

Cellulose Derivatives-Based Dressings for Wound-Healing Management

Subjects: Materials Science, Biomaterials | Cell & Tissue Engineering

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Notwithstanding the progress regarding wound-healing management, the treatment of the majority of skin lesions still represents a serious challenge for biomedical and pharmaceutical industries. Thus, the attention of the researchers has turned to the development of novel materials based on cellulose derivatives. Cellulose derivatives are semi-synthetic biopolymers, which exhibit high solubility in water and represent an advantageous alternative to water-insoluble cellulose. These biopolymers possess excellent properties, such as biocompatibility, biodegradability, sustainability, non-toxicity, non-immunogenicity, thermo-gelling behavior, mechanical strength, abundance, low costs, antibacterial effect, and high hydrophilicity. They have an efficient ability to absorb and retain a large quantity of wound exudates in the interstitial sites of their networks and can maintain optimal local moisture. Cellulose derivatives also represent a proper scaffold to incorporate various bioactive agents with beneficial therapeutic effects on skin tissue restoration. Due to these suitable and versatile characteristics, cellulose derivatives are attractive and captivating materials for the development of multiple biomedical and pharmaceutical applications, such as wound dressings, drug delivery devices, and tissue engineering.

Keywords: cellulose derivatives ; wound dressings ; wound management ; bioactive agents delivery systems

1. Introduction

Skin is the largest and the main organ that forms the body covering, with a complex structure of tissues, and creates an exterior defense barrier, which protects the internal organs from mechanical impairments, radiation, chemicals, and foreign invaders (bacteria and viruses) ^[1]. More than being a passive barrier, the skin defends the body against contamination, infection, and surrounding environment influence ^[2]. Skin is also a sensory organ and contains a large category of sensory neuron subtypes (thermoreceptors, nociceptors, pruriceptors, and low-threshold mechanoreceptors), that take over and transfer to the brain information about the environment ^[3]. Moreover, the skin has an important role in homeostasis, elimination of toxins, sustaining regular hydration levels, prevention of electrolytes loss ^[4], and in control of body temperature and blood pressure. The skin is made up of three particular layers: epidermis, dermis, and hypodermis or subcutaneous layer ^[5].

The epidermis is a physical protective barrier against the external factors, which does not contain blood vessels. It is comprised of two main categories of cells: dendritic cells and keratinocytes (keratin synthesis), along with Langerhans cells (engaged in the immune reaction), Merkel cells (sensory corpuscles), and melanocytes (melanin synthesis) ^{[6][7]}. The dermis is situated between the epidermis and hypodermis, and it is responsible for skin thickness. The dermis structure is principally fibrous because it contains collagen and elastic fibers ^[8]. Moreover, this layer also includes hair follicles, sebaceous glands, sweat glands, nerves, and blood vessels. The fundamental component of the dermis is collagen and the most abundant are type I and type III (approximately 95%) ^{[9][10]}. The dermis plays an essential role in thermoregulation, skin protection, preservation of skin support, and perception of sensation ^[11]. The hypodermis (subcutaneous tissue), the widest and the thickest part of the skin, is located between the dermis and muscles or bones beneath it and it is made up of elastin and loose connective tissue ^[12]. The principal roles of subcutaneous tissue are thermal insulation, energy resource, nutritional reserve, and mechanical conservation ^{[13][14]}.

There are many factors and systemic diseases that can alter skin functions, for example, pathogens, pollution, radiation exposure, smoking, malnutrition, obesity, diabetes mellitus, peripheral vascular diseases, pressure ulcer, inflammatory, bleeding, or metabolic conditions and immunosuppression ^{[15][16]}. In many cases, all these factors can delay wound healing, with harmful risks for patients, such as oxidative stress, chronic inflammation, infection, increased tissue loss, and necrosis ^[17]. Thus, skin tissue disorders are a public health problem worldwide, with a higher incidence from year to year. For example, in 2005 there were estimated ~5 million skin and subcutaneous conditions, in 2015 ~6.1 million ^[18], and in 2018 there were ~8.2 million people, who suffered from wounds. Total costs of treatments for wound healing vary between

\$28.1 billion and \$96.8 billion ^[19]. With a prevalence of 1–2% in the global population, chronic wounds have the largest frequency from all types of skin tissue injuries, especially surgical wounds, and leg/foot ulcers (pressure ulcer and diabetic foot ulcer) ^[20]. An injury involves physical impact, such as pain, inflammation, mobility limitation, disturbance of sleep, alterations of skin appearance, and restriction of daily activities; consequently, these effects have a negative impact on the patient quality of life, affecting emotional, social, and physical states ^[21]. To restore the impaired tissue and to rebalance the quality of life for patients with wounds, optimal and multidisciplinary wound management has an essential role. Its main purpose is to obtain a proper functional, structural, and cosmetic result ^[22]. Frequently, to alleviate the pain and inflammation, which accompany the wounds, analgesic and anti-inflammatory drugs are prescribed. Because of their side effects on the gastrointestinal system when they are administered orally ^[23], a more advantageous and simple treatment is to apply on the lesion site a wound dressing ^[24]. The main purpose of wound management is to reduce the period of wound healing through the prevention of infection, alleviation of inflammation and pain, and diminishing the scars ^[25].

2. Wound Dressings: Properties and Classification

In past years, due to the technology's noteworthy progress, various wound dressings were formulated worldwide to cure all types of tissue lesions. Dressings play a fundamental role in wound healing management, because these protect tissue lesions from external invasion (wound dressings are permeable for oxygen and moisture and function as physical barriers) ^[26], preventing the infection on the wound site ^[27]. Moreover, dressings contribute to the regeneration and restoration of epidermis and dermis layers ^{[28][29]}.

2.1. Wound Dressing Properties

For the development of dressings, which allow rapid healing, with minimal scars on the body surface, it is necessary to develop new biopolymeric materials that accomplish some properties to create the ideal wound dressing that are reviewed in Figure 1.

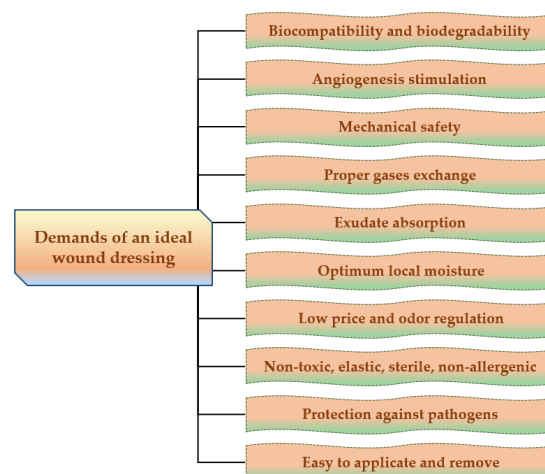


Figure 1. Major demands of an ideal wound dressing.

The ideal wound dressing preferably presents the following features: biocompatibility, biodegradability, non-toxicity, chemical inertness ^[30], to be applied effortlessly, to have the capacity to keep local moisture, to ensure a suitable exchange of gases (O_2 and CO_2), to absorb exudates that form on the lesion site ^[31], to stimulate the angiogenesis, to protect against extraneous pathogens, to clear the injured tissue, to eliminate nonviable tissues, to reduce the exposed area ^[32], to be able to be removed and replaced without difficulty ^[33], to adjust the odor, to sustain an adequate temperature to the lesion bed, to promote the blood circulation, and to stimulate cell expansion, to ensure mechanical safety ^[34]. Also, wound dressings materials must be elastic, sterile, non-adherent, non-allergenic ^[35], to have an acceptable price and to provide thermal insulation ^[36].

2.2. Wound Dressing Classification

A potential classification of wound dressings comprises passive dressings and active dressings, depending on the presence or absence of one or more pharmacologically active substances or natural substances ^[37], which can act to the site of the lesion, with local or systemic action, conditioned by the depth of the wound. Moreover, the progress of manufacturing led to the evolution of wound dressings from traditional dressings to modern (advanced) dressings ^[38].

Passive dressings can be considered dry traditional dressings, which are fundamental for a faster wound healing process. There is a wide simple range of passive dressings for several types of skin lesions: cotton wool, lint, gauze, natural and synthetic bandages – they work as primary dressing or secondary dressing [34][39]. Active dressings contain a large variety of pharmacologically active substances (antibiotics or other antimicrobials, non-steroidal anti-inflammatory, analgesic, antifungal, and local anesthetics drugs) or natural substances (plant extracts) with anti-inflammatory, astringent, emollient, epithelializing, antioxidant, demulcent, antimicrobial properties [28].

Modern or advanced dressings were designed to cover tissue lesions and in this category are included the hydrogels, hydrocolloids, semi-permeable films, semi-permeable foams, and alginate dressings [40][41]. The biggest difference between traditional and modern dressings is the local moisture maintenance. Thus, traditional dressings have a lower capacity to maintain the local moisture on the wound site [38], and modern dressings sustain excellent local moisture to enhance wound healing [42]. The classification of wound dressings is illustrated in Figure 2.

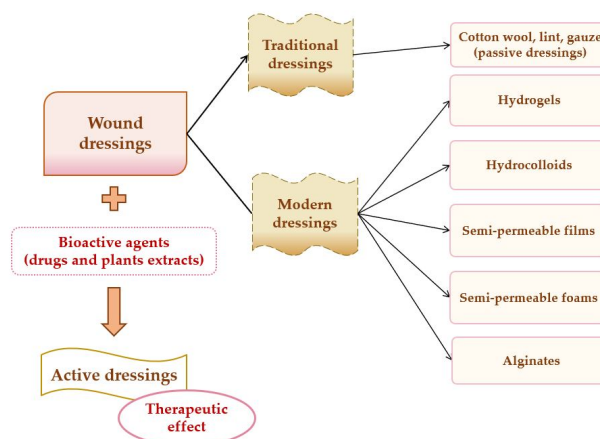


Figure 2. Wound dressings classification.

The main materials underlying the modern wound dressings are polymers, which can be natural (collagen, gelatin, cellulose, hemicellulose, chitin, chitosan, pectins and gums, chondroitin sulfate, alginic acid and alginates, agar, dextran, carrageenan, elastin, hyaluronic acid, silk fibroin, fibrinogen, and fibrin) [43][44], semi-synthetic (cellulose derivatives) [45] or synthetic (poly(α-ester)s, polyanhydrides, polycarbonates, poly(amide), poly(esteramide)s, polyphosphazenes, polyurethanes, pseudo poly(amino acids), polyacetals) [46][47][48].

3. Cellulose Derivatives as Wound Dressings

During the last decades, cellulose derivatives, also known as cellulose derivatives, have become extensively used in many fields, from food, cosmetics, biomedical, and pharmaceutical industry [49] to biofuels and oilfield industry (petrochemicals) [50]. These semi-synthetic biopolymers present many advantageous characteristics, such as biocompatibility, biodegradability, non-toxicity, sustainability, abundance, and a suitable price; therefore, cellulose derivatives represent the first option for wound dressings development [51][52].

3.1. Cellulose Derivatives Classification

Cellulose, discovered by Anselme Payen in the 19th century, is a natural polymer, an organic polysaccharide from plant origin, non-toxic, with a structural role, being the most plentiful and renewable biopolymer on Earth [53]. Structurally, cellulose is a linear macromolecule composed of many molecules of D-glucose (the number of the glucose units can reach more than ten thousand), which are bound through 1-4-β-glycosidic linkages and its chemical formula is $(C_6H_{10}O_5)_n$ [54]. The chemical structure of cellulose shows the presence of free hydroxyl groups at C₂, C₃, and C₆ of each molecule of glucose, which have a good capacity to form powerful inter- and intramolecular hydrogen bonds [55]. As a result of this property, cellulose has a crystalline and stiff structure and, consequently, it is insoluble in water and the majority of the organic solvents; moreover, this natural biopolymer cannot be digested by the human digestive system [56][57]. Cellulose has good stability to pH fluctuations and temperature [58].

To improve the solubility problems of cellulose and to extend its applications, the chemical structure of this polymer can suffer several changes to obtain the cellulose derivatives, which have suitable physicochemical properties to be used in many fields, especially in the pharmaceutical and biomedical industry [59]. The modifications in the cellulose molecule can be chemical, physical, or biological [50], but the most used and significant of the three is the chemical modification. Targeted by this method are the hydroxyl groups, which suffer an esterification or an etherification reaction [60]. Therefore, the cellulose derivatives can be classified in two major classes: cellulose esters derivatives and cellulose ethers

derivatives, which have particular mechanical and physicochemical characteristics [61]. The chemical structures of cellulose and cellulose derivatives are presented in Figure 3.

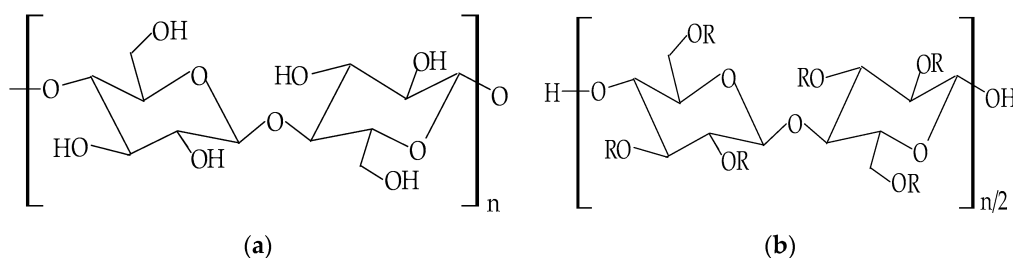


Figure 3. Chemical structures of: (a) cellulose; (b) cellulose derivatives.

Cellulose ethers derivatives are characterized by high molecular weight and the greatest applicability in the pharmaceutical domain of all these derivatives are: sodium carboxymethylcellulose (NaCMC), hydroxypropylmethylcellulose (HPMC), methylcellulose (MC), hydroxyethylcellulose (HEC), ethylcellulose (EC), hydroxypropylcellulose (HPC), hydroxyethylmethylcellulose (HEMC) and benzylcellulose (BC) [62][63]. The cellulose ethers are illustrated in Table 1.

Table 1. Main cellulose ether derivatives according to R groups [64].

Cellulose Ethers	R Groups
Methylcellulose	H, CH ₃
Ethylcellulose	H, CH ₂ CH ₃
Benzylcellulose	H, C ₆ H ₅ CH ₂
Sodium carboxymethylcellulose	H, CH ₂ COONa
Hydroxyethylcellulose	H, [CH ₂ CH ₂ O] _n H
Hydroxypropylcellulose	H, [CH ₂ CH(CH ₃)O] _n H
Hydroxyethylmethylcellulose	H, CH ₃ , [CH ₂ CH ₂ O] _n H
Hydroxypropylmethylcellulose	H, CH ₃ , [CH ₂ CH(CH ₃)O] _n H

Cellulose esters derivatives are extensively used in the pharmaceutical industry as enteric coated drug delivery devices, and they also have excellent properties to form films. There are two categories of cellulose esters: organic and inorganic, but the most common in the pharmaceutical practice are organic esters [65]. Among them are cellulose acetate (CA), cellulose acetate butyrate (CAB), cellulose acetate phthalate (CAP), cellulose acetate trimellitate (CAT), hydroxypropylmethylcellulose phthalate (HPMCP), and hydroxypropylmethylcellulose acetate succinate (HPMCAS). With fewer applications in the pharmaceutical industry are inorganic esters, such as cellulose nitrate (CN) and cellulose sulphate (CS) [66]. The cellulose esters are illustrated in Table 2.

Table 2. Main cellulose ester derivatives according to R groups [64].

Cellulose Esters	R Groups
Acetate	H, I
Acetate trimellitate	H, I, II
Acetate phthalate	I, III
Hydroxypropylmethylphthalate	H, CH ₃ , CH ₂ CH(OH)CH ₃ , III, IV
Hydroxypropylmethylphthalate acetate succinate	H, CH ₃ , CH ₂ CH(OH)CH ₃ , III, V

Due to the general properties of wound dressings presented in Section 2.1., but also the particular properties, such as hydrophilicity, mechanical toughness, pH stability, and rheological characteristics, cellulose and cellulose derivatives have multiple applications in many fields [67]. Areas of the applicability of all these biopolymers involve: biomedical and pharmaceutical industries, where they can act as drug-delivery devices, wound dressings, muco- and bioadhesive drugs,

excipients for drug formulations, and support for tissue engineering [68]; also, they can be used for cosmetic and hygienic products, in the textile area, in the food industry and agriculture [64][69]. The representation of cellulose derivatives-based wound dressing on an open wound is illustrated in Figure 4.

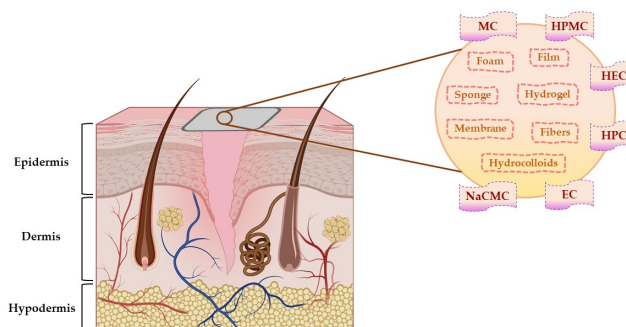


Figure 4. The representation of cellulose derivatives-based wound dressing on an open wound. This illustration has been created with BioRender.com, Inkscape, and PowerPoint.

3.2. Sodium Carboxymethylcellulose-Based Wound Dressings

Carboxymethylcellulose (CMC), also known as carmellose, is a semi-synthetic and hydrophilic polymer, a water-soluble cellulose ether derivative, and one of the polymers with the lowest price [70]. Sodium carboxymethylcellulose (NaCMC) is the sodium salt of CMC, an anionic polymer, with a great solubility in water [71]. NaCMC was the first compound from the group of cellulose derivatives; therefore, all the researchers' attention was focused on it because, compared to other cellulose derivatives, NaCMC can be synthesized through simple methods with low-cost materials [72]. It results from the etherification reaction of the cellulose with sodium monochloroacetate in an alkaline solution (NaOH) [73]. In the cellulose molecule, three hydroxyl groups (from 2, 3, and 6 positions) are substituted by carboxymethyl groups [74], resulting in different values of substitution degree from 0.4 to 1.5 and different molecular weights of NaCMC, varying from 90,000 to 2,000,000 g/mol [75]. The optimal substitution degree to be used in the pharmaceutical industry is from 0.60 to 1.00 [73]. The chemical structure of NaCMC is shown in Figure 5.

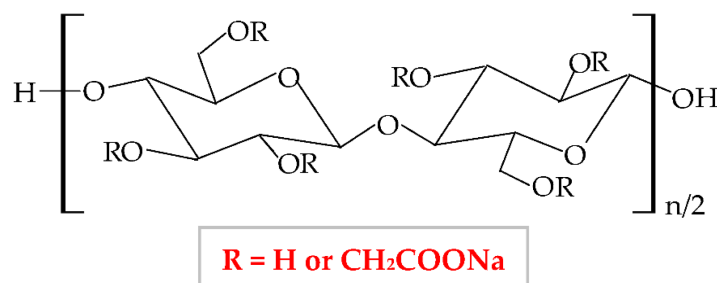


Figure 5. Chemical structure of sodium carboxymethylcellulose (NaCMC).

The NaCMC network illustrates a thixotropic behavior to generate 3D structures through intermolecular attraction. Its thixotropy is influenced by concentration and degree of substitution [76]. NaCMC presents excellent physicochemical and mechanical properties [77], optimal biocompatibility and biodegradability, proper capacity to absorb the water and to swell, high gelation behavior, non-toxicity, and low-immunogenicity [78]. It is the most used cellulose derivative in the pharmaceutical industry, mainly for the development of new wound dressings because it has the capacity to absorb heavy exudates [79][80], to ensure excellent moisture at the lesion site, and to avoid skin tissues water loss and tissues necrosis. Moreover, an optimal local humidity can impede dehydration, facilitate the synergy between target cells and growth factors, promote angiogenesis advancement, the mitigation of the ache, and the disruption of the fibrin network [81]. NaCMC is also used as a drug-delivery device and excipient for drug formulations (used as an emulsifier, thickener, stabilizer, and film-maker) [82]. Besides its applicability in the pharmaceutical area, this biopolymer possesses different usefulness in the food (E466 food additive) industry [83], in paper, textile and cosmetics domains [73][84], for tissue culture and dental medicine field [85].

NaCMC can be combined with other polymers to enhance its properties and to develop its applicability. Thus, it is more advantageous to blend two or more polymers for the development of a new material comparative to the chemical industrial development of that material. Moreover, the new material obtained by mixing other well-known polymers presents all the properties or is more favorable than the component polymers [30]. Furthermore, the blend of polymers can be realized to compensate for their drawbacks. Hence, Liu et al., combined NaCMC with HEC by electrostatic complexing

and obtained a sponge and a membrane with a porous network, enhanced viscoelastic properties, and high swelling behavior [86]. Hu et al., mixed NaCMC with PVA and quaternized chitosan and designed a new composite with enhanced flexibility, water absorption rate, mechanical strength, swelling ratio, and humidity permeability [87]. A novel NaCMC/PVA-based composite was formulated, with higher properties than two polymers: improved swelling capacity, elasticity, water solubility, porosity, water vapor transmission rate, bioavailability, and biodegradability for the tissue repair process; this formulation also presented an extension of its applicability, such as agriculture, biomedical field as drug delivery systems and food packaging [88][89]. NaCMC was blended with PEG through a photo-click reaction based on thiol-norbornene. It formed a pH-sensitive hydrogel with an augmented swelling ratio [85]. Zhang et al., designed a novel hydrogel based on NaCMC and sodium alginate. In a ratio of 1:4, the hydrogel exhibited high biocompatibility, mechanical characteristics, degradation rate, and local humidity [90]. Shin et al., blended NaCMC with PVA and PEG 400 through cyclic freezing/thawing method and obtained a hydrogel with improved properties: the swelling rate, the compressive strength, and cytocompatibility [91].

3.3. Hydroxypropylmethylcellulose-Based Wound Dressings

Hydroxypropylmethylcellulose (HPMC), hypromellose [92], is a semi-synthetic hydrophilic polymer, a nonionic cellulose ether derivative [93], with higher stability at a lower pH. In terms of physical properties, HPMC is a white, fibrous, or granular powder, whose particles are not cohesive, and it does not have a taste and odor [94]. This biopolymer results from hydroxyl groups substitution from cellulose molecule with methyl and hydroxypropyl groups. The chemical structure of HPMC is illustrated in Figure 6.

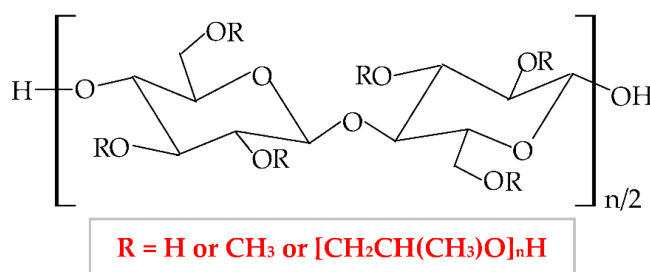


Figure 6. Chemical structure of hydroxypropylmethylcellulose (HPMC).

Therefore, HPMC presents many degrees of substitution, that give to this biopolymer different molecular weight and physicochemical features (rheological properties and crystalline nature) [95][96]. The hydrophilic or hydrophobic nature is related to the values of the degree of substitution (DS) and the molar substitution (MS). Thus, the HPMC molecule with decreased values of DS and MS is more hydrophilic and the HPMC molecule with increased values of DS and MS is more hydrophobic [97]. Following this chemical substitution, HPMC gets both polar (hydroxypropyl) and non-polar (methyl) character; consequently, it can form hydrophobic, intermolecular, and intramolecular linkages with many other materials [95]. The non-ionic character leads to a limited adhesive capacity [98]. At high temperature, the biopolymer can suffer a thermoreversible phase transition from sol to gel, with a temperature of gelation over 60°C, superior to the temperature of the body (37°C) [99]. HPMC-based hydrogels are temperature-responsive [100].

According to United States Pharmacopeia (USP), there are four distinct forms of HPMC, which are categorized by the content of methoxy, respectively hydroxypropoxy groups in: HPMC 1828, HPMC 2208, HPMC 2906, and HPMC 2910 [101]. This biopolymer has been approved as a food additive, E464 [102], by the American Institute, Food and Drug Administration (FDA), by the European Institution, European Parliament, and Council Directive, and by the Joint Expert Committee on Food Additives [103].

HPMC has a proper solubility in water, and it is one of the most used cellulose derivatives in many industries. It is widely used in the biotechnological field (construction, food, cosmetics, biomedical, and pharmaceutical industry), due to its excellent characteristics, such as biocompatibility, biodegradability, superior stability, large availability, excellent swelling, high surface activity, and mechanical properties [104], remarkable ability to form films and poor toxicity [105]. Regarding the applicability of HPMC in biomedical and pharmaceutical domains, it is used as a drug-delivery device, with a large practice for wound dressings development and it can also have remarkable applicability in tissue engineering [106]. HPMC can also be used as an excipient because it possesses proper abilities of emulsification, stabilization, suspension, and thickening [107][108].

HPMC can be combined with other polymers to enhance its properties and to develop its applicability [109]. To improve the physicochemical properties of a new composite, HPMC has been blended with several natural, semi-synthetic, or synthetic polymers [110]. In this way, to improve the thermal stability, HPMC has been blended with collagen [111][112],

gelatin [109], chitosan [113], chitosan, and xanthan gum [114]; to improve the mechanical properties (tensile strength and ultimate elongation), HPMC has been mixed with chitosan [115], collagen [112], poloxamer 407 [116], silk fibroin [117], PVA and PVP [118], chitosan and xanthan gum [114]; to increase the swelling rate, HPMC has been combined with methylcellulose [119], κ -carrageenan [120], chitosan and hyaluronic acid [121], chitosan and xanthan gum [114].

3.4. Methylcellulose-Based Wound Dressings

Methylcellulose (MC) is a semi-synthetic and non-ionic polymer, a cellulose ether derivative with high solubility in water, which is influenced by temperature [122]. It forms through the etherification of cellulose molecule with methyl chloride or dimethyl sulfate in basic solution [123] when the hydroxyl groups from the mother molecule are substituted with methyl groups, which leads to a diminishing of crystallinity [124]. The chemical structure of MC is presented in Figure 7.

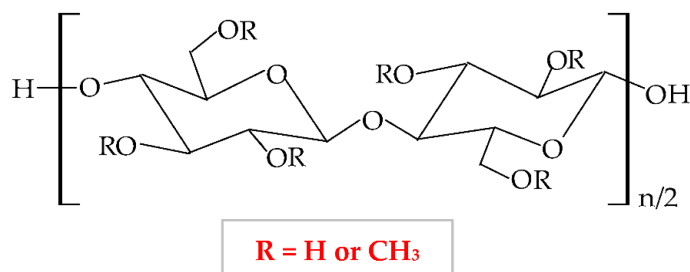


Figure 7. Chemical structure of methylcellulose (MC).

At a variation of temperature, MC has a thermo-sensitive behavior with a reversible sol-gel transition in an aqueous solution [125]. At a lower temperature than lower critical solution temperature, it realizes the hydration of the MC network in solution, with the formation of hydrogen bonds. At a higher temperature than lower critical solution temperature, the MC aqueous solution takes in the heat, with the disintegration of hydrogen bonds [100]. Thus, MC presents increased viscosity at higher temperatures, and at lower temperatures it exhibits a reduced viscosity [126].

The degree of substitution for commercial MC varies from 1.7 to 2.2 when it results in a semiflexible biopolymer because the inter-and intra- hydrogen bonds from cellulose molecule break off [127]. There are many substances, which influence the gelation behavior of MC, such as inorganics salts, ethanol, propylene glycol, polyethylene glycol 400, sucrose, glycerin, sorbitol, and different surfactants (sodium dodecyl sulfate and cetyltrimethylammonium bromide) [128]. MC is extensively used in biomedical, pharmaceutical, cosmetic, and food industries as a thickening, binding, and film-forming agent because it possesses excellent biocompatibility, biodegradability, and reduced toxicity [129][130][131].

To improve the characteristics of MC, it can be blended with other polymers in different ratios to enhance the physicochemical, morphological, and structural properties of both polymers and of the resulting composite [131]. Abu et al., illustrated that a higher concentration of MC led to increased hydrophilicity and porosity of the MC-chitosan scaffold due to the hydroxyl groups from the MC molecule, which can attract water molecules. The higher wettability has been described by the suitable results of the water uptake capacity [132]. Another combination of MC and chitosan was studied by Tan et al., They illustrated that an augmented concentration of MC led to improved tensile strength, moisture content, whitish index, and elongation at break [133]. El-Naggar et al., mixed MC with PVA and doxycycline hyclate (drug model) to develop a new drug delivery device, which showed a proper swelling capacity and a high drug release at basic medium [129]. The combination between MC and poly(acrylic acid) presented optimal mechanical properties and thermal stability [134]. The novel composite resulting by blending MC and tragacanth gum exhibited a higher capacity to form a gel and adequate mechanical and rheological properties [135].

3.5. Hydroxyethylcellulose-Based Wound Dressings

Hydroxyethylcellulose (HEC) is a semi-synthetic, nonionic, and inert polymer, a water-soluble cellulose ether derivative [136]. It forms through etherification of alkaline cellulose with chlorohydrin or ethylene oxide, when hydroxyl groups from cellulose molecule are substituted with hydroxyethyl groups [137]. The chemical structure of HEC is illustrated in Figure 8.

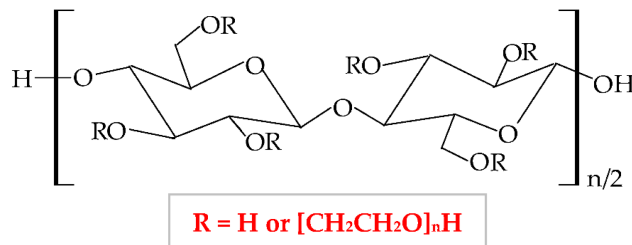


Figure 8. Chemical structure of hydroxyethylcellulose (HEC).

It has a low price, without taste and smell, with no color to light yellowish ^[138]; presents optimal stability at pH values between 2 and 12 ^[139]. HEC exhibits a proper capacity to scavenge free radicals and to form hydrogen and electrostatic bonds ^[140]. HEC is regarded as a hydrogel-like material, with two important characteristics: liquid-like and solid-like. Due to its polysaccharide structure, this hydrophilic biopolymer exhibits a high capacity to absorb and hold a large quantity of water or wound exudates. The elastic strength of its structure leads to an expansion of the molecule dimensions, without the modification of the structural stability and the gel form ^[141]. HEC possesses excellent physicochemical properties: rheological, hydrodynamic, and thermodynamic ^[142]. HEC also presents adequate biocompatibility, biodegradability, insignificant toxicity, immunogenicity, and cementing properties ^[143]. Due to its nonionic behavior, HEC exhibits the ability to coexist with a large field of other polymers, which have an appropriate solubility in water, salts, or surfactants. Therefore, HEC presents optimal toughness in a dielectric solution with a large concentration ^[144]. This biopolymer presents the largest commercial availability from all cellulose derivatives ^[145]; therefore, HEC is a noticeable biopolymer, which can be used successfully as an emulsifier, film-coating, stabilizer, suspender, and thickener agent in biomedical, pharmaceutical (wound dressing development) ^[146], cosmetic, food, adhesive, and textile industries ^{[138][147][148]}. The most predictive method for hydrogels synthesis is the crosslinking of free radicals generated by irradiation (electron beam and gamma-radiation) ^[149].

To enhance its properties, HEC can be blended with other polymers. For example, Zia et al., mixed HEC with poly(lactic acid) and polyurethane. They obtained a new composite with higher thermal stability and mechanical (tensile strength and elongation) properties compared to other polymers ^{[150][151]}. Moreover, HEC has been blended with polyvinyl alcohol (PVA), resulting in suitable electrical conductivity, viscoelasticity, stretchability, and thermosensitivity ^[152]. Guo et al., combined HEC with poly(caprolactone) by trimethylsilyl group technology and the result was the formation of a new copolymer with enhanced thermal properties ^[153]. HEC was also blended with chitosan to obtain a copolymer with improved physicochemical and mechanical characteristics ^[154], with gelatin to obtain a superparamagnetic composite ^[155], with sodium alginate to form a copolymer with enhanced swelling efficacy and drug delivery profile.

3.6. Ethylcellulose-Based Wound Dressings

Ethylcellulose (EC) is a nonionic semi-synthetic polymer, a cellulose ether derivative insoluble in water ^[156]. It forms through the etherification of alkali cellulose with ethyl chloride when the hydroxyl groups from cellulose molecule are substituted with ethyl groups ^[123]. The chemical structure of MC is presented in Figure 9.

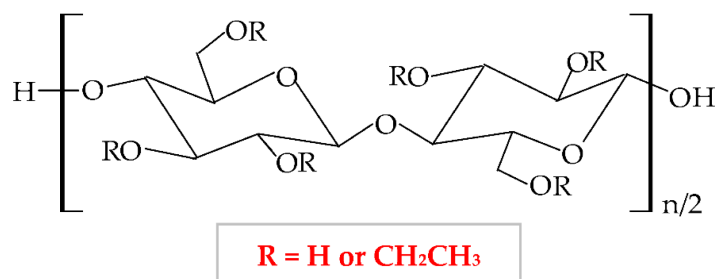


Figure 9. Chemical structure of ethylcellulose (EC).

This biopolymer presents numerous advantageous characteristics, such as mechanical properties, biodegradability, flexibility, lowcity, hydrophobicity, gelling capacity ^[157], light, moisture, oxygen resistance, thermoplasticity ^[158], and low price, which make EC an excellent material for use in different industries (pharmaceutical, cosmetic and food) ^[159]. Moreover, this biopolymer has several particular features in addition to the other cellulose derivatives: high film-forming capacity, suitable chemical strength, and optimal mechanical properties ^[160]. EC represents the most extensively analyzed biopolymer due to its capacity to form film for coating solid pharmaceutical forms (tablets, microcapsules, and microspheres) and formulation of new topical forms ^[161]. EC is a promising material to be used for encapsulation due to

its optimal optical transparency, processing temperature, and electronic insulation [162]. It also presents a good capacity to bind, preserve and dissolve [163], and possesses a proper control of drug delivery [164]. Films based on EC are brittle because of the stiffness of hydrogen linkages from its molecule. This biopolymer has high stability to chemical substances and can be associated with different plasticizers to design heavy and impermeable films [165].

EC can be mixed with various polymers to enhance the physicochemical and mechanical properties and thus, its applicability. To develop a novel drug-delivery device, Li et al., blended EC by electrospinning method with poly(di(ethylene glycol) methyl ether methacrylate), a thermosensitive polymer. The new formulation showed normal morphology, a large porosity, and an increased wettability at a higher temperature, which led to more hydrophobic behavior, causing an extended release of the drug [166]. EC was mixed with poly (ethylene-co-vinyl acetate) and resulted in a new composite with higher mechanical properties [167]. Chen et al., mixed EC and poly(β -hydroxybutyrate) when EC acted as a thickening agent because it increased the viscosity of the new composite. In a concentration of 1%, EC augmented the tensile strength [168]. Li et al., blended EC with konjac glucomannan to formulate a novel composite with higher mechanical properties, moisture resistance, permeability of oxygen, and stability at a high temperature [169]. EC was also associated with another cellulose derivative, HPC, and obtained a scaffold with enhanced mechanical properties and 3D printing capacity [170].

3.7. Hydroxypropylcellulose-Based Wound Dressings

Hydroxypropyl cellulose (HPC) is a semi-synthetic hydrophilic polymer, a cellulose ether derivative, with proper solubility in water and organic solvents [171]. Its solubility depends on the degree of substitution. At values smaller than 12%, HPC is water-soluble and at values higher than 12%, HPC is ethanol-soluble [172]. This biopolymer results from the etherification reaction of alkali cellulose with 1,2-propylene oxide. Thus, the 2,3,6-hydroxyl groups from the cellulose molecule are replaced with hydroxypropyl groups [123]. The chemical structure of HPC is presented in Figure 10.

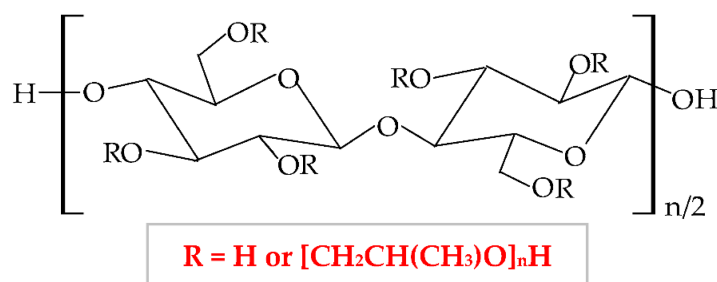


Figure 10. Chemical structure of hydroxypropylcellulose (HPC).

It has numerous advantageous properties, such as amphiphilicity, low price, electrical neutrality, biocompatibility, biodegradability, non-toxicity, high power of swelling the wounds exudate [173][174], adequate chemical strength, and film-forming efficiency [175]. At a high temperature and in a concentrated aqueous solution, HPC generates a cholesteric liquid crystalline network, depending on its concentration [176]. HPC exhibits a thermoplastic behavior and develops temperature-responsive hydrogels [100][177]. Regarding the HPC-based films, these are defined by high flexibility, good impermeability for oil and fat, and a low value of T_g (glass transition temperature) at excessive humidity. The LCST (lower critical solution temperature) water value is about 41°C. At a slightly higher temperature than LCST, HPC presents a phase change because the water solution of this biopolymer generates metastable nanosphere aggregates [178]. Moreover, the solubility of HPC is influenced by LCST values. At a lower temperature than LCST, HPC dissolves easily in water and at a higher temperature than LCST, HPC does not dissolve [179]. Thus, this cellulose derivative is an optimal material to be used in biomedical and pharmaceutical fields as a binding, disintegrating, emulsifying, thickening, filler, and coating agent [180][181] and in the construction domain [182]. It can also be used in the food industry because the United States Food and Drug Administration (FDA) authorized HPC as a safe food additive [183].

HPC can be blended with other polymers to improve the physicochemical and mechanical properties and thus, to extend its applicability. For instance, Veerapur et al., combined HPC and chitosan, and the new formulated composite presented higher hydrophilicity, swelling capacity, and permeation rate [184]. By mixing HPC with cellulose acetate phthalate resulted a composite with higher properties than compounds: increased pseudoplasticity and viscoelastic behavior [185]. Gan et al., prepared a high-performance hydrogel with enhanced tensile strength, toughness, biocompatibility, wear resistance, and low friction coefficient from HPC, sodium alginate, and poly(vinyl alcohol); these excellent characteristics extend the area of use to biosensors and nerve replacement [186]. Lu et al., blended HPC with poly(vinyl alcohol) to obtain a new scaffold with augmented toughness, elasticity, conductivity, and mechanical strength that is a promising material for the development of biosensors and interaction between humans and machines [187].

3.8. Combinations of Cellulose Derivatives-Based Wound Dressings

One or more cellulose derivatives may combine with other cellulose derivatives to formulate novel wound dressings, with enhanced properties that can accelerate the wound-healing process and alleviate the pain, inflammation, and stress caused by damaged skin tissue. Moreover, they can be combined to counteract their drawbacks [30]. The main combinations are summarized in Table 3.

Table 3. Recent studies on the use of combinations of cellulose derivatives as wound dressing.

Biopolymer/-s	Active Pharmaceutical Ingredient (Natural or Synthetic Substances)	Type of Wound Dressing	Main Findings	References
EC/HPMC	Paromomycin and Gentamicin	Film	Optimum drugs release and inhibition of <i>Leishmania tropica</i> growth.	[188]
	Aloe vera	Nanofibers	Nanofibers with 10% Aloe vera showed suitable mechanical properties, biocompatibility, bioadhesion, and suitable antibacterial activity.	[189]
NaCMC/HPMC	Grapefruit seed extract	Film	Suitable elongation at break, stability in water, and proper antibacterial action.	[190]
	CuO	Film	Good biocompatibility and antibacterial effect.	[191]
	Tetracycline/Methylene blue	Film	Nanoporous network, increased T_g and elongation at break, sustained drug release for 72 h and high antibacterial effect.	[192]
	ZnO NPs	Film	Biocompatibility and optimum antibacterial action.	[193]
NaCMC/HPMC/CAB	Resveratrol	Membrane	Excellent adhesive capacity, hydration efficiency, and higher porous structure; in vivo studies showed accelerated wound healing.	[194]
NaCMC/MC	Simvastatin	Membrane	In a ratio of 2:1, the membrane exhibited appropriate flexibility, viscosity, stability, and sponginess; optimal drug delivery for suppurating injuries.	[195]

Abbreviations: CAB—Cellulose acetate butyrate, CuO—Copper oxide, T_g —Glass transition temperature, ZnO NPs—Zinc oxide nanoparticles.

4. Conclusions and Future Perspectives

Herein has focused on different types of wound dressing (gel, hydrogel, sponge, hydrocolloid, film, membrane, foam, and nanofibers) based on cellulose derivatives as biopolymeric scaffolds, and various bioactive agents, from plant extracts to chemical drugs. Herein has considered the cellulose ethers derivatives (NaCMC, HPMC, MC, HEC, EC, and HPC). It has been illustrated that cellulose derivatives can manifest a therapeutic effect on wound healing, alone or in combination with other natural, semi-synthetic, and synthetic polymers. The major advantage of mixing two or more biopolymers is, besides the beneficial action on damaged tissue, the improvement of physicochemical properties of the novel dressing. Cellulose derivatives have a particular chemical structure, obtained by etherification of hydroxyl groups from cellulose molecule with different alkyl groups, the consequence being the improvement of water solubility. Therefore, these biopolymers can be successfully used as a base for diverse formulations, due to their high gelation properties. Cellulose derivatives exhibit an efficient capacity to absorb the exudates on the site of the lesion, retain them, and swell. Consequently, the newly formulated wound dressings show an excellent ability to maintain relevant moisture on the wound bed and allow gas exchanges with the environment. Due to their high biocompatibility, biodegradability, physicochemical properties, eco-friendliness, and low cost, cellulose derivatives are promising materials for biomedical and pharmaceutical domains (electrochemical biosensors for medical diagnosis, bone tissue engineering, hemodialysis, drug delivery and 3D printing), for oilfields, carbon capture and the food industry.

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