

Article

The Impact of the COVID-19 Pandemic on the Amount of Plastic Waste and Alternative Materials in the Context of the Circular Economy

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Abstract: The COVID-19 pandemic was first reported on 31 December 2019, in Wuhan. Since then, the rapid spread of the virus has directly impacted various aspects of people's lives, including culture, society, education, and the economy. The environment has also been affected, as the disposal of thousands of tons of single-use personal protective equipment has resulted in a significant increase in waste. The challenge was to create environmentally friendly materials for personal protective equipment. One of the alternatives to polypropylene materials is a biodegradable nonwoven produced using spun-bonded technology. The article discusses various physical and mechanical parameters, the biodegradation process, and the distribution of molar masses during the weeks of nonwoven biodegradation. Additionally, the paper presents the results of in vitro cytotoxicity tests conducted on the material. Biodegradable materials are a viable solution to the challenges posed by a circular economy.

Keywords: COVID-19; waste management; circular economy; nonwoven; biodegradation



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1. Introduction

Polymers are chemical substances with a very high molecular weight, they are divided into thermosetting or thermoplastic. Modifying the processing procedure of a polymer does not alter the structure of the material. Rather, it changes the physicochemical properties of the material to give it the desired functional properties. Plastics find application in almost every industry, including clothing, nonwoven industry, medical supplies, water bottles, food packaging, electrical goods, and endodrials [1–4]. It is estimated that since 1950, global plastic pollution has amounted to 8.3 billion million tons [5–7]. The COVID-19 pandemic has caused an increase in the amount of plastic waste [8]. Unfortunately, plastic waste has an adverse impact on the environment and the organisms living in it [9]. Forecasts show that by 2028 the demand for plastics in various sectors will increase by approximately 4.2% [10]. Therefore, plastic waste constitutes a serious threat to the ecosystem as well as a global challenge requiring urgent solutions in this area [11].

These materials also introduce pollutants into the environment in the form of microplastics, mesoplastics [12,13], and nanoplastics [14–16]. Microplastics and nanoplastics are of the greatest concern since they can move in the environment, have the ability to release the chemicals they contain, and can also migrate through animal tissues and thus enter living organisms, including humans [17]. Li et al. [18] discussed the sources, occurrence of plastics, and their impact on the marine environment. Karapanagioti et al. [19]

discussed the dangers of plastic debris to marine animals. An alternative to traditional polymer materials are biodegradable polymers, which enable production within the principles of a circular economy. Currently, leather is trendy as an alternative to synthetic materials. Vanessa Gatto et al. [20] described a collagen stabilization method mediated by 2-chloro-4,6-diethoxy-1,3,5-triazine (CDET) and tert-amine. The authors obtained good quality leather with environmentally friendly parameters. Due to the durability of polymer materials and their large amount of waste, a significant portion accumulates in the environment. As the literature shows [21], a significant part of waste is generated by packaging materials. Currently, many activities are being undertaken to recycle plastic materials such as PP, PE, PET, or PS [21]. Actually, plastic waste management includes landfilling, incineration, recycling and energy recovery [22]. The burning of waste materials causes the emission of dangerous gases, and plastic waste landfills contribute to the contamination of groundwater [23]. To reduce the amount of plastic waste, two main strategies can be used, i.e., the use of biodegradable materials [24,25] and recycling [26–29]. According to EU legislation and Briassoulis and colleagues, the best alternative for valorization of post-consumer polymer waste from fossil fuels as well as biopolymers followed by chemical recycling is mechanical recycling [30,31]. An alternative to traditional polymer materials are biodegradable polymers, which enable production within the principles of a circular economy. Good examples are environmentally friendly biopolymers, such as polybutylene succinate (PBS) [32], polyhydroxyalkanoate (PHA) and polyhydroxybutyrate (PHB) [33]. PBS is characterized by good processability. As the literature shows, composites made of natural fibers based on PBS are completely biodegradable and have good mechanical properties [34,35]. In recent years, there has been an increase in the use of bioplastics such as PBS, which has raised awareness about the environmental issues caused by non-renewable and non-biodegradable plastics, as well as the rapid depletion of fossil fuel resources. The biodegradability of PBS is an attractive feature of this polymer and therefore gives it an advantage in single-use applications. This polymer can degrade at a high rate in a short period of time and has also been listed as compostable [36]. Therefore, it was proposed as an element of personal protective equipment. A cheap source from which PHA can be obtained is wastepaper [37]. PHAs are an alternative to synthetic plastics due to their physicochemical properties comparable to those of synthetic plastics and their biodegradable and biocompatible nature [38,39]. Biodegradable polymers degrade to low-molecular-weight compounds under the action of enzymes or micro- and/or macroorganisms. The circulation of biodegradable polymers in the environment is shown in Figure 1. The figure shows the circulation of biopolymers from biological sources (e.g., chitosan, cellulose, starch or polylactide). The product life cycle begins when the raw material is obtained. After undergoing manufacturing processes such as synthesis, modification, and conversion into usable material, the product eventually becomes waste. This step is a key point in a circular economy. When a product is discarded in a landfill, its life comes to an end. Non-biodegradable polymers, when reused as raw material, e.g., re-PET, also fit into the circular economy. But it is still not common practice. Unfortunately, in many parts of the world today, this is still the primary method of utilization [40,41]. The concept of the circular economy involves looking at waste not as something to discard, but as a valuable resource that can be repurposed. This can be achieved by processing it into new functional material or allowing it to decompose, such as in compost, which adds organic matter to the soil for use in agriculture. This approach helps to create a more sustainable system of production and consumption [42]. Such a management system, which treats waste as a source of biomass or as a renewable material, is supported in Europe. The data shows that Europe is the region with the lowest percentage of landfill waste [41].

The impact of plastic waste on the ecosystems has aroused growing interest. Plastic waste poses a critical threat to the environment, i.e.:

- Reducing the efficiency of soil nutrient use,
- Introducing pollutants (microplastics) into agricultural products,
- Increase in morbidity in society,

- Increase in ecological problems.

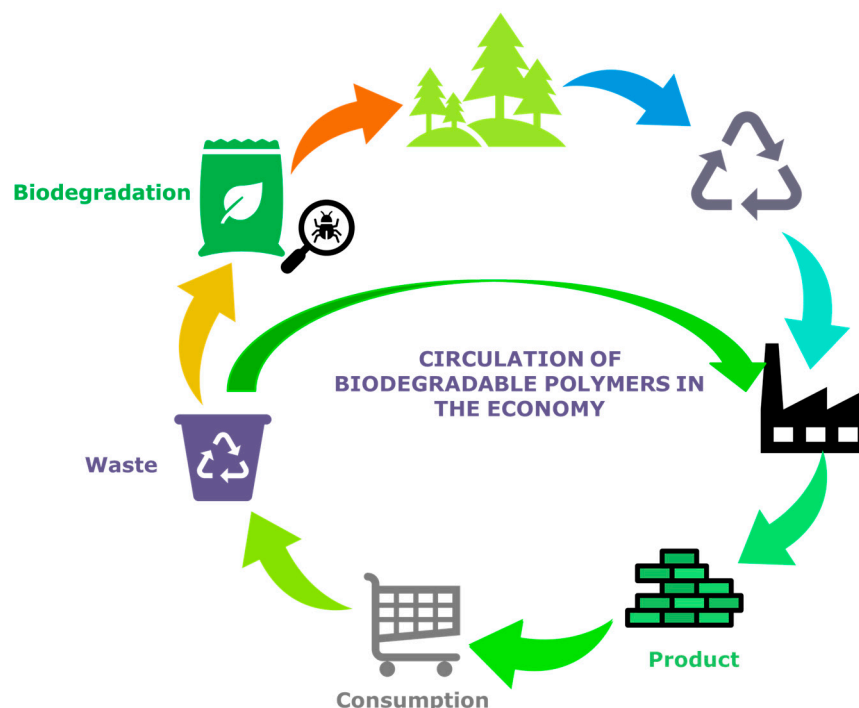


Figure 1. Life cycle of biodegradable polymers in the circular economy.

Researchers and the media have reported extensively on the amount of plastic produced and the negative impact of polymer waste on the environment. However, there is still a lack of detailed data regarding the amount of microplastics that enter the environment as plastics decompose. This area requires further research by scientists. Therefore, alternatives based on polymers of natural origin or that degrade more rapidly are being sought [43–45]. Currently, there are discussions and numerous studies on whether biodegradable or renewable materials are a better solution. Studies show a variety of data both favorable to bio-based plastics and unfavorable [46–48]. The use of bioplastics is not a complete replacement for petrochemical/non-biodegradable polymers.

Given the current environmental crisis caused by the excessive accumulation of plastic waste, it is crucial to work towards developing eco-friendly solutions. In light of this, the authors conducted research to produce spun-bonded nonwoven fabric using the PBS polymer. The details of this study are described in the article. The purpose of this article is to provide inspiration for the desire to replace plastics with biodegradable polymers and thus reduce the amount of harmful polymer waste on the environment. The article cites statistical data on the production of plastics, definitions of biodegradation, degradation and composting processes. The importance of biodegradation is discussed.

2. COVID—Problem with Waste Management

The number of plastic wastes has significantly increased during COVID-19 pandemic and plays an important role in environmental pollution [49]. An unprecedented increase in the use of single-use plastics (SUPs) and personal protective equipment (PPE) was noticed. The literature [50] reports that European plastics production in 2022 amounted to 58.7 million tons, while global production was 400.3 million tons. The distribution of plastics production in individual years of the COVID-19 pandemic depending on the type of raw material is shown in Figures 2 and 3. There is an enormous amount of unmanaged waste that directly threatens ecosystems. According to the literature, it is estimated that globally, 1.6 million tons of plastic waste and 3.4 billion face masks are produced and disposed of every day, respectively [49,51]. During the pandemic, global

petrochemical plastic production was slowed down (Figure 2A). However, in 2021, there was an increase. The challenge was to ensure the delivery chain and production continuity. At the same time, the world market's interest in biopolymer alternatives and the recycling of petrochemical plastics has been recognized. Since 2018, the production from these categories has been increasing annually (Figure 2B,C). The European plastics market shows a different trend than the global market. The COVID-19 pandemic has reduced the production of plastics made from fossil fuels since 2018 (Figure 3A). On the other hand, similar to the global market, the interest in recycled materials as well as bio-based plastic has increased (Figure 3B,C). Significantly increased production of biopolymers in 2022 (Figure 3C). This is due to EU policies and greater concern for the environment. The concepts of green economy and green growth are crucial to sustainable development in Europe. These initiatives promote a shift towards more sustainable production and consumption patterns, with a focus on environmental sustainability and social justice. The implementation of policies related to green economy and green growth can play a significant role in achieving sustainable development goals while creating new opportunities, which is a high priority for EU policymakers [52]. Such an increase in production is the result of EU regulations, i.e., Directive (EU) 2019/904 on the reduction of the impact of certain plastic products on the environment, Directive (EU) 2018/851 on waste. In November 2022, the EU Commission proposed new EU packaging regulations. They are intended to reduce packaging waste and improve packaging design including promoting reuse and recycling. They demand a transition to biobased, biodegradable and compostable plastics. The above measures are reflected in the statistics of EU plastics production in 2022 (Figure 3).

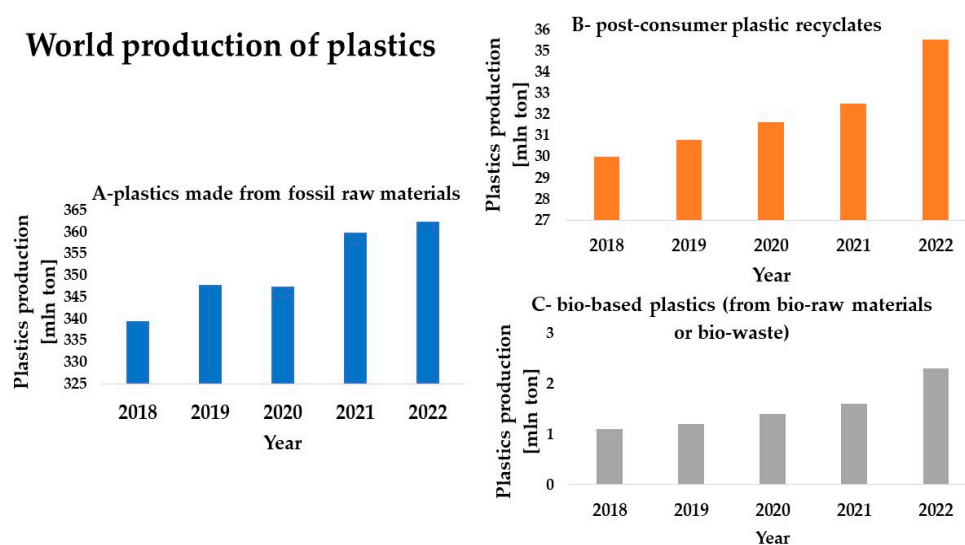


Figure 2. World production of plastics during the COVID-19 pandemic and immediately before the outbreak of the COVID-19 pandemic (from (A)-fossil raw materials/(B)-post-consumer plastic, (C)-bio-based plastic).

According to the literature, the COVID-19 pandemic has had a significant impact on nature [53]. The increased production and use of medical face masks has resulted in increased emissions of greenhouse gases and other harmful gases and has also led to waste that harms animals and entire ecosystems. Gadomska A. and Korzeniowska K. reported that during the pandemic, humanity used about 3 million disposable masks per month, making a total of as many as 130 billion masks. Assuming that a disposable surgical mask weighs about 3.5 g, it turned out that the total weight of masks used every month exceeded 450 tons [54]. In Polish enterprises alone, from March to December 2020, 43 million medical masks were produced. Over 24 h, the use of medical masks during the COVID-19 pandemic in Europe alone compared to use worldwide was 13.2%. In March 2020, the WHO estimated that personal protective equipment (PPE) production should increase by 40% to

meet the demand for protective materials. According to the Plastic Waste Innovation Hub at University College London, eliminating single-use products and replacing them with reusable products would reduce the amount of pandemic “waste” by 95% [55]. During the first half of the pandemic, the import of masks to the European Union more than doubled, according to experts. An additional 170,000 tons of masks were imported to Europe, which amounts to an average of 0.75 masks per person per day. There was also an increase in local production. The demand for personal protective equipment, such as filtering half-masks or disposable protective masks made of plastic and intended for single-use, significantly surged during the pandemic [56–58]. Experts have highlighted that the COVID-19 outbreak has led to a surge in demand for personal protective equipment, which in turn has resulted in a significant increase in waste generation. The production of masks, in particular, has reached an almost equivalent scale as that of plastic bottle production, with approximately 43 billion masks being produced every month worldwide [54].

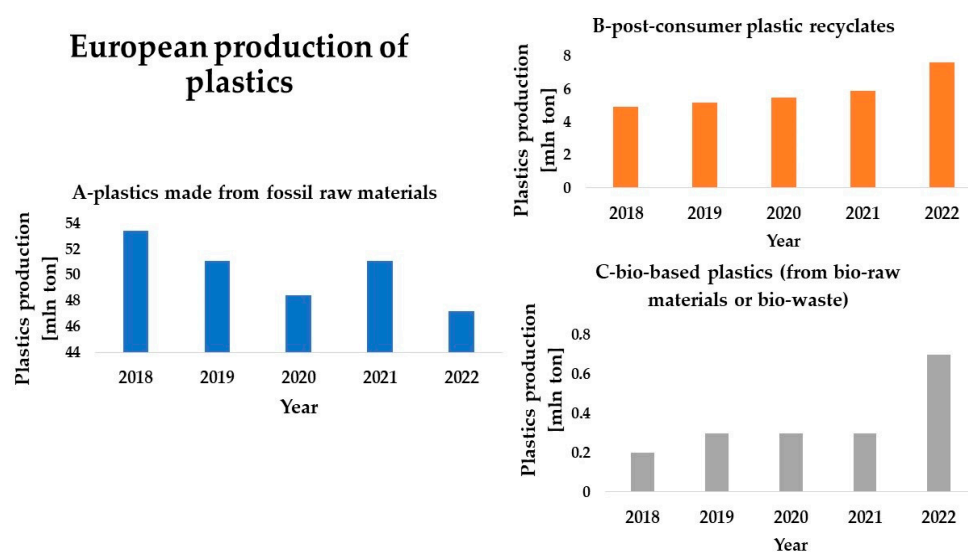


Figure 3. European production of plastics during the COVID-19 pandemic and immediately before the outbreak of the COVID-19 pandemic (from (A)-fossil raw materials/(B)-post-consumer plastic, (C)-bio-based plastic).

The most common protective materials are nonwoven materials made of petroleum-based polymers, such as polypropylene (PP), polyethylene (PE), and polyethylene terephthalate (PET) [59–61]. Plastic and other harmful products are ending up in our oceans, damaging the environment. Scientific research has shown that plastic production has quadrupled in the past 40 years. If this trend continues, plastic production will be responsible for 15% of greenhouse gas emissions by 2050 [62]. Currently, all forms of transport contribute the same amount of plastic waste as other sources. Studies indicate that eight million tons of plastic waste are dumped into the oceans annually, and this trend continues each year [63]. However, personal protective equipment poses an even greater risk than ordinary plastic. Plastic gloves or bags may be mistaken as food by sea turtles or jellyfish, leading to their death. This can result in the decomposition of animals in the water, which increases the level of harmful substances in the water [64]. An additional factor is that many personal protective equipment contains viruses, fungi and bacteria [65]. Such products may decompose and pollute the environment in the form of microplastics, which, despite their small size, constitute a very dangerous pollution of ecosystems. During the COVID-19 pandemic, the focus has been on ensuring public health and safety. However, it is crucial to recognize that the pandemic has also highlighted the significance of the waste issue. Products made from biodegradable polymers derived from biomass offer a sustainable and eco-friendly alternative to traditional plastics. These materials possess similar functional properties as plastics but are designed to break down naturally without

harming the environment once they are no longer needed. The present paper proposes a biodegradable nonwoven fabric produced using spun bonded technology, which can be used, among others, for the production of single-use protective materials.

The circular economy affects the sustainable development of public finances and the issue of stability of public finances, which was a priority challenge for most countries during the COVID-19 pandemic, especially in the context of financing economic growth [66]. One of the primary ways to finance economic development is by supporting and developing enterprises that utilize modern production technologies based on circular economy solutions. Entrepreneurship development is crucial in the current post-crisis reality. However, it should be noted that encouraging entrepreneurial behavior remains one of the most significant challenges in the modern economy, particularly during periods of economic uncertainty [67]. Despite their negative impact, both economic crises and global pandemics can also serve as an opportunity to introduce new business tactics and promote progress. This is particularly evident in areas such as disrupted supply chains and waste management, which have been affected by the COVID-19 pandemic. For instance, the production of plastic products has undergone significant changes in this regard.

3. New Materials as a Way to Solve the Problem

Biodegradable Materials

The topic of biodegradability of products is gaining popularity. Biodegradation is a recycling method known as organic recycling, which is an excellent alternative to managing generated waste. Microbiological decomposition allows natural breakdown of products at the end of their lifecycle, reducing the burden on landfills and minimizing the persistence of non-degradable waste in the environment. The inclusion of biopolymers is in line with the broader objective of conserving natural resources and reducing dependence on petrochemical-derived raw materials [68–70].

Biodegradability is defined as a process of biological decomposition of materials. Simpler substances such as carbon dioxide, water, and ammonia are the products of this process. Bacteria and fungi (yeasts and molds) are among the microorganisms responsible for biodegradation. The growth and reproduction of microorganisms is based on the availability of energy, organic substances, phosphorus, sulfur, calcium, magnesium, and several metals [71,72]. The conversion of organic substances into carbon dioxide and water leads to release of heat (exothermic process), which can be observed in composting. Decomposition can be conducted both under aerobic and anaerobic conditions in various environments, such as water compost and soil. The duration of the process can vary greatly depending on the material involved. It can range from a few weeks to several centuries [72].

Due to the fact that biodegradation can be conducted in a compost environment, it is often confused with compostability. The latter is proper for material that biodegrades under specific conditions (temperature, humidity, airflow) and results in the production of an end product beneficial to soil health. Tests include chemical characterization of a sample, biodegradation, disintegration and phytotoxicity. Therefore, a compostable product must be biodegradable, but a biodegradable product does not have to be compostable.

Biodegradability is a highly desirable feature for manufactured materials as it contributes to the reduction of pollution. Unfortunately, many plastic products are resistant to natural degradation, which means that when they end up in landfills or are littered in the environment, they can persist for decades or even centuries, contributing to environmental pollution. However, biodegradable materials offer an advantage as they help reduce the demand for fossil fuels, leading to the conservation of resources. Their application can also protect ecosystems, especially aquatic ones. [73–75].

As the consumption of a wide range of polymers has increased in almost all areas of application, there is a need to identify the most ecological way to manage them, especially at the end of the product's life cycle [76]. The SARS-CoV-2 pandemic has shown how important a problem it is to design the appropriate method of waste disposal. According to the WHO [77] it is estimated that approximately 87,000 tons of personal protective

equipment (PPE) has been produced between March 2020 and November 2021 and shipped to support countries through a joint UN emergency initiative. It is expected that most of this will have ended up as waste. The presented data indicate the scale of the waste problem. It should be highlighted that the numbers refer only to measures registered under the UN. It is important to remember about additional production and distribution outside the organization.

A wide range of methods can be applied in biodegradability and compostability studies. Figure 4 presents selected standards divided into research environments.

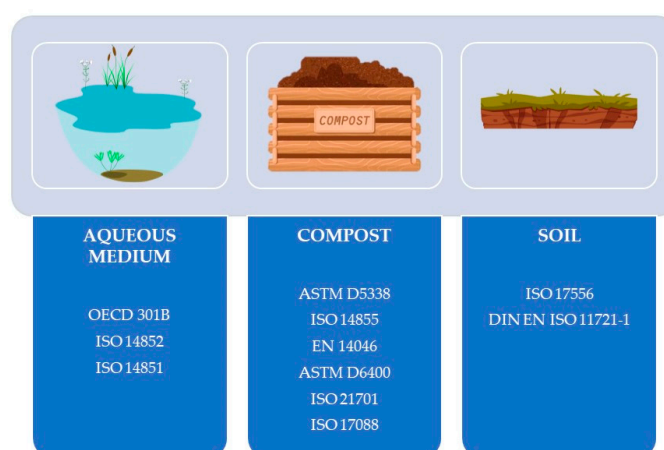


Figure 4. International standards applied in biodegradability and compost ability studies [78–89].

4. Materials and Methods

The nonwoven was composed of polybutylene succinate (Bionolle™ 1001 MD, Showa Highpolymer Co., Ltd., Bankok, Tajlandia) and produced directly from the polymer using the spun-bonded technique. The general diagram of the spun-bonded nonwoven fabrication process is shown in Figure 5. The spun-bonded technique consists of introducing the polymer into the extruder through a feeder. To process polyesters such as PLA or PBS, it is necessary to reduce the water content level to ppm [90,91]. The polymer is melted in the extruder's heating zone. The extruders can be single or twin-screw with various arrangements. The temperature gradient should be adapted to the polymer, taking into account the melting and decomposition temperature and the melt flow index. If the temperature is too low, it can cause blockage in the extruder system. Conversely, if the temperature is too high, the melt flow index of the polymer will increase as a result of decrease of viscosity, leading to improper fiber formation and material degradation. Therefore, careful selection of the melt temperature is important [92]. The polymer melt is filtered and fed to the spinning head where it is formed into fibers. Depending on the head used as well as its parameters (e.g., number of holes, diameter and length of holes), fibers with different properties can be obtained (e.g., diameter, degree of primary crystallization). The filaments are next drawn in the spinning channel under the influence of hot air and collected on the belt under vacuum. At this stage, the fibers are loosely laid and only pre-bonded into the webbing. It is necessary to use a calendar at a certain temperature to bond the fibers into a nonwoven [93,94]. The parameters of the process are shown below.

The Łukasiewicz-LIT (Łódź, Poland) construction process line was used to form spun-bonded nonwovens. The polymer was dried in a rotary dryer (Fourné Maschinenbau GmbH, Alter, Germany) during 13 h at a temperature of 55 ± 5 °C. The biopolymer was extruded using a single-screw extruder with the temperature of heating zones in the range of 165–240 °C. The melted polymer at 240 °C was pressed through the spinning head. The fibers from the head were directed to a 9/17 cm channel, where the fibers were stretched at a draw ratio of 1500 Pa in the chamber. The stretched fibers, after passing through the forming channel, were deposited in the form of a web on a transport grid with a 24 Hz fleece pickup vacuum. This web was then thermally bonded using two calenders, with

calender I operating at 50 °C and calender II at 60 °C. The manufacturing process of the spun-bonded nonwovens used a spinneret containing 467 holes with a diameter of 0.4 mm and a length of 2 mm. Spun-bonded technology includes polymer melting, and then transportation and filtration of the polymer melt. The next steps are:

- Filament extrusion.
- Filament drawing.
- Filament deposition.

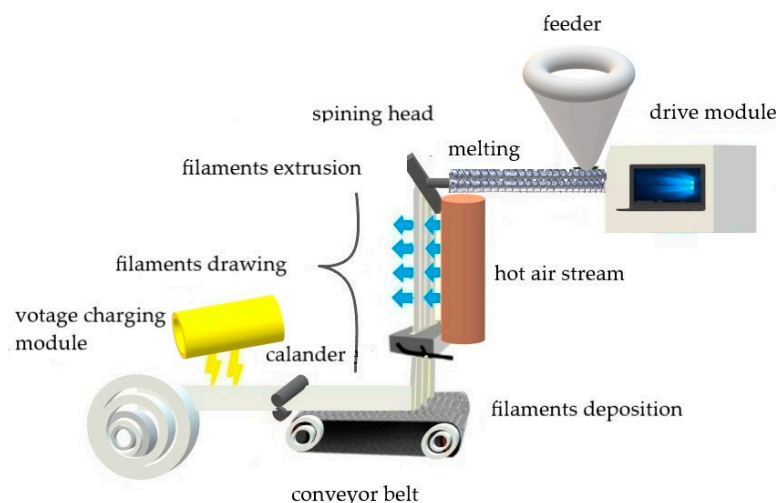


Figure 5. Spun-bonded technology.

The process of making nonwovens is finished by bonding by using, e.g., calender.

The physico-mechanical characterization of the nonwoven produced is shown in Table 1, and structural studies using a scanning electron microscope SEM were carried out (Figure 6).

Table 1. Results of physico-mechanical tests.

Parameter	Spun-Bonded Nonwoven
Thickness (mm)	0.24 ± 0.01
Surface density (g/m^2)	30.9 ± 0.8
Breaking force, along (N)	32.5 ± 1.8
Elongation, along (%)	30.4 ± 6.6
Tear strength, along (N)	35.6 ± 4.7

The biodegradation test was carried out for the nonwoven sample designed in Łukasiewicz Research Network—Lodz Institute of Technology and polypropylene facemask commercially available. Simultaneously, Cotton (100%; reference) and polypropylene face masks were tested. The analysis was carried out on a laboratory scale. Each 5×5 cm sample was tested in three repetitions under the conditions of repeatability and reproducibility. The results obtained at the end of the process were subjected to statistical analysis, and the values of the measurement uncertainty components were determined. The method used has been validated and accredited by the Polish Centre of Accreditation. The criterion of product biodegradability is the sample distribution in min. 90% over a maximum period of 24 weeks.

The study was conducted in compost under the controlled conditions of temperature (58 ± 2 °C) and humidity (40–65%). The designed method assumes that the medium (compost) used for testing must have a microbiological activity of at least 10^6 cfu in order to ensure appropriate conditions. Research reactors were filled with the test medium (unsifted

compost). Test samples in triplicate were weighed and placed in reactors, which were then placed in the calving test chamber while maintaining constant temperature and humidity conditions. The photo documentation was taken during the process.

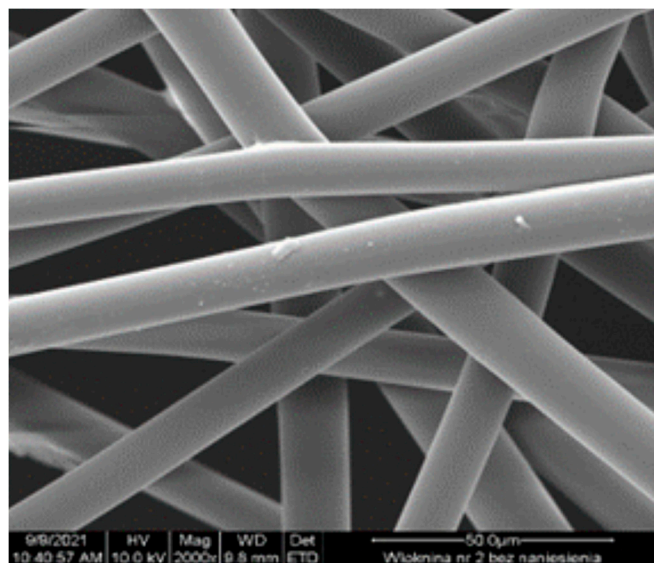


Figure 6. SEM images of spun-bonded nonwoven (mag. $\times 2000$).

Biocompatibility testing was also carried out in accordance with the standard [95]. The study was conducted on L922 (mouse fibroblast) cell lines from Sigma Aldrich (St. Louis, MO, USA). The cell cultures before analysis took 49 days in medium Minimum Essential Medium -MEM Eagle with Earle's Salts Base with supplement Fetal Bovine Serum (FBS) (Biological Industries, Beit-Haemek, Israel).

Incubation with the test material was carried out over 24 h at a temperature of 37 °C and 5% CO₂. The density of cultured cells was 10⁴ cells/well. The incubation plates were applied with solutions of 100% polyethylene extract, which is the negative control, 100% exact of the test material and its dilution in the range of 50–0.1%, and 0.01% Triton X-100 solution, which is the position control. The results were developed based on the absorbance value measured at the analytical wavelength of 450 nm. Absorbance was measured on a BioTek Synergy H1 microplate reader (Agilent Technologies, Santa Clara, CA, USA). Structural analysis of fibers was SEM-inspected using a microscope Quanta 200 (FEI, Eindhoven, the Netherlands). Microscopic analysis was performed on samples covered with a layer of gold in a high vacuum (electron-beam-accelerating voltage was 10 KV). A molecular analysis to determine the weight average molar mass, polydispersity index and distribution of molar masses was performed using the technique Gel Permeation Chromatography/Size Exclusion Chromatography. The tests using Agilent Series (Agilent Technologies, Santa Clara, CA, USA) equipped with the Optilab refractometric detector (Wyatt Technology, Goleta, CA, USA) were performed. Chloroform was used as an eluent in the analysis at a flow rate of 0.7 cm³/min. The PL gel Mixed-C 300 mm chromatographic column (Agilent Technologies, Santa Clara, CA, USA) to separate the polymer molecules was used. The conventional calibration technique was applied using polymer polystyrene standards.

Physico-mechanical properties of nonwovens were determined under environmental conditions (20 $\pm$ 2 °C and RH 65 $\pm$ 4%) according to PN-EN ISO 139:2006 [96]. For the material, the thickness was determined under PN-EN ISO 9073-2:2002. The TILMET—64 thickness gauge constructed at University of Technology (Łódź, Poland) with a pressure of 0.5 kPa was used. The surface density was applied based on PN-EN 29073-1:1994 [97]. The breaking force, elongation and tear strength were determined according to PN-EN 29073-3:1994 [98]. The measurements were made on the tenacity tester Instron model 5544 (Norwood, MA, USA).

5. Results and Discussion

The most popular nonwoven available on the market are spun-bond and melt-blown. Spun-bond is a nonwoven that is the first barrier to germs in specialized medical masks or personal protective equipment. In response to environmental challenges related to reducing plastic waste, a nonwoven fabric made of a biodegradable polymer was produced.

In medical masks, SMS nonwoven is typically used: spun-bond, melt-blown interlayer, and spun-bond nonwoven (Figure 7) [99,100]. The nonwoven melt-blown fabric is used as the main filter of the mask. The degree of filtration of the nonwoven is dependent on the diameter of the fibres and, therefore, the diameter of the pores. Standard melt-blown nonwovens contain fibres with a diameter of 1–7 μm , while spun-bond contains fibres with a diameter of 10–30 μm [94,101]. The spun-bond nonwoven fabric manufactured by the authors can be used in a protective face mask as a protective layer of the melt-blown nonwoven fabric.

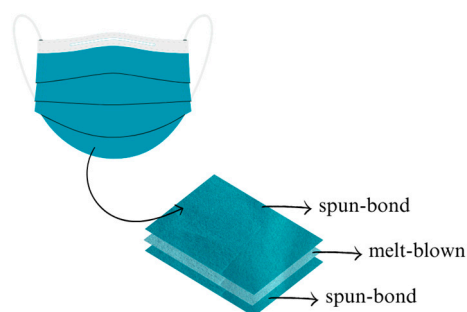


Figure 7. SMS nonwoven structure.

The obtained nonwoven was characterized by physico-mechanical parameters listed in Table 1. A spun-bonded nonwoven must have the appropriate parameters to be effective in its application. Breaking force, for example spun-bonded nonwoven made from non-biodegradable polymers, i.e., linear low-density polyethylene was 33 N [102]. In the commercial market, nonwoven fabrics made of spun-bonded polypropylene are available with a braking force of 10–200 N and an elongation of 50–300%, depending on their surface density. Different nonwoven fabrics are used based on the application. The newly developed biononwoven has similar physico-mechanical parameters as commercially available products [103,104].

A measurement of the diameter of elementary fibers was carried out on the basis of the SEM image. The analysis allowed us to determine the type of fibers distribution of fibers using Statistica 12 software, but also allowed us to evaluate the process of spinning the nonwoven using the melting method (Figures 8 and 9). The mean of the elementary fibers was 10.47 μm , while the median was 10.10 μm . Based on a statistical test Shapiro-Wilk enabling the examination of the normality of the distribution of features, it was found that the diameter of elementary fibers is not a random variable with a normal distribution, since the p -value is less than $\alpha = 0.05$. The value of kurtosis and skewness was determined. Kurtosis and skewness are measures of asymmetry that describe properties such as the shape and asymmetry of the analyzed distribution. They provide us with information about how variable values deviate when compared to the average value. They allow us to answer the question of whether the mean is in the center of the distribution (and therefore close to the median), how individual observations are distributed around this mean and what is the intensity of extreme observations. For nonwovens, the distribution of fiber diameters has a leptokurtic distribution what was presented at Figure 9. This means that the values of the characteristic of interest are concentrated around the mean and there is a greater chance of outliers appearing since a positive kurtosis value of 1.30 was obtained. The skewness coefficient above 0 indicates the right asymmetry of the distribution, for both nonwovens was above 1.23. The statistical data indicate that homogeneous elementary fibers were obtained, and the presence of outliers appeared -extreme values is due to the

characteristics of the processes (Figure 8). In the spinning process, fibers from the outer spinneret are subjected to the weakest tensile and blowout forces, resulting in extreme fiber diameter variations.

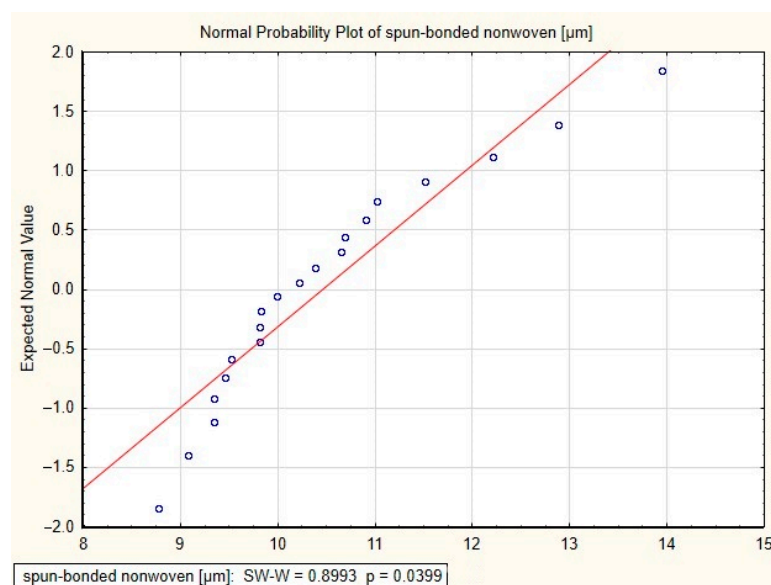


Figure 8. The normal probability plot of spun-bonded nonwoven fibers diameter.

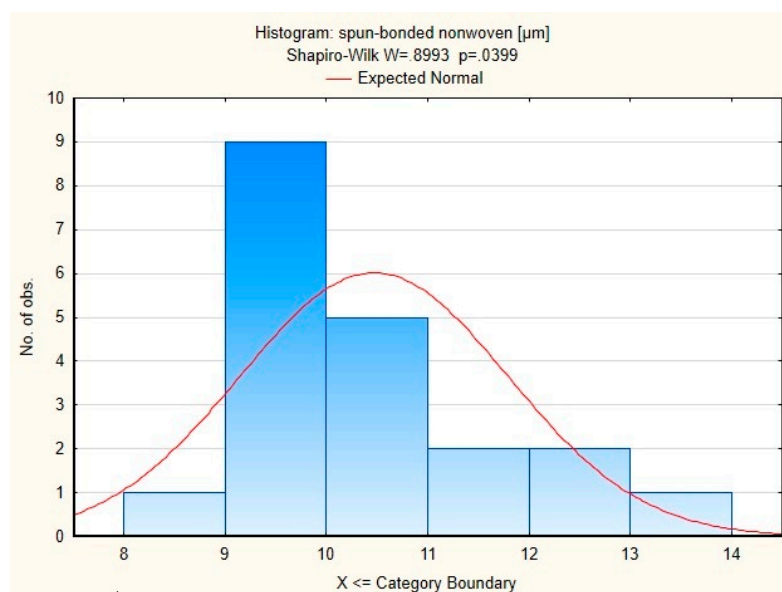


Figure 9. The histogram of the fibers diameter distribution in spun-bonded nonwoven.

The fiber obtained using the spun-bonded technique showed favorable mechanical properties; overall, the fibers were continuous and had a random, slightly aligned orientation [105].

Biodegradation tests of the nonwoven were conducted. The biodegradation degree (mass loss) was calculated. After 24 weeks the level of biodegradation of designed nonwoven reached an average of $91.4\% \pm 0.35$. The reference material (Cotton (100%)) reached 100% within 24 weeks, which confirms that the process was carried out correctly. Simultaneously the biodegradability of polypropylene facemask reached $0\% \pm 0.0$. Figure 10 presents the obtained results. Table 2 shows photo documentation of the process progress (macro and SEM).



Figure 10. Results of biodegradation process of PBS nonwoven, polypropylene mask and cotton 100%.

Table 2. SEM images and photographic documentation of the progress of the biodegradation process.

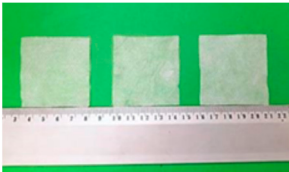
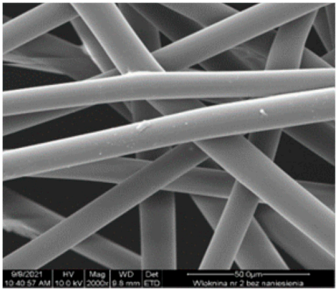
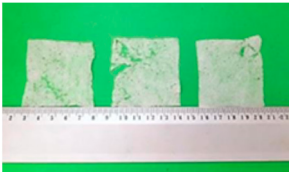
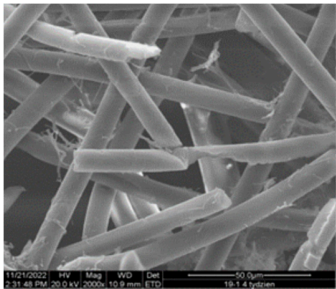
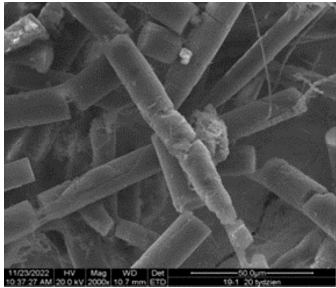
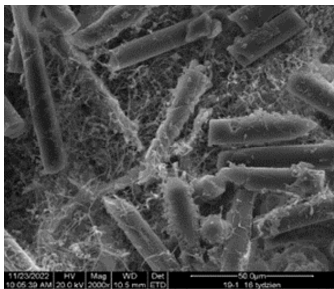
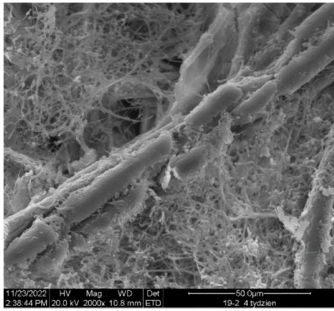
Week of Biodegradation Process	Photo Documentation	SEM ×2000 (mag)
1		 9/6/2021 HV Mag WD Det 10.40 kV 10.0 kV 2000x 10.8 mm ETO 50.0µm Width of 2 test specimens
4		 11/21/2022 HV Mag WD Det 2.31 kV 20.0 kV 2000x 10.8 mm ETO 50.0µm 19.14 kV/mm
16		 11/23/2022 HV Mag WD Det 10.31 kV 20.0 kV 2000x 10.7 mm ETO 50.0µm 19.14 kV/mm

Table 2. Cont.

Week of Biodegradation Process	Photo Documentation	SEM ×2000 (mag)
20		
24		

In accordance with environmental standards and guidelines, a product can be considered biodegradable in a compost environment if it biodegrades at least 90% within 24 weeks (6 months). The tested nonwoven reached $91.4\% \pm 0.35$ and can be described as biodegradable. The molar mass of the samples during the biodegradation process was also measured. After 24 weeks the measurement could not be made since the sample signal was on the noise line. Figure 11 shows the distribution of molar masses for the initial spunbonded sample and up to 20 weeks of biodegradation. During the biodegradation process, depolymerization, which means the degradation of the terminal mers of the polymer chain, occurred in the forefront. This is confirmed by the dispersion index, which increases only slightly during degradation (Table 3).

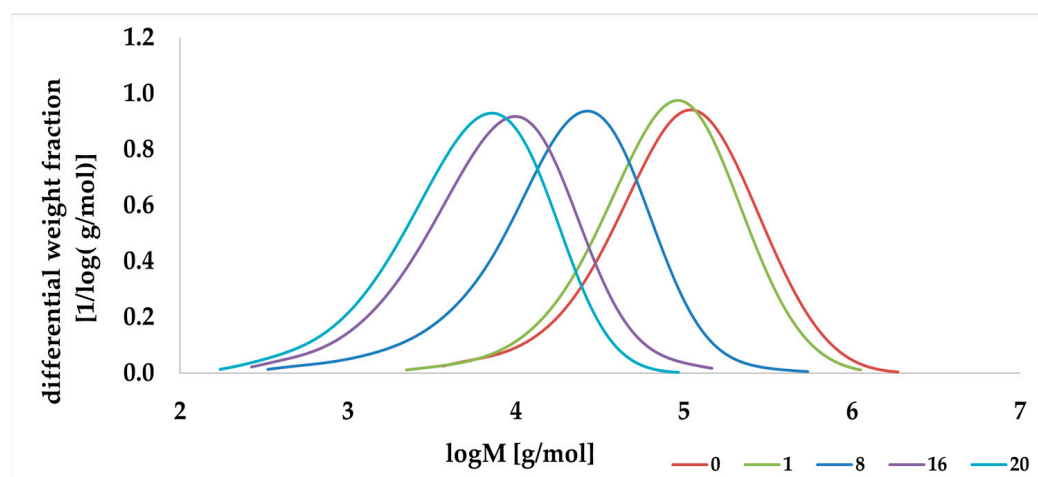


Figure 11. Molar mass distribution (MMD).

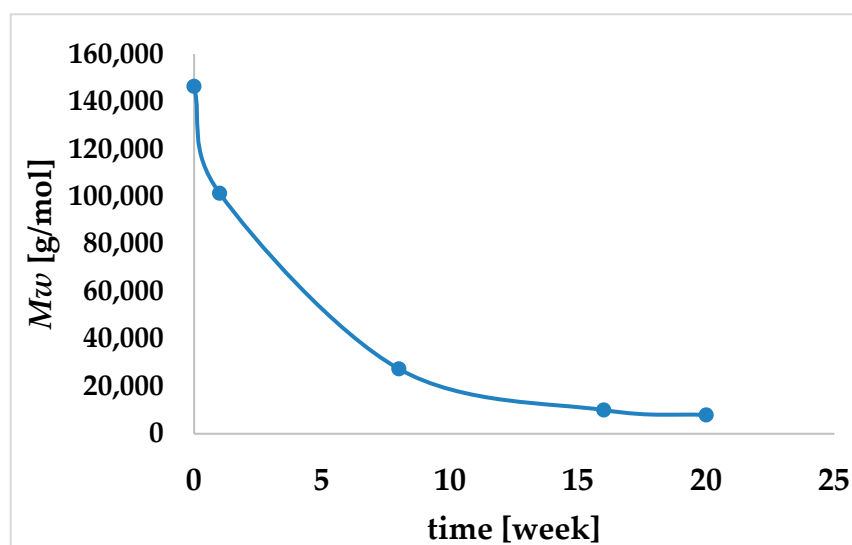
Table 3. Molecular parameters of spun-bonded.

Week of Biodegradation Process	M_w [g/mol]	Index Dispersion
1	146,400	2.59
4	101,300	2.24
8	27,300	2.92
16	10,000	2.84
20	7900	2.74
25	<900	-

An analysis was conducted to determine the order of biodegradation rates based on the change in M_w value. The experimental data in Table 3 was used to fit the algebraic rate laws that best describe the temporal decay of molar mass. These laws are shown as continuous lines in Figure 12 with the following equation:

$$\frac{1}{M_{wt}} = \frac{1}{M_{w0}} + kt$$

where M_{w0} is the average molar mass of the initial sample and M_{wt} the value at biodegradation time t [106]. The above equation corresponds to the second-order reaction. The results obtained from the GPC analysis of the nonwoven material residue after biodegradation are shown in Figure 13. The coefficient of determination R^2 was obtained at a very high level, while the reaction rate constant was $K 5.75 \times 10^{-6}$ and the half-life based on secondary biodegradation was 1.2 weeks. The knowledge of the ordinality of the degradation reaction and its parameters will allow the design of materials with controllable degradation times. The biodegradation rate parameters allow for modifications to slow down or speed up the process but also allow for a comparison of materials and degradation conditions.

**Figure 12.** The correlation of M_w values during the biodegradation process.

Biocompatibility testing was also carried out in accordance with the standard [95]. These methods specify the incubation of cultured cells in contact with extracts of a materials directly. These methods are designed to determine the biological response of cells in vitro using appropriate biological parameters (Figure 14). After incubation with spun-bonded nonwoven fabric, the average survivability of cells was 70.5%, which according to the standard allows us to conclude that the material is not cytotoxic. In Figure 14, the positive

control showed a decrease in cell count, while the nonwoven extract caused a significant reduction during incubation.

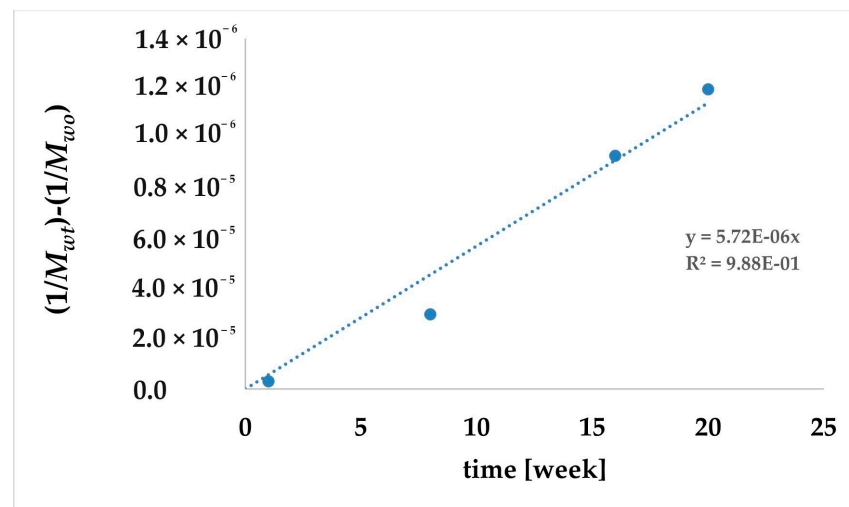


Figure 13. The biodegradation graph according to the second order reaction.

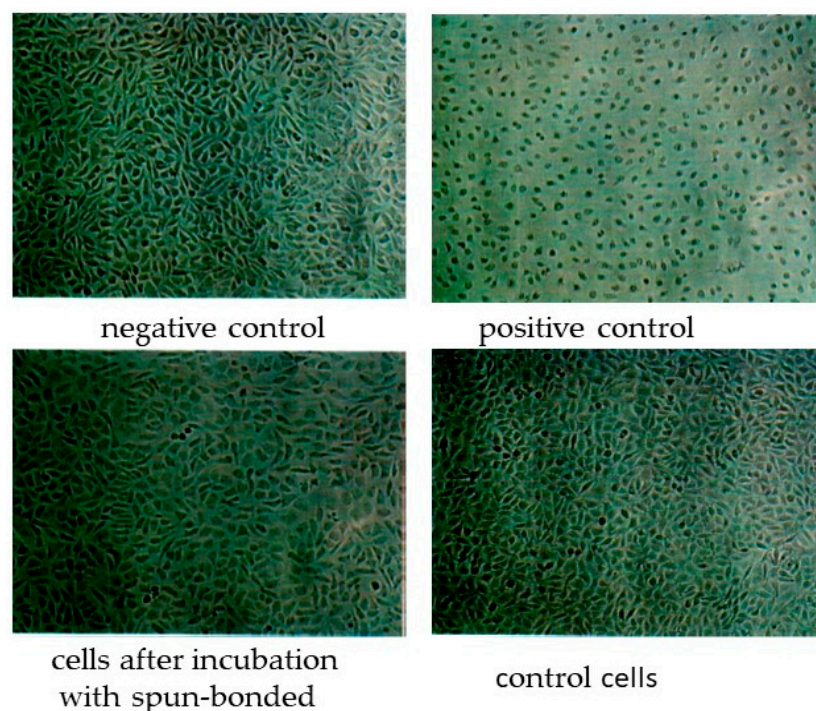


Figure 14. Photos of cells during incubation with the spun-bonded nonwoven.

The proposed nonwoven fabric meets the requirements for biodegradable materials (>90% of biodegradation within 24 weeks). Simultaneously, polypropylene masks did not show susceptibility to biodegradation (0% of biodegradation within 24 weeks). Cotton sample biodegraded in the same period of time.

The susceptibility to biodegradation of polybutylene succinate (PBS) was widely described in the literature in various environments, including soil, water, activated sludge and compost [107–109]. PBS can be decomposed into water and carbon dioxide via enzymatic or hydrolytic degradation [110]. The degradation of materials depends on chemical structure, glass transition temperature, melting point, crystallinity, polydispersion, etc. [111,112]. PBS is a versatile semi-crystalline polymer, which has an ester group in its chemical structure.

The polymer degrades into low molar mass polymers when exposed to water. These properties of the polymer translate into its susceptibility to microbiological degradation.

The need to use PEE is unquestionable. Nevertheless, from an environmental perspective, it is worth looking for new solutions that will not burden ecosystems. It should be pointed out that conventional masks are made of plastic. A good solution seems to be an application of biodegradable polymers.

The described nonwoven can be successfully used in the production of facemasks. The produced nonwoven fabric can be used as the first protective layer of a face mask, providing a barrier to larger particles.

6. Conclusions

Conventional polymers such as PET, PE, and PP have received criticism due to their environmental impact, and there is a growing demand for bio-based alternatives. However, completely replacing these polymers with alternatives is not currently feasible. PP is the second most widely used polymer after PE, and many industries are unable to completely eliminate plastic usage [47]. The COVID-19 pandemic has made it clear that sometimes the use of certain things is the only option. To protect human health and life, this aspect was more important than the environment. However, the amount of waste turns out to be significant and problematic for the environment after pandemic. Pollution affects not only the environment but also the economy, adversely affecting the implementation of sustainable development goals. Plastic waste harms health and has become a serious global environmental problem. The COVID-19 pandemic has led to increased demand for single-use products, increasing demand in an already out-of-control area.

The spun-bonded fabric presented in the article is biodegradable in a compost environment and additionally does not have toxic properties, so it can be used as an outer layer in a protective face mask or disposable medical devices. PBS is a well-known biopolymer that has been around for a long time. But unfortunately, its interest is still in the scientific community. Increasingly, manufacturers and entrepreneurs are looking for new solutions. Simple and adaptable to their production lines. In the article, we show that on industry-owned spun-bonded lines currently producing PP, PET or PE nonwovens, it is possible to easily re-brand their products for bioproduction. In this article, we indicate the processing parameters and the material that can be obtained from PBS. We present research methods that can be used for quality control. The research is extended to biodegradation, which makes it possible to obtain, among other things, a coefficient, but also biological, which will allow use in medicine as a safe product for humans. We also indicate its potential application. The previously available protective face masks, considered biodegradable, were made of polypropylene materials to which substances were added to only facilitate their fragmentation. Now, manufacturers can suppress the above products with biopolymer materials.

It is necessary to work out consensus and, above all, ensure the rational use of polymers and support the longest possible life of the product. Biodegradable materials can be an alternative, but in their case, too as long-term use will be positive. Humanity must dispense with single-use, short-lived products. No green technology can neutralize pollution and be the ultimate solution.

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