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Plasma-Assisted Antimicrobial Finishing of Textiles: A Review

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ABSTRACT

Owing to the ongoing pandemic, the importance of and demand for antimicrobial textiles have reached new heights. In addition to being used for medical purposes, antimicrobial textiles could be a self-defense entity against microbes for the general population. Because textiles are widely used, they can effectively be used to prevent the spread of microbes worldwide. The conventional antibacterial finishing process of textiles is the wet treatment method using either the pad-dry-cure or exhaustion techniques. However, the textile wet treatment industries are major contributors to worldwide pollution, which is extremely concerning. Given the current and near-future high demand, it is imperative to include plasma in antimicrobial finishing to achieve high efficiency in production, while retaining a safe environment. Hence, this paper reviews the rationale of plasma use in textile antimicrobial finishing through a critical analysis of recent studies and emphasizes the types and mechanisms of plasma techniques available for application.

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1. Introduction

Microbes are living organisms that are perceived only on a microscopic scale. They are found almost everywhere on earth, either in unicellular form or in a colony of cells [1]. The most common examples of microbes are fungi, bacteria, and viruses, of which the first two are primarily responsible for outbreaks on textile materials [2]. However, textiles can also be processed to achieve antiviral properties, thus helping to prevent the spread of viruses [3]. Although studies on the antiviral properties of textiles are still in the emerging phase, the antifungal and antibacterial properties of textiles have been widely investigated.

Antimicrobial finishing can protect textiles from microbial damage and enhance durability, while protecting the wearer from microbial infections. Fig. 1 shows a schematic representation of microbial disturbances on unfinished textile material compared with the textile finished with an antimicrobial agent. In addition to fungi and bacteria, the significance of and opportunity for using textiles to hamper the spread of viruses has come to the forefront during the current pandemic, if the textiles are provided with an antiviral finish. Therefore, antimicrobial finishing on textiles is becoming a matter of high importance and has received significant attention.

To date, several methods have been used for the application of antimicrobial agents to textiles. A convenient method of antimicrobial finishing is to use the finishing agent in the dope solution and form the textile fibers through a spinneret and coagulation bath during spinning [4]. This method produces a very durable finish because the finishing agent becomes an integral part of the fiber itself. However, this method can only be applied to regenerated or synthetic fibers, not natural fibers. The pad-dry-cure technique is an extensively used method for applying finishes to textiles made from either natural or synthetic fibers. Nevertheless although this is a practical method with industrial-scale use, it has some major drawbacks. For example, padding produces 70%–100% wet pickup, which requires the evaporation of water through an energy-intensive drying process. In addition, during evaporation, migration of the finishing agent occurs on the fabric surface, which often results in uneven finishing [2]. Another common technique of applying the finish is exhaustion or impregnation, which also requires water as a medium and further drying [5]. Some advanced methods for antimicrobial finishing have also been reported, including the sol-gel technique and layer-by-layer deposition [6,7]. The sol-gel technique is a method in which the fabric is impregnated in a sol (a colloidal solution that gradually changes into a gel form) and then passes through a subsequent padding and drying-washing system [7]. Layer-by-layer deposition is a technique in which fabric is dipped into a cationic polymer solution in one step and an anionic polymer solution in another step

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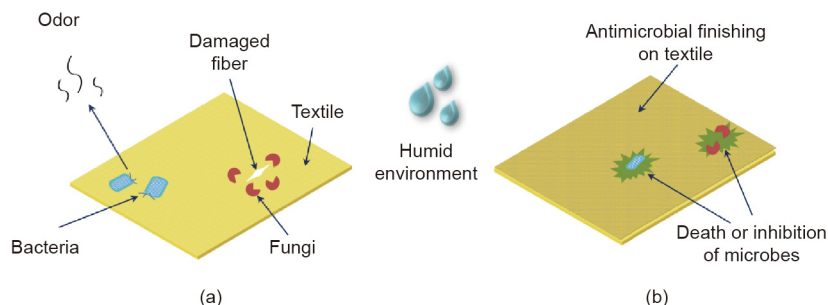


Fig. 1. Schematic representation of (a) microbial attack on unfinished textile and (b) antimicrobial activity of finished textile toward the microbes.

to deposit polymer layers sequentially [6]. Rinsing and drying of the fabric are required between the dipping operations in this technique. Although these methods are comparatively more effective than traditional wet finishing, the use of water and energy for drying is still a matter of concern. A few relatively dry techniques for antimicrobial finishing have been reported in the literature. For example, the deposition of ultraviolet-cured chitosan on cotton and silk to confer antimicrobial properties has been reported, where the fabric was dipped in a chitosan solution containing a photo initiator and then dried prior to the curing process [8]. In another study, *in situ* generation and deposition of zinc oxide nanoparticles (ZnONPs) on cotton were reported, where the fabric was immersed in a zinc acetate water/ethanol solution in a sonication flask for irradiation for 30 min (20 kHz, 750 W), followed by washing and drying [9]. Although the antimicrobial properties attained were encouraging, these methods are not completely dry or energy-efficient, given the necessity for water and subsequent drying.

The requirement of a large amount of water (followed by wastewater generation) and subsequent energy-intensive drying processes in conventional processes implies that an efficient and environmentally friendly alternative solution is of great interest to the industry. In this context, using plasma in textile finishing is a unique approach that can significantly reduce the use of water and energy, as plasma treatment does not require water or drying, which result in considerable water and energy savings [10,11]. Fig. 2 illustrates the advantage of using plasma in antimicrobial finishing, compared with conventional wet techniques, such as the pad-dry-cure method. Plasma-assisted antimicrobial finishing of

textiles is achieved by polymer deposition or graft polymerization. Polymer deposition involves the incorporation of an antimicrobial finishing polymer by spreading it in the form of a thin film on the textile substrate, whereas graft polymerization is the integration of the antimicrobial finish with the textile surface [10,12,13]. In addition, even if the plasma is used as a pretreatment process before finishing, the essential functional properties of the textiles (e.g., uptake) can be greatly improved, and a similar finishing effect can be achieved using less water and time.

Considering the importance of antimicrobial finishing on textiles and the radical improvement in finishing efficacy when plasma is involved, plasma-assisted antimicrobial finishing on textiles is a topic of utmost interest. However, existing relevant reviews are based on either the antimicrobial finishing agents used on textiles or achievable functionalities and efficiency when using plasma. To date, no detailed review has focused on the importance of plasma-assisted antimicrobial finishing on textiles. Therefore, the main aim of this paper is to focus on and discuss the use of plasma for antimicrobial finishing on textiles and to investigate the rationale and future opportunities. To achieve this, the mechanism of microbial attack, types of antimicrobial agents, methods of antimicrobial testing, and plasma and its mechanisms are discussed, followed by a critical evaluation of plasma-assisted antimicrobial finishing on various textile materials.

2. Mechanism of microbial attack on textiles

Microbes (mostly fungi and bacteria) can propagate on textile materials during their use and storage. A humid environment

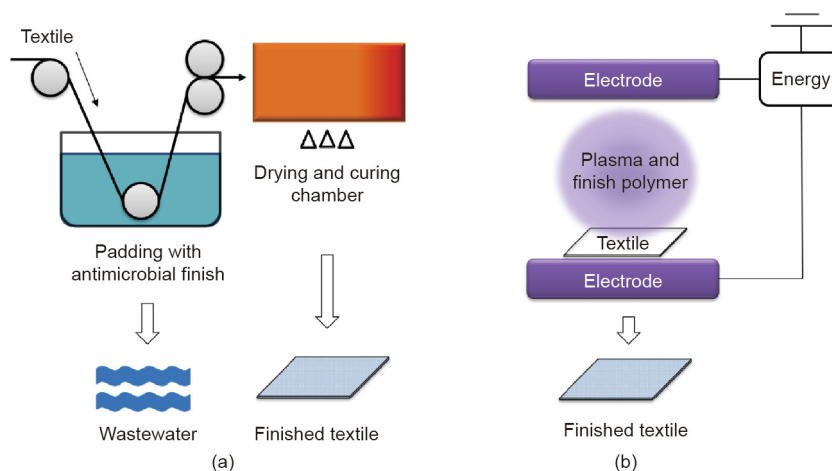


Fig. 2. Schematic illustration of the (a) pad-dry-cure method and (b) typical plasma application for antimicrobial finishing of textiles.

and the tendency of textiles to absorb moisture promotes the growth of microorganisms [14]. Because of their comparatively higher moisture absorption ability, textiles from natural fibers are more susceptible to microbe attack than synthetic fibers [15]. Microbes can cause visual and functional alterations, as well as cause unhygienic issues on textiles that can be harmful to the wearer. As mentioned above, among microbes, fungi and bacteria are the most detrimental to textile materials. Among these, fungi are mostly responsible for discoloration, stains, and fiber damage. Although bacteria are not as damaging as fungi, they produce an unpleasant odor and can lead to a slimy texture on the textile surface [2].

The effect of microbes on textile materials is usually related to two main phenomena: assimilation and degradation. Assimilation is the stage when microbes (i.e., fungi and bacteria) use textiles as their nutrition source [16]. Carbohydrates in plant-based fibers (e.g., cotton) and proteins in animal fibers (e.g., wool) act as a nutrient source for microbes. For example, cotton is more prone to fungal attack than it is to attack by bacteria, whereas wool is more prone to bacterial attack than it is to attack by fungi [2].

Microbes can attack the whole material or only a single component, such as dirt present on the surface or any additive incorporated in textiles, that is suitable for their growth. Microbes produce extracellular enzymes for collecting food, which causes physical changes in textile properties, such as loss of strength and flexibility [17]. Plant fibers (e.g., cotton, jute, hemp, and flax) are more prone to attack by cellulase enzymes produced by cellulolytic fungi [2]. Moreover, many fungi can produce pigments and are thus capable of causing discoloration. Because of their structure, which is similar to that of cellulose, regenerated cellulose fibers (e.g., viscose, acetate, and triacetate) are also susceptible to microbial attack. However, protein fibers, such as wool and silk, have higher resistance to fungi than plant fibers. Nevertheless, in adverse conditions, damage can occur because of the actions of proteolytic (protein-degrading) enzymes created by fungi and bacteria [17]. Synthetic fibers, such as polyester (PET), nylon, and acrylic, are quite resistant to microbes. However, the presence of additives in their chains, such as antistatic agents, lubricants, and thickeners, and the existence of dirt, soil, and dust can encourage the growth of microbes. In addition, the body waste of the wearer, that is, sweat and sebum, promotes the growth of microbes in textiles [2].

Small spots or bubbles seen on the textile surface often occur during the initial stage of microbe growth. Then, the degradation stage becomes dominant via the penetration of microbes inside the cavities of fibers and breakage of bonds, which adversely affects the physical properties (e.g., mass loss), mechanical properties (reduction of breaking strength), and chemical properties (e.g., degradation of cellulose or protein) [16].

3. Types of antimicrobial finishing agents

Various antimicrobial finishing agents have been proposed over the years to prevent microbial attacks on textiles. These include metallic compounds and nanoparticles, organic compounds (quaternary ammonium compounds (QACs), polybiguanides, *N*-halamines, and triclosan), natural polymers, and dyes, such as chitosan and plant extracts. Table 1 lists the most common types of antimicrobial agents used in textile applications and their advantages and disadvantages [15,18–35].

Heavy metals, such as silver, copper, and zinc, as well as metal oxides, such as titanium dioxide and metal salts, have been commonly used in the antimicrobial finishing of textile materials. These metals or metallic compounds show effective antimicrobial performance because of their ability to prevent DNA replication of microbes, cause irregular operation of the cytoplasmic mem-

brane, discharge intracellular constituents, and break protein linkages [15]. These compounds are toxic to microbes at very low concentrations and can make microbes inactive or kill them. Among these inorganic compounds, silver is most commonly used in textiles because of its low toxicity toward humans [36]. There are a number of silver-based commercial antimicrobial finishing products available on the market that can be directly applied to textiles, for example, AlphaSan (Milliken, USA), MicroFresh (O'Mara, USA), toxicity concern associated with metal nanoparticless, Canada) [2].

Recently, the application of metallic compounds in textiles for antimicrobial activity has been improved by using metallic nanoparticles. This is because nanoparticles have distinct physicochemical properties and have a high surface area to volume ratio, which acts favorably during contact with microorganisms [37]. Although silver nanoparticles (AgNPs), TiO₂ nanoparticles (TiO₂-NPs), ZnONPs, and copper nanoparticles (CuNPs) are the most frequently reported antimicrobial finishing agents used on textiles, AgNPs remain the optimal material for this purpose. Although there is a toxicity concern associated with metal nanoparticles when using small particle sizes (< 10 nm) that can penetrate human skin, the application of AgNPs has been widely investigated because of their low toxicity and wide spectrum of antimicrobial activity [38,39]. Many studies have reported an approximately 99.9% reduction in microbes when AgNPs are used in key textile fibers, such as cotton, wool, silk, polyester, and polyamide [18–25]. Comparatively, other nanoparticles for antimicrobial finishing on textiles have been reported mostly on cotton, with some exceptions [39].

In addition to the inorganic sources stated above, various organic compounds are also extensively used in textiles for antimicrobial finishing. For example, QACs are widely used for this purpose. The antimicrobial performance of QACs is contingent on their alkyl chain length, with approximately 12–18 carbons commonly showing good antimicrobial activity [2]. The cations in QACs assist their attachment to the negatively charged textile fiber surface as well as the formation of a QAC/microbe complex with an electronegative cell membrane [28,29,40]. The formation of the QAC/microbe complex disrupts the protein activity and functions of microbes [40]. It also reduces the propagation ability of microbes by disturbing their DNA [41].

In addition to QACs, polybiguanides, *N*-halamines, and triclosan are three other groups of synthetic organic antimicrobial agents used in textiles. Polybiguanides are composed of cationic biguanides separated by long hydrocarbon chains [30]. A longer polymer chain of polybiguanides delivers more cationic sites, which results in higher antimicrobial activity. Among the polybiguanides used, polyhexamethylene biguanides (minimal inhibitory concentration of 0.5–10 parts per million (ppm)) are the most commonly used antimicrobial finishing agents in textiles [2]. *N*-halamines are heterocyclic compounds with one or two halogens (X) covalently bonded with nitrogen (N) [31]. In the presence of water, the halogen ion is replaced by a hydrogen ion (N–H), which then binds with microbes and stops their metabolic and enzymatic processes. Because the application of *N*-halamines leaves a large amount of free halogen (commonly chlorine) on the fabric surface, a further reduction process is required to avoid discoloration and unpleasant odor from the fabric. Triclosan (2,4,4-trichloro-2-hydroxydiphenyl ether), an organic synthetic polymer, is an antimicrobial agent suitable for inhibiting the growth of a wide variety of microbes [30]. Because of its small molecule size, triclosan is exhausted into textile materials such as disperse dyes. The slow release of triclosan during the use of textiles leads to antimicrobial activity [2].

Although the synthetic antimicrobial agents mentioned above have been proven to be effective and durable on textiles, one of their drawbacks is the hazardous effect toward human health

Table 1
Common types of antimicrobial agents used in textiles and their merits and demerits.

Type	Action	Merits	Demerit	Applications	References
Ag and other metals	Producing reactive oxygen species, demolition of protein, lipid, and DNA	Effective and durable	Chance of depletion	Cotton, wool, silk, polyester, nylon, and regenerated cellulose	[15,18–27]
QACs	Formation of complex with microbes, denaturing protein, disturbing DNA to reduce propagation	Effective and durable	Often hazardous	Cotton, polyester, nylon, and wool	[26–29]
Polybiguanide	Damaging lipids, leakage of cytoplasmic sources	Effective and durable	Large amount required	Cotton, polyester, and nylon	[26,27]
Triclosan	Prohibiting lipid biosynthesis, cell membrane integrity depletion	Effective and durable	Breaks into toxic dioxin	Polyester, nylon, polypropylene, cellulose acetate, and acrylic	[26,27,30]
N-Halamines	Binding with microbes, preventing enzymatic and metabolic processes	Effective and durable	Needs regeneration, can cause odor	Cotton, polyester, nylon, and wool	[27,31]
Chitosan	Blocking protein synthesis, obstructing transportation of solutes toward cells	Eco-friendly	Poor durability, opposing effect on handle	Cotton, polyester, and wool	[26,32–35]

and the surrounding environment. In this respect, some natural polymers and dyes could be considered because of their environment-friendly nature and confirmed antimicrobial activity. Among the natural antimicrobial agents, chitosan is possibly the most widely used polymer with proven activity against microbes [30]. Chitosan is a deacetylated chitin, which is the second most abundant polysaccharide after cellulose [35,42]. Because the amine groups in chitosan provide positive charges, they interact with the negative charges in microbes and change the cell surface and permeability of microbes, while producing leakage in their molecules. This can inhibit the synthesis of messenger RNA (mRNA) proteins via penetration into the nuclei of the microorganisms. Furthermore, chitosan can form chelates with metal ions, which are essential for microbial growth. Chitosan has been frequently investigated on cotton, silk, polyester, viscose, and so forth, and as an antimicrobial finish (even as nanoparticles), and its durability on textiles can be further enhanced using cross-linking agents [32–35]. However, because it is effective only at higher concentrations and has a propensity to alter other important properties of textiles (e.g., handle and permeability), it is still not recommended as a commercial finishing agent on the same level as synthetic antimicrobial polymers [2].

Various natural dyes and extracts with antimicrobial activity are also used in textile finishing. The antimicrobial performance of natural dyes and extracts largely depends on the chemical structure and functional groups, as well as the presence of tannins (a naturally occurring polyphenol) in their composition. Natural dye sourced from gull nuts (*Quercus infectoria*) showed higher reduction (97.4%–99.5%) of the microbes' colony forming units compared with a commercial synthetic antimicrobial agent (96.2%–98.4%) [43]. In addition, many other natural dyes, such as turmeric (*Curcuma longa*), pomegranate (*Punica granatum*), amala (*Mallotus philippinensis*), catch (*Acacia catechu*), myrobalan (*Terminalia chebula*), and pine cones, have shown antimicrobial performance when used on textile materials such as cotton and wool [43–45]. The use of mordants (metal salts) resulted in a further increase in the durability of natural dyes and antimicrobial performance. In addition to dyes, various natural extracts and polymers, such as neem (*Azadirachta indica*), aloe vera (*Aloe barbadensis*), ginkgo (*Ginkgo biloba*), alginate, cinnamon essential oil, and propolis, have also been effectively used for antimicrobial finishing of textiles [46–50].

However, the major problem in using natural compounds is their initial composition as they are usually a complex mixture of various elements, and the composition varies when collected from different sources. In addition, for natural polymers, the required concentration for the inhibition of microbes is often high, and thus other properties of textiles could be altered. Therefore, a combination of natural materials with synthetic polymers, such as alginate/

QACs, chitosan/AgNPs, and chitosan/ZnONPs, have also been considered as antimicrobial finishing agents, showing positive results [33,49,51].

4. Methods of testing antimicrobial properties of textiles

Several standard methods are available for testing the antimicrobial performance of textiles. These techniques allow microbes to grow in the presence of a textile substrate and then assess the resistivity of the substrate toward that particular microbe (using fungi, bacteria, or viruses). Although standards are available for antifungal, antibacterial, and antiviral testing of textiles, the former two are widely practiced because of their greater impact on the physical and chemical properties of textiles resulting from the influence of fungi and bacteria [2].

These testing methods can be divided into qualitative and quantitative test methods. Qualitative methods present a fast and easy approach to determine antimicrobial activity, particularly when the test samples are large in quantity and require screening, whereas quantitative methods are generally cumbersome processes that consume a lot of material [52].

Qualitative test methods are also known as agar diffusion methods because the textile material is placed on nutrient agar plates (containing bacterial cells) during the experiment [53]. ISO 20645:2004 [54], AATCC 147:2004 [55], and JIS L 1902:2008 [56] are some of the best-known examples of agar diffusion testing. In the ISO 20645 method, the test sample is placed between two layers of agar plates, where the upper layer is inoculated with microbes and the lower layer consists of agar only. In the JIS L 1902 method, the test sample is placed on one agar layer containing microbe cells, and in the AATCC 147 method, the agar layer is streaked with microbes before the test sample is placed on it [52]. These methods measure the antimicrobial activity by observing the halo formation on test samples, that is, the places where microbes do not grow. Although a larger halo size could be an indication of higher antimicrobial performance, quantification is not usually performed using these methods [38].

The quantitative methods of antimicrobial activity testing are also known as absorption or suspension tests. These methods can provide values for antimicrobial performance, depending on the reduction in microbial growth [2,57]. Generally, in quantitative methods, a bacterial inoculum is placed directly on the test sample, leading to the adsorption of all liquid on the textile material. After incubation for a certain period, the bacteria are removed from the test sample by successive dilution and the total bacterial number is determined. The antimicrobial performance of the test sample is calculated as a percentage of bacterial reduction compared with a control sample that is not treated (finished) with an antimicro-

bial agent [52]. ISO 20743:2007 [58], JIS L 1902:2008 [56], and AATCC 100:2004 [59] are some common examples of quantitative methods that are commonly used to test the antimicrobial properties of textiles.

5. Plasma treatment

5.1. Function of plasma

Plasma is composed of a high concentration of reactive species and is capable of altering the physicochemical properties of a polymer surface [11]. Because it is distinct from solid, liquid, or vapor states, plasma is referred to as the fourth state of matter. The plasma state is achieved by applying energy to a neutral gas, for example, heating or exposure to electromagnetic fields [11,60]. Thus, a quasi-neutral mixture of various active species, such as electrons, ions, neutrons, radicals, photons, excited molecules, and metastable atoms, is produced with high energy. Hence, when plasma is guided to the surface of a material, it dissociates ranges of chemical bonds on the surface (usually at a depth < 10 nm) and thus alters the functionality. In addition, the application of plasma produces various simultaneous recombination mechanisms, which can be used to deposit a polymer layer on the textile surface through grafting or coating [61]. Fig. 3 shows a schematic representation of the functional properties and polymer grafting on a textile surface using plasma treatment [60].

By choosing a suitable gas, or a combination of gases (mostly O₂, H₂, N₂, NH₃, air, and inert gases), and selecting the correct plasma parameters (e.g., pressure, energy, time, and gas flow rate), definite alteration of the textile surface can be achieved [62]. For example, the correct use of plasma parameters and treatment conditions can improve the wettability, chemical reactivity, chemical and mechanical resistance, and adhesion properties of a material [63]. Depending on the plasma environment and parameters, four key phenomena (simultaneous and interconnected) are commonly observed on a textile substrate: etching, chain scission, formation of radicals, and polymer deposition [60].

Etching is the elimination of particles from the textile surface within a very narrow limit (i.e., a few hundred angstroms) without changing the bulk characteristics [64]. This phenomenon is also connected to the deposition of polymers on textiles because the etched particles are ionized in the plasma environment and deposited on the surface, and they thus continue to undergo recombination [65]. The collision of the active species with the molecules on the textile surface leads to chain scission and abstraction of atoms

(by etching). In addition, new groups are created on the surface when plasma radicals interact with the surface radicals, causing the surface to become functionalized (Fig. 3(a)) [65]. Furthermore, chain cross-linking occurs through the recombination of radicals. When a finishing polymer (such as antimicrobial finishing) is introduced into the plasma chamber, the polymer is grafted onto the textile substrate through the simultaneous cross-linking of plasma radicals (as shown in Fig. 3(b)) [60].

5.2. Plasmas used in the processing of textiles

Plasma can be applied either at high or low temperatures. Because most textile fibers are heat-sensitive, only low-temperature plasma (also referred to as cold plasma) is applied to textiles [66–70]. Plasma treatment can be conducted through direct current (DC) or alternating current (AC) using low-frequency (1–500 kHz), radio-frequency (RF) (commonly 13.56 or 27.12 MHz), and microwave (commonly 915 MHz or 2.45 GHz) energy [66,71].

Plasma can be produced either at low pressure in a closed chamber or at atmospheric pressure [72]. Low-pressure (1–100 Pa) plasma is usually applied using RF or microwave energy [11]. Although this technique can produce a uniform effect and has good reproducibility with respect to textiles, while consuming a small amount of gas, it is difficult to adapt to large-scale continuous production of textiles because the sample size is limited to the size of the closed chamber [66,71]. Therefore, the application of plasma under atmospheric conditions is considered more practical for continuous textile line production [72].

As illustrated in Fig. 4, four types of atmospheric-pressure plasmas are commonly used in textiles, namely, corona discharge (CD), dielectric barrier discharge (DBD), atmospheric-pressure glow discharge (APGD), and atmospheric-pressure plasma jet (APPJ), as listed in Table 2 [11,61,63,73]. In the CD method, the electrodes used are dissimilar: One is needle-like, and the other is like a cylinder or plate [11]. Plasma exists in an area of extending gas near the needle tip called the ionization region. The plasma species diffuses toward the other electrode, producing a drift region (Fig. 4(a)). The distance between the two electrodes is usually very small and suitable for thin textiles [61]. However, the ionization in this method is very weak and has an inhomogeneous effect on the surface. Hence, the use of CDs in textiles is currently very limited.

DBD is an upgraded technique (compared with CD), where an insulating material is coated by at least one of two electrodes that are placed 2–5 mm apart (Fig. 4(b)). The applied voltage for the

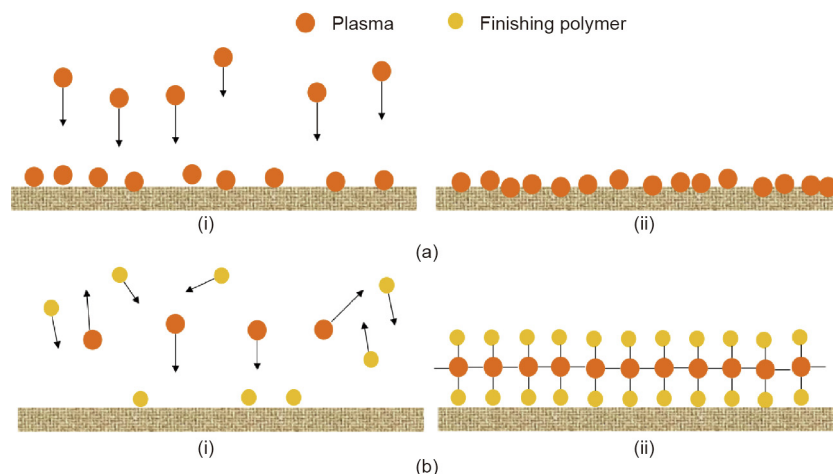


Fig. 3. Schematic illustration of (a) achieving functional property and (b) polymer grafting on a textile surface (i) during and (ii) after plasma treatment.

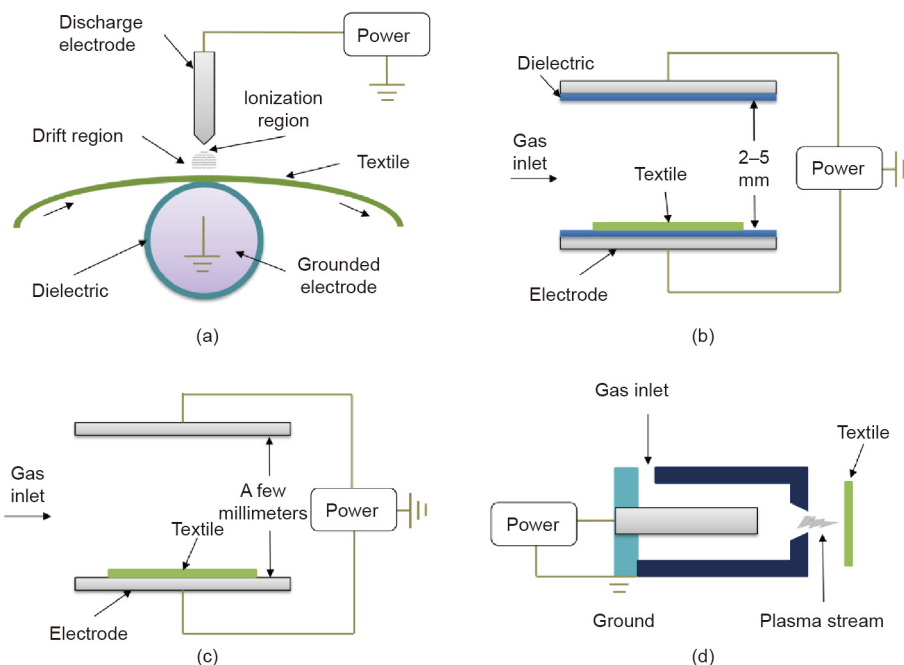


Fig. 4. Schematic illustration of different atmospheric-pressure plasma treatments on textiles: (a) CD, (b) DBD, (c) APGD, and (d) APPJ.

Table 2
Common methods of atmospheric plasma treatment in textile processing.

Application method	Characteristics	Common parameters	References
Corona discharge	Weak ionization, inhomogeneous effect	Near 1 mm inter-electrode spacing	[11,61]
Dielectric barrier discharge	Mostly uniform or filamentous effect	20 kV (AC)	[11]
Atmospheric-pressure glow discharge	Uniform and homogenous effect, requires expensive helium (He) gas	High frequency (2–60 MHz) and low voltage (~200 V)	[11]
Atmospheric-pressure plasma jet	Uniform toward any shape though only toward one side of textiles	RF, 100–250 V	[63,73]

common DBD technique is approximately 20 kV (AC) [11]. Although two forms of DBD can occur, homogeneous or filamentous, uniform and homogeneous surface treatment can be achieved by careful selection of the treatment conditions. The third technique, APGD, is usually conducted at a high frequency (2–60 MHz) and low voltage (~200 V) using two bare electrodes (uncoated metal) placed at a distance of a few millimeters (Fig. 4(c)) [11]. Although this technique commonly produces a uniform and homogenous effect on textiles, a shortcoming is the necessity to use expensive He gas to avoid arc formation between the electrodes. To offset this problem, other gases are sometimes used (e.g., Ar and N₂) as alternatives [71,73]. Finally, the APPJ technique is the most recent inclusion, in which two electrodes are placed in a concentric manner (Fig. 4(d)). The gas passes through the electrodes, and the applied energy (RF, 100–250 V) converts the gas into plasma. Plasma then exits toward the surface of the textile substrate through a nozzle. The APPJ technique can be uniformly applied to any shaped textile [11,73].

In addition to those mentioned above, there are a few other types of plasma application techniques commonly used in textile finishing, including vapor deposition and inductively coupled plasma [74,75]. Plasma vapor deposition is the projection of a con-

tinuous vapor phase toward a textile substrate to achieve a thin film layer. This thin layer is mostly achieved in textile industries by plasma sputter deposition in the presence of a magnetic field (also known as a magnetron sputter deposition system) (Fig. 5(a)) [74]. The textile substrate is placed on the anode, and a metal or alloy target is held with the cathode. The magnetic field is placed parallel to the target near the cathode to trap electrons near the target. Commonly, argon (Ar) gas is used for this purpose; Ar breaks down with the application of energy and forms an abnormal glow discharge. The presence of a magnetic field increases the plasma density and the number of sputtered atoms that hit the target, resulting in a higher deposition on the textile substrate.

The other type of plasma, that is, inductively coupled, can be either cylindrical (Fig. 5(b)) or planar (Fig. 5(c)), and is commonly powered by RF energy [75]. The cylindrical form is maintained by the axial electrostatic or electromagnetic field of the primary coil. However, in a planar coil system, a flat helix is coiled from the axis to the outer radius, and multipole magnets are used outside to enhance the outward plasma uniformity. Although inductively coupled plasma can be used either at low pressure or atmospheric pressure, most previous studies have used low-pressure conditions to achieve a higher plasma density.

5.3. Textile characterizations for assessing plasma modification

Common methods for evaluating textile modification by plasma treatment include both physical and chemical analyses. The application of plasma commonly disrupts the surface of textiles (often called plasma etching) at a very narrow depth. This can be observed through the morphological analysis of the textile surface, for example, scanning electron microscopy (SEM) images [35]. However, because the changes in the surface are nominal, they are sometimes not perceived in SEM images. In such cases, other techniques for analyzing surface topography, such as scanning probe microscopy, are useful, providing numerical values of the surface roughness [68].

The chemical changes in textiles by plasma treatment largely depend on the chemical structure of the textile itself and the

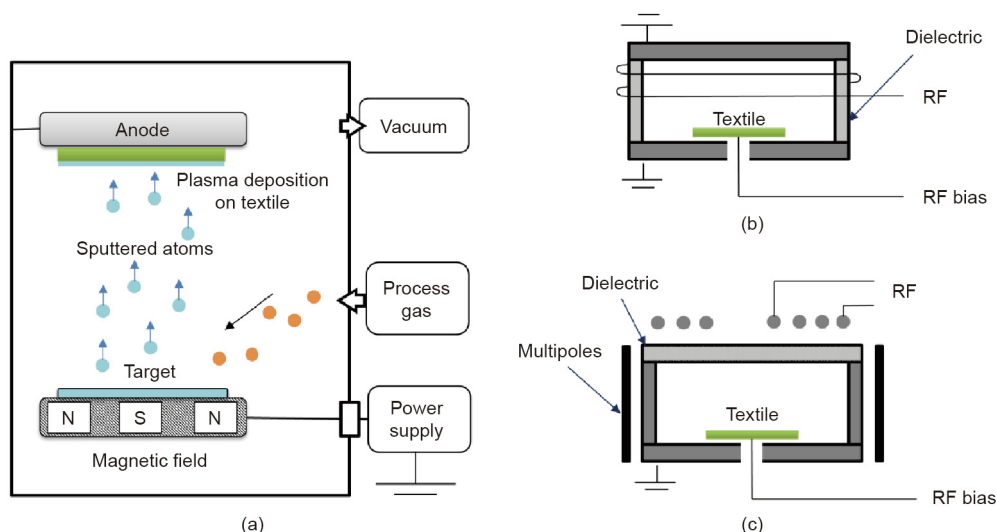


Fig. 5. Schematic diagrams of (a) magnetron sputter deposition system and inductively coupled plasma in (b) cylindrical and (c) planar geometries using RF energy.

plasma gas used. Different plasma gases can produce different functionalities on the textile surface by introducing new chemical groups. For example, oxygen (O_2)-containing plasma can produce new C=O or O–C–O groups on cellulosic fibers, whereas nitrogen-containing plasma can produce C–N or O=C=NH groups [76]. Fluorine-containing gases (e.g., C_2F_6 , C_3F_6 , and SF_6) are often used to produce a thin hydrophobic layer on a textile substrate [60]. The changes in chemical structure can be investigated using various techniques, including Fourier transform infrared spectroscopy (FTIR) and X-ray photoelectron spectroscopy (XPS). The application of plasma on textiles affects the surface energy, wettability, and color (nominal change caused by etching, which alters the light reflection pattern). Hence, plasma modifications on textiles are also often assessed by investigating the lightness of the surface, surface energy measurement, and capillary height measurement [60,77,78].

6. Applications of plasma treatment in antimicrobial finishing of textiles

6.1. Grafting and polymerization of antimicrobial compounds

Unlike common processes such as pad–dry–curing, which are employed for the grafting of various compounds on textiles, plasma treatment can activate the substrate and monomers to induce the grafting reaction without heating or immersion in a chemical bath, reducing water and energy consumption and minimizing environmental pollution [79]. Polymerizable precursors such as vinyl, aromatic, cyclic, and saturated hydrocarbons or metalorganic compounds can be directly polymerized on the surface of a substrate with the aid of plasma. If the polymerizable precursors cannot be directly used in the plasma chamber, reactive gases (such as O_2 or N_2) or non-reactive gases (such as Ar and He) can be used for surface activation. Free radicals are created on the surface during the collision of energetic species present in the plasma medium with the polymeric chains of the substrate [80,81]. Vinyl monomers can react with free radicals produced by plasma and undergo graft polymerization on activated substrates. Usually, the surface of the textile substrate is activated by plasma, and free radicals are produced on the surface. Then, the activated substrate is subjected to the vinyl monomer solution by immersion, padding, or spraying methods. Heating the plasma-treated substrate, the

monomer-treated substrate may enhance the grafting yield. The deposition of the monomer on the textile substrate by padding, evaporation, or spraying enables the process to be carried out continuously in line with atmospheric-pressure plasma treatment, reducing the use of chemicals, energy, and time [12,26].

QACs containing vinyl groups can be grafted onto textile fibers using plasma and impart antimicrobial functionality. Plasma treatment creates free radicals on the surface of the fibers. Peroxy radicals are formed upon exposure of the initially formed radicals to O_2 or air, which initiates the grafting polymerization of vinyl monomers on the substrate. Addition of Mohr's salt ($Fe(NH_4)_2(SO_4)_2 \cdot 6H_2O$) can prevent homopolymerization in the solution, increasing the grafting yield. Cornelius et al. [12] employed atmospheric plasma (DBD and APPJ) to graft (3-acrylamidopropyl) trimethyl ammonium chloride (as a vinyl QAC) on polypropylene (PP) and cotton nonwoven fabrics. The process sequence was plasma–pad–dry–plasma. The grafting was confirmed by XPS, SEM, and acid dye adsorption investigations. The mechanism of the grafting process is shown schematically in Fig. 6. This process resulted in a high grafting yield and uniformity without the use of heat or wet solvents [12].

Diallyldimethylammonium chloride (DADMAC) was grafted onto PP nonwoven fabric by pre-activation and post-treatment by APGD plasma (99% He/1% O_2). The samples were subjected to a process including plasma pre-activation, padding with DADMAC and pentaerythritol tetraacrylate (as a cross-linker to increase the durability of the coating), drying, plasma-induced graft polymerization, and rinsing. A schematic diagram of the process and free radical mechanism of plasma-induced graft polymerization is shown in Fig. 7. The grafting of poly-DADMAC on PP fibers was confirmed by SEM, FTIR, and time-of-flight secondary ion mass spectrometry (TOF-SIMS). The sample prepared under optimized conditions showed good antimicrobial activity against *Staphylococcus aureus* (*S. aureus*) and *Klebsiella pneumoniae* (*K. pneumoniae*) bacteria [10]. The same process was applied to a nylon/cotton (50%/50%) blend fabric, and a 99.9% reduction in bacterial growth was reported. The high degree of cross-linking led to the high durability of the antibacterial coating prepared by this method [13].

Arik et al. [82] examined the effect of Ar DBD plasma treatment (130 W, 40 s) on the finishing of cotton with commercial antimicrobial products based on Ag, dichlorophenol, triclosan, and diphenyl alkane derivatives using a pad–dry–cure procedure. The energy-dispersive X-ray spectroscopy (EDX) results confirmed that

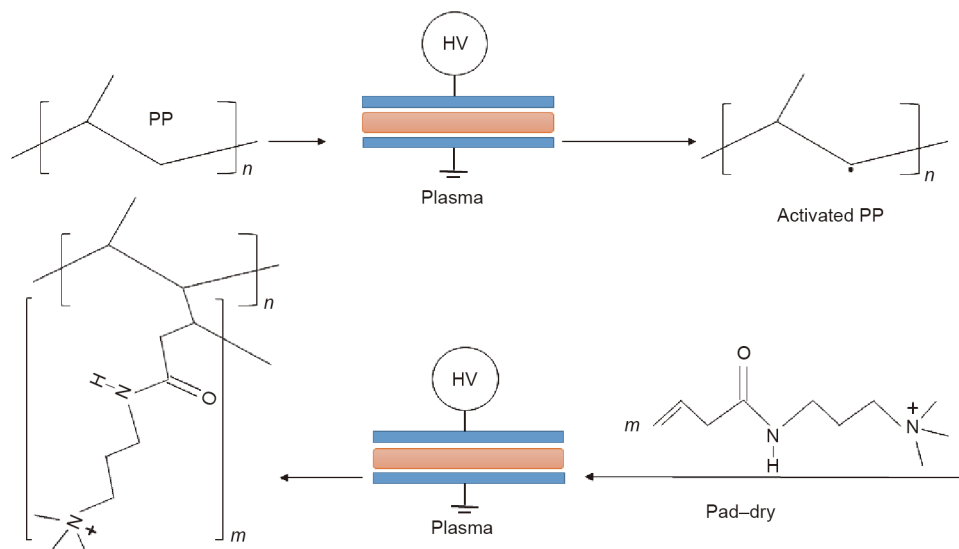


Fig. 6. Schematic mechanism of grafting of (3-acrylamidopropyl) trimethyl ammonium chloride on PP nonwoven initiated by DBD plasma [12]. HV: high voltage.

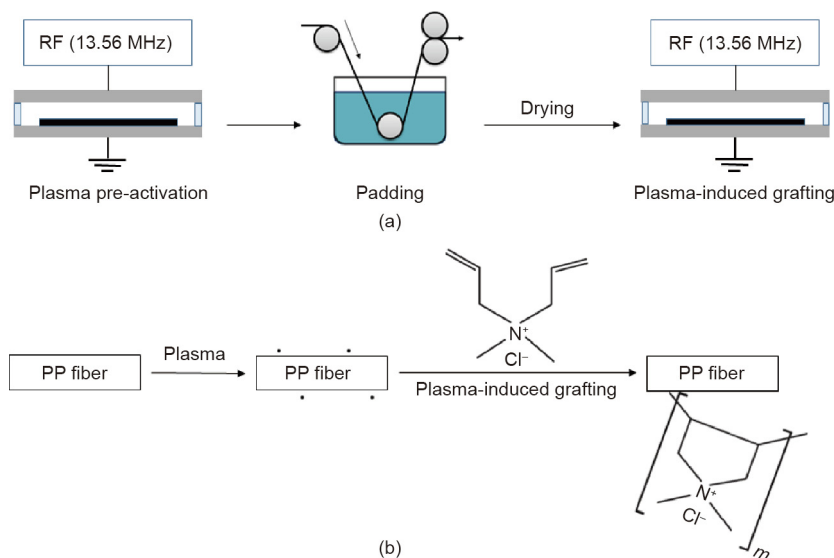
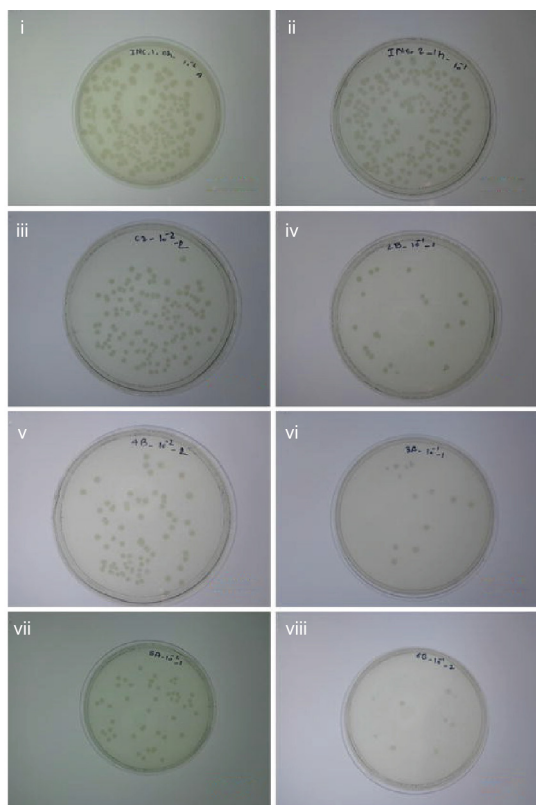


Fig. 7. Schematic presentation of plasma-induced graft polymerization: (a) process and (b) mechanism of attachment of DADMAC on PP nonwoven by plasma activation.

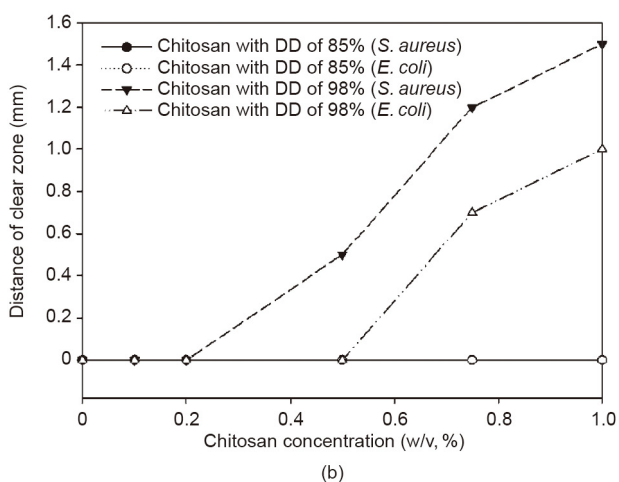
the Ag content of the plasma-treated cotton was higher than that of the untreated sample. The antibacterial activity and durability were improved significantly by plasma treatment, and it was more effective for the loading and durability of diphenyl alkane derivatives [82].

Plasma treatment can enhance the adsorption and attachment of chitosan to textile fibers. Naebe et al. [35] used helium and He/O₂ atmospheric-pressure plasma to attach chitosan to cotton fabric using a pad-dry-cure process. The surface energy and thickness of the chitosan coating improved after the plasma treatment. The finished fabric showed significant antimicrobial activity against Gram-negative *Escherichia coli* (*E. coli*) bacteria (Fig. 8 (a)). However, the results indicated that plasma treatments alone and without any further chitosan coating were also capable of reducing bacterial activity (Fig. 8) because of the formation of active agents, such as helium metastable species (He*), O, and OH [35]. Low-pressure oxygen plasma treatment (800 W, 27.12 MHz, 75 Pa, 30 s) of viscose fabric enhanced the loading of chitosan and conferred excellent antibacterial activity to the fin-

ished fabric [83]. Haji et al. [84–89] showed that O₂ plasma treatment enhanced the attachment of chitosan to cotton and wool fibers and improved the dyeability and antibacterial activity of the fabrics. DBD plasma increased the number of O₂-containing groups on the surface of the PET fabric and enhanced the deposition of chitosan by immersion in chitosan acetate solution (2% (w/v)) and vacuum drying. The chitosan-coated sample showed high antimicrobial activity against *E. coli* and *S. aureus* (Fig. 8(b)) [90]. Similar results were obtained when the Ar/O₂ plasma-treated PET samples were coated with chitosan polymers and oligomers using a pad-bake procedure [91]. The activation of nylon fabric with an APPJ at a power of 1000 W, using air as the processing gas, improved the grafting of chitosan on the fabric and enhanced the antimicrobial activity of the coated fabric. Two types of chitosan, that is, chitosan oligomers (molecular weight *M_w* = 12 000 Da) and chitosan polymers (*M_w* = 170 000 Da), were used for grafting. The plasma-treated fabrics were immediately impregnated in a chitosan solution for 6 min and cured at 95 °C for 8 min, followed by washing. Surface activation, introduction



(a)



(b)

Fig. 8. Antibacterial activity of (a) (i) an inoculum only after 0 h, (ii) inoculum only after 1 h, (iii) control cotton fabric, (iv) chitosan-treated cotton fabric, (v) helium plasma-treated cotton fabric, (vi) helium plasma/chitosan-treated cotton fabric, (vii) He/O₂ plasma-treated cotton fabric, and (viii) He/O₂ plasma/chitosan-treated polyester fabric; and (b) DBD plasma/chitosan-treated polyester fabric. DD: degree of deacetylation. Reproduced from Refs. [35,90] with permissions of Springer Nature, © 2016, 2010.

of new O₂-containing groups, and grafting of chitosan onto nylon fibers were confirmed by XPS analysis. Fabric samples grafted with chitosan polymer showed higher antibacterial activity than the samples grafted with the oligomer. The antibacterial activity and hydrophilicity were further improved by plasma post-treatment [92]. The antibacterial activity of chitosan-based antimicrobial finishes depends on the molecular weight, degree of deacetylation of chitosan, and pH of the medium. Although chitosan has a broad antimicrobial spectrum, its efficiency is reduced at alkaline pH. The introduction of a permanent positive charge by chemical mod-

ification of chitosan improves its antibacterial activity, regardless of the pH of the medium [93,94].

Guanidine-based antimicrobial agents are well-known for their excellent antimicrobial and biocidal action because of their cationic character, which causes electrostatic interactions with the bacteria or organism cell membrane, leading to their death. Yim et al. [95] used a DBD system for the deposition of 1,1,3,3-tetramethylguanidine (TMG) on ultra-high-molecular-weight polyethylene (UHMWPE) film through an atmospheric-pressure plasma-enhanced chemical vapor deposition (AP-PECVD) process. The precursor aqueous solution was heated to 25 °C, and the vapor was transferred to the space between the electrodes using helium as the carrier gas. Plasma treatment was conducted at 330 W for 30–180 s (90 kHz). The coating of the surface with the island-like guanidine polymer was confirmed by SEM, atomic force microscopy (AFM), attenuated total reflection (ATR)-FTIR, and XPS analyses. The samples coated under optimal conditions showed a complete reduction in *E. coli* and *S. aureus* growth. The advantage of this process is the cationic and alkaline nature of the guanidine compound leads to antibacterial activity at all pH ranges [95]. Table 3 provides an overall comparison of the antimicrobial finishing achieved through various plasma treatment techniques on various textile fibers [10,13,35,36,38,57,80,82–92,95–141].

6.2. Loading improvement of antimicrobial agents through surface activation

Surface activation or functionalization by plasma treatment can be considered a fast and economical pretreatment process for promoting the loading of non-polymerizable antimicrobial agents on textile substrates. Usually, the loading and fastness properties of antimicrobial agents such as QACs, nanoparticles, and drugs on textiles, especially those made of hydrophobic fibers, are low. Surface treatment is needed to improve the wettability, surface tension, and reactivity of textile fibers.

QACs possess advantages such as thermal stability, low human toxicity, and oxidative properties (without deterioration of the physical properties of textiles), which has led to the widespread application of these compounds in antimicrobial finishing of textile surfaces at low cost and with adequate germicidal performance. Song et al. [97] employed a DBD plasma treatment to improve the interaction between alkyldimethylbenzylammonium chloride (ADBAC) as a QAC and cotton, PET, and cotton/PET wipes. DBD plasma treatment increased the adsorption of ADBAC on PET and cotton/PET wipes because of the interaction with the plasma-generated O₂-containing groups on their surfaces. Although the adsorption of ADBAC on the untreated cotton sample was higher than that on untreated PET and cotton/PET samples, the amount of ADBAC on the surface of cotton decreased after DBD plasma treatment, which may have been due to the penetration of ADBAC inside the fibers. Therefore, the plasma-treated PET sample showed the highest antimicrobial activity compared with the other fabrics because it had the highest concentration of ADBAC on the surface. The antibacterial activity of the plasma-treated cotton sample was at its lowest level because of the penetration of ADBAC into the bulk of the hydrophilic cotton fibers, reducing its concentration on the surface Fig. 9 [97]. Overall, DBD plasma treatment improved the antimicrobial activity and increased the shelf life of the antibacterial efficacy of PET-containing wipes [96].

To increase the loading of ampicillin as an antimicrobial agent on PP mesh used for hernia repair, the surface of PP fibers was functionalized by plasma polymerization of tetraethylene glycol dimethyl ether. Low-pressure RF plasma, using Ar as the carrier gas, was employed. The process was initiated by a short pre-activation step using Ar plasma for 30 s at 100 W. Then, tetraethylene glycol dimethyl ether vapor was introduced into the plasma

Table 3
Common plasma treatment techniques for antimicrobial finishing on different textile fibers and reported outcomes.

Substrates	Antimicrobial agents	Type of plasma	Method of application	Properties	References
PP	DADMAC	APGD (He/O ₂)	Pre-activation and post-treatment	Good antibacterial activity	[10]
Nylon/cotton	DADMAC	APGD (He/O ₂)	Pre-activation and post-treatment	99.9% reduction in bacterial growth	[13]
Cotton	Ag, dichlorophenol, triclosan and diphenyl alkane derivative	DBD (Ar)	Pre-activation and pad-dry-cure	Improved antibacterial activity and durability	[82]
Cotton	Chitosan	DBD (He and He/O ₂)	Pre-activation and pad-dry-cure	Significant antimicrobial activity	[35]
Viscose	Chitosan	Low-pressure O ₂ plasma	Pre-activation and pad-dry	Excellent antibacterial activity	[83]
Cotton and wool	Chitosan	Low-pressure O ₂ plasma	Pre-activation and pad-dry	Improved dyeability and antibacterial activity	[84–89]
PET	Chitosan	DBD (air)	Immersion-vacuum drying	High antibacterial activity	[90]
PET	Chitosan	DBD (Ar)	Pre-activation and pad-cure	Good biocompatibility and antibacterial activity	[91]
Nylon	Chitosan	APPJ (air)	Pre-activation and pad-cure	Good biocompatibility and antibacterial activity	[92]
UHMWPE	TMG	DBD	Plasma-enhanced chemical vapor deposition	Excellent antibacterial activity	[95]
PET	Alkyldimethylbenzylammonium chloride (ADBAC)	DBD (air)	Pre-activation and immersion	Good antimicrobial efficacy with increased shelf life	[96,97]
PP mesh	Ampicillin	Low-pressure Ar plasma	Pre-activation, grafting with tetra ethylene glycol dimethyl, loading of ampicillin by pad-dry-cure	Antibacterial activity used for hernia repair	[98]
PET and PP	Octenidine	DBD (air)	Ink-jet printing of nanoparticles	Continuous antibacterial finishing	[99]
Nylon	Poly(N-vinylpyrrolidone) (PVP)-coated AgNPs	DBD (air)	Spray and exhaustion	Antibacterial activity using very low amount of AgNPs	[100]
Nylon	AgNPs	DBD (air)	Pre-activation, immersion, and curing	Enhanced hydrophobicity, long-term antibacterial effect	[36,101]
PET	AgNPs	Low-pressure air plasma	Pre-activation, immersion, and curing	Durable antibacterial activity	[102]
Cotton	Ag nitrate	Corona (air)	Pre-activation-immersion-pad-dry-cure	Enhanced loading and durability of antibacterial effect	[103]
Cotton	CuNPs and ZnONPs	Corona (air)	Pre-activation-exhaustion-drying	Improved self-cleaning and antibacterial activity	[104]
Bamboo	AgNPs	DBD (air)	Pre-activation- <i>in-situ</i> synthesis of AgNPs using microwave	Excellent ultra violet (UV) protection and antibacterial activity	[105]
Cotton	AgNPs	Low-pressure CF ₄ plasma	Simultaneous reactive dyeing and nano-finishing (exhaustion)	Good antibacterial activity without affecting the color of the fabric	[106]
PET	Ag nano-gel and chlorhexidine	DBD (CO ₂)	Immersion and drying	Excellent antibacterial and healing properties	[107]
PP	AuNPs	DBD and diffuse coplanar surface barrier discharge (DCSBD) (air)	Immersion and drying	Good antibacterial activity	[108]
Viscose	Ag ⁺ and Cu ²⁺ ions	DBD (air)	Immersion and drying	Enhanced antimicrobial activity, improved by ageing	[109]
Cotton/PET	Ag ⁺ ions	DBD (air)	Immersion and drying	Enhanced antimicrobial activity	[110]
Cotton	AgNPs	Sputtering	Simultaneous sputtering of AgNPs and plasma deposition of hexamethyldisiloxane (HMDSO)	Hydrophobic, durable antibacterial activity with controlled release of nanoparticles	[38]
PET	AgNPs, CuNPs, and ZnONPs	APPJ (O ₂ /N ₂)	Embedding of NPs between two plasma-polymerized HMDSO layers	Hydrophobic, durable antibacterial activity with controlled release of nanoparticles	[57,111,112]
Cotton	AgNPs	APPJ	Sputtering	Good antibacterial activity	[113]
Modal	ZnONPs	APGD	Pre-activation and <i>in-situ</i> synthesis of ZnO NPs	Wash-fast antibacterial property	[114]
Cotton	ZnONPs	Low-pressure O ₂ plasma	Pre-activation-immersion-pad-dry-cure	UV protection	[115]
Cotton	5,5-Dimethyl hydantoin (DMH)	APPJ (N ₂)	Pad-plasma-dry-cure	Regenerable antibacterial activity	[80,116–119]
Bamboo	Extract of <i>Aloe barbadensis miller</i> leaves and <i>Rosa damascene</i> flowers	Low-pressure air plasma	Pre-activation-pad-dry-cure	Wash-fast antibacterial property	[120]
Banana	Green tea and tulsi extracts	DBD (air)	Pre-activation-immersion-dry-cure	Enhanced antimicrobial activity	[121]
Cotton	Thymol	Low-pressure plasma (O ₂ and N ₂)	Pre-activation and exhaustion	Great antibacterial activity durable after 50 washing cycles	[122]
Cotton	Neem leaf extract	Low-pressure plasma (air or O ₂)	Pre-activation and pad-dry-cure in presence of citric acid	Excellent and durable antifungal and antibacterial activity	[123–127]
Cotton	Neem oil vapor	Low-pressure plasma (air)	Pre-activation and vapor treatment	Good antibacterial activity	[128]
Cotton	Onion skin extract	Low-pressure O ₂ plasma	Pre-activation and exhaustion dyeing	Good antibacterial activity	[129]
Wool	Berberine	Low-pressure O ₂ plasma	Pre-activation followed by β-cyclodextrin grafting and dyeing	Significant antibacterial activity	[130]
Wool	Berberine	DBD (air)	Exhaustion dyeing	Good antibacterial activity	[131]

(continued on next page)

Table 3 (continued)

Substrates	Antimicrobial agents	Type of plasma	Method of application	Properties	References
Cotton	Ag	Low-pressure plasma	DC magnetron sputtering	Durable antibacterial and UV protective	[132]
PET	Ag/TiO ₂	Low-pressure plasma	DC/RF sputtering	Structural coloration, significant antibacterial activity and improved antistatic and UV protection properties	[133]
Cotton	Ag and Zn	Low-pressure plasma (Ar)	Magnetron sputtering	Biocompatibility, wound healing and antimicrobial activity	[134]
PET	Ag	Hollow discharge cathode plasma (Ar)	Sputtering	antibacterial activity	[135]
PET/silk	Cu	Low-pressure plasma (Ar)	Sputtering	Conductivity and antibacterial activity	[136]
Cotton	Titanium oxynitride (TiON)/Cu	Low-pressure plasma (Ar, O ₂ , and N ₂)	Co-sputtering	Good antibacterial activity	[137]
Cotton	Ag and SiO ₂	Low-pressure plasma (Ar)	Co-sputtering	High antibacterial activity	[138]
PP	AgNPs	DBD (H ₂ /Ar)	<i>In-situ</i> reduction of Ag ions by plasma	Self-cleaning property	[139]
Cotton	AgNPs	DBD (H ₂ /Ar)	<i>In-situ</i> reduction of Ag ions by plasma	High antimicrobial activity with good fastness	[140]
Cotton	AgNPs	APGD (Ar)	<i>In-situ</i> reduction of Ag ions by plasma	Significant antimicrobial activity	[141]

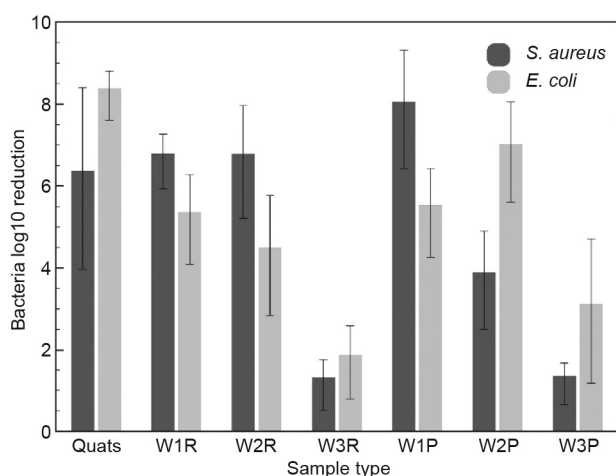


Fig. 9. Bacteria log reduction with the untreated (R) and plasma-treated (P) wipe samples. W1–W3 are the samples of pure polyester, cellulose/polyester (55%/45%), and 100% bleached cotton, respectively. Reproduced from Ref. [97] with permissions of American Chemical Society, © 2019.

chamber by bubbling Ar through the liquid monomer. Polymerization was performed at a pressure of 40 Pa for 2 h at a power of 200 W. Ampicillin loading was performed by immersing the plasma-polymerized sample in a 4% aqueous solution of ampicillin for 24 h, followed by padding and drying. The loading of ampicillin on the modified PP mesh was 3-fold higher than that of the untreated samples, and the samples showed antimicrobial activity against *S. aureus* and *E. coli* bacteria. This process resulted in a high drug loading while fibroblast properties such as chemotaxis, adhesion, and morphology remained unaffected [98].

Ivanova et al. [99] applied poly(L-lactide) (PLLA) polymeric nanoparticles containing octenidine as an antimicrobial agent on PET and PP nonwoven fabrics using a continuous process including plasma treatment and inkjet printing. Briefly, the fabric sample was pretreated with atmospheric air plasma and then printed with antibacterial nanoparticles using an inkjet printer. Plasma treatment improved the wettability, distribution, and diffusion of

nanoparticles over the fabric surface. This process is continuous and has the potential to be used for the preparation of antimicrobial textiles via a cheap, easy, fast, and fully automatic procedure [99].

DBD treatment improved the deposition of low concentrations (10 mg·L⁻¹) of polyvinylpyrrolidone (PVP)-coated AgNPs on polyamide 66 fabric using spray and exhaustion methods. The exhaustion method at 30 °C showed the best results, and the antibacterial effect of AgNPs on the plasma-treated fabric remained unchanged after five washing cycles. Plasma treatment increased the roughness of the polyamide fibers and generated new functional groups on the surface, resulting in better adsorption and adhesion of AgNPs. The advantage of this method is the use of a very low but effective amount of AgNPs for antibacterial finishing [100]. Zille et al. [101] also investigated the effect of DBD plasma treatment and aging on the loading of AgNPs with different sizes and the antibacterial activity of polyamide 66 fabric. The results showed that the ionic and covalent bonds between the nanoparticles and nylon fibers were promoted by the formation of O₂-containing chemical species, which increased the roughness, surface energy, and wettability after plasma treatment. Both untreated and plasma-treated polyamide fabrics showed high antimicrobial activity, even after 30 days of aging. Plasma treatment induced a three-fold increase in AgNP adsorption and improved the durability of the coating. The amount of AgNP loading increased with decreasing particle size. Comparing the antibacterial activity of plasma-treated samples coated with AgNPs with particle sizes in the range of 10–100 nm, the results showed the highest and most durable functionality when using 40 to 60 nm AgNPs. This is an advantage given the higher toxicity of smaller AgNPs [36,101]. Surface activation with low-pressure air plasma (27 Pa, 100 W, 2.5 min) enhanced the binding efficiency, antimicrobial activity, and stability of colloidal AgNPs on the PET fabric. Despite the durability of the antibacterial activity after five washing cycles, Ag was released into the washing bath [102].

Nourbakhsh [103] reported that corona treatment of cotton increased the carboxyl group content, improved the adsorption of Ag ions from an Ag nitrate solution, and enhanced the antimicrobial activity and wash fastness of the fabric. Corona pretreatment also improved the self-cleaning and antibacterial activity of cotton

fabric when coated with Cu and ZnO nanoparticles [104]. Pretreatment of bamboo fabric with atmospheric-pressure air plasma enhanced the loading of AgNPs. In this study, the plasma-treated bamboo fabric was impregnated in a bath containing Ag nitrate and trisodium citrate, and AgNPs were synthesized on the fibers using microwave heating for 3 min. Synthesis of AgNPs on the surface of the bamboo fabric improved ultraviolet protection and increased the water contact angle [105]. Low-pressure tetrafluoromethane (CF_4) plasma treatment (40 Pa, 27.12 MHz, 1200 W, 10 s) of cotton introduced C=O, O–C–O, C–O, and O=C–O groups on the surface and increased the roughness. No fluorine (F)-containing groups were observed on the surface, as determined by XPS analysis. CF_4 plasma treatment enhanced the loading of AgNPs (30 nm), and the finished cotton fabric showed good antibacterial activity [106].

Anjum et al. [107] prepared a nano-Ag-loaded gel by dropwise addition of 1000 ppm Ag nitrate solution to 1% polyethylene glycol solution and stirring for 15–120 min at 60 °C. The size of the synthesized nanoparticles was in the range of 10–50 nm. Carbon dioxide plasma (60 s, 40 W) was employed for the functionalization of the PET monofilament sutures prior to the attachment of AgNPs and chlorhexidine digluconate. Plasma treatment increased the carboxyl group content on the surface of the PET filament. The plasma-treated samples were immersed in the as-prepared AgNP-loaded gel or 1% aqueous solution of chlorhexidine digluconate for 2 h at 25 °C, then washed and dried under vacuum. The prepared sutures showed excellent antibacterial and healing properties compared with those of the control sample.

Radić et al. [108] compared the effect of two types of atmospheric-pressure plasma treatments on the deposition of as-prepared gold nanoparticles on nonwoven PP. AuNPs were prepared by the reduction of Au^{3+} (HAuCl_4 , 1 mmol·L⁻¹) using gallic acid. DBD and diffuse coplanar surface barrier discharge (DCSBD) using air as the processing gas were applied for the surface activation of the nonwoven PP. The configuration of the plasma treatment system is shown in Fig. 10 [108]. In the DBD setup, zeolite granules were used on the ground electrode to adsorb humidity and ensure homogenous discharge. Inductively coupled plasma atomic emission spectroscopy (ICP-AES) showed that both DBD and DCSBD plasma treatments increased the amount of AuNPs deposited on the PP fibers. The contents of AuNPs in DBD-treated and DCSBD-treated samples were four- and three-fold that of the untreated sample, respectively. The best antibacterial activity was recorded when the PP samples were pretreated with DCSBD for 12 s (24 J·cm⁻²) or DBD for 120 s (14.4 J·cm⁻²) and coated with AuNPs [108]. Pretreatment of the viscose fabric with air plasma using the DBD setup shown in Fig. 10 increased the sorption of Cu^{2+} and Ag^+ ions, thereby enhancing the antimicrobial activity of the finished product. Aging of the samples after plasma treat-

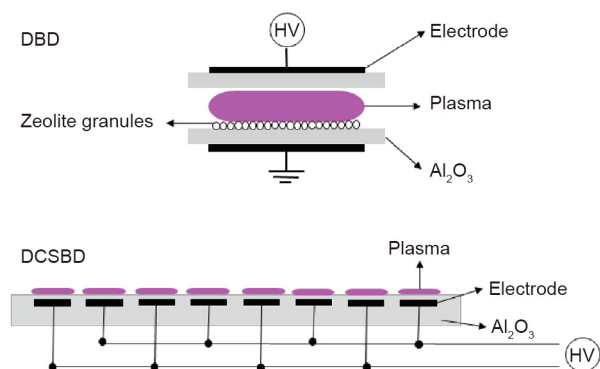


Fig. 10. Configuration of DBD and DCSBD atmospheric-pressure plasma systems.

ment and before Ag ion loading for 7 d increased the loading of Ag^+ ions up to 100% [109]. The loading of Ag ions and antibacterial activity of the resultant sample improved when cotton/polyester fabric was pretreated with DBD plasma, as mentioned above [110].

Although plasma treatment of textile surfaces before application of nanoparticles can improve their adhesion, the inclusion of nanoparticles into a polymeric matrix can further improve the stability of the nanoparticles. Plasma polymers are created through plasma polymerization of monomers in the gas or liquid state. The thickness, porosity, and rigidity of plasma polymers can be easily controlled by tuning the process parameters, and the release behavior of metal ions (e.g., Ag) can be adequately controlled by embedding the nanoparticles in plasma polymers [142,143].

Irfan et al. [38] functionalized cotton fabrics by simultaneous sputtering of AgNPs and plasma deposition of hexamethyldisiloxane (HMDSO) on the surface of fibers. The composite thin film deposited under the optimized conditions resulted in the preparation of highly hydrophobic cotton fabrics with antibacterial activity that was stable against 10 washing cycles [38]. In another study, HMDSO was first polymerized on the surface of a PET nonwoven fabric using O_2/N_2 plasma to obtain an organosilicon coating with a thickness of 70 nm. Then, the samples were immersed in different suspensions of Ag, Cu, and ZnO nanoparticles in ethanol for 1 min and dried. Finally, another layer of organosilicon coating with a thickness of 10 nm was deposited, as described earlier. Ag- and Cu-coated samples showed high antimicrobial activity, while the antibacterial activity of the ZnO-coated sample was slightly lower, which was attributed to the larger size of the ZnO nanoparticles used [57]. The second organosilicon layer acted as a barrier against the detachment and uncontrolled release of the nanoparticles, and the samples coated with this layer showed long-lasting release of the nanoparticles, which were stable after 10 washing cycles [111,112].

A novel APPJ was utilized for the sputtering of Ag particles on cotton fabric to obtain an antimicrobial coating [113]. The device consisted of two Ag electrodes placed in two glass tubes. A mixture of O_2 and Ar was passed through the electrodes, and a high voltage was applied (15 kV, 450 W). The distance between the cotton fabric and the nozzle was 5 mm. A schematic of the APPJ device is shown in Fig. 11 [113].

Optical emission spectroscopy confirmed that the plasma sputtered Ag, and SEM images confirmed that Ag particles were deposited on the cotton samples. The prepared samples showed antimicrobial activity against Gram-positive and Gram-negative bacteria, and the inhibition zone increased with increasing treatment time [113].

Atmospheric-pressure DC glow discharge plasma treatment of the modal fabric improved the coating with ZnONPs and enhanced the antibacterial activity of the fabric. FTIR analysis showed that O_2 and air plasma treatments created C=O and –OH groups on the surface of the modal fibers, led to a decrease in the water contact angle, and improved the ZnONP loading [114]. Jazbec et al. [115] showed that the treatment of cotton fabric with low-pressure

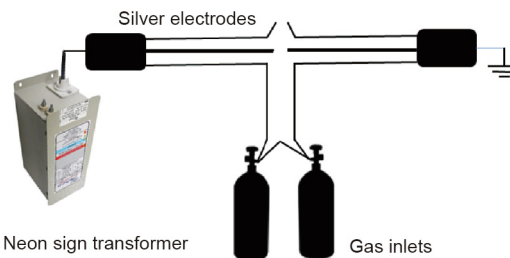


Fig. 11. Schematic diagram of the APPJ device designed for sputtering of Ag.

inductively coupled RF O₂ plasma at 400 W for 10–30 s increased the surface functional groups and roughness of cotton fibers, resulting in better loading of ZnONPs and enhanced ultra violet (UV) protection. The breaking strength and breaking elongation of the samples also improved after plasma treatment because of the increased friction between the yarns and fibers caused by plasma etching [115].

Zhou et al. [80] applied 5,5-dimethyl hydantoin (DMH) to cotton fabric using a pad-dry-plasma-cure method. The finished fabric was chlorinated using sodium hypochlorite to convert the amide groups of DMH to *N*-halamine, which can kill bacteria. The atmospheric-pressure He/N₂ plasma treatment improved the durability of the antimicrobial activity against *S. aureus* bacteria, and the imparted antimicrobial activity was generated by chlorination. The chlorination reaction of DMH is shown in Fig. 12 [80,116–119].

Plasma pretreatment can enhance the loading of natural antimicrobial extracts on textiles. Kongarasi et al. [120] showed that low-pressure air plasma treatment enhanced the antibacterial and antifungal efficiency and durability of bamboo fabrics when finished with a combination of two herbal extracts, *Aloe barbadensis miller* leaves and *Rosa damascene* flowers. The ethanolic extract showed the highest antibacterial activity compared with the water, chloroform, and petroleum ether extracts. The antibacterial activity was retained after 25 washing cycles [120]. In another study, air DBD plasma treatment for 4 min improved the wettability, increased the surface polar groups on banana fibers, and enhanced the antibacterial activity and durability of banana fabric when finished with green tea (*Camellia sinensis*) and tulsi (*Ocimum sanctum*) leaf extracts [121]. Low-pressure O₂ and N₂ plasma treatment of cotton improved the loading of thymol on cotton fabric and imparted great antibacterial activity to the samples, which were stable for 50 washing cycles. The antibacterial activity of the cotton samples loaded with thymol without plasma activation was stable over five washing cycles [122].

Low-pressure RF air plasma pretreatment improved the wettability of cotton fabric and enhanced the uptake of neem leaf extract as a natural antimicrobial agent. The extract was applied with citric acid as a cross-linking agent using a pad-dry-cure process. The highest antimicrobial activity was obtained when the sample was plasma-treated at a power of 50 W for 5 min, while the distance between the electrodes was 3 cm. Enzymatic hydrolysis of cotton with cellulose showed the same effect, and a synergic effect was observed when the samples were first enzyme-treated and then plasma-treated. ATR-FTIR analysis confirmed the introduction of new carbonyl functional groups on the cellulose chains. Fig. 13

shows the chemical changes in cellulose during the air plasma treatment [123]. The cotton samples treated with cellulose and air plasma and finished with neem leaf extract showed antifungal activity and 100% bacterial reduction for both Gram-positive and Gram-negative bacteria. The antimicrobial effect was stable after 30 washing cycles [123–125]. O₂ plasma showed slightly better results than air plasma [126,127]. Air plasma-treated cotton subjected to neem oil vapor at 150 °C for 60 min also showed good antibacterial activity [128]. Cotton fabrics pretreated with low-pressure O₂ plasma and dyed with onion skin and onion pulp extracts showed antimicrobial activity against *S. aureus* [129].

Pretreatment of wool fabric with low-pressure O₂ plasma enhanced the attachment of β-cyclodextrin to wool fabric through a pad-dry-cure process with citric acid as a cross-linking agent. The plasma-treated and β-cyclodextrin-finished wool fabric was loaded with berberine, which showed significant antibacterial activity [130]. Air DBD treatment of wool enhanced the dyeability of wool with berberine as a natural colorant, and the sample prepared and dyed under optimal conditions showed antimicrobial activity against Gram-positive and Gram-negative bacteria [131].

6.3. Plasma sputtering

The coating of cotton fabric with an Ag nanolayer by DC magnetron sputtering (base pressure: 0.02 mTorr (1 mTorr = 0.133 Pa), working pressure when feeding Ar: 0.05 Torr, 5 min) resulted in antibacterial and UV protective properties on the finished fabric, which was stable after 10 washing cycles [132].

Yuan et al. [133] used a continuous sputtering system for the deposition of an Ag/Ti dioxide nanocomposite on polyester fabric. Rotating cylindrical Ag and Ti targets were used as the cathodes. The chamber pressure was 0.006 Pa. DC and DC/RF sputtering methods were used. In DC sputtering, Ag was sputtered first, followed by Ti sputtering. The Ti sputtered layer was converted to TiO₂ upon a short exposure to air. TiO₂ nano-coating was obtained directly when reactive sputtering of Ti was performed using Ar/O₂ as the processing gas. The polyester fabrics were structurally colored, and the physical properties of the sputtered fabrics decreased slightly. The sputter-coated fabrics showed significant antibacterial activity and improved antistatic and UV protection properties [133].

During metal sputtering coating of textiles, the entire surface is coated by a uniform thin layer of the metal. It has been reported that when using a textile for wound healing, coating the entire surface is detrimental to the biocompatibility of the product. Liu et al.

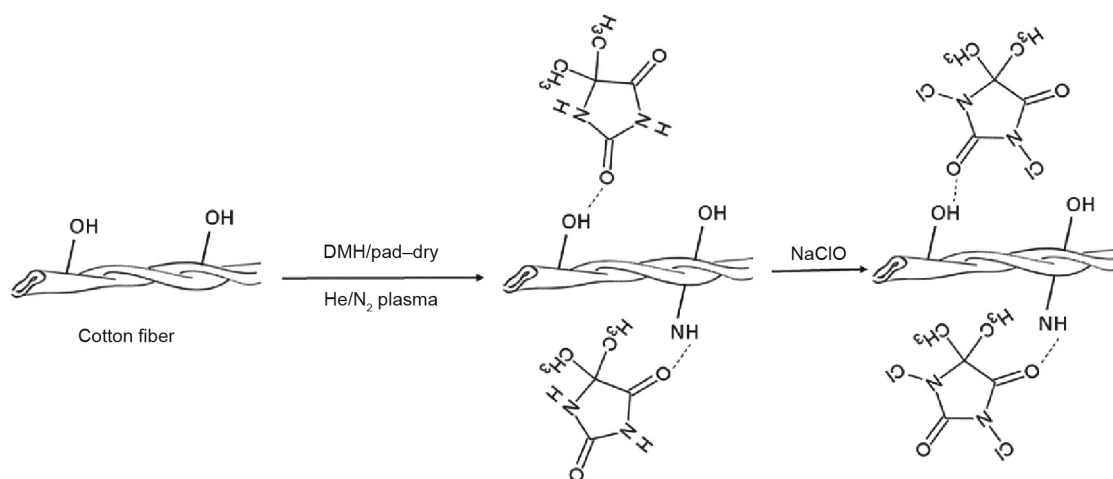


Fig. 12. Schematic mechanism of DMH attachment on cotton using He/N₂ plasma and chlorination by NaClO.

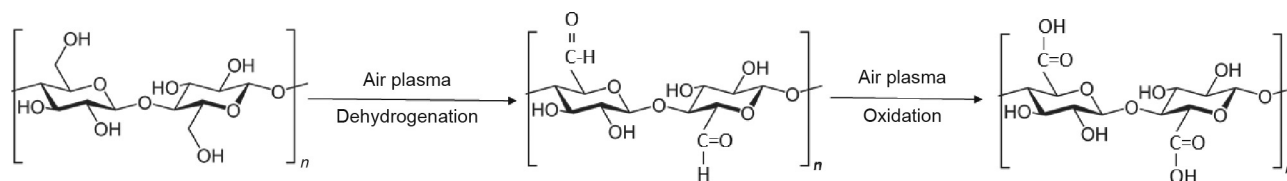


Fig. 13. Chemical changes induced on cellulose by air plasma treatment [123].

[134] used a PET template on cotton nonwovens to sputter Ag and Zn dots on the surface to obtain high antibacterial activity, while retaining the biocompatibility and accelerated wound healing properties. The PET template prepared by laser ablation was placed on top of the cotton fabric. Ag and Zn targets were separately employed for sputtering using Ar as the processing gas (15 standard cubic centimeters per minute (scm)), with a power of 100 W. The samples coated with both metals showed a synergistic effect on wound healing and antimicrobial activity that was improved compared with those of the samples coated with Ag or Zn alone [134].

Naeem et al. [135] used a hollow discharge cathode plasma system to deposit Ag on PET fabrics to obtain antibacterial properties. High-purity Ag was used in the center of the hollow cathode, and the deposition was carried out for 10–60 min under a pressure of 1 Pa and Ar flow rate of 10 sccm. The voltage was 340 V, and the current was 0.4 mA. Fig. 14(a) shows the contact angles of water

and glycerol on the surface of the Ag-coated PET fabrics under different plasma treatment durations. An increase in the contact angle resulted in a reduction in bacterial adhesion on the surface and an improvement in the antimicrobial activity. Fig. 14(b) shows that the increase in plasma treatment time to 60 min increased the particle size and density slightly. The antibacterial activity of the Ag-coated samples improved with increasing plasma processing time [135].

Uniform and high-purity thin films of metallic or non-metallic nature can be deposited on various textile materials via magnetron sputtering. The thickness and adhesion of the film to the surface can be easily tuned by appropriately selecting the process parameters. Different functional properties, including electromagnetic interference (EMI) shielding, UV protection, IR protection, anti-static, electrical conductivity, gas sensing, hydrophilicity, hydrophobicity, structural coloration, radar reflection, and improved dyeing can be obtained by sputtering of selected metal or metal oxides on textile fabrics. Copper, silver, titanium, aluminium, platinum, zinc, brass, zinc oxide, copper oxide, magnesium oxide, and titanium dioxide are examples of metals and metal oxide targets used for antimicrobial finishing of textiles through sputtering [144,145]. Preparations such as laser pretreatment can enhance the adhesion between the sputtered metal coating and the substrate [146]. Plasma sputtering of Cu on polyester/silk fabric for 40 min increased the water contact angle to 146° and significantly decreased the surface resistivity. The coated fabric showed antimicrobial activity against *E. coli* and *S. aureus* [136]. Titanium oxynitride (TiON)/Cu composite coating was sputtered on cotton fabrics using Ti and Cu targets in the presence of Ar, O₂, and N₂ as the working gases. The TiON-coated cotton fabric showed 90% bacterial reduction, which reached 100% when Cu was co-sputtered [137]. RF co-sputtering of Ag and SiO₂ on cotton fabric for 15–80 min resulted in the embedding of Ag into the SiO₂ film and controlled release of Ag ions, which imparted high antibacterial activity to the coated samples [138].

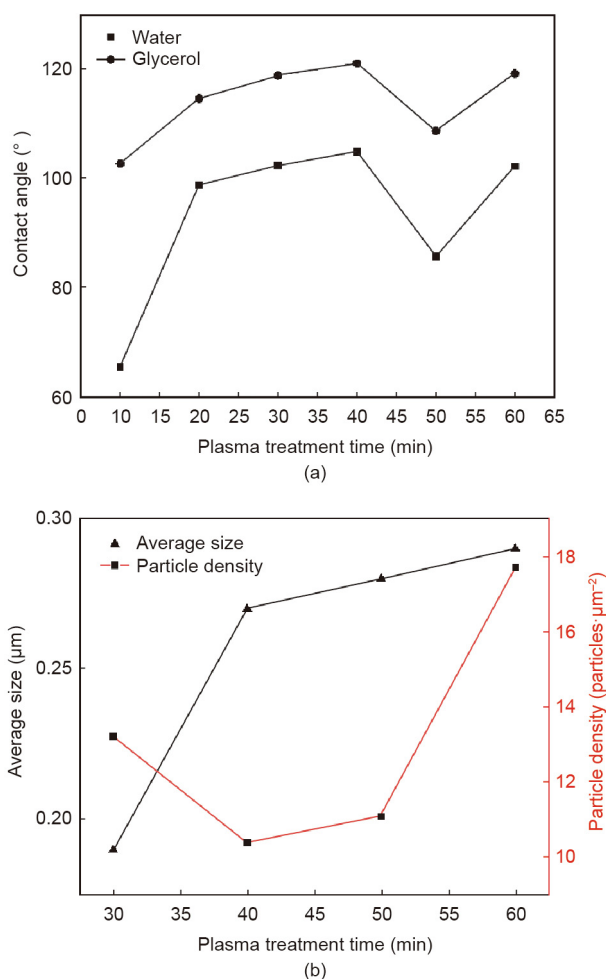
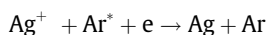
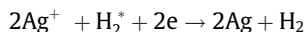
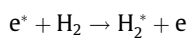
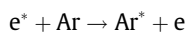


Fig. 14. Effect of plasma treatment time on (a) contact angle and (b) size and density of Ag-coated PET fabrics [135].

6.4. Synthesis of nanoparticles

There are several methods for preparing nanoparticle-coated textile materials. One of the most convenient and popular methods is the *in situ* reduction of metal ions using various reducing agents. In this approach, the metal ions are first deposited on the textile fibers and then converted to nanoparticles through chemical reduction. Sodium borohydride is one of the most well-known reducing agents used for the synthesis of nanoparticles, such as Ag, on textile fibers [147,148]. Recently, there has been an increasing demand for the use of environmentally friendly processes such as biosynthesis (e.g., using plant extracts), photo or UV reduction, and electron reduction or reduction by cold plasma. Cold plasma is considered an environmentally friendly, fast, and facile method for synthesizing small metal nanoparticles with high dispersion on the surface. By using plasma treatment for the synthesis of metal nanoparticles on the surface, aggregation is avoided and the catalytic activity and stability of the nanoparticles are enhanced. When applying cold plasma, energetic electrons and hydrogen species (hydrogen-containing gases such as ammonia,

methane, hydrogen, ethanol, or water vapor are used as working gases) can act as reducing agents and convert the metal ions into atoms and nanoparticles. In atmospheric-pressure plasma, the energy of electrons is reduced by the frequent collisions between electrons and other heavy atoms and molecules; thus, the energetic electrons alone are not able to reduce the metal ions efficiently, and hydrogen-containing gases must be used as well [149]. The mechanism of synthesis of AgNPs by Ar/He plasma is shown in the following reactions [139,150]:



Fan et al. [140] used DBD plasma (5.7 kV, 10.4 kHz) for the synthesis of AgNPs on cotton. The process involved the impregnation of cotton samples with Ag nitrate (AgNO_3) and PVP, centrifugation, and DBD plasma treatment. An Ar/ H_2 mixture was used as the processing gas. Active hydrogen species, including H, H^* , and H_2^* , reduced Ag ions to nanoparticles. The color of the cotton samples changed from white to yellow and brown after the synthesis of the AgNPs. The fabrication of AgNPs on cotton fibers was confirmed using SEM, X-ray diffraction, FTIR, XPS, SEM, and transmission electron microscopy (TEM). The average size of the synthesized nanoparticles was approximately 5 nm. The prepared coating showed good fastness under ultrasonic treatment for 30 min. Cotton samples coated with this method showed high antimicrobial activity against Gram-positive and Gram-negative bacteria [140].

Li et al. [141] used Ar glow discharge to synthesize AgNPs on a cotton fabric. The cotton samples were immersed in a solution containing Ag nitrate and polyvinyl pyrrolidone for 1 h at room temperature and then subjected to Ar glow discharge plasma with a power of 6–12 W for 3 min. The size of the synthesized nanoparticles ranged from 4.4 to 6.3 nm (Fig. 15) [141]. The cotton sample coated with AgNPs showed significant antimicrobial activity against Gram-positive and Gram-negative bacteria [141].

Dong et al. [139] used DBD plasma in two steps for the surface activation and synthesis of Ag nanoparticles on nonwoven PP. In the first step, air DBD plasma was used for the surface activation of PP to improve the wettability and enhance the loading of TiO_2 -NPs on the surface. Then, the prepared samples were immersed in

an AgNO_3 solution, and ammonia was added dropwise. AgNO_3 was converted to AgOH and then to Ag_2O by drying at 60 °C for 30 min. The Ag ions were converted to Ag nanoparticles by subsequent treatment with H_2/Ar (1:1 volumetric ratio) DBD plasma for 5 s at a flow rate of 30 mL·min⁻¹ at a power of 22.5 W. The diameters of the obtained AgNPs ranged from 4 to 11 nm, and the average diameter was 7 nm. The synthesized AgNPs enhanced the photocatalytic degradation of methylene blue by TiO_2 NPs. The dye removal increased from 73% to 99% in the presence of AgNPs on TiO_2 NP-coated PP nonwovens under irradiation with simulated sunlight for 4 h [139].

7. Future prospects

The current trend of living active and healthy lifestyles worldwide has fueled interest in antimicrobial finishes, particularly on textiles. Currently, people are more concerned about the harmful effects of microbes on human hygiene that might be carried by textiles. Therefore, antimicrobial finishing has become a key process in the current textile trends. Commercial antimicrobial products are already available, particularly Ag, QACs, polyhexamethylene biguanides, and triclosan, which can cover most common textile fibers (e.g., cotton, polyester, nylon, wool, regenerated cellulose, acrylic, and PP) [28]. There is also interest in natural antimicrobial products, such as chitosan and its derivatives. In addition, plasma-assisted finishing is a promising technique that can be applied to a textile product, as it is fast, economical, and environmentally friendly.

The application of plasma to textiles poses some critical challenges. Although plasma can deliver economic production in the long run, the initial setup cost is high and requires radical changes in the conventional setup that is already in place [63]. This often discourages industries from adopting this technology. In addition, there are a few practical problems related to the three-dimensional structure and higher surface area of textiles compared with a flat film [151]. Overall, the use of plasma in large-scale textile production has been progressing slowly, considering that the first application was in the 1980s. However, the progress is quite steady given commercially available machines and encouraging examples of industrial setups [63]. For instance, Europlasma (Belgium), Textilveredelung Grabher GmbH (Austria), and HTP Unitex (Italy) use low-pressure plasma to treat textile surfaces to increase wettability and adhesion for improved textile finishing [152]. Sefar AG (Switzerland) uses an atmospheric plasma arrange-

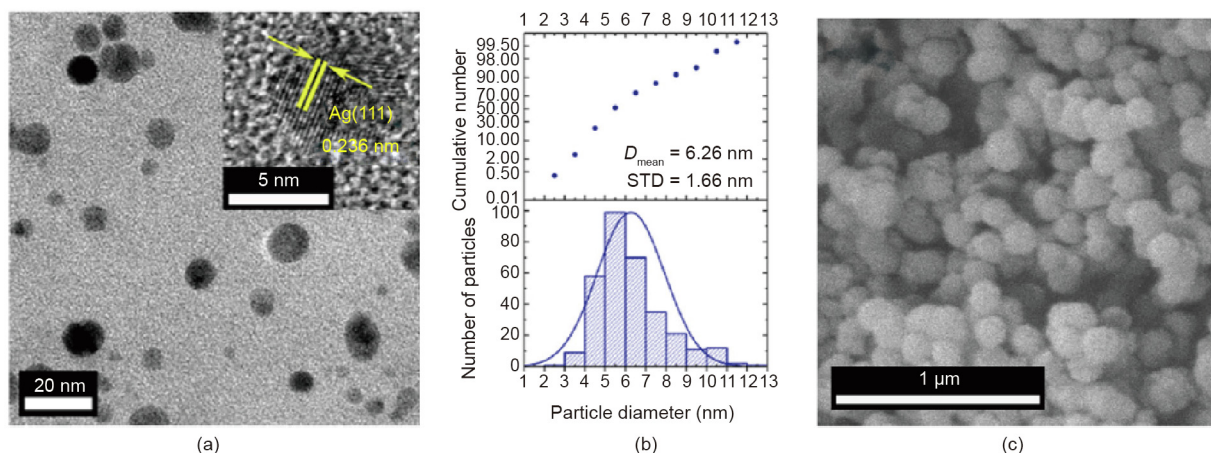


Fig. 15. (a) TEM, (b) particle size distribution, and (c) SEM images of AgNPs synthesized on cotton using Ar glow discharge. STD: standard deviation. Reproduced from Ref. [141] with permission of Elsevier Ltd., ©2017.

ment that can run at 25 m·min⁻¹ while treating textiles that are up to 4 m wide [152]. Several suppliers of plasma machinery and equipment are also currently present in the market, such as IPLAS, Ahlbrandt, Softal Corona & Plasma GmbH and Diener electronic (Germany), Coating Plasma Innovation (CPI) and AcXys (France), Tri-Star (USA), GRINP, Arioli and Mascioni (Italy), and Plasmatreat (Singapore) [63], providing support and opportunities for plasma incorporation and progress in the textile field.

Textile industries, particularly conventional wet processes, contribute to a significant proportion of worldwide pollution. The growing environmental concern is also pushing industries into adopting environmentally safe techniques such as plasma. Studies on the antimicrobial finishing of textiles using plasma also show promising results and justification for using plasma on a large scale. Although earlier antimicrobial finishing on textiles mostly focused on antibacterial and antifungal products, development of antiviral finishes on textiles is also emerging. For example, Iyigundogdu et al. [3] reported a sodium pentaborate pentahydrate–triclosan-treated cotton fabric with antiviral, antifungal, antibacterial, and anticandidal properties. Parthasarathi et al. [153] reported surgical gowns prepared from nonwoven spun-bond PP treated with plasma-enhanced fluorocarbon, which are capable of providing antiviral properties as well as having level 4 liquid barrier protection as per the Association for the Advancement of Medical Instrumentation (AAMI) classification.

Therefore, considering the potential of plasma and concerns related to conventional wet finishing, adopting plasma technology in textile antimicrobial finishing could be a rational approach, given the high demand for hygiene in clothing during and after the current pandemic.

8. Conclusions

Microbes are responsible for detrimental effects on textiles and often have consequences for the wearer of textiles. The current global pandemic underlines the obligation to protect humans from microbes. Using antimicrobial-finished textiles could be the most important armor for the masses to become protected from microbes and limit their spread. Therefore, antimicrobial finishing of textiles is gaining importance, and faster, economical, and environmentally friendly techniques are sought. To this end, plasma applications in textiles are becoming essential. To date, studies on antimicrobial finishing using plasma assistance have been conducted using various approaches. These include graft polymerization of the finishing agent on textile substrates, altering the functionality of textiles (e.g., wettability) for the enhanced loading of finish, plasma sputtering, and synthesis of nanoparticles on textiles for antimicrobial protection. All of the studied techniques showed positive results and were suitable for the use of plasma in antimicrobial finishing. Hence, plasma application in textile antimicrobial finishing could usher in a new era of textile manufacturing, enabling a sustainable environment and healthier life.

Compliance with ethics guidelines

Maryam Naebe, Abu Naser Md Ahsanul Haque, and Aminoddin Haji declare that they have no conflict of interest or financial conflicts to disclose.

Nomenclature

AAMI	Association for the Advancement of Medical Instrumentation
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AATCC	American Association of Textile Chemists and Colorists
AC	Alternating current
ADBAC	Alkyldimethylbenzylammonium chloride
AFM	Atomic force microscopy
APGD	Atmospheric pressure glow discharge
AP-PECVD	Atmospheric-pressure plasma-enhanced chemical vapor deposition
APPJ	Atmospheric pressure plasma jet
ATR	Attenuated total reflection
AgNPs	Silver nanoparticles
AuNPs	Gold nanoparticles
CD	Corona discharge
CuNPs	Copper nanoparticles
DADMAC	Diallyldimethylammonium chloride
DBD	Dielectric barrier discharge
DC	Direct current
DCSBD	Diffuse coplanar surface barrier discharge
DMH	5,5-Dimethyl hydantoin
DNA	Deoxyribonucleic acid
EDX	Energy-dispersive X-ray spectroscopy
EMI	Electromagnetic interference
FTIR	Fourier transform infrared
IR	Infra-red
ISO	International Organization for Standardization
JIS	Japanese Industrial Standards
HMDSO	Hexamethyldisiloxane
ICP-AES	Inductively coupled plasma atomic emission spectroscopy
mRNA	Messenger ribonucleic acid
NPs	Nanoparticles
PP	Polypropylene
PET	Polyester
PVP	Poly(<i>N</i> -vinylpyrrolidone)
PLLA	Poly(<i>L</i> -lactide)
RF	Radio frequency
SEM	Scanning electron microscopy
SPM	Scanning probe microscopy
TEM	Transmission electron microscopy
TiON	Titanium oxynitride
TiO ₂ NPs	Titanium dioxide nanoparticles
TMG	1,3,3-Tetramethylguanidine
TOF-SIMS	Time-of-flight secondary ion mass spectrometry
QACs	Quaternary ammonium compounds
UHMWPE	Ultra-high molecular weight polyethylene
UV	Ultra violet
XPS	X-ray photoelectron spectroscopy
ZnONPs	Zinc oxide nanoparticles

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