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Development and Characterization of Sustainable Coatings on Cellulose Fabric and Nonwoven for Medical Applications

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Abstract: The modification of cellulose woven fabrics and viscose nonwovens was carried out with the aim of preparing sustainable coatings from biodegradable natural polymers. The modification of fabrics with biodegradable natural polymers represents an ecological alternative to other textile modifications, such as the sol-gel process. Coatings were prepared from erythritol, gelatin, and collagen in various formulations with the addition of propolis and alginate fibers and a natural plasticizer (glycerin). The morphology of the materials was determined before and after modification with Dino-Lite. Moreover, the pH value, the drop test method, the angle recovery angle, the thickness, and the mass per unit area were monitored before and after modification. The results have shown that modifications had no significant effect on the thickness or mass per unit area. In contrast, in a larger proportion, they show hydrophilic properties, which favor their application for medical purposes—for example; for the absorption of exudates in wound dressings; etc. In addition, due to the neutral and slightly alkaline pH values of the modified samples, they can be suitable for external application on the skin. The results of the recovery angle of the modified samples proved that the samples did not tend to crease and that they retained their elasticity after modification with a very pleasant textile feel (fabric hand), making them even more suitable for everyday applications.

Keywords: textiles; modification; sustainable coatings; natural biodegradable polymers; alginate fibers; propolis; wound dressings

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1. Introduction

Polymers are advanced materials found in almost all everyday materials. By definition, polymers are large molecules (macromolecules) formed by bonding (chemically linking) a series of building blocks. The word polymer comes from the Greek, which means "many parts" [1]. There are two types of polymers, depending on their origin: synthetic and natural. Synthetic polymers are obtained from petroleum. Examples of synthetic polymers are fibers, flexible films, adhesives, resistant paints, and tough but lightweight solids. Natural polymers are found in nature and can be extracted. The importance of bio-based polymers lies in the large variety of renewable raw materials and the environmentally friendly prospects of the materials [2]. Therefore, as well as due to growing environmental awareness and the promotion of sustainable development, the development of new biodegradable and environmentally friendly materials is strongly encouraged.

For biodegradable polymers, whether synthetic or natural, the focus is on their development, on the development of the biodegradation process, and on the modification of the structure and properties of the polymer [3]. Such biodegradable polymers are often used in the field of environmental protection, in the textile, food, pharmaceutical, and cosmetics industries, etc. Natural biodegradable polymers, known as biopolymers, are also characterized by their biocompatibility [4]. Such materials can be modified for specific

applications or functionalized with various additives (fillers, dyes, and stabilizers). As they are biodegradable, they can easily be broken down by specific microorganisms. The speed of biodegradation is influenced by environmental factors and the properties of the individual polymer materials [5]. Biopolymer materials must not be toxic, must have suitable processing properties, and should preferably be produced from renewable sources. If these biopolymers are filling, then they can be used in the food industry as packaging material, in the textile industry with applications in medicine, in cosmetics, etc. The biopolymers that are suitable for food packaging are also suitable for contact with the skin, wounds, etc. (Table 1).

Table 1. An overview of biopolymer sources.

Source of Biopolymer	Biopolymer	Characteristics	Application
polysaccharides	agarose [6]	extremely hydrophilic, high porosity, and very stable under alkaline conditions	in the production of capsules, tablets, tablet liquid, other drug coating materials, food, research fields, etc.
	alginates [7]	renewable, nontoxic, control swelling properties, low cost, biocompatibility, good mechanical properties, chemical stability, good water barrier properties, good mechanical properties, stiffness	food, biomedical, pharmaceutical, drug delivery systems (DDSs), traditional wound dressings, dental impression material, in some formulations, preventing gastric reflux, etc.
	cellulose [8]	renewable, nontoxic, low energy consumption, high surface area, good oxygen, hydrocarbon barrier properties, high mechanical strength, high water vapor permeability, low cost, low density, high specificity, biocompatibility, odorless, tasteless, low cytotoxicity, chemical stability	developing paper and textiles, biomedical fields—medical implants; tissue engineering; wound healing; dressing; bone regeneration; cartilage renewal; orthodontic applications; drug delivery; etc.
	glucomannan [9]	great capacity to capture water and hydrate, forming a viscous gel	food additive (emulsifier and thickener) with the E number E425
	hemicellulose [10]	highly hydrophilic, soluble in alkali, and easily hydrolyzed by acids	functional food and pharmaceutical fields, etc.
	chitosan [11]	renewable, nontoxic, increased absorption properties, high antimicrobial activity, high biocompatibility, low production cost, good gas/aroma/UV/oil barrier properties, wettability, antioxidant, water-insoluble, good film-forming ability, good optical properties, transparent, flexible	biodegradable antimicrobial food packaging, bioprinting, temperature-sensitive hydrogels, wound management, winemaking and fungal source chitosan, natural biocontrol and elicitor, agricultural and horticultural use, etc.
	starch [12]	renewable, nontoxic, low cost, abundance, transparent, colorless, flavorless, tasteless, good lipid/oxygen/UV barrier properties, great film-forming ability, low water vapor permeability	food, processing industry, pharmaceutical, biomedical—tissue engineering of bone; bone fixation; carrier for the controlled release of drugs and hormones; as hydrogels; etc.
proteins	casein [13]	an amorphous white solid, tasteless and odorless	ointments, paper, paints, glues, textiles, varnishes, food, beverages, pharmaceuticals, health and personal care products, agriculture, etc.
	collagen [14]	renewable, nontoxic, excellent film formation ability, biocompatibility, antioxidant properties, good moisture/oxygen barrier properties, ensure structural integrity	orthopaedic, sports medicine, dental, wound care, cardiovascular, general, plastic, and reconstructive surgery, etc.

Table 1. *Cont.*

Source of Biopolymer	Biopolymer	Characteristics	Application
proteins	whey proteins [15]	antioxidant, antihypertensive, antitumor, hypolipidemic, antiviral, antibacterial, chelating agent	beverages, breads, snack items, bakery, confectionary products, and other nutritional food products in the treatment of cancer, HIV, hepatitis B, cardiovascular disease, osteoporosis, antimicrobial agents, etc.
	soya proteins [16]	highly soluble, dispersible, and dissolves rapidly and steadily	food, beverage, pharmaceutical, health and personal care products, agriculture, animal feed, poultry, biodegradable foams, edible films, packaging materials, biomedical materials, etc.
	zein [17]	renewable, nontoxic, good oxygen/gas barrier properties, high thermal resistance, high tensile strength, hydrophobic properties, high antimicrobial potential, good antioxidant properties, form adhesive film, high toughness, low water vapor permeability	pharmaceuticals, coatings, fibers, films, plastics, adhesives, inks, etc.
	gelatin [18]	renewable, nontoxic, low-cost, abundant, excellent film-forming ability, biocompatible, flexible, transparent, excellent water/UV/aroma/oxygen barrier properties, low water vapor permeability	foaming, emulsifying, and wetting agents in food, pharmaceutical, medical, and technical applications
sugar alcohol	erythritol	low hygroscopicity, good crystallinity, refreshing sweet taste, stable at high temperatures, stable in a wide pH range	food, medicine, cosmetics, chemical industry, pharmaceuticals, etc.
	glycerol	soluble, clear, nearly colorless, odorless, viscous, hygroscopic liquid with a high boiling point	processing aid in cosmetics, toiletries, personal care, pharmaceuticals, foodstuffs, etc.
lipids and waxes	vegetable oil and animal fats [19]	More cost-effective, float on water but are not soluble in it; greasy; lubricating	petroleum and metal processing, chemical industry, pharmaceutical
	waxes [20]	extremely hydrophobic	foods, cosmetics, pharmaceuticals, chemical engineering, paintings, etc.

Among the biopolymers derived from natural sources, polysaccharides attract a lot of attention due to their biomedical and physicochemical properties, such as biodegradability, biocompatibility, non-toxicity, renewability, and availability. Natural macromolecules, e.g., starch, gelatin, and collagen, are generally degraded in biological systems by a hydrolysis reaction and subsequent oxidation. Not surprisingly, most synthetic biodegradable polymers contain hydrolysable bonds along the polymer chain, e.g., amide, enamine, ester, urea, and urethane bonds, which can be biodegraded by microorganisms and hydrolytic enzymes. Since many proteolytic enzymes specifically catalyze the hydrolysis of peptide bonds adjacent to substituents in proteins, substituted polymers containing substituents such as benzyl, hydroxy, carboxy, methyl, and phenyl groups have been prepared in the hope that the introduction of these substituents may increase biodegradability [21]. In addition, most enzyme-catalyzed reactions take place in aqueous media, and the hydrophilic/hydrophobic nature of synthetic polymers has a significant impact on biodegradability. It appears that polymers containing both hydrophilic and hydrophobic segments are more biodegradable than polymers containing either only hydrophilic or only hydrophobic structures [3]. In view of this, the modification of textiles with biodegradable polymers is certainly an alternative to the usual textile treatments, in particular, the sol-gel process [22]. The sol-gel process offers great possibilities in terms of adaptability and

the achievement of targeted modifications, albeit through the combination of different inorganic and organic starting materials. The sol-gel process, in its narrower sense, comprises hydrolysis and condensation reactions of metal alkoxides, whereby a continuous three-dimensional metal oxide network is formed [23]. The sol-gel process, like many other processes in the textile industry, essentially stands for the modification of textiles with synthetic compounds, while the modification of textiles with biopolymers represents a switch to sustainable, biodegradable, and natural polymers. Natural polymers have a much more complex structure than synthetic polymers, which have a relatively simple structure. The basic constitutional units of natural polymers are more complex than those of synthetic polymers, which affects the conformation and configuration of the macromolecules. This complexity of natural polymers offers a number of advantages in the modification of textiles with the aim of obtaining potentially biodegradable medical or cosmetic materials (for e.g., wound dressings). The general principle of action of most wound dressings is that they dissolve within 48 h on an open wound by interacting with microorganisms and other bodies [24]. In this way, they eliminate necrosis and promote the formation of "young skin". Wound dressings are usually based on synthetic compounds, but they can also be based on bioderivative polymers and hydrogels, namely collagen and alginate. **Collagen** belongs to the group of multifunctional proteins most commonly found in bones, skin, tendons, and ligaments (Figure 1). The word "collagen" comes from the Greek words "kola", which means gum, and "gen", which means producing. Collagen is biodegradable and biocompatible, i.e., it rarely causes immune reactions in the body. It is therefore suitable in biomedicine for the production of implants and in various modifications as a carrier of biomass or as an active ingredient in a drug [25]. It is a component of dental composites, skin regeneration templates, and biodegradable matrices. Moreover, it is used in cardiovascular surgery, plastic surgery, orthopedics, urology, neurology, and ophthalmology [26]. Collagen can be extracted from natural animal and plant sources or obtained from recombinant protein production systems using bacteria, yeast, insects, plants, mammalian cells, or artificial fibrils [27]. The most common animal sources of collagen are human collagen, bovine collagen, porcine collagen, and fish collagen, with bovine collagen being widely used in collagen-based products. Collagen is a great protein that does not cause unwanted reactions in the body; it is sterile and contains no fever-producing substances; it does not cause allergic reactions on the skin (only in rare cases); it increases fibroblast production; it promotes platelet distribution at the site of injury; and it preserves leukocytes and macrophages. Collagen plays a crucial role in the wound healing process as it promotes cell proliferation, angiogenesis, and the deposition of collagen in the wound bed. In a chronic wound, the deposition of new collagen is delayed, and there are problems when certain processes delay healing. One of these processes is matrix metalloproteinase (MMP) [28]. Another important factor that can delay the healing process is the formation of a biofilm. The biofilm then protects the microorganisms from the body's immune response and delays wound healing. Collagen as part of the wound dressing can create a moist healing environment that enables the wound to heal. It is able to inhibit or inactivate the MMPs while providing the enzymes with additional collagen sources so that the body's own collagen can be utilized for new tissue growth. When collagen dressings are combined with silver or other active ingredients, they prevent biofilm from entering the wound bed and prevent infection. This was also the idea behind this work, but using only natural, biodegradable polymers and their combinations to achieve a synergistic approach.

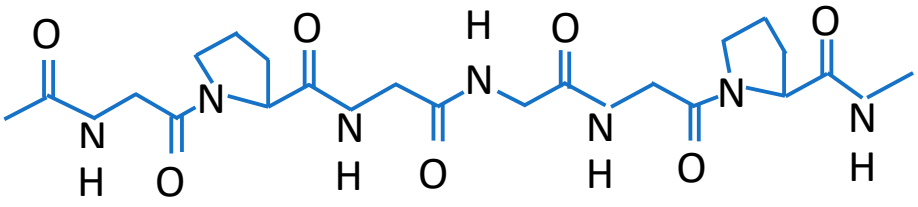


Figure 1. Chemical structure of collagen [29].

Alginate can be synthesized from the cell walls of various species of brown algae: *Laminaria hyperborea*, *Ecklonia maxima*, *Ascophyllum nodosum*, *Eisenia bicyclis*, *Macrocystis pyrifera*, *ecc*., and from various species of bacteria: *Azotobacter* and *Pseudomonas*. The alginate obtained from brown algae is of commercial importance for the food, pharmaceutical, and cosmetics industries, etc. The extraction of alginates from brown algae is carried out in an alkaline medium with sodium carbonate, sodium hydroxide, or aluminum hydroxide in several steps after the collected algae have been dried and crushed. The FDA (Federal Drug Administration) has approved the use of sodium alginate in the food, biomedical, and pharmaceutical sectors due to its biological properties, i.e., its lack of toxicity and immunogenicity, its biocompatibility, and its biodegradability. Alginates belong to the group of polysaccharides with a linear structure that are often used to produce hydrogels, which are widely used in medicine due to their biocompatibility. For the use of alginate hydrogels in medicine, it is necessary to improve the mechanical properties so that covalently cross-linked alginate hydrogels are used instead of ionically cross-linked hydrogels. They are prepared by mixing alginate with suitable biocompatible and biodegradable polymers of natural or artificial origin, whose chains are much more flexible compared to the rigid polysaccharide chains of alginate [30]. Applications include wound closure, the treatment of burns, hemostasis, hernia repair, and the repair of bone and cartilage defects, as well as various dental applications and guided bone repair. With this aim, alginate fibers were used in this work, where it was necessary to achieve sustainable coatings.

Erythritol belongs to the group of sugar alcohols, also known as polyols, which are formed by hydrolysis processes of the aldehyde or ketone group of various carbohydrates. Polyols are naturally abundant in fruit and vegetables, as well as in fermented foods. Erythritol is also a symmetrical molecule and therefore only exists in one form, the meso form (Figure 2).

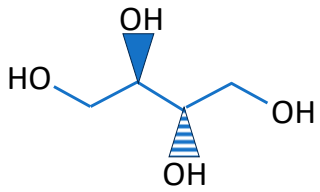


Figure 2. Chemical structure of erythritol [31].

Erythritol is currently found alone or in combination with other polyols in foods, cosmetics, and pharmaceuticals. Polyols are frequently used in the personal care industry, e.g., in toothpaste, mouthwashes, creams and lotions, make-up, perfumes, or deodorants. Erythritol can be used in a variety of solid and liquid formulations, including granulated powders, tablets, tablet coatings, consumer-friendly lozenges, medicated chewing gum, syrups, and oral care products. For pharmaceutical use, its interaction with water and its high stability at high temperatures and in acidic or alkaline environments are crucial [31]. Due to its properties, erythritol offers good flowability and stability as an excipient, which makes it an ideal carrier for active ingredients in sachets and capsules. Erythritol can suppress the growth of bacteria in the mouth as it has antibacterial potential against certain pathogens. While sugar alcohols such as erythritol are said to have caries-preventive properties, they have been found to have a positive effect on the prevention of gingivitis by preventing the maturation of oral biofilms [32]. When 10% erythritol is present, bacterial growth is slowed, and DNA/RNA synthesis of the periodontitis bacterium *P. gingivalis* is reduced in biofilms containing *Streptococcus gordonii* [32]. Based on the above-mentioned properties of erythritol, it was assumed that erythritol can serve as an active ingredient against biofilms for possible use in chronic wound dressings.

Gelatine is a naturally occurring, biodegradable, and multifunctional protein-type biopolymer that is thermos-reversible in nature. It is a tasteless and odorless substance that is transparent and pale yellow in color. It is used in a variety of biomedical, medical, and pharmaceutical applications. Due to its biocompatible and biodegradable properties,

gelatin is used in the manufacture of capsules or tablets or as a component of wound dressings, hemostatic sponges, or blood volume substitutes. In drug delivery systems, gelatin nanoparticles have been extensively used to improve drug delivery and the controlled release of anti-cancer drugs [33]. It is a non-irritating, relatively low antigenic, inert, and inexpensive ingredient. The gelatin structure has numerous functional groups, such as amine and carboxyl groups, that enable structural modifications such as coupling with targeted ligands, crosslinkers, and shielding agents (Figure 3). Like albumin, the numerous functional groups of gelatin enable further surface functionalization to achieve active targeting of cancer cells.

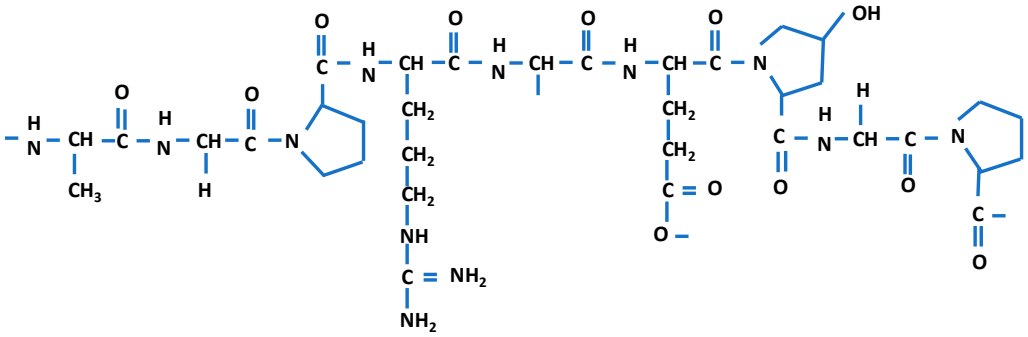


Figure 3. Chemical structure of gelatin [34].

Propolis, or bee glue, is a resinous mixture that honeybees collect from tree buds, sap streams, or other botanical sources. The chemical composition of propolis varies and depends on the geographical region, time of collection, season, lighting, altitude, and availability of food during propolis collection. Propolis is a non-toxic natural product, but some cases of allergies and contact dermatitis have been described, especially among beekeepers. Together with other bee products (honey, royal jelly, and pollen), propolis has great therapeutic properties and has been used in popular medicine in various parts of the world since ancient times. Since ancient times, propolis has been used and considered a medicine for skin diseases. Hippocrates, a Greek physician who is considered to be the father of modern Western medicine, was the one who recognized the healing properties of propolis [35]. The biological activities of propolis are attributed to a variety of main chemical constituents, including phenolic acids, phenolic acid esters, flavonoids, and terpenoids such as CAPE, artepillin C, caffeic acid, chrysin, galangin, quercetin, apigenin, kaempferol, pinobanksin 5-methyl ether, pinobanksin, pinocembrin, and pinobanksin-3-acetate [36]. It is assumed that flavonoids are the most important compounds responsible for the positive effects of propolis. They are defined as phenolic compounds from plants that act in various physiological processes, including the absorption of vitamins, the healing process as antioxidants, and the exertion of the antimicrobial and modulating functions of the immune system [37]. Propolis is said to have antiseptic, antibacterial, antifungal, astringent, spasmolytic, anti-inflammatory, anesthetic, antioxidant, antifungal, anti-ulcer, anti-cancer, and immunomodulatory effects. An important factor in impaired wound healing is the formation of biofilms. Propolis, as an antimicrobial agent, can reduce the formation of biofilms and lead to accelerated healing. Although propolis is a natural product that is currently heavily marketed, skin contact can cause allergies due to some components of the formulation. Clinical and safety studies on propolis are still needed. Propolis could be described as a natural antibiotic of a broad spectrum, which as such is ideal against biofilms in chronic wounds, alone or in synergy with some of the natural biodegradable polymers, which is the aim of this work.

Glycerol is the simplest trivalent alcohol (Figure 4). It is an essential component of compounds that build biological membranes and is found in all lipids (fats) of plant and animal origin. There are three types of glycerol: crude glycerol, which consists of about 40% to 88% water, and other impurities such as methanol, sodium chloride, sodium

hydroxide, etc. The technical grade glycerol is about 95% to 98% pure and contains water and other impurities. It is mainly used for industrial manufacturing purposes [38]. The third grade is 99.7% pure and is referred to as glycerol with a safe, tested purity of up to 99.7%, which fulfills the requirements of the European Pharmacopoeia (PhEur), the US Pharmacopoeia (USP), and the Food Chemistry Code (FCC), contains no GMOs, and is gluten-free [39]. It is used in the cosmetics industry (creams, soaps, lotions, shower gels, etc.), in oral hygiene products (toothpaste, mouthwash, etc.), in the pharmaceutical industry (as a binder for tablets, in medicines for burns, bites, cuts, psoriasis, etc.), in the food industry (as a preservative—E422 and natural stabilizer), as an ingredient in e-liquid for e-cigarettes, etc. In this work, glycerol was used as a plasticizer and distilled water as a solvent. Given its properties, it is considered that it can contribute to the development of sustainable coatings as a potential equivalent active ingredient in wound dressings (it retains moisture, which is very important as wounds heal faster in a moist medium and complies with pharmacopoeia requirements).

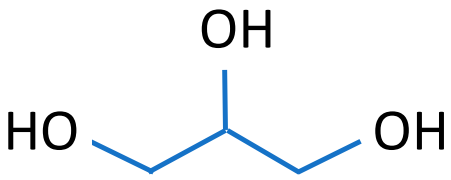


Figure 4. Chemical structure of glycerol [38].

Wounds colonized with biofilms are one of the greatest challenges in chronic wound care. As wound dressings fulfill the so-called post-turner criteria (monitoring exudate and infection, ensuring adequate moisture and temperature of the wound, appropriate, constant pH in the wound, non-toxic and semi-permeable dressings for gases, etc.), sustainable coatings must first be developed that can be treated medically later if necessary [40]. Every good wound dressing must reduce the biofilm and/or prevent the formation of a new biofilm. The biofilm is a structured community of microbes with genetic diversity and variable gene expression (phenotype) that produces behaviors and defense mechanisms designed to generate unique infections (chronic infections) characterized by high tolerance to antibiotics and biocides while being protected from host immunity [41]. Wound dressings should be used as an aid to support biological wound healing. The correct course of wound healing therefore depends not only on the type of wound and the systemic factors but also on the design of the wound dressing and the material interactions within the wound area. Wound dressings should be designed to support the progression of acute wound healing, prevent the transition from acute to chronic wounds, help wounds reverse from chronic to acute, or enable a combination of these processes [42]. The effectiveness of wound dressings varies as it depends on the type of bacteria forming the biofilm, the amount of organic matrix, the hyper-variability of the biofilm, and the environment. No single dressing is effective against all types of microbes in it. This work is part of an active multimodal approach to solving the above problem using biopolymers and the development of sustainable coatings. Sustainable coatings were developed in this work on the most commonly used materials by domestic manufacturers for medical textiles (i.e., cotton fabrics for the production of medical work wear, sheets, blankets, and medical compresses; viscose nonwovens for disposables for versatile medical use, from personal care, respiratory, and wound care to orthopedic products and filters). In the case of sustainable coatings, the aim was to ensure that sustainable coatings do not impair the pleasant textile feel (fabric hand), the pH value, the increase in the value of the mass per unit area and the thickness of the samples, clear and transparent coatings, good absorbency (five seconds or less), and the uniformity of the hydraulic properties. Sustainable coatings have been designed as bio-based coatings that are environmentally friendly (soil, air, and water) and meet the requirements of the Food and Drug Administration (FDA) and the European Medicines Agency (EMA). The advantage of the sustainable coatings in this

work is that they consist of compounds that can be taken orally and are therefore suitable for external use. In this work, only the developed sustainable coatings were analyzed, observed, and theoretically considered for possible usage in chronic wound dressings.

2. Materials and Methods

2.1. Preparation of Materials

2.1.1. Preparation of the Textile Materials

Nonwoven fabrics for the medical program were used (versatile medical use, from personal care, respiratory, and wound care to orthopedic products and filters). The composition was determined according to ISO/TR 11827:2012 [43] and revealed that the nonwovens are viscose fibers; the mass per unit area determined according to ISO 3801 [44] is 101 g m^{-2}, and the thickness determined according to ISO 5084 [45] is 0.34 mm.

Woven fabrics for the medical program were used (for the production of medical workwear, sheets, blankets, medical compresses, etc.). The composition of the fabric was determined according to ISO/TR 11827:2012 and revealed that the fabrics are cotton fibers, the mass per unit area determined according to ISO 3801 is 104 g m^{-2}, and the thickness determined according to ISO 5084 is 0.33 mm. The fabric was bleached according to its main use, i.e., as a standardized fabric for hospitals and surgical procedures.

Mass per unit area and thickness are the basic characteristics of textile materials. Fabric thickness is defined as the distance between the top and bottom surfaces of a fabric under standard pressure. It is measured in millimeters. The fabric weight is measured in grams. In the metric system, the mass per unit area of all types of textiles is expressed in grams per square meter (g m^{-2}). Variations in either mass per unit and/or thickness determine variations of local fabric packing density and porosity as well as pore size distribution and therefore influence the appearance, permeability, thermal and sound insulation, filtration, tensile, liquid barrier, penetration properties, etc.

2.1.2. Preparation of Sustainable Coatings

Based on the advantages of the properties of natural biodegradable polymers mentioned in the introduction, it was decided that the "basis" of sustainable coatings would be erythritol, gelatin, and collagen (Table 2). Each of them in itself can be a transparent and translucent sustainable coating and modify textile materials in such a way that the pleasant textile feel (hand fabric) is not disturbed. Of course, the above depends on the processing parameters. At the beginning, different ratios of the polymers to water as a solvent, duration of the preparation process, and temperature were selected. Numerous preliminary tests were carried out in this way. The main idea was to choose the best treatment of erythritol, gelatin, and collagen, taking into account the requirements for maintaining the textile character of the newly created textile protective material.

Table 2. Properties of the polymers.

Polymer	**Erythritol** $C_4H_{10}O_4$	**Gelatin** $C_6H_{12}O_6$	**Collagen** $C_{57}H_{91}N_{19}O_{16}$	**Glycerol** $C_3H_8O_3$	**Propolis** $C_{17}H_{16}O_4$	**Sodium Alginate Fibres**
Molar mass [g mol^{-1}]	122.12	45,00	1302.5	92.09	281.31	/
CAS number	149-32-6	9000-70-8	9000-70-8	56-81-5	/	/
Note	from corn	100% beef gelatin	fish collagen	/	propolis extract in an aqueous solution with niacin and sage	sodium alginate fibers with sodium and calcium carbonate

The best treatment should serve as a basis for the separate addition of propolis and alginate fibers. Glycerol was used as a plasticizer to prevent denaturation of the chains during the reaction. Each polymer and each compound initially had great properties, but it was necessary to modify the textile materials. To modify textile materials and to achieve the desired properties (pleasant textile feel (fabric hand), the neutral pH value, the increase in

the value of mass per unit area and thickness of the samples, clear and transparent coatings, good absorption capacity (five seconds or less), and the uniformity of hydraulic properties).

Each polymer (erythritol, gelatin, and collagen) has biocompatible and biodegradable properties, but the most important effects for sustainable coatings in this work are, in short:

- erythritol slows down bacterial growth in biofilms.
- gelatin has numerous functional groups that enable further surface functionalization to achieve active targeting of diseased cells.
- collagen can create a moist healing environment that enables wound healing, and it is able to inhibit or inactivate the MMPs while providing the enzymes with additional collagen sources so that the body's own collagen can be utilized for new tissue growth.

The treatment of erythritol, gelatin, or collagen with propolis or alginate fibers could achieve a synergistic approach because:

- propolis is a natural broad-spectrum antibiotic, which, as such, is ideal against biofilms in chronic wounds.
- alginate fibers have the task of maintaining a physiologically moist microenvironment, minimizing bacterial infection at the wound site, and facilitating wound healing.

Any treatment on textile materials could be a single-layer product or part of a multi-layer wound dressing against biofilms.

In the first step of the treatment with erythritol, a solution of distilled water, erythritol (bio&bio, Zagreb, Croatia), and propolis (Medex, Ljubljana, Slovenia) was prepared. The solution was mixed thoroughly. Then, glycerol, $C_3H_8O_3$ (Gram-Mol, Zagreb, Croatia), was added dropwise to this solution, increasing the speed of mixing. The process was carried out under constant magnetic stirring until a homogeneous solution was obtained. In the second step, the 5 × 5 cm^2 samples were coated using the dip coating method on a dip coater at a predetermined drawing speed of 1 mm s^{-1} to obtain a thin coating (Figure 5).

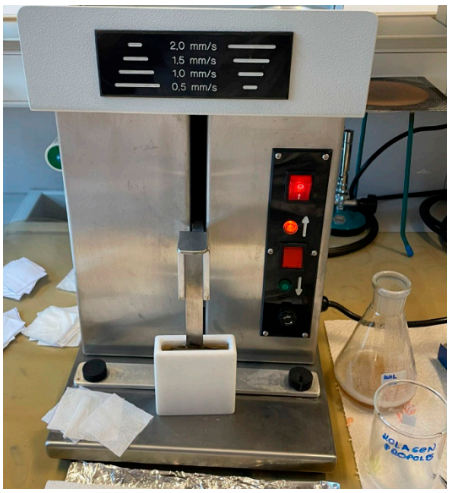


Figure 5. Apparatus for dip coating.

The modified samples were dried at room temperature for 24 h and then at 40 °C for 60 min (Figure 6).

The erythritol solution with alginate fibers (Biofarm, Lučko, Croatia) was prepared in the same way as that with propolis, with the difference that sodium alginate fibers (Biofarm) were added instead of propolis. Gelatine (Nutrimedica, Zagreb, Croatia) and collagen (Mipama, Opatówek, Poland) were prepared separately, as was erythritol, first with propolis and then with alginate fibers. The second step was the same for all modifications. A schematic representation of the modifications carried out can be found in Table 3.

Figure 6. Samples dried at room temperature.

Table 3. Schematic representation of the modifications carried out.

Erythritol (1 g) + distilled water mixing on a magnetic stirrer with a triangular magnet		**Gelatin (5 g)** + distilled water mixing on a magnetic stirrer with a triangular magnet		**Collagen (5 g)** + distilled water mixing on a magnetic stirrer with a triangular magnet	
↓	↓	↓	↓	↓	↓
+ propolis 10 mL + glycerol 5 mL	**+ alginate 10 mL + glycerol 5 mL**	**+ propolis 10 mL + glycerol 5 mL**	**+ alginate 10 mL + glycerol 5 mL**	**+ propolis 10 mL + glycerol 5 mL**	**+ alginate 10 mL + glycerol 5 mL**
20 ± 2 °C 15 min ↓ The samples were kept at room temperature for 24 h ↓ The samples were fixed at 40 °C for 60 min ↓ Materials morphology with Dino-Lite pH of the Water-Extract from Wet Processed Textiles Drop test method Determination of recovery by measuring the recovery angle Determination of thickness and mass per unit area, before and after treatment					

Table 4 shows the codes of the samples and the polymers used.

Table 4. Sample code with biopolymers and active compounds.

Code		Biopolymer	Active Compound	Note
Nonwoven fabric	NN	/	/	untreated
	NEP NEA	Erythritol	propolis sodium alginate	
	NGP NGA	Gelatin	propolis sodium alginate	
	NCP NCA	Collagen	propolis sodium alginate	
Cotton fabric	FN	/	/	untreated
	FEP FEA	Erythritol	propolis sodium alginate	
	FGP FGA	Gelatin	propolis sodium alginate	
	FCP FCA	Collagen	propolis sodium alginate	

2.2. Determination of the Morphology of the Materials

The surface properties of untreated and treated nonwoven and woven fabrics were determined using the Dino-Lite microscopy system. The device used was the Dino-Lite Pro AM413T (Torrance, CA, USA), a digital microscope with a resolution of 1.3 megapixels that can achieve a magnification of up to 200×. The Dino-Lite digital microscope is a universal portable USB microscope that is easy to use. It offers the user crystal-clear images in combination with access to advanced software features via the DinoCapture 2.0 software. The high-quality optics enable extremely sharp image display with pronounced brightness, natural color display without deviations, and better image quality for superficial textile modifications. It is possible to observe the morphological structure of the material, the homogeneity or heterogeneity of the coatings, possible agglomerates of the coatings, thickened and thinned areas of the fibers, etc.

2.3. Activity of Hydrogen Ions

The hydrogen ion activity, or pH, of the water extract from wet-treated textiles was determined according to AATCC test method 81-1988 [46]. The sample (10 g) was boiled in distilled water (250 mL) for 10 min (80 °C). The water extract was cooled to room temperature, and the pH was determined using a pH meter according to the manufacturer's instructions.

2.4. Drop Test Method

The drop test method, known as absorbency of bleached textiles, was performed in accordance with AATCC 79-2000 [47] and under standard atmospheric conditions (20 ± 2 °C, 65 ± 4%). In this test method, a drop of water is dropped from a height of 1 cm onto the surface of a test sample. The time it takes for the reflection of the water drop to dissipate is measured and recorded as the wetting time. Five seconds or less is generally considered sufficient absorption capacity. In addition to the time taken for the droplet to be absorbed, the appearance of the remaining droplet was also evaluated, resulting in an assessment of the uniformity of the hydrophilic property. To facilitate the evaluation of the uniformity of the hydrophilic property, a drop of methylene blue solution can be added. Absorbency is one of several factors that determine the suitability of a fabric for a particular use. It is important for fabrics that are to be dyed or for fabrics that are to be treated with resin or other special finishes. Absorbency is the ability of a fabric to absorb moisture and retain liquids in its structure, which affects skin comfort, water repellency, crease recovery, and other properties. Good absorbency requires fast absorption and holding capacity.

2.5. Determination of the Crease Recovery Angle

The determination of the crease recovery of horizontally folded samples by measuring the recovery angle was carried out in accordance with EN ISO 2313 [48] and under standard atmospheric conditions (20 ± 2 °C, 65 ± 4%). A conditioned rectangular sample of specified dimensions is folded and held folded for a specified time (5 min) under a specified load (1.019 kg) using a loading device. The crease load is removed, and the sample is allowed to recover for 5 min in the crease recovery tester. The crease recovery angle was read on the scale of the tester. The crease recovery angle measures how effectively the fabric can restore its original structure and smoothness when the external force that caused the crease is removed. Fabrics with excellent crease recovery have the ability to bounce back quickly and effectively, minimizing the appearance of creases. The crease recovery ability of a fabric depends on several factors, including the type of fiber, the fabric construction, and the finishing methods used. Natural fibers such as cotton, wool, and silk generally have good crease recovery, while synthetic fibers such as polyester and polyamide require additional treatments or modifications to improve their crease resistance.

3. Results and Discussion

The results include the morphology of the materials, the hydrogen ion activity, the hydrophilicity, and the wrinkle recovery properties.

3.1. Results of the Morphology of the Materials

The morphology of the coatings, as determined by Dino-Lite analysis, is shown in Table 5 to demonstrate the morphological differences between the sustainable coatings produced with three natural biodegradable polymers—erythritol; gelatin; and collagen.

Table 5. Morphology of the sustainable coatings.

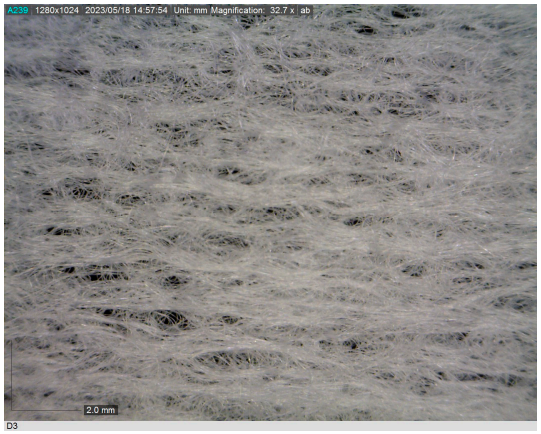
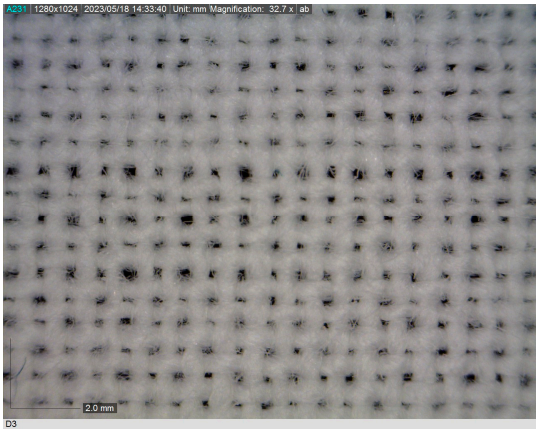
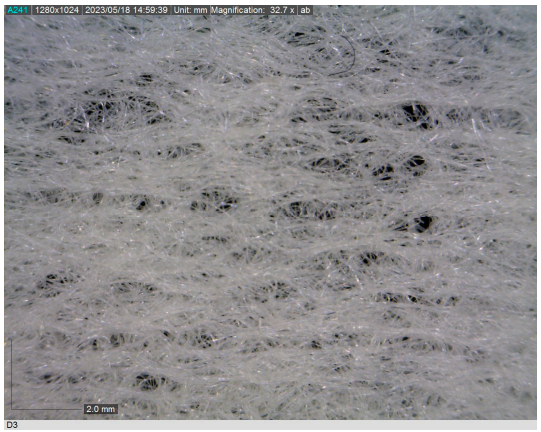
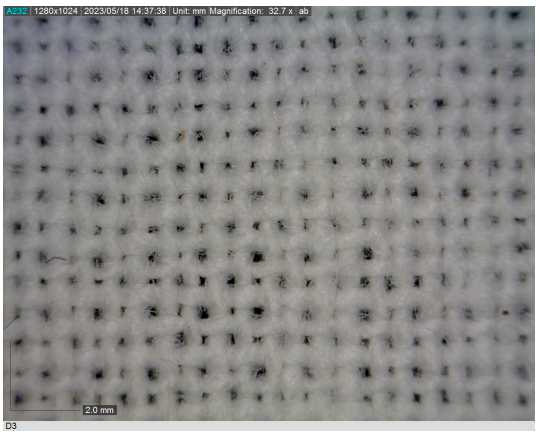
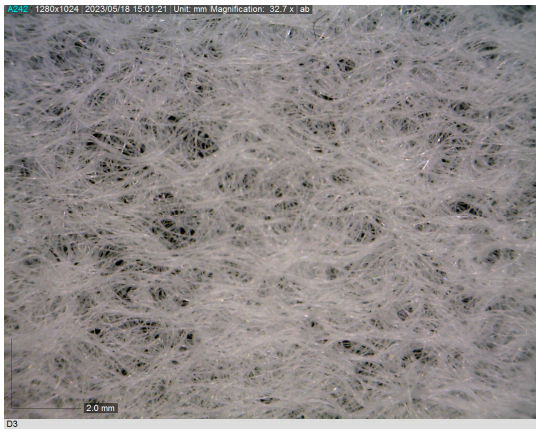
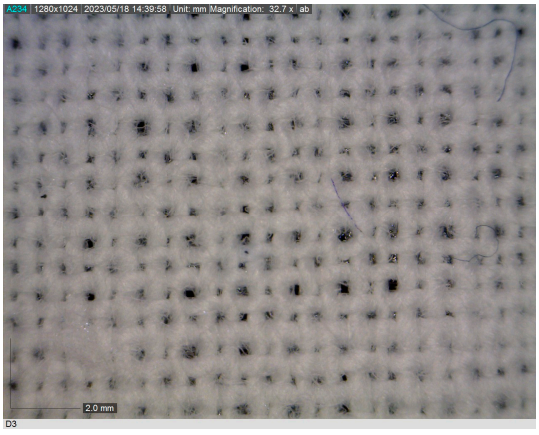
Code	Morphology of the Materials	Code	Morphology of the Materials
NN		FN	
NEP		FEP	
NEA		FEA	

Table 5. *Cont.*

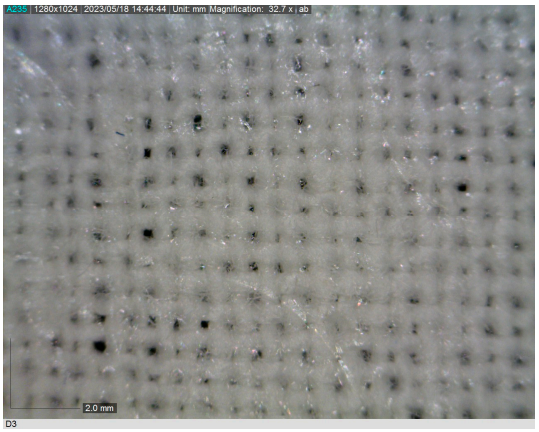
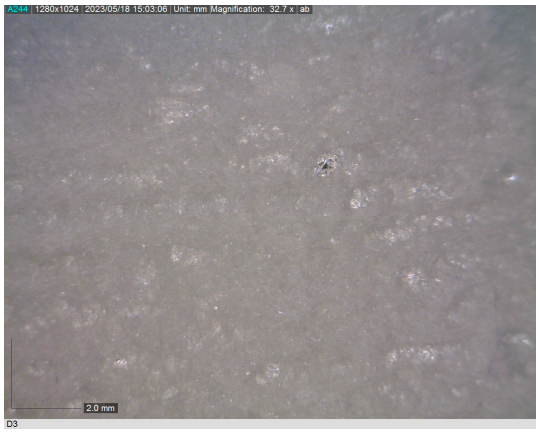
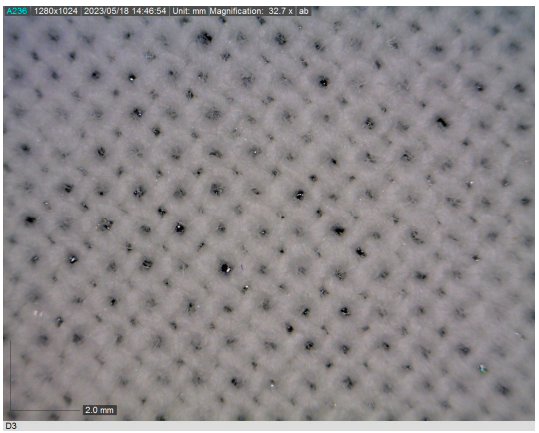
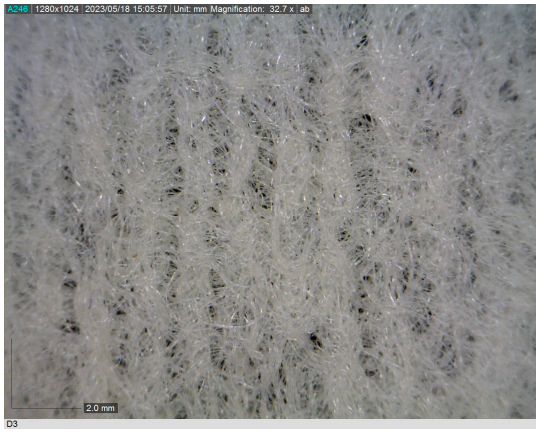
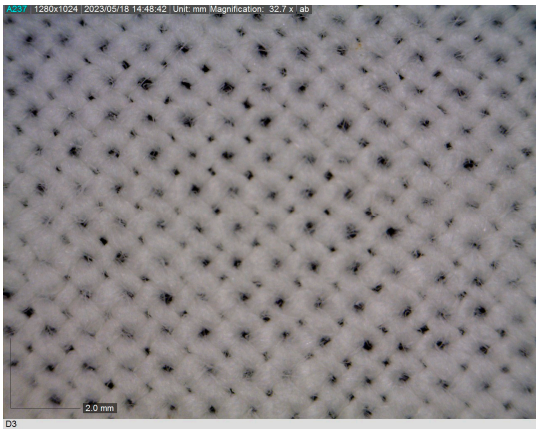
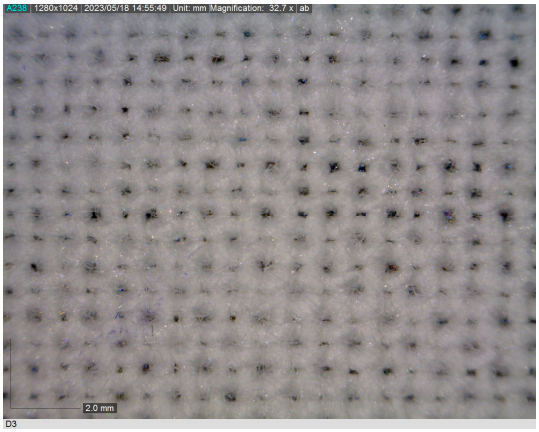
Code	Morphology of the Materials	Code	Morphology of the Materials
NGP		FGP	
NGA		FGA	
NCP		FCP	

Table 5. *Cont.*

Code	Morphology of the Materials	Code	Morphology of the Materials
NCA		FCA	

All coatings were clear, transparent, and heterogeneous. The coatings were not affected by the incorporation of propolis or alginate fibers; there were no signs of agglomeration, cracking, etc. on nonwoven or cotton fabric. Coatings with gelatin, a non-toxic biomacromolecule of bioactive polypeptides from beef, are assumed to form a gel on a nonwoven fabric. The gels formed by gelatin are naturally transparent, elastic, and thermoreversible. A coating prepared with collagen and alginate fibers on a nonwoven fabric exhibits the same behavior. The morphology of the coatings on the fabric is smooth and homogeneous, and the biodegradable polymers—erythritol; gelatin; and collagen—have not affected their appearance. The morphological properties observed on nonwovens with erythritol (propolis or alginate fibers) show the same behavior as the coatings on the fabrics.

3.2. Results of the Activity of Hydrogen Ions

The effect of the coatings on the pH value is shown in Table 6. All coatings on cotton fabrics have a neutral pH value of (7). Nonwoven fabric has a neutral pH value of (7) for all coatings except for coatings with alginate fibers. Coatings with alginate fibers have a pH value of 8, like seawater. Seawater is a weakly alkaline solution with a pH close to 8.0, close enough to neutral pH that marine organisms adapted to this salty environment can thrive in it. It is assumed that the commercial alginate fibers used in this work were obtained from brown algae (*Phaeophyceae*) such as *Laminaria hyperborea*, *Laminaria digitata*, *Laminaria japonica*, etc. by treatment with aqueous alkaline solutions, typically with NaOH, which affects the pH of the alginate fibers used.

Table 6. Results of the pH value.

Code	pH	Code	pH
NN	7	FN	7
NEP	7	FEP	7
NEA	8	FEA	7
NGP	7	FGP	7
NGA	8	FGA	7
NCP	7	FCP	7
NCA	8	FCA	7

Most biochemical processes in the body are related to its pH value. The optimal pH value of healthy skin on the face and body is slightly acidic and lies between 4.7 and 5.75. This is an important aspect of the skin's barrier function, as it regulates bacterial flora and prevents infections. When a wound occurs, the pH of the skin is disrupted, and the more neutral pH (7.4) of the underlying tissue is exposed [49]. With successful healing and re-epithelialization, the skin returns to the acidic range.

If wound healing is delayed, the pH will fluctuate and become increasingly alkaline over time. At this stage, the wound is described as chronic. The pH environment of chronic wounds has been recorded in the range of pH 7.15 to 8.9 [50]. Studies have shown that the pH value of the wound shifts towards an acidic value in the course of healing. Most bacterial organisms grow best at pH values of 6.5 to 7.0; however, some thrive under very acidic (e.g., Acetobacter) or very alkaline conditions (e.g., Candida) [49]. Each microbial species has its own pH range in which it grows best. Many studies have now shown the presence of bacteria and biofilms in acute and chronic wounds, which can delay the healing process [49].

Various environmental factors influence the growth of bacteria, including temperature, pH, dissolved gases, osmotic pressure, and water availability. Wound healing is a complex process that requires a more advanced approach.

The samples tested in this article have a pH value of 7 (two samples have a pH value of 8). A pH of 8 can remove the skin's natural oils in the case of healthy skin and promote the growth of Candida spp. in the case of chronic wounds. Even the samples with a pH of 7 may or may not affect the growth of bacteria. Each chronic wound is a story in itself; human organisms are different, and the addition of propolis or alginate fibers could also play a role in minimizing bacterial infection at the wound site and facilitating wound healing.

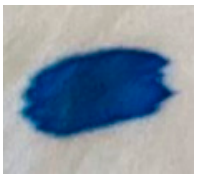
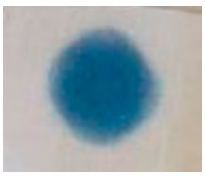
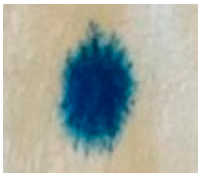
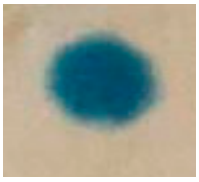
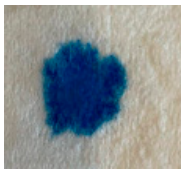
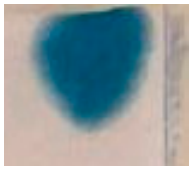
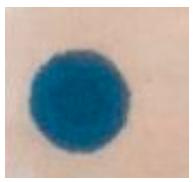
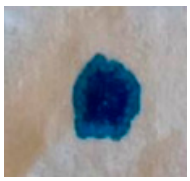
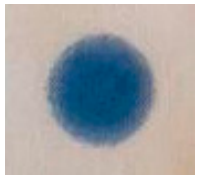
Our results can also be analyzed in other ways. It should be noted that they act primarily according to the important effects briefly mentioned above (Section 2.1.2) and are an excellent substrate for the addition of microcapsules containing substances against biofilms. In this way, a double effect on the biofilm can be achieved. On the one hand, by the sustainable coating itself, and on the other hand, by a microcapsule, which can also be of natural origin, e.g., microcapsules made of sodium alginate in the shell and filled with natural antimicrobial agents [51].

3.3. Results of the Drop Test Method

The results of the absorption test with drops (methylene blue) can be found in Table 7. The table shows the test results for cotton and nonwovens. Untreated samples and samples treated with erythritol, gelatin, and collagen in combination with propolis and alginate fibers are tested to determine the properties of hydrophilicity and hydrophobicity.

The main objective of this test was to visually determine the absorption and dispersion of methylene blue on cotton fabrics and nonwoven samples. The results depend on the type of modification and on the sample itself. Table 7 shows that the drop is evenly distributed in most samples, except for FEA, FGP, and FGA. A regular circular shape of the droplet was observed for all samples, except for the samples mentioned, where a longer absorption time of the droplet was measured. The results of the absorption time are inconsistent. FN has the shortest absorption time with 3 s 8 cs, and FGA has the longest with 12 s 0 cs. From the results, it can be concluded that FN has the best hydrophilicity results. The table shows that not a single sample has a regular circular droplet shape, so that all droplets are unevenly distributed. The absorption time results are also inconsistent. The shortest absorption time is found for the NCA sample and is 0 s 8 cs; the longest for the NGA sample is 9 s 3 cs. From the results, it can be concluded that NCA has the best hydrophilicity. Table 7 shows that the nonwoven sample is more hydrophilic. It can also be seen that both samples treated with gelatin and alginate fibers have the longest absorption times.

Table 7. Results of the drop test method.

Code	Time	A Drop of Methylene Blue Solution	Code	Time	A Drop of Methylene Blue Solution
NN	1 s 6 cs		FN	3 s 8 cs	
NEP	1 s 7 cs		FEP	4 s 1 cs	
NEA	1 s 0 cs		FEA	4 s 3 cs	
NGP	7 s 1 cs		FGP	5 s 1 cs	
NGA	9 s 3 cs		FGA	12 s 0 cs	
NCP	0 s 9 cs		FCP	5 s 0 cs	
NCA	0 s 8 cs		FCA	3 s 9 cs	

Where is: s—a second; cs—hundredth of a second.

Hydrophobic samples could protect the wound from dust and external fluids, while samples with a hydrophilic surface could adhere to the wound site, provide a moist environment, and absorb the exudate from the wound to promote wound healing. When a wound occurs, the cells must be able to communicate with each other by sending and receiving signals to repair the tissue loss by secreting growth factors and other signaling molecules that require a fluid medium for intercellular cross-talk to promote healing. In a moist environment, the epithelia heal the wound more efficiently than in a dry environment [24]. The dressing that has been used clinically for decades is the wet-dry gauze bandage, which is simple and inexpensive but can be intense and further damage the wound site if allowed to dry [41]. Gauze is usually made from viscose, polyester, or cotton. Other common dressings

include foams, alginates, hydrocolloids, hydrogels, and bioengineered dressings, although a large number of formulations are under patent protection and not publicly known.

The hydrophilic properties of the treated samples can be refined by adjusting the formulation parameters, such as the different ratios of the polymers to water as a solvent, the duration of the preparation process, and the process temperature, as well as the presence of catalysts or initiators. When modifying textiles, hydrophilic silicone softeners (hydrophilizing agents) are the simplest and quickest way to give textiles softness, smoothness, and water absorption properties. They are based on silicone polymers and contain hydrophilic functional groups that make them compatible with water and enable them to improve the water absorption properties of fabrics, nonwovens, and knitted fabrics. In addition, additives such as surfactants, wetting agents, and rewetting agents can be used to develop a hydrophilic material from a naturally water-repellent material. Fabrics with a superhydrophilic surface can be obtained by plasma treatment under low pressure with nitrogen, oxygen, or air.

3.4. Results of the Crease Recovery Angle

Table 8 shows the results of the determination of the recovery angles for the nonwovens and Table 9 for the fabric.

Table 8. Results of the angle of recovery of nonwoven textiles.

The Angle of Recovery												
Code/Direction of Production	**Machine Direction (°)**						**Cross Machine Direction (°)**					
	1.	**2.**	**3.**	**X (°)**	**σ**	**V [%]**	**1.**	**2.**	**3.**	**X (°)**	**σ**	**V [%]**
NN	101	94	98	97.7	2.87	2.94	107	96	93	98.7	6.02	6.10
NEP	93	98	94	95	2.16	2.27	91	94	97	94	2.45	2.61
NEA	65	74	79	72.7	5.79	7.96	87	84	91	87.4	2.87	3.28
NGP	92	96	98	95.4	2.49	2.61	94	98	101	97.7	2.87	2.94
NGA	91	89	94	91.4	2.05	2.24	93	98	90	93.7	3.30	3.52
NCP	94	89	90	91	2.16	2.37	98	102	107	102.4	3.68	3.59
NCA	93	103	98	98	4.08	4.16	110	114	105	109.7	3.68	3.35

Where X is the arithmetic mean, σ is the standard deviation, and V is the coefficient of variation.

Table 9. Results of the angle of recovery of fabric.

The Angle of Recovery												
Code/Direction of Production	**Machine Direction (°)**						**Cross Machine Direction (°)**					
	1.	**2.**	**3.**	**X (°)**	**σ**	**V [%]**	**1.**	**2.**	**3.**	**X (°)**	**σ**	**V [%]**
FN	79	90	71	80	7.79	9.74	86	77	90	84.4	5.44	6.45
FEP	59	69	69	65.6	4.71	7.18	82	84	90	85.4	3.40	3.98
FEA	55	59	53	55.6	2.49	4.48	63	61	62	62	0.82	1.32
FGP	69	64	67	66.7	2.05	3.07	73	75	76	74.7	1.25	1.67
FGA	51	56	60	55.7	3.68	6.61	74	71	69	71.4	2.05	2.87
FCP	75	71	73	73	1.63	2.23	69	86	84	79.7	7.59	9.52
FCA	63	62	69	64.7	3.09	4.78	74	72	76	74	1.63	2.20

Where X is the arithmetic mean, σ is the standard deviation, and V is the coefficient of variation.

Table 8 shows that the recovery angles for nonwovens are evenly distributed, both in the machine direction and the cross-machine direction. The smallest recovery angle in the machine direction and cross-machine direction was found for the sample NEA: 72.7° in the machine direction and 87.4° in the cross-machine direction. NCA has the highest recovery

angle in both directions. It is 98° in the machine direction and 109.7° in the cross machine. It can be concluded that the recovery angle results were influenced by the treatment with different biopolymers. The cotton fabric and nonwoven samples treated with erythritol have the smallest recovery angles.

Table 9 shows that the recovery angles for all cotton fabric coatings are larger in the direction of the weft. The FEA pattern has the smallest recovery angle in the direction of the warp, which is 55.6°; in the direction of the weft, it is 62°. The largest recovery angle is FN in the direction of the warp, which is 80°, and FN in the direction of the weft FEP, which is 85.4°. Samples with the largest recovery angle are more elastic, flexible, and more appropriate for bandages and wounds on knees and similar locations with dynamic movements. Wound dresings and bandages also must be resistant to abrasive shear, torsional forces, and mild impact forces [41]. Future dressings definitely need to improve the limitations of current traditional dressing formulations by improving their current properties that promote a favorable healing environment and also taking the next step in adapting their antimicrobial and biological activity. Several studies have shown that many of the traditional modern dressings are more effective when fused into a hybrid dressing rather than being used as stand-alone dressings [41].

3.5. Results of the Determination of Thickness and Mass per Unit Area

The influence of the coating on the thickness of the sample is shown in Tables 10 and 11.

Table 10. Results of the thickness of nonwoven textiles.

Code/n	1	2	3	x	σ	V [%]
NN	0.34	0.34	0.34	0.34	0	0
NEP	0.34	0.34	0.34	0.34	0	0
NEA	0.34	0.34	0.34	0.34	0	0
NGP	0.22	0.25	0.22	0.23	0.014	6.13
NGA	0.34	0.24	0.20	0.26	0.06	22.65
NCP	0.29	0.24	0.30	0.27	0.03	9.70
NCA	0.31	0.29	0.30	0.30	0.008	2.74

Where X is the arithmetic mean, σ is the standard deviation, and V is the coefficient of variation.

Table 11. Results of the thickness of fabric.

Code/n	1	2	3	x	σ	V [%]
FN	0.33	0.33	0.33	0.33	0	0
FEP	0.33	0.32	0.31	0.32	0.008	2.56
FEA	0.34	0.34	0.33	0.34	0.005	1.38
FGP	0.33	0.32	0.32	0.32	0.005	1.47
FGA	0.31	0.31	0.32	0.32	0.005	1.47
FCP	0.32	0.32	0.32	0.32	0	0
FCA	0.33	0.33	0.34	0.33	0.005	1.43

Where X is the arithmetic mean, σ is the standard deviation, and V is the coefficient of variation.

The coatings with erythritol, gelatin, and collagen have no significant effect on the thickness of the fabric, but the treatments with gelatin (0.23 mm and 0.26 mm) and collagen (0.27 mm and 0.30 mm) have a smaller effect on the thickness of the nonwoven fabric sample than the initial sample (0.34 mm). From the results, it was concluded that the samples have uniform thickness without excessive thin and thick spots, nodules, or admixtures as factors affecting the thickness of the fabric. In addition, the biopolymer coating is evenly distributed on all samples.

Table 12 shows that the smallest surface mass of the cotton fabric in the untreated sample, i.e., FN, is 39.15 g m^{-2}, and the largest in the sample treated with gelatin and propolis, i.e., FGP, is 47.87 g m^{-2}. For the nonwoven samples, the smallest surface mass is also for the untreated sample, i.e., NN, and is 11.7 g m^{-2} and the largest is in the sample treated with gelatin and alginate fibers, i.e., NGA, at 26.37 g m^{-2}. All treated samples showed an increase in surface mass after modification of the samples, both for woven and nonwoven fabrics. The gelatin-treated samples have the highest surface mass (fabrics and nonwovens), and the erythritol-treated samples have the lowest (fabrics and nonwovens), although this is greater than the surface mass of the untreated samples. The specific density of the active ingredients used for the modification can explain this. Coatings did not significantly influence the results of thickness and mass per unit area. Higher values of thickness as well as mass per unit area can be uncomfortable for the patient.

Table 12. Results of the mass per unit area.

Code	Mass per Unit Area (g m^{-2})	Code	Mass per Unit Area (g m^{-2})
FN	39.15	NN	11.7
FEP	45.96	NEP	18.27
FEA	44.96	NEA	15.64
FGP	47.87	NGP	20.66
FGA	47.21	NGA	26.37
FCP	45.22	NCP	21.08
FCA	46.73	NCA	24.16

4. Conclusions

A study of the scientific and technical literature leads to the conclusion that sustainable coatings with biopolymers on textiles are a topical issue. The properties of nonwovens make them suitable for wound dressings, as they are lightweight and have suitable properties for wound care such as absorbency, softness, and elasticity. Nonwovens are also an important component in the development of advanced wound care products. They offer features such as the creation of a moist wound healing environment with controlled vapor permeability, absorbency, and low skin adhesion. There is currently no dressing that is suitable for all types of wounds. As the healing of a wound progresses and the amount of exudate decreases, a single dressing is not optimal for the different phases of healing. For one phase of healing, alginate dressings and propolis dressings have great potential to optimize the microenvironment of the wound. It can be concluded that after the modification of the cotton fabric and the nonwoven fabric, no significant changes in the basic technical properties (thickness, mass per unit area) compared to the untreated samples can be observed. A larger proportion of samples exhibit hydrophilic properties, which favor their use for medical purposes—for example; the absorption of exudates. Samples with better hydrophilic/hydrophobic properties can be refined by adjusting the formulation parameters. Due to the neutral and slightly alkaline pH values of the processed samples, they are suitable for external application on the skin. The recovery angle of the processed samples proves that the samples do not tend to wrinkle and that they retain their elasticity even after modification and have a pleasant textile feel (hand value). Based on the results obtained, it can be concluded that it would be good to find an optimal formulation for the samples treated with erythritol in combination with propolis and alginate fibers in order to improve the properties of fabrics and nonwovens through sophisticated computer algorithms, machine learning, or statistical methodology, such as the design of experiments (DOE). The design of experiments is a powerful tool for data collection and analysis that can reduce the number of experiments, the duration of experiments, the costs, and the amount of human energy required. In our future work, DOE will be a tool for optimizing the modification of the surface of textiles, as many insights can

be gained from a carefully structured set of factor combinations, allowing conclusions to be drawn about their influence on a particular output parameter. Different ratios of polymers to water as a solvent, the duration of the preparation process and the temperature, the amount of erythritol, gelatin, and collagen, as well as the amount of propolis and alginate fibers, are investigated to determine the optimum conditions. The optimal conditions to achieve the desired properties of sustainable coatings are a pleasant textile feel, a high pH value, clear and transparent coatings, hydraulic properties, etc.

This work has identified unique properties of textiles as possible wound dressings in the treatment of chronic wounds, for which there is still no ideal or universal wound dressing. Only natural, biodegradable polymers that are environmentally friendly and fulfill the requirements of the Food and Drug Administration (FDA) and the European Medicines Agency (EMA) were used in the development of sustainable coatings in this work. The advantage of the sustainable coatings in this work is that they consist of natural compounds that can be taken orally and are therefore suitable for external use and safe for humans and the environment. By choosing erythritol, gelatin, or collagen with propolis or alginate fibers and by varying the process parameters without using a catalyst or hydrophilic silicone softeners, a synergistic approach of natural compounds was achieved. All treatments are natural treatments with modifications of cellulosic fibers (woven fabrics) and regenerated cellulosic fibers—viscose (non-woven textiles). This work is part of an active multimodal approach to solving the problem of chronic wounds using biopolymers and the development of sustainable coatings.

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