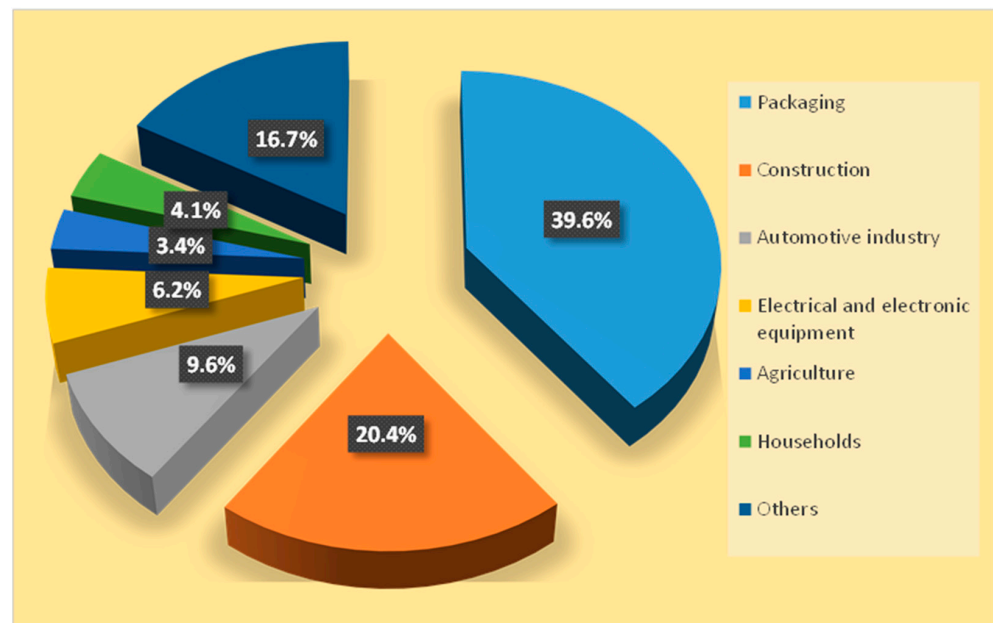


Figure 1. Europe plastics production by type of use in 2019 (Source: Plastic facts & Figures, 2022; <https://www.plasticsoupfoundation.org/en/plastic-facts-and-figures/>, accessed on 22 June 2022).

The most important areas of application of plastic films in agriculture include walk-in tunnels and low tunnel covers, mulching, and greenhouses [12,13]. The use of plastics in plant cultivation has gained the term commonly known as ‘plasticulture’ [14]. According to FAO data, in 2019, the agricultural sector is responsible for the consumption of around 12.5 million tons of plastic products [12]. The largest users are plant and animal production departments (around 10 million tons per year). The relatively high consumption of plastics is also generated by fisheries and aquaculture (around 2.1 million tons). On the other hand, the annual demand of forestry is estimated at around 0.2 million tons. In regional terms, Asia (around 6 million tons per year) is the largest user of plastics in agriculture. In addition, a further 37.3 million tons of polymer materials were food packaging. FAO estimates that global demand for films used for mulching, and films used in greenhouses and in silage production will increase to 9.5 million tons by 2030 as compared to 6.1 million tons in 2018. Estimates from other sources confirm the indicated trends [15].

The growing use of plastics in agriculture is determined by their usefulness, a wide range of applications, and a relatively low price [16]. The materials from which agricultural films are made are usually LDPE and copolymers such as ethylene-butyl acrylate (EBA) or ethylene-vinyl acetate (EVA). Films used for mulching are mainly made from linear low-density polyethylene (LLDPE). Due to the multitude of plastic film applications, the product range is very wide [17–20].

2.2. Polymer Plastic Films in Silage Production

In regions with unfavorable climatic conditions, plastic films are primarily utilized for crop protection purposes [21]. In contrast, in temperate climate zones with more favorable agricultural conditions, plastic films are extensively employed in silage production—specifically in bale wrapping, pass-through silos, and foil sleeves [13,22]. The efficiency of the ensiling process is critically dependent on the rapid and airtight sealing of the plant material, ensuring effective protection from atmospheric exposure. Accordingly, plant matter intended for ensiling in bales is typically wrapped multiple times with layers

of stretch film [23]. Recent technological advancements have enabled the development of silage films that provide an effective oxygen barrier, enhancing preservation efficiency. The use of such technology offers farmers the potential to reduce production costs [24]. Additional advantages of polymer film-based silage systems include reduced storage costs, minimal nutrient losses, and decreased dependency on weather conditions [25–27].

Film for haylage preservation ought to be ductile, durable, puncture-resistant, leakproof, highly viscous, and it should protect the material from harmful sun rays and temperature changes. The films used for silage production are mainly made of polyethylene resistant to biotic and environmental factors [28]. These films are effective in protecting the haylage thanks to a multi-layered polymer structure containing a strong plastic core, which makes them resistant to tearing, punctures, or abrasion. Proper color and opacity are also important features of a film. Silage films are mainly made from polyethylene (PE), and the material used for their production is usually LDPE [29–31].

2.3. Environmental Impact of Using Plastics in Agriculture

Numerous advantages resulting from the use of polymer plastics in agriculture should not obscure environmental risks, damage to ecosystems, and the adverse effects that plastic waste has on human health [32–34]. A precise global assessment of the impact of using polymer materials in agriculture is not possible due to insufficient documentation of the volume of plastic consumption and, above all, to the lack of reliable data on the handling of plastic products after their use. Reliable statistics are collected mainly in developed countries. Data suggests that only small fractions of plastics used in agriculture, mainly in developed economies, are collected and recycled. In other regions, there is no regular record of the management of plastic waste in agriculture. However, the estimates made indicate the widespread incineration, landfilling, or burial of plastic waste [35]. Inadequate disposal of plastic waste or its incineration on farms is a source of toxic emissions to the atmosphere, including furans and polychlorinated dibenzo-p-dioxins.

The widespread use of polymer materials in agriculture results in the accumulation of their waste in the environment [36,37]. The accumulation in the soil of residues of plastics reduces yields [38–41]. Microplastic particles may be transferred at trophic levels and adversely affect human and animal health [42,43]. Larger sized plastic waste could potentially pose a risk to wild animals as a result of swallowing it or entangling in it. In the aquatic environment, microplastics are vectors of spreading pathogens and toxic chemicals over significant distances [44].

In most plastics, the basic polymer is supplemented by various chemicals designed to improve its properties, functionality, and resistance to aging. Commonly used additives are as follows: plasticizers, pigments, antioxidants, light and heat stabilizers, flame retardants, antistatic agents, slip compounds, and acid scavengers [45]. Some polymers contain toxic additives, such as bisphenols and phthalates. These substances lead to disturbances in the hormone balance of living organisms [46–48]. Most plastics are made from fossil-based sources, which reinforce greenhouse gas emissions.

When collating the benefits of using plastics in agriculture with the environmental damage caused by plastic waste, both the positive and negative effects of polymer materials on food safety and food security should be noted. Sustainable development can only be achieved through a comprehensive approach to the issue of plasticulture—taking into account the life cycle and applying the principles of the closed-loop circulation of plastic products [49,50].

3. Recycling of Plastics

Consumption and Recycling of Plastics

It is estimated that between 1950 and 2017 a total of 9.2 billion tons of plastic was produced. Of this, only 600 million tons of plastic waste has been recycled. Approximately 2.700 million tons is still in use, 900 million tons of waste has been disposed of through incineration, and 5000 million tons has become burdensome waste that is deposited on landfills or has entered directly into the environment (including oceans) [51]. The recycling of plastics has now become one of the most important industrial challenges. Due to the huge quantities of plastic waste produced by different industries, it is first necessary to look for methods of waste application and, if this is not possible, for the least environmentally burdening disposal methods. In 2018, 24.9% of total plastic waste was recycled in the EU. According to data for 2019, the percentage of processed plastic packaging waste (the widest range of applications of polymer materials) was higher, namely 41% [52]. However, taking into account plastic waste exports outside the EU, the recycling rate should be reduced to 15% [53].

A wide range of end-use industries, including agriculture, is responsible for LDPE's continuously increasing global consumption [54]. The annual consumption of LDPE films in agriculture is more than 2 MT [21]. The upward trend is strongest in developing countries, especially in India and China. Smaller increases in consumption, or even inhibition of the upward trend of LDPE, can be expected in developed countries. In developed countries, the use of LDPE is significantly hampered by the proliferation of strict rules regarding the use of non-biodegradable materials. A strategy that can respond to the problems caused by rapid economic development, and the accompanying environmental changes, is a circular economy that takes into account the demands of sustainable economic development [55].

Recycling of Silage Films

The films used for wrapping bales and the films used for sleeves are usually fragmented in such a way that they cannot be reused [56]. The low level of films reuse results from the high costs of bringing the films back to be reused [57]. Due to the fragmentation, it may not be possible to collect plastics [58], and additives such as plasticizers, stabilizers, antioxidants, or dyes, enter the environment [59,60]. Plastic waste in agriculture contains numerous contaminants, such as biomass, sand, earth, stones, metal fragments, moisture [61,62], and sometimes residues of fertilizers and pesticides [63].

The used bale-wrapping films become burdensome waste that takes a long time to decompose [64]. As waste, these films are usually stuck in waste landfills (legal and illegal ones) or incinerated [65]. The effect of film decomposition is the release of many harmful substances into the environment [57,66,67]. Because of their structure, they are multi-layer films which can combine polymer or non-polymer materials [68,69]. Waste that is a mixture of polymers of unknown composition and contains different types of contaminants becomes more difficult to recycle [70,71].

Polyethylenes, of which stretch-type films are made, are structurally simple and highly durable polymers. LDPE is flexible and is, therefore, widely used for film production. LDPE has a highly branched structure which reduces material density [72]. Branched structures have lower thermal stability. During processing, LDPE recycling is dominated by mechanisms that lead to an increase in molecular weight [73,74]. Since LDPE is mainly used for products with a short life cycle, it is usually not stabilized against reprocessing degradation, which causes problems at the recycling stage [75]. To reduce thermo-oxidative degradation and to maintain recycle quality, it is desirable to add stabilizers to the PEs during reprocessing [76]. Due to potential antagonistic effects between polymer stabilizing systems, Peña et al. [77] proposed a system of three additives that overcomes

most antagonistic effects. The use of stabilizers improves the quality of plastics and can reduce thermal oxidation during recycling. However, the role of stabilizers in many processing cycles has not yet been sufficiently investigated [78].

The share of agricultural films recycled varies from country to country. The EIP-AGRI Focus Group study shows that only a few European countries have a national system for collecting agricultural plastic waste. The percentage of waste collected in those countries varies between 30% and 100%. It is estimated that a significant part of the material collected is recycled (80% for France). Waste for which no recycling solutions have been found is landfilled [79]. In Germany, an initiative has been taken to achieve a 65% recycling level for this type of film by 2022 [80]. In 2021, approximately 30,200 tons of silage and stretch film was collected and recycled, which constitutes 56% of the German market volume [81]. However, Korol et al. [82] estimate that the recycling rate for agricultural films does not exceed 30%.

4. Method

4.1. Aims of the Research

The research aimed at the following:

- Producing materials meeting the criterion for recycling or biodegradation.
- Assessing the properties of new materials with regard to the requirements for the production of haylage
- Comparing the characteristics of the new generation films to the films commonly used in silage.

4.2. Films Used in the Study

Properties of four types of films were examined:

- A—a film produced according to a standard recipe (commonly used for silage preservation).
- B—a film with 8% microcellulose content.
- C—a film with 5% additive based on nanosilver.
- D—a film with a 5% zinc-based microbiological additive.

Silver and zinc preparations were introduced to the films in quantities of 400 ppm.

These materials were introduced into a thermoplastic polymer EVA (ethylene copolymer/vinyl acetate) using a Leistritz type ZSE 27 HP double screw extruder. Between the film commonly used (without modifiers) and modified films, there were no differences in the strength characteristics.

4.3. Scope of Field and Laboratory Work

The films produced under the study project and the standard film were transferred to a farm specializing in milk production, where each type of film was used to wrap 20 cylindrical bales (Figure 2). Each bale was wrapped with four layers of film of the same type. The material intended for ensiling, formed into cylindrical bales, was a mixture of grasses and papilionaceous plants.

From the bales indicated above, samples of film and of haylage for laboratory testing were taken four times: 4, 8, 12, and 18 months after the date of bale formation. Squares measuring 5 cm × 5 cm (25 cm²) were cut out of the sheet of film the bales were wrapped with. The squares were then placed in a Petri dish containing 25 mL of sterile distilled water to clean the film of impurities. After washing the film, the water was drained and the impurities were weighed.



Figure 2. Films used for wrapping bales with plant material (Source: Materials prepared by the authors).

Imprint preparations for the films were also made: 25 cm² squares, immediately after being cut out of the film covering the bale, were pressed against the appropriate medium for a few seconds. The following media were used:

- Enriched agar (EA)—2.5%, Biocorp. General medium for the determination of the bacterial count. Incubation at temp. 22–25 °C for 72 h.
- DeMan, Rogosa, Sharpe (MRS) medium—5.2%, Biocorp, with a 1% addition of bacteriological agar. Selective medium for lactic acid bacteria growing. Incubation at temp. 37 °C for 72 h.
- Sabourauda (SAB) medium—6.5%, Biocorp, with a 1% addition of bacteriological agar. General medium with the addition of chloramphenicol for the cultivation of yeast and mold fungi. Incubation at temp. 30 °C for 72–96 h.

The microorganism population of the film was evaluated on a 4-grade scale:

- No growth of micro-organisms.
- Low abundant growth (a small number of colonies, below 30).
- Medium abundant growth (a large number of colonies, below 300).
- Abundant growth (uniform throughout the surface, so-called ‘lawn’).
- Standard laboratory methods were used to assess haylage quality:
- Total nitrogen content was determined by the Kjeldahl method, and total nitrogen was converted using a factor of 6.25 into crude protein.
- Ammonia content was determined by the Conway method.
- The content of monosaccharides was determined by the Luff–Schoorl method.
- pH was determined using a stationary pH-meter TOLEDO MA 235.
- The lactic acid content was determined using the Varian 3400 CX gas chromatograph, a flame ionization detector (FID), J&W Scientific DB-FFAP column (30 m long, 0.53 mm in diameter), and argon carrier gas, dispenser temperature of 200 °C, detector temperature of 240 °C, and column temperature of 60–210 °C.
- The acetic acid content was determined using an INGOS liquid chromatograph LCP 5020, with a steel column 8 × 250 mm filled with OSTION LG-KS 0800 H+ (Tessek company, Praha, Czech Republic), mobile phase: 5 mM H₂SO₄.

The ANOVA with post-hoc Tukey HSD test ($p < 0.05$) was used to assess the differences between the compared measurements (the analysis was performed using the TIBCO Statistica™ version 13.0).

5. Results

The purpose of developing new generation materials is to facilitate the recycling of the films or their biodegradation while maintaining the quality of the haylage.

5.1. Silage Quality Evaluation

After the first visual inspection (4 months of storing) of the film with 8% microcellulose (B), many outbreaks of mold growth in the silage were noted (Figure 3). This type of film was eliminated from further testing. Visual inspection of silage stored in other types of films yielded very good results. For this reason, only from those bales were the haylage samples taken for further laboratory testing in three replicates. The important silage parameters were very good, and they did not vary statistically significantly (Table 1). Only silage stored in type A film was richer in lactic acid, and silage stored in type C film was richer in sugars.



Figure 3. Bale wrapped in type B foil (with added microcellulose) with visible mold spots (Source: Materials prepared by the authors).

Table 1. The effect of the type of film on essential quality parameters of silage.

Film Type	Content (%)					
	In Dry Matter			In Fresh Matter		
	Crude Protein	N-NH ₃	Sugars	pH	Lactic Acid	Acetic Acid
1st evaluation						
A	15.3 ^a	0.07 ^a	9.5 ^a	4.5 ^a	2.0 ^b	1.3 ^a
C	14.9 ^a	0.06 ^a	12.1 ^b	4.4 ^a	1.5 ^a	1.4 ^a
D	15.0 ^a	0.05 ^a	9.0 ^a	4.4 ^a	1.4 ^a	1.5 ^a
2nd evaluation						
A	15.1 ^a	0.07 ^a	9.4 ^a	4.3 ^a	4.4 ^a	1.7 ^a
C	14.9 ^a	0.08 ^a	11.4 ^b	4.4 ^a	4.9 ^b	2.0 ^a
D	15.0 ^a	0.07 ^a	8.8 ^a	4.3 ^a	4.0 ^a	1.3 ^a
3rd evaluation						
A	14.8 ^a	0.07 ^a	9.6 ^a	4.5 ^a	4.0 ^a	1.5 ^a
C	12.9 ^a	0.09 ^b	10.5 ^a	4.3 ^a	3.5 ^a	1.3 ^a
D	13.5 ^a	0.08 ^a	8.5 ^a	4.4 ^a	3.5 ^a	1.1 ^a

Table 1. Cont.

Film Type	Content (%)					
	In Dry Matter			In Fresh Matter		
	Crude Protein	N-NH ₃	Sugars	pH	Lactic Acid	Acetic Acid
4th evaluation						
A	14.4 ^a	0.13 ^a	7.6 ^a	4.9 ^a	2.7 ^a	1.2 ^a
C	11.4 ^a	0.11 ^a	7.9 ^a	4.6 ^a	3.3 ^a	1.5 ^a
D	13.5 ^a	0.08 ^a	8.3 ^a	4.4 ^a	3.5 ^a	1.4 ^a

The table shows arithmetic means. Values marked with the same symbol (letters a–c) in the same study period (1st–4th) do not differ significantly at $p = 0.05$ (Source: Own study).

The second evaluation (8 months of storing) showed a reduction in pH and slightly lower levels of sugars as well as a double increase in lactic acid content and a slight increase in acetic acid level in the silages. In the third evaluation (12 months of storing), pH increases, as well as decreases in protein, sugars, and lactic acid and acetic acid content were found in all silage types. The last evaluation (18 months of storing) showed a slight loss of protein and sugars and an increase in the N-NO₃ and pH content in silage stored in type A and C film. Silage stored in type D film had similar parameters as in the evaluation after 12 months.

5.2. Population of Micro-organisms on Films

On type A film, after 4, 8, 12, and 18 months of storing, the number of colonies of lactic acid bacteria was in the range 30–300 (Table 2). This film had a similar number of colonies of yeast and mold fungi at the first three times of evaluation. At the time of the last evaluation, yeast and mold fungi colonies covered the entire surface of the film. Type B film was completely colonized by yeast and mold fungi at the first evaluation time, and lactic bacteria formed sparse colonies. In contrast, in the first three test periods, type C film was characterized by a much lower population of lactic acid bacteria and fungi colonies. At the fourth time of evaluation, the number of bacteria colonies increased and ranged from 30 to 300 colonies, and fungi covered the whole surface. The number of colonies of lactic acid bacteria and fungi on type D film in all test periods was low (between 0 and 30).

Table 2. The degree of colonization of lactic acid bacteria as well as mold and yeast on the inner side of the film.

Film Type	Lactic Acid Bacteria				Yeast and Mold Fungi			
	Time of Evaluation							
	1st	2nd	3rd	4th	1st	2nd	3rd	4th
	Degree of Colonization							
A	30–300	30–300	30–300	30–300	30–300	30–300	30–300	lawn
B	0–30	-	-	-	lawn	-	-	-
C	0–30	0–30	0–30	30–300	0–30	0–30	30–300	lawn
D	0–30	0–30	0–30	0–30	0–30	0–30	0–30	0–30

The table shows arithmetic means (Source: Own study).

5.3. Contamination of the Films

Considering that the degree of contamination represents a critical constraint for the recyclability of used silage films, this parameter played a pivotal role in the research.

Contamination levels were assessed based on the mass of residual silage material adhering to the film and the presence of microbial colonies on its surface.

During the first evaluation, bales wrapped with type B film were dirty on the outside and the film layers were not cohesive. On the inner layer of this film, there were 2.5 to 3 times more impurities in relation to the other types of film, and that was a statistically significant difference (Table 3). Other types of films had a similar degree of contamination with silage residues. As silage was stored in type A and type C film for an extended period, an increase in contamination with silage residues was recorded. The number of impurities on the type D film was low and almost constant at all the test times.

Table 3. Mass of residues of silage contaminating individual types of film over the area of 0.25 m² (g).

Film Type	Time of Evaluation			
	1st	2nd	3rd	4th
A	0.07 ^a	0.07 ^b	0.12 ^c	0.14 ^c
B	0.15 ^c	-	-	-
C	0.05 ^a	0.06 ^b	0.09 ^b	0.11 ^b
D	0.05 ^a	0.04 ^a	0.06 ^a	0.06 ^a

The table shows arithmetic means. Values marked with the same symbol (letters a–c) do not differ significantly at $p = 0.05$. (Source: Own study).

5.4. Recycling of Waste Films in the Study

The processing of plastic waste had the following stages:

- Sorting. This treatment includes waste sorting and discarding plastics that are not suitable for further processing in subsequent stages of the process.
- Grinding and washing. The goal of this stage is to prepare the processed material for the main process, namely, regranulation. The film strips must be completely cleaned and dried.
- Granulation of cleaned plastic flakes.

The processing of waste from bale wrapping films in the process of material recycling yielded regranulate, which is intended to be used in the further production of any type of film (Figure 4). During the processing of used silage films, a 100% recycling rate of the waste material was achieved, with the waste converted into regranulate. However, the physicochemical properties of the obtained regranulate were insufficient to allow its use as the sole feedstock for the production of new silage films. From a technological standpoint, the addition of non-recycled polymer was necessary to meet the required performance standards.



Figure 4. Granulate—the result of the material recycling process (Source: Materials prepared by the authors).

6. Discussion and Research Implications

The processing of burdensome waste remaining after the use of silage films may be regarded as recycling. Stretch film used in silage production is recycled only to a limited extent due to organic contaminants that are difficult to remove from its surface. The solution proposed by the authors for the disposal problem enabled full-scale recycling (up to 100% of used silage films) of this problematic waste. At the same time, the composition of materials used in the film's production ensured the desired oxygen barrier properties.

However, adapting the silage film requires the material to be redesigned for reuse and regeneration. The following facts are particularly important from the research:

- Type B film (with 8% microcellulose content) is not suitable for feed preservation.
- Deterioration of silage quality in bales wrapped with type A film (commonly used in agriculture) and type C film (with a 5% additive based on nanosilver) after 12 months of storage.
- A relatively small population of lactic acid bacteria on the inner side of type C film and type D film (with a 5% zinc-based microbiological additive).
- A positive relationship between the fungal and mold colony population and the amount of contamination of the inner side of the films with silage residues.

Type B film had little viscosity, which resulted from the introduction of the additive in the form of microcellulose. The low viscosity of the film layers did not limit the penetration of atmospheric air into the bales, which caused the mold to spread within the silage already in the first 4 months. The proper course of the ensiling process is conditioned by cutting off the air access to the material being preserved [83]. Deterioration of some quality parameters of silage stored in A and C type film, assessed in the fourth term, was the result of a reduction in the long-term barrier to air of these films. Increased air access was a factor favoring the growth of fungi and mold on the outside of the silage and on the film adjacent to it. The development of this group of micro-organisms contributed to the contamination of the films with silage residues.

The reduced population of lactic acid bacteria on films with the addition of Ag or Zn after 8 months of silage storage proves the inhibitory effect of these elements on their development. On the other hand, the development of fungi and mold colonies proves the low sensitivity of these micro-organisms to the Ag and Zn concentrations used.

A comprehensive review of research on silage preservation techniques can be found in studies by Coblenz et al. [84], Baldasano et al. [85], Han et al. [86], Nowak [87], Zdobytskyy [88], and Stankiewicz [89]. Perspectives and directions of silage production development are addressed in the study by Wilkinson and Rinne [90]. The silage parameters, depending on the type of film used, were subject to numerous studies [91,92]. The authors stress the significance of stable anaerobic conditions [93–95] and the validity of using LDPE films [96]. Wilkinson and Fenlon [97], based on comparisons of standard PE films with oxygen barrier films (OB), concluded that OB films increase aerobic stability in the outer layers of bales and reduce silage losses. However, some studies do not show a clear advantage of the OB covers over standard PE films over a long period of time [98]. Silage exposure to air causes oxidation of fermentation acids and other substrates by aerobic bacteria, molds, and yeasts [99,100]. With improper fermentation, undesirable and even pathogenic micro-organisms, which can produce toxic metabolic compounds, may develop in silage [101,102]. Micro-organisms that produce toxins in aerobically degraded silage pose a serious risk to milk quality and animal health [103,104].

The process of feed preservation by ensiling is a source of large quantities of post-consumer plastics that require proper collection and disposal [12,105]. Prata et al. [106] indicated that recycling is one of the key strategies for combating the environmental burden of plastic waste. Singh et al. [107] noted that the greatest challenge for the re-

cycling of agricultural films is the complex nature of waste and contamination. Other authors' studies proved that the presence of contaminants reduces the homogeneity of the material [108] and can significantly affect the material properties, limiting its potential range of applications [109,110].

Recycling problems resulted in research on technologies for the production of plastics based on natural raw materials [111,112], the decomposition of which is relatively fast, and the environmental impact is lower [113,114]. Many authors discuss factors that stimulate interest in such materials [115–118]. Degradation-resistant polymers pose problems of disposal at the end of their life cycle [119]. Thus, some authors point to the degradability (mainly bio-) of the material and the possibility of converting the used material into a new secondary product as the direction of development for material engineering [120–126]. The most acceptable method of disposal of biodegradable polymers is to compost them. However, this is not a practical solution to the problem of most plastic waste in agriculture [127]. In the case of silage films, adding a biodegradable composite may reduce their leak-proofness, which disqualifies such bale covering material. Some authors [94,95,128] indicate that, within a short period (up to 6 months), biodegradable film may retain the desired properties of the plant material being ensiled in silos. In similar applications, Tabacco et al. [129] demonstrated the applicability of fully biodegradable film only for a period of up to 3 months.

7. Conclusions

Reducing the environmental burdens caused by plastic films used for feed preservation requires a closed-loop approach to materials used in these technological processes. This entailed the need to develop material for films that could be subjected to material recycling. The silage production method commonly used in agriculture is based on the wrapping of cylindrical bales of plant material with LDPE film. Therefore, four versions of such films were tested in the study in terms of their impact on micro-organisms involved in the ensiling process and of the possibility of inexpensive recycling of the resulting waste.

The basis for the evaluation of the film variants were the functional properties of the product based on the following:

- The ability to maintain the quality of silage and its storage period.
- The possibility of recycling the waste film.

The developed new generation silage films made it possible to achieve 100% recycling, while this indicator for traditional films did not exceed 50%:

- The film widely used in agriculture (type A) and the film with a 5% additive based on nanosilver (type C) provided good silage quality for a storage period of approximately one year.
- The film containing the zinc-based microbiological additive (type D) is a material that guarantees both meeting the technological requirements of feed production and is fully recyclable.
- The lowest contamination on the film type D due to its specific characteristics makes it easier to recycle the burdensome waste.
- The film with 8% addition of microcellulose (type B), due to the low oxygen barrier capacity, did not provide adequate conditions for the preservation of silage.

The long-term ecotoxicological effects of incorporating nanosilver and nanozinc into films have not been evaluated in this study, particularly under natural environmental conditions. Although nanosilver and nanozinc exhibit beneficial antimicrobial properties, they may pose a risk to the natural environment due to their toxicity, bioaccumulation

potential, and possible disruption of ecosystem balance. This issue warrants further in-depth investigation prior to the widespread application of such films.

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