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Review

Nanoparticle/biopolymer-based coatings for functionalization of textiles: recent developments (a minireview)

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Abstract: This minireview presents recent developments of surface nano-structured textiles and their biomedical applications by an up-to-dated achievements, summarizing the coatings made of biopolymer films and nanoparticles on different textile substrates for enhanced medical applications diminishing the incidence of multiplied range of hospital-acquired infections. The combination of metal and metal oxides nanoparticles with biopolymers is an efficient technique to generate enhanced antibacterial, virucidal and antifungal properties to textiles. Only a few review articles offer a comprehensive insight into the surface tailoring of textiles by nanoparticles-biopolymers use as an alternative for surface modification of textiles, granting them with biocidal performance. The overview points out the compelling reasons for scientists and experts to enhance the already existing results in the biomedical textiles domain, with an emphasis on the antimicrobial responsivity, highlighting: (i). the benefit of the simultaneous NPs - biopolymers deposition on textiles by various deposition techniques, meaning the wash fastness of the antibacterial attributes and the biocompatibility of the material in comparison with only NPs coating; (ii). the use of biopolymers to stabilize colloidal dispersions of NPs, granting the nanoparticles with functionalities for covalent immobilization on textiles with long lasting antibacterial effect; (iii). the most usual metal and metal oxide NPs and biopolymers for the antibacterial textile applications.

Keywords: nanoparticles-biopolymers composites; textile functionalization; antibacterial; germicide

1. Introduction

Recent developments of surface nano-structured textiles and their biomedical applications by nanoparticles-biopolymers proved a promising alternative for surface modification of textiles as coatings made of biopolymer films and nanoparticles on different textile substrates for enhanced medical applications. The synergy between environmentally friendly biopolymers and nanoparticles leads to the improved functionality of nanocomposite materials, in terms of barrier, antimicrobial and antioxidant properties. An example of nanoparticles-biopolymers composite materials schematic development is presented graphically in the figure. There are various available methods for the textiles functionalization by using nanocomposite coatings consisting on direct functionalization methods – the nanocomposite coating is formed directly onto the textile fibers – and indirect methods – the nanocomposite is fabricated and then applied onto the textile material. Each of those techniques requires a priori specific preparation of the textile substrates. There are a huge number of materials that can be used to form functional composites for textile surfaces modification. This minireview will focus on the overview of the benefit of the simultaneous NPs - biopolymers deposition on textiles by various deposition techniques, meaning the wash fastness of the antibacterial attributes and the biocompatibility of the material in comparison with the only NPs coating. Secondly the use of biopolymers to stabilize colloidal dispersions of NPs, granting the nanoparticles with functionalities for covalent immobilization on textiles to impart long lasting antibacterial effect will be approached. Finally, a synthetic overview of the most usual metal and metal oxide NPs and biopolymers for the antibacterial textile applications will be provided.

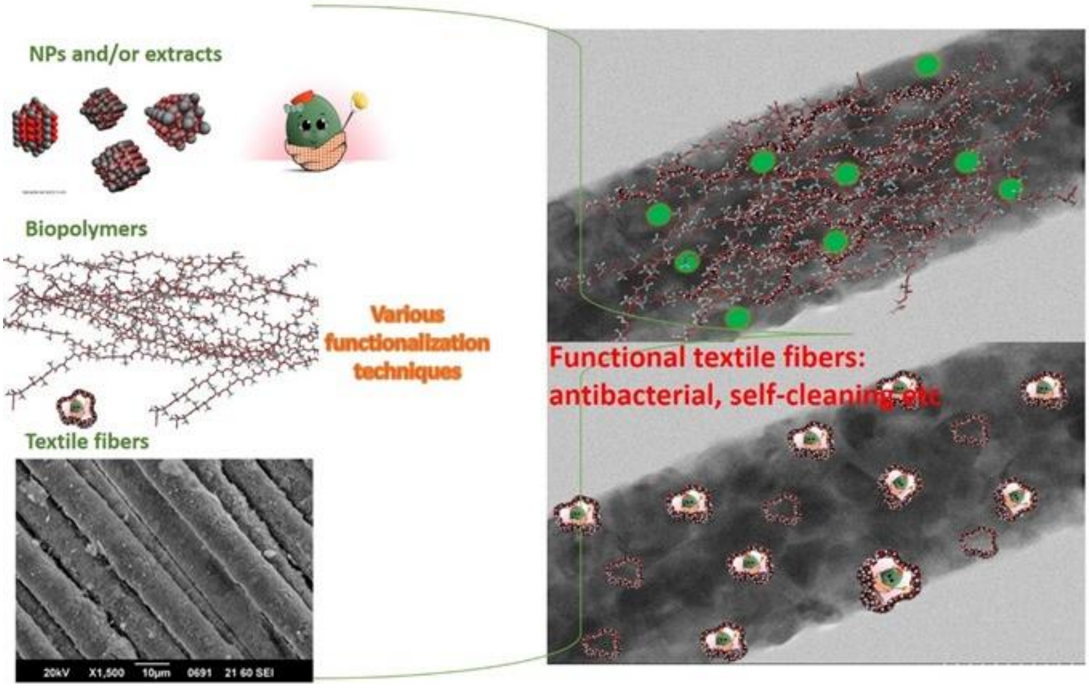

Figure 1. Nanoparticles-biopolymers composite materials schematic development.

2. Ultrasound-assisted coating

One of the most usual techniques for added functionality to textiles is sonochemical coating. Textile finishing processes accompanied by ultrasounds exposure have been reported in literature since 1975 by deeper penetration of cross-linking resins such as urea–formaldehyde under ultrasonic irradiation on cotton fabric and an excellent review regarding textile sonoprocessing was published by Harifi et al. in 2015 explaining in detail the technique and up to the respective date achievements on various metal, metal oxide and combinations surface finishing of fabrics [1]. The schematic representation of this technique is inserted in the Figure 2.

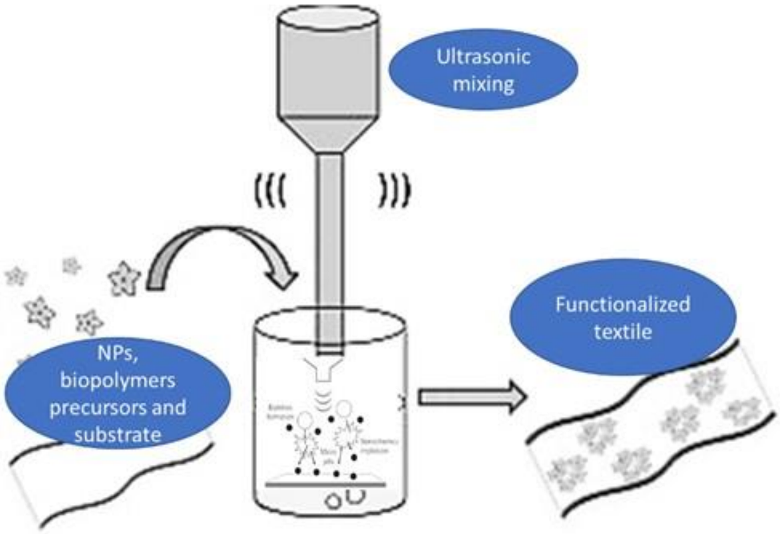

Figure 2. Sonochemical coating of textiles.

Plenty of research was done for functionalization of textiles with inorganic nanoparticles (CuO, ZnO, TiO2, MgO, Ag, Cu, Ag-TiO2, Zn-CuO, etc) [2-8], by the sonochemical method. The metal nano-oxides have a large surface area and suitable for coating textile fibers. This made the metal oxide NPs a good alternative to triclosan, quaternary ammonium salts, and other compounds with high toxicity that were dominating the antimicrobial market. The antibacterial efficiency of the sonochemically coated textiles was still present after 65 washing cycles. Moreover, two functions can be added to textiles simultaneously by sonochemical coating, color and biocide [7]. A recent good review of the subject was published in 2019 by Perelshtein et al. [8]. In 2014, Petkova at al. used sonochemical coating of textiles with hybrid ZnO/chitosan nanoparticles to achieve antimicrobial activity of textiles. Hybrid antimicrobial layers were produced on cotton supports by a one-step simultaneous sonochemical deposition of ZnO nanoparticles (NPs) and chitosan. The process was supplementary optimized in terms of precursors concentration and processing time in order to improve the antibacterial properties of the textile material and ensure their biocompatibility. The best antibacterial action against two pathologically relevant bacterial species was attained in a 30 min sonochemical coating process using 2 mM ZnO NPs suspension. When chitosan was simultaneously deposited with the same amount of ZnO, the result is a hybrid NPs coating with 48% and 17% higher antibacterial responsivity against *Staphylococcus aureus* and *Escherichia coli*, respectively as compared to only ZnO typical finishing. The existence of the biopolymer improved as well the robustness of the antimicrobial effect by 21% for S*taphylococcus aureus* and 40% for *Escherichia coli*, assessed after multiple washing cycles applications in hospital laundering regimes. Finally, 87% biocompatibility enhancement proved by fibroblast viability was detected for the hybrid ZnO/chitosan coating compared to the steady decrease of cells viability over one week in contact with the fabrics coated only with ZnO [9]. Chitosan, as well as its precursor, chitin is also widely used as biopolymers in textile functionalization. Chitin is the second most abundant natural polysaccharide found in the various marine, terrestrial, and microorganism sources. Chitosan is obtained by partial deacetylation of chitin. Both of them are widely used in different industries such as pharmaceutical, agriculture, water purification, biotechnology, biomedical applications, and production of fibers and finishing process of textile fibers. The large use base on their interesting properties such as nontoxicity, biocompatibility, biodegradability, low allergenic action, that they are bioactive, low cost, etc. The most important applications of chitosan in textile finishing include antimicrobial, blood coagulant, antistatic, antiodor, and crease-resistant finishing [10]. Chitosan can be modified by using metal and metal oxide nanoparticles to achieve new functional materials. In Türemen et al. 2021 study, binary chitosan-zinc oxide nanocomposite was successfully prepared by using precipitation method. Cotton fabrics were treated by the respective bio-nano-composites using pad-dry-cure and sol-gel methods to increase their washing resilience at multiple cycles. (3-Glycidyloxypropyl) trimethoxysilane was used to improve washing sturdiness of the coatings. Bionanocomposites coated fabrics were tested for their antibacterial and UV protection performances. A ternary chitosan-ZnO-TiO_2 nanocomposite was also synthesized to detect the changes in UV properties. The results revealed that chitosan-ZnO binary complex provided very good antibacterial and UV protective properties. The results also proved that the sol-gel application by (3-Glycidyloxypropyl) trimethoxysilane improved the effects of multi washing cycles of the treated cotton fabrics in comparison to simple chitosan treated fabrics. The use of the ternary coating treatment changed the UV protection factor to the "excellent protection" category.

The use of ultrasonication for the preparation of eco-friendly cellulose fabrics containing silver or gold nanoparticles was reported by Kwiczak-Yiğitbaşı et al. (2020). According to them, the mechano-chemistry of cellulose is based on the breakage of glycosidic bonds and the formation of mechano-radicals. These mechano-radicals can reduce Au3+ and Ag+ ions in solution, and the reduced metals can be stabilized by the cellulose chains on nanoparticles. The preparation method is shown to produce antibacterial silver nanoparticles-fabric and catalytically active gold nanoparticles-fabric composites, having up to a 14% yield of metal ion reduction. Since the method comprises on only the sonication of the fabric in aqueous solutions, and no hazardous reducing and stabilizing agents are used, it provides quick and environment-friendly availability of fabric nanocomposites, for applications in medical textiles [11].

Xu et al. (2021) reported on durable antibacterial and UV protective properties of cotton fabric coated with carboxymethyl chitosan and Ag/TiO2 composite nanoparticles. Ag/TiO2 colloid solution was prepared with using carboxymethyl chitosan as a stabilizer, then the carboxymethyl chitosan and Ag/TiO2 composite nanoparticles were coated on the fabric via finishing technology of pad-dry-cure. The modified fabric proved to have excellent antibacterial and UV protective properties, with the values of bacterial reduction and UV protection factor of 99.5 % and 79.0, respectively. Furthermore, even after 50 washing cycles, these properties of the finished fabrics were not changed [12]. Another suitable biopolymer for use alone and in combination with NPs for antibacterial activity achievement onto textile surfaces are the cyclodextrins. Cyclodextrins are cyclic oligosaccharides with hydrophilic outer surface and a lipophilic central cavity. Cyclodextrins show great feasibility in sustainable textile finishing. It exists 3 derivatives of commercial cyclodextrin: α-cyclodextrin, β-cyclodextrin, and γ-cyclodextrin - that are composed of six, seven, and eight α-1,4-glycosidic bonds. β-Cyclodextrin (β-CD) is the most consumed, used and attractive cyclodextrin due to its availability, lower price, facile synthesis, no skin sensitization and irritation, and no mutagenic effect. The ability of cyclodextrins to form complexes with host molecules finds significant application in distinct commercial sectors. Various application of cyclodextrins in textile to aid properties like antimicrobial, fragrance, and dyeing were intensely studied. A clear overview of this can be found in Singh et al. 2019 chapter [13]. Other natural polymers such as starch derivatives, cellulosic materials, maltodextrins, agar, alginate, Arabic gum, chitosan, and gelatins have been reported as excellent materials for microencapsulation. Plant extracts such as limonene, Geranium leaves extracts, Calendula officinalis, Mexican daisy, neem oil, tulsi leaves extract, ozonated red pepper seed oil, Vitex neguno leaves extract, Polyphenolic olive extracts etc., are the ingredients that have been applied to textile material in an encapsulated form to improve the antimicrobial activity and their durability to laundering [14-18]. By microencapsulation, the active ingredient can be released in a controlled manner instead of directly discharge from the textile fibers. A major advantage of microcapsulation is that it prevents loss of essential oils present in extract which are highly volatile in substances in air. This kind of biopolymers used in microencapsulation can be combined as well with metal and metal oxides NPs for fabrication of coatings onto textile fibers surfaces in order to obtain enhanced germicide properties of textile materials. Some of the recent NPs-biopolymers coating combinations reported in the scientific literature and their specific properties are presented in Table 1.

Table 1. Some of the recent NPs-biopolymers coating combinations reported in the scientific literature and their specific properties.

NPs	Used Polymer	The Effect of Nanoparticles Addition	Reference
Lignin capped Silver nanoparticles	agar	No changes in elongation at break. Reduction of water vapor permeability (by up to ~22%), water contact angle (by up to ~9%), water solubility (by up to ~16%), and swelling ratio (by up to ~50%) Enhancement of antimicrobial activity: *E. coli* (complete destroy after 6 h) and *L. monocytogenes* (complete destroy after 12 h)	19
Silver nanoparticles; Silver nanoparticles nanocellulose; Gold nanoparticles; Silver nanoparticles chitin	CHTS	Enhancement of antimicrobial activity against *E.coli* and methyl resistant *Staphylococcus Aureus* Gold nanoparticles has better activity: *A. niger* than Silver nanoparticles (from 0 to 25 mm of inhibition zone) Silver nanoparticles has better activity: *C. albicans* than Gold nanoparticles (from 6 to 19 mm of inhibition zone) No significant difference between antimicrobial activity of Gold nanoparticles and Silver nanoparticles against *S. aureus* and *P. aeruginosa;* Enhancement of tensile strength (by up to ~37%) and elongation at break (by up to ~18%) and reduced water vapor permeability CHNF improved water solubility, swelling ratio, water vapor permeability, tensile strength, reduced Young modulus and color properties	20,21,22
,Sulphur nanoparticles	CHTS	Increment of tensile strength (by up to ~18%), elastic modulus (by up to ~18%) and water contact angle (by up to ~6%) Reduction of elongation at break (by up to ~39%), water vapor permeability (by up to 14%); Enhancement of thermal stability Antimicrobial activity: *L. monocytogenes* (complete destroy after 12 h) and *E. coli* complete destroy after 6 h	23

Zinc oxide nanopartiles	chitosan	Enhancement of antimicrobial activity: *E. coli* (3.4 log reduction after 0.5 h) and *S. aureus* (4 log reduction after 0.5 h) Biocompatibility and nontoxicity	24
Silver nanoparticles	CHTS/cellulose	Enhancement of antimicrobial activities: *S. aureus* (~0.8 mm of inhibition zone) and E. Coli (1.2 mm)	25
Zinc oxide nanopartiles	CHTS/CMC	Enhancement of antibacterial activity: bacteria *S. aureus* (from 5 to 11 mm of inhibition zone) *P. aeruginosa* (from 3 to 11 mm), *E. coli* (from 3 to 9 mm), and fungi *C. albicans* (from 3 to 15 mm) Enhancement of tensile strength (by up to ~85%)	26
Silver nanoparticles	CHTS-gelatin	Enhancement of antimicrobial activity: *P. aeruginosa* (to ~28 mm of inhibition zone), *S. aureus* (to ~37 mm), and MRSA (Methicilin-resistant Staphylococus aureus) (to 24.73 mm), depending on Silver nanoparticles concentration Reduction of tensile strength (~27%) and Enhancement of elongation at break (~34%) Increased the shelf-life of red grapes on which the film was applied (to ~37 mm), and Methicilin-resistant *S.aureus* (to 24.73 mm), depending on Silver nanoparticles concentration	27
Silver nanoparticles	CHTS/PVA	Enhancement of antioxidant activity by up to ~33% (DPPH/2,2-diphenyl-1-picrylhydrazyl radical scavenging activity), up to ~37%	28
Zinc oxide nanopartiles	mahua oil-based polyurethane/chitosan	Enhancement of antimicrobial activity: *E. coli* (~25 mm) and *S. aureus* (~20 mm)	29
Zinc oxide nanopartiles; Graphene Oxide and CNC	PLA	Enhancement of antibacterial activity: *E. coli* (from 10 to 3.5 log after 12 h) and *L. monocytogenes* (from 12 to 8 log after 12 h	30,31
Zinc oxide nanopartiles -CHTS	starch	Antibacterial activity against *E. coli* and *S. aureus*	32
Silver nanoparticles inside gelatin-montmorillonite (AgM)	cellulose acetate	Tensile strength (by up to ~6%) and elastic modulus (by up to ~18%), but reduction in elongation at break (by up to~50%) Reduction of oxygen permeability (by up to ~14%) ability	33

		Enhancement of antimicrobial activity: *E. coli* (from 0 to 36 mm of inhibition zone), *S. aureus* (from 0 to 34 mm), *Salmonella* (from 0 to 32 mm), *Psuedomonas* (from 0 to 35 mm), *A. niger*, and *A. flavus*, depending on the Silver nanoparticles and thymol concentration	
Silver nanoparticles Selenium nanoparticles	furcellaran	Enhancement of moisture content (with Silver nanoparticles ~11.5% and with SeNPs ~14%), water solubility, elastic modulus (with Silver nanoparticles and with SeNPs ~10%), but reduction in swelling ratio (with Silver nanoparticles ~13% and with SeNPs ~20% Silver nanoparticles enhanced the UV-blocking effect. No changes in elongation at break SeNPs improved antimicrobial activity: *E. coli* (SeNPs from 0 up to ~38 mm of Silver nanoparticles from 0 to ~10 mm), *S. aureus* (SeNPs from 0 up to ~22 mm), and Methicilin-resistant Staphylococus aureus (SeNPs from 0 up to ~26 mm inhibition zone;	34
Silver and Silver-Copper nanoparticles	gelatin	Enhancement of antibacterial effect from 0 up to 14 mm of inhibition zone: *S. typhimurium* (from 3.5 to 7 log), *B. cereus, L. monocytogenes* (from 0.5 to 3 log)., *E. coli*, and *S.aureus* Reduction of tensile strength and Young modulus by up to ~25 % and ~36%, respectively, depending on Silver nanoparticles concentration; Enhancement in tensile strength (by up to ~49%) but reduction in elongation at break (by up to ~40%)	35,36
Titanium dixide nanopartiles	gelatin	Irradiation of the film with UV-A light (365 nm) resulted in the most effective antibacterial activity against *E. coli*	37
Zinc oxide nanoparticles; Zinc oxide nanorods	gelatin	Enhancement of antimicrobial activity: *E. coli* (from 9 to 5 log) and *L. monocytogenes* (from 9 to 1 log); Enhancement of UV-blocking effect and antimicrobial activity against *S. aureus* (from 0 to 80 mm of inhibition zone)	38,39
Titanium dixide nanopartiles	gelatin–agar/CHTS	Enhancement of antimicrobial activity against bacteria (S. aureus, E. coli, S. typhimurium, and *P.*	40

		aeruginosa) and fungi (*Aspergillus spp.* and *Penicillium spp.*)	
Zinc oxide nanorods	gelatin/clove essential oil	Enhancement of antimicrobial activity: *L. monocytogenes* (from 10 to 0 log after 7 days) and *S. typhimurium* (from 10 to 0 log after 7 days)	41
Zinc oxide nanorods	soybean polysaccharide	Enhancement of antimicrobial activity: *E. coli* (from 7 to 5 log after 12 h) and *S. aureus* (from 6 to 1 log after 12 h)	42
PVA/Graphene Oxide/starch Silver nanoparticles	PVA	antibacterial properties	43
Zinc oxide nanopartiles Copper oxide nanopartiles	carrageenan	ZnO NPs strongly improved antimicrobial activity against *E. coli* and *L. monocytogenes*	44
Zinc oxide nanorod nano-kaolin	semolina	Enhancement of UV barrier properties and antimicrobial activity against *E. coli* (from 0 to ~3 mm)	45
Cellulose nanostructures			
rice cellulose nanocrystals; betonine nanoclays; lignin NPs	CHTS/PVA chitosan PVA	Without changes in antifungal response *C. gloeosporioides* and *L. theobromae* and antimicrobial against *S. mutans S. aureus, E. coli*, and *P. aeruginosa* activities Enhancement of antimicrobial activity against *E. coli* (efficiency 48.50 %), *P. aeruginosa* (efficiency 40%), *S. aureus* (efficiency 8%), *Erwinia carotovora* subsp. *carotovora* and *Xanthomonas arboricola* pv. *Pruni*	46, 47,48
Copper oxide nanocomposites	CHTS	Enhancement of antimicrobial activity against *E. coli, P. aeruginosa, S. aureus, B. cereus* (all results were depending on the concentration and ratio of MMT and CuONPs	49
flax cellulose nanocrystals	CHTS	Enhancement of antimicrobial activity: *P. aeruginosa, E. faecalis, L. monocytogenes, E. coli,* and *S. aureus* (from 6.31 to 16.05 mm of inhibition zone)	50
nanocrystals and Silver nanoparticles	CHTS	Enhancement of antimicrobial and antifungal activity (from 0 to 96 mm^2 of inhibition zone depending on the concentration and ratio of Silver nanoparticles and BCNC	51

nanocrystalline erbium doped hydroxyapatite	CHTS	Enhancement in antimicrobial activity against *E. coli* and *S. aureus*	52
hallosite nanotubes with metal ions (Ag, Zn, Cu); sodium montmorillonite nanoclay Zinc oxide; chitin nanowhiskers /hybrid ZnO-Ag nanoparticles	CMC	Enhancement of antimicrobial activity: *E.coli* (from 6 to 0 log after 6h) and *L, monocytogenes* (from 7 to 4 log after 9 h) Addition of ZnO NPs enhance antimicrobial activity against *E. coli* and *S. aureus*	53,54,55
Halloysite nisin	starch	Nisin increased antimicrobial properties against *L. monocytogenes, C. perfringens*, and *S. aureus*	56
Lysozyme nanofibres	Pullulan	Enhancement of antioxidant activity (from 0 to ~80% DPPH method) and antimicrobial activity against *S. aureus*	57
Cellulose nanofibers Titanium dioxide nanoparticles	whey protein	TiO_2 enhances antimicrobial activity against *L. monocytogenes* and *S. aureus* and antioxidant properties	58
CHTS NPs	rice straw nanofibrillated cellulose	Enhancement of antimicrobial activity against bacteria (*S. aureus, E. coli),* and yeast (*S. cervisiae*)	59
halloysite nanotubes Zinc oxide nanoparticles	alginate	Enhancement in antimicrobial activity against *E. coli* (from 7 to 0 log after 3 h) and *L. monocytogenes* (from 6 to 0 after 9 h	60
Cloisite 30B Silver nanoparticles	gelatin	Enhancement of antimicrobial activity against *E. coli* and *L. monocytogenes*	61
Na+ montmorillonite halloysite Nanomer®I.44 P halloysite nanotubes loaded	fenugreek seed gum	Antimicrobial activity against *L. monocytogenes* (all results were depending on the type of nanoclays) No influence on antimicrobial activity against *E. coli, S. aureus, B. cereus*	62

with the essential oil			
CHTS NPs	tara gum	Antimicrobial activity against *E. coli* (from 0 to 87.32 mm^2 of inhibition zone) and *S. aureus* (from 0 to 111.71 mm^2)	63
CHTS/gallic acid NPs	konjac glucomannan	Enhancement of antimicrobial activity: *S. aureus* (from 0 to 20 mm of inhibition zone) and *E. coli* (from 0 to 12 mm)	64
Potatoes starch Tapioca starch CHTS	Turmeric nanofibres	Antimicrobial activity: *B. cereus, E. coli, S. aureus*, and *S. typhimurium* (the values were depending in the type of biopolymer)	65

3. Discussion

Some of the recent NPs-biopolymers coating combinations reported in the scientific literature and their specific properties are presented in Table 1.

These combinations of nanoparticles and biopolymers proved potential suitability for use onto textile fabrics for medical applications such as medical apparel, blankets, bed linings etc. as well as wound dressing in some cases. An example of recent work on wound dressing applications of combined NPs-biopolymer functionalized textile materials is the Vijayakumar et al. report in 2019 "Recent advancements in biopolymer and metal nanoparticle-based materials in diabetic wound healing management" [66], a review regarding natural polymers in combination with bioactive nanoparticles with antimicrobial, antibacterial, and anti-inflammatory activities for wound care with a role in accelerating the healing process of diabetic wound infectious. The sequence of antibacterial nanoparticles like Silver nanoparticles, Silver nanoparticles, Copper nanoparticles etc. with biocompatible and bioactive polymeric matrices accurately restrain bacterial advancement. At the same time, a wound's healing process is accelerated.

A recent report of Guan et al. (2021) account on the nanocomposite film (SA-CS@CuO/ZnO) composed of sodium alginate (SA) and chitosan (CS) functionalized by copper oxide nanoparticles (CuONPs) and zinc oxide nanoparticles (ZnONPs) fabrication and antibacterial mechanisms against *Escherichia coli (E. coli)* and *Staphylococcus aureus (S. aureus)*. At contents of 1.5 % (w/w) and 0.5 % (w/w), respectively of CuONPs and ZnONPs, the SA-CS@CuO/ZnO composite films exhibit excellent optical, mechanical, and shielding activities. Incorporation of ZnONPs adds photocatalytic ability of SA-CS@CuO/ZnO, producing a high level of reactive oxygen species under light irradiation. Further, antibacterial results showed that SA-CS@CuO/ZnO coatings inhibited the growth of *E. coli* and *S. aureus* over 60 % in the dark and over 90 % under light irradiation. This was also accompanied by incompleteness of bacterial cell structure, unstable cellular redox balance and DNA disruption. "The functions of differentially expressed genes screened by transcriptome analysis were mainly involved in membrane transport, cell wall and membrane synthesis, cellular antioxidant defense system, cell membrane and DNA repair system. The changes in bacterial transcriptional regulation reflected the disturbance in the physiological activities and loss of cell integrity, leading to damage of bacterial cells or death" [67]. "Wound dressing properties of functionalized environmentally biopolymer loaded with selenium nanoparticles" were recently published by Ahmed et al. using a polymeric blend based on chitosan (CS)/poly(vinyl alcohol) (PVA) containing different concentrations of selenium nanoparticles (SeNPs) and fabricated via casting technique. The results illustrated that, the nanocomposite kill and inhibit the growth of *E. coli* and *S. aureus* bacteria [68]. Smart polymeric films may act as surfaces that not only kill bacteria but also limit their adhesion and interaction with surfaces. An elaborate account of the recent advances and updated accomplishments of nanoparticle-impregnated biopolymeric films to combat microbial biofilms, thus inspiring innovations for cutting-edge research and development in this area was just published by Ghosh et al. (2021). In this review are speculated various passive and active mechanisms behind the inhibition and disruption of biofilms using nanoparticles-polymer composite films [69].

“Preparation of antibacterial film-based biopolymer embedded with vanadium oxide nanoparticles using one-pot laser ablation” was recently reported by Menazea et al. (2021). An environmentally and cost effective film of vanadium oxide nanoparticles (V_2O_5 NPs) embedded poly(vinyl alcohol)/chitosan (PVA/CS) was fabricated. Authors used one step pulsed laser ablation in liquids technique for the preparation of V_2O_5 NPs followed by mixing the prepared nanoparticles with polymer solution prior to film formation. The use of V_2O_5 NPs enhanced the antibacterial properties of the produced PVA/CS film. The antibacterial efficacy of the PVA/CS/V2O5 NPs was increased with increasing V_2O_5 NPs concentration [70-74].

With respect to the advantages and disadvantages of using the various biopolymers in combination with NPs onto textile fabrics, some of the most usual characteristics are summarized in Table 2.

Table 2. Advantages and disadvantages of using some usual biopolymers onto textile fabrics.

Type of Biopolymer	Advantages	Drawbacks
cellulose-based films	tasteless, odorless, resistant to oil and fat, hydrophilic nature [75]; thermal and chemical stability [76]	hardly dissolves or melts due to high crystallinity (Wang et al., 2018) non antimicrobial activity [77,78]
Starch-based films	odorless, tasteless, good O_2 and CO_2 barrier properties 79	poor water vapor barrier 80
pullulan-based films	highly impermeable to both oil and oxygen [86] 81	low solubility [87] 82 hydrophilic nature [88] 83
chitin and chitosan-based films	good CO_2 barrier properties, antimicrobial activity 84	non antioxidant and antifungal activity 85; limited oxygen and water impediment ability 86
gelatin-based films	Shielding properties 87	low water vapor permeability 88
pectin-based films	excellent oxygen barring capacity 89	high water vapor permeability 90
Alginate-based films	good water solubility, gel ability, and film-forming properties 91	poor water resistance 92

A summary of types of nanoparticles used for germicide properties of textile fibers and fabrics enabling is presented in Table 3.

Table 3. Referenced summarized data regarding use of metal nanoparticles for antibacterial or antifungal performance

Type of NPs	Deposition process	Functionalized textile fabric	Antimicrobial activity	Ref.
ZnO (30–60 nm)	Pad-dry-cure method Electroless deposition	cotton/polyester	*E. coli* and *Micrococcus luteus*.	[93]
Silver	Dip-coating	Polyester, Polyamide	*E. coli, S. aureus, S. epidermidis, P. aeruginosa*, and *C. albicans*	[94-96]
Silver ammonia complex		Polyamide	*E. coli* and *S. aureus*	[97-99]
Silver nanoparticles (in situ synthesis)		Polyester	*E. coli* and *S. aureus*	[100]
Ag/ZnO, Ag/SiO_2		cotton/polyester	*E. coli* and *M. luteus*	[101-103]
SiO_2	Dip-pad-cure process	Polyester	*E. coli* and *S. aureus*	[104]
silver-doped silica-complex nanoparticles	Spin-coating	Different textile supports	*S. aureus* and *E. coli*	[105]
Chitosan and silver-loaded chitosan nanoparticles		polyester	S. *aureus*	[102]
Ag and TiO_2		polyester	*E. coli, S. aureus*, and fungus (*C. albicans*).	[103]
silica sols containing silver		Polyamide/polyester	*E. coli*	[106]
Gold, nanosilver colloids	Solvent swelling method	Padded and non-padded nonwoven polypropylene or polypro-	*E. coli* and *S. aureus*	[107, 108]

		pylene/polyethylene		
Mixture of silver and TiO_2 nanoparticles	Pulse laser deposition	Polyester	*E. coli*, *S. aureus* and *C. albicans*	[103]
Copper nanoparticles	in situ synthesis	Polyamide	*S. aureus*	[109]

4. Conclusions and perspectives

Recent developments of surface nano-structured textiles coatings made of biopolymer films and nanoparticles on different textile substrates for enhanced medical applications to diminish the incidence of multiplied range of hospital-acquired infections were summarized. Their up-to-date biomedical applications and attributes/performance were synthetically revised. Combination of metal and metal oxides nanoparticles with biopolymers proved to be an efficient technique to generate enhanced antibacterial, virucidal and antifungal properties to textiles as shown by the most recent publications included in this minireview. The surface tailoring of textiles by nanoparticles-biopolymers uses as an alternative for surface modification of textiles, in order to grant them with biocidal performance is an important research and development topic that is growing day by day. The benefits the synergistic effects resulting from the simultaneous NPs - biopolymers deposition on textiles by various deposition techniques are the wash fastness of the antibacterial additives to surface and enhanced biocompatibility of the material in comparison with NPs coating alone. The use of biopolymers to stabilize colloidal dispersions of NPs is granting the particles with functionalities for covalent immobilization on textiles to convey higher durability of antibacterial effect. A synthetic overview of the most usual metal and metal oxide NPs and biopolymers for the antibacterial textile applications was presented. The present state of the art research on the subject open large perspectives for further development of green and sustainable routes for enhanced functionality textiles creation as well as environmentally friendly solutions for fashion and industrial applications.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used

“Conceptualization, N.V., C.M.R., M.S.;

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project administration, N.V.

funding acquisition, N.V.

All authors have read and agreed to the published version of the manuscript." Please turn to the CRediT taxonomy for the term explanation. Authorship must be limited to those who have contributed substantially to the work reported.

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