Synthetic Antimicrobial Finishing Agents: Types, Mechanisms, and Future Prospects

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***Abstract*- In a world increasingly conscious of microbial threats, the development and utilization of antimicrobial finishing agents have gained considerable attention. These agents serve as a linchpin in the battle against pathogenic microorganisms, preventing their proliferation and safeguarding a broad spectrum of products, from medical textiles to industrial surfaces. This paper offers a description of antimicrobial finishing agents, delving into their intricate mechanisms of action, and promising avenues for the future.**

***Key word*: Antimicrobial, textile finishing, synthetic agent, microorganism.**

Introduction

Microorganisms can be found almost everywhere in the environment, they play both beneficial and harmful roles in our daily life. Some of the beneficial roles include the production of oxygen via photosynthesis, nitrogen fixation, formation of food items etc, and some of the virulence of pathogenic microorganisms, i.e., infection-causing bacteria such as *Staphylococcus aureus (S.aureus)*, *Escherichia coli (E.Coli)*, and *Enterococcus faecalis (E.faecalis*). Healthcare associated infections can be controlled by inhibiting the various routes of transmission that cause an infection to spread from an infected person to a healthy person. Textiles have been recognized as a medium for the growth of microorganisms such as fungi and bacteria. The growth of these microorganisms on textiles inflicts unwanted effects not only on the textile material but also on the consumer. These effects can include the generation of unwanted odour, discolouration in the fabrics, an increased probability of contamination, and an overall reduction in the fabric's mechanical strength.

The spread of infections through textile materials can be controlled by the use of antimicrobial textiles that kills pathogens on contact or hinder their ability to reproduce before being transferred onto another material or person. Antimicrobial textiles are made by treating the textile substrate with antimicrobial agents or by using textile fibre with inherent antimicrobial efficiency. Antimicrobial agents can be applied on textiles by different methods depending on the chemistry between the antimicrobial agents and the textiles.

Requirement of antimicrobial finishing agent

Antimicrobial agents add value to textiles and garments by protecting in different ways, such as improving resistance against microorganisms, increasing fabric durability and protecting textiles against the colonization of odour-forming bacteria (Hooda S. 2003). A good antimicrobial agent should be effective against a broad spectrum of bacterial and fungal species and must also exhibit low toxicity to consumers and the environment while remaining allergy and irritation-free [1].

Though many antimicrobial agents are available commercially, the ones that satisfy the needs of the textile industry are few. An ideal antimicrobial agent for textiles must have the following qualities [2]

- It should show activity against a wide range of microbes
- It should be non-irritant to the skin of the user
- It should be active in the presence of organic material, acids and alkalis
- It should penetrate deep into the structure of the fabric
- It should not interfere with the performance of other finishes

Antimicrobial finishing agents

Antimicrobial finishing agents refer to substances or treatments applied to textiles, surfaces, or other materials to inhibit the growth and proliferation of microorganisms such as bacteria, fungi, and viruses. The primary purpose of an antimicrobial agent is to create surfaces that resist or reduce microbial contamination, thereby enhancing the overall hygiene, longevity, and performance of the treated materials. Thus, the antimicrobial agent adds value to textiles by providing protection in different ways. An ideal antimicrobial agent for textiles would have to fulfil the basic requirements, like, it must not be harmful to the user; specifically, cytotoxicity, allergies, irritation, or sensitization must be prevented. The treatment should not affect the textile's quality, hand, or look and should have good fastness for frequent washes, dry cleaning, and ironing. In order to minimize negative effects on the manufacturers, the application technique should be straightforward and simple to incorporate into the finishing process.

Antimicrobial agents are classified into two main categories on the basis of their origin: natural and synthetic. Natural antimicrobial agents are derived from natural sources and they exhibit antibacterial action. These compounds have the potential to have an effective antimicrobial impact while remaining safe, readily available, non-toxic to the skin, and environmentally friendly [5]. Strong antimicrobial materials, including tannin, flavonoids, and quinonoids, as well as alkaloids, saponins, terpenoids, and phenolic chemicals that are taken from various plant parts such as bark, leaves, roots, and flowers.

Synthetic antimicrobial textile finishing agents are chemical substances designed to impart antimicrobial properties to textiles, thereby inhibiting the growth and proliferation of microorganisms on fabric surfaces [6]. These agents are engineered in laboratories through chemical synthesis, offering tailored solutions to address specific antimicrobial requirements in the textile industry. Synthetic antimicrobial finishing agents shows antimicrobial activity against protein fibre, cellulose-based fibre, synthetic-based polyamides, and polyester. There are various types of synthetic antimicrobial agents and it is shown in Figure 1.

metal

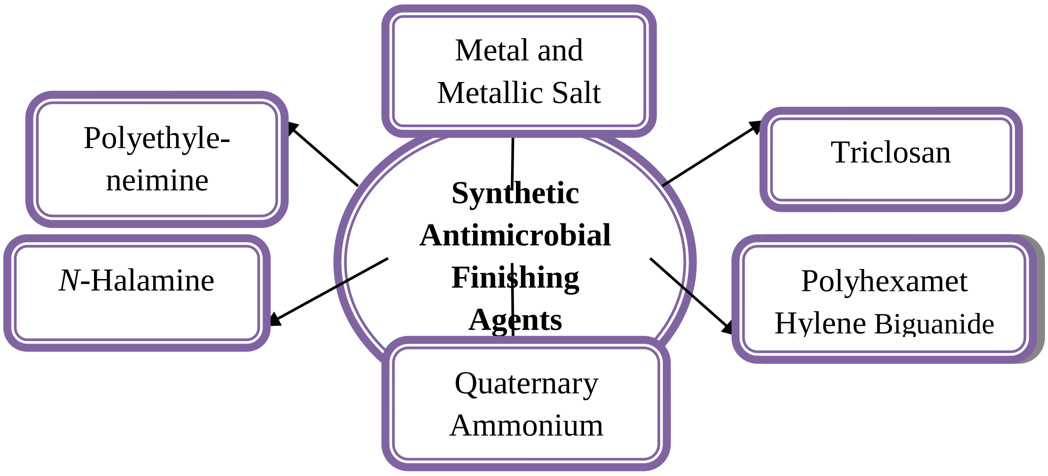

Figure 1: Synthetic antimicrobial agents

Synthetic antimicrobial agents

1. Metal and Metallic Salt

Silver, copper and mercury compounds are the most effective antimicrobial agents which come under this category.

1.1. Silver

Silver kills bacteria by strangling them in a warm and moist environment [6]. Highly bioactive silver ions bind with proteins inside and outside bacterial cell membranes, thus inhibiting cell respiration and reproduction. Silver is 3-4 times more active at pH 8 than at pH 6. Silver products are effective against bacteria but not as good against other organisms like fungi, mould, and mildew; they give good results with polyester. Alginate and chitosan have also been used to make novel antimicrobial materials in combination with silver [7] [8]. Various techniques have been explored to attach silver to textile materials, for preparation of antimicrobial fabric suitable for sterilization of air, cellulose was grafted with acrylic acid and treated with silver nitrate to bind the silver ions to the –COOH group of graft copolymer [9]. For developing a durable finish on wool, it was treated with a complexing agent such as tannic acid or ethylene diamine tetra acetic dianhydride. Silver kills bacteria by strangling them in a warm and moist environment [10]. Highly bioactive silver ions bind with proteins inside and outside bacterial cell membranes, thus inhibiting cell respiration and reproduction. Wool thus treated can react easily with copper and silver and inhibit the propagation of *S. aureus* and interstitial precipitation of tetra silver tetroxide crystals within the interstices of fibres, yarns or fabrics has also been reported in a US patent [11] [12].

AgNP (Silver Nanoparticles), a nanometric form of silver element without an ionic charge, can be used as a catalyst, an optical sensor and an antibacterial agent [13] [14]. The antibacterial activities of the silver ion and salts are well studied, but research about the antibacterial mechanism of AgNP is relatively recent [15]. Different methods have been developed to synthesize and incorporate AgNP in some biomedical applications, and some reports have proven AgNP to be a potent antibacterial agent, that is effective against both Gram-positive and Gram-negative bacteria.

1.2. Copper

Broad-spectrum antimicrobial and antimite activities have been introduced in copper-impregnated fibres and polyester products for the production of antiviral gloves and filters (which deactivate HIV-1 and other viruses), antibacterial self-sterilizing fabrics (which kill antimicrobial-resistant bacteria), antifungal socks (which alleviate symptoms of athlete‘s foot), and antidust mite mattress covers.

Copper compounds are extensively used for the preservation of tents, canvas, bags, and geotextiles. A familiar compound, copper naphthenate, is available under trade names such as cuprimol and Nuodex. Mixtures of copper and zinc naphthenate with mercuric or phenylmercuric naphthenate are better for treatment of cellulosic fabric with succinic anhydride, followed by metallic salts such as copper sulphate and zinc sulphate which also impart antimicrobial activity durable up to 10 laundering cycles [16]. Copper-carboxymethyl starch and trimethylated melamine with cotton fabric also have excellent antimicrobial properties.

1.3. Other metals

Among other metals, zirconium salts are effective against algae. The use of zirconium compounds along with copper, mercury, and some phenol on cotton increases the solubility of insoluble mold. Cadmium selenide and cadmium sulfoselenide are good mildew- and algae-inhibitors. Water-soluble selenium is slowly lost from fabric and is activated when exposed, even intermittently, to solar energy, but not in the dark. The colour of these compounds and the toxicity issues associated with them make them less useful as antimicrobial agents [17]. For woven cotton and cotton/polyester blended fabrics, magnesium hydroperoxyacetate (MHPA), magnesium dihydroperoxide (MDHP), and their reaction products with hydrogen peroxide have also been utilized as antibacterial agents [18]

2. Triclosan

Triclosan is a member of the antiseptic and disinfectant family. Triclosan (Figure 2) is a halogen-containing derivative of phenol and is used in cosmetics and toothpaste. It has a wide range of action against gram-negative and gram-positive bacteria. This compound contains the acaricide benzyl benzoate, which offers protection against mites and is used in acaricide (spray or powder) formula as well as in a solution (25% concentration) for the treatment of scabies. This compound is non-toxic. Benzyl benzoate is an acaricide that acts chemically and directly on the mites.

Triclosan inhibits the growth of microbes by using an electrochemical mode of action to penetrate and disrupt the cell walls of microbes. When incorporated within a polymer, it migrates to the surface and protects the material (Glaser, A. 2008). When embedded in β-cyclodextrin, triclosan forms a complex and can exhibit antimicrobial action with minimum quantities [19]. Some researchers also reported that triclosan inhibits a specific function, i.e., lipid synthesis in bacteria [20]. One of the greatest concerns regarding triclosan is that when exposed to sunlight, it breaks down into 2, 8-dichlorodibenzo-p-dioxin, a chemical related to other harmful polychlorinated dioxins. Therefore, it has raised a lot of concern in European governments, and its application in consumer products is banned in some countries [21].

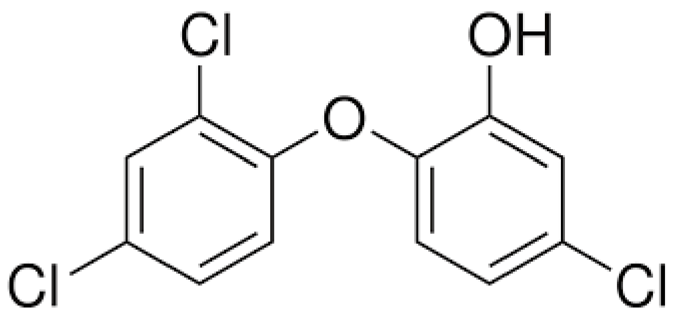

Figure 2. General molecular structure of triclosan.

3. Polyhexamet hylene biguanide (PHMB)

PHMB is a hector dispersed mixture of polyhexamethylene biguanide (Figure 3). Polyhexamethylene biguanide (PHMB, commercially known as Vantocil) is a broad-spectrum antibacterial agent with low toxicity, having a MIC = 0.5–10 ppm. It has been previously used as a disinfectant in pool sanitisers, mouthwashes, wound dressings, and in the food industry. PHMB can disrupt the integrity of cell membranes.

The halide form of PHMB i.e., polyhexamethylene biguanide hydrochloride is applied on cellulosic materials. PHMB is found to form hydrogen bonds with cellulosic fibres. With the increase in the concentration of PHMB, there is a dominant increase in hydrogen bond formation between PHMB and fibres [22]. When the fabric treated with PHMB is exposed to a bacterium, the biocide interacts with the surface of the bacteria and is transferred to the cytoplasm and cytoplasmic phospholipids in the bacterial membrane. This biocide is positively charged, and therefore it mainly reacts with negatively charged species and includes aggregation, leading to increased fluidity and permeability. This results in the leakage of inner material from the outer membrane and eventually causes the death of an organism [23].

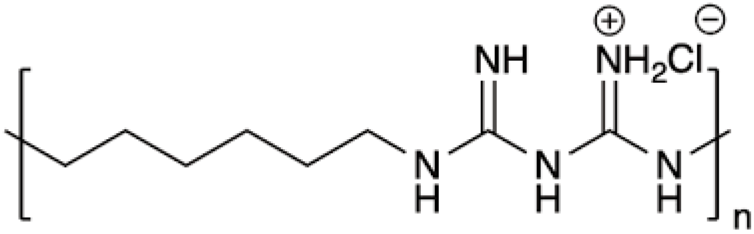

Figure 3. General molecular structure of PHMB

4. Quaternary ammonium (QAC)

Quaternary ammonium compounds (Figure 4) seem attractive because their target is primarily the microbial membrane, and they accumulate in the cell driven by the membrane potential to maximize efficiency. Quaternary ammonium compound is used as a monomeric link in the polymeric leash and poly4-vinylpyridine (PVP) is usually selected as the carrying polymer. A study showed that the surface of commercial polymers treated with N-alkylated PVP groups was lethal on contact with both gram-positive and gram-negative bacteria, and it was also shown that the N-alkyl chain of six carbon units in length was the most effective. In recent years, trialkyl ammonium chlorides have been reported to possess germicidal effects in dilute aqueous solutions [24]. It can be applied in two categories of antimicrobial finishes: one category is part of the fibre-forming process, and the other category is the one incorporated in the finishing process. It can also be used as a perfluoroalkyl-containing monomer in the polymer field, which is a convenient method of incorporating a perfluoroalkyl chain in the polymer [25].

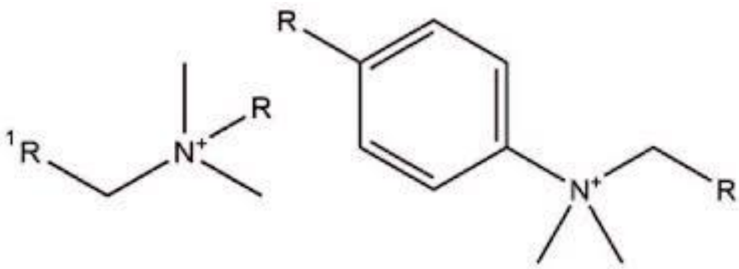

Figure 4. General molecular structure of QAC

5. *N*-Halamine

N-halamines are heterocyclic organic compounds (Figure 5) with one or two covalent bonds between nitrogen (N) and halogen [25]. These compounds are biocides, which are active against a broad spectrum of bacteria, fungi, and viruses.

Halamine can be applied to different textiles including cellulose, polyamide, and polyester fibres. It has also been found to have extraordinarily durable biocidal functions in a series of laundering tests. However, N-halamine materials are found to be decomposed upon exposure to ultraviolet irradiation, such as in direct sunlight [22]. According to the researcher [26], the main problem with N-halamines was that they result in a significant amount of absorbed chlorine (or maybe other halogens), which can remain on the fabric surface, resulting in an unpleasant odour and fabric discoloration. The use of bleach and the presence of strong oxidizing agents degrade the dye on the textiles, which leads to discoloration of the textile. This antimicrobial technology is best used on bleach-resistant textiles. One method known to resolve this problem is using a reduction step to remove the residual unbounded halogen from the surface of the fabric.

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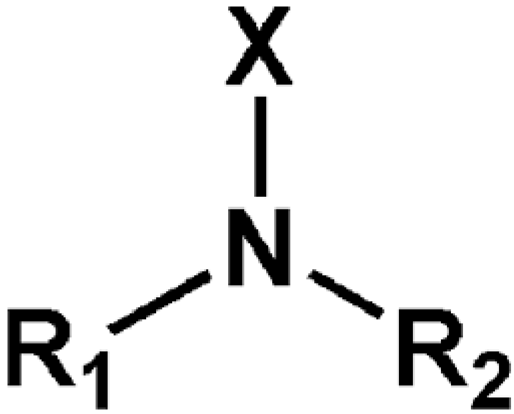

Figure 5. General composition of N- Halamine

6. Polyethyleneimine

Polyethyleneimine (PEI) is well known as a non-biodegradable, cationic, and synthetic polymer containing primary, secondary, and tertiary amino functional groups (Figure 6). It is manufactured in both branched and linear-shaped polymers via acid-catalyzed polymerization of aziridine and ring-opening polymerization of 2-ethyl-2-oxazoline, followed by hydrolysis [28].Due to the presence of amino groups in the backbone of polyethyleneimine, it has been widely exposed to chemical modifications to acquire some desirable physicochemical properties. It was reported that the unsubstituted polyethyleneimine did not exhibit any antimicrobial activities. However, it was realized that hydrophobicity and positive charge density are vital requirements for antimicrobial activity. Therefore, polyethyleneimine was modified to be incorporated with alkyl groups to potentiate both of these requirements [29]. Different researchers studied certain methods for incorporation of *N*-alkyl-polyethyleneimine in all commercial plastics, textiles, and glass for acquiring these immobilized surfaces complete inactivation of bacteria (both water-borne and air-borne bacteria) and fungi (including pathogenic and antibiotic-resistant strains), where the biocidal action was interoperated via cell-membrane rupturing [26]. *N*-alkylated polyethyleneimine was also reported to be immobilized over woven cotton textiles, and the modified textiles were found to exhibit strong antimicrobial properties against numerous airborne Gram-positive and Gram-negative bacterial strains. The application of high-molecular-weighted polyethyleneimine resulted in the acquirement of excellent antimicrobial activity, while the application of low-molecular-weighted polymers displayed negligible activity [27].

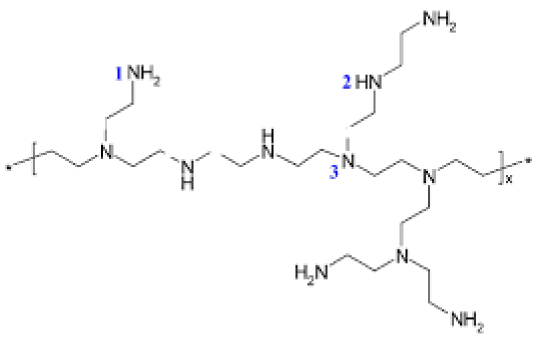
Figure 6. General composition of Polyethyleneimine

Challenges and future prospects

- **Sustainability:** The environmental impact of antimicrobial agents and their potential contributions to antimicrobial resistance are ongoing concerns. Future research should focus on developing more sustainable and eco-friendly solutions
- **Novel Antimicrobial Agents:** The discovery and development of new, effective, and non-toxic antimicrobial agents will be pivotal in addressing the challenges of antimicrobial resistance.
- **Regulatory Standards:** Developing consistent and internationally recognized standards for antimicrobial finishing agents will ensure their safe and effective use across industries
- **Integration with Nanotechnology:** Advances in nanotechnology can lead to more efficient and targeted delivery of antimicrobial agents, reducing their overall use and potential environmental impact.

Conclusion

Textiles are susceptible to microorganism growth because of their structure and the ability to hold moisture. The growth of microorganisms on fabric surfaces can generate multiple undesired consequences, such as creating odour, mould, degradation, discolouration and biofouling. Textiles can be treated with antimicrobial agents to reduce, slow, or eliminate microbial growth and spread. There are various synthetic antimicrobial agents discussed in this paper. Some synthetic antimicrobial agents may create health and environmental risks, like *N*- halamine but there are a few agents which are synthetic in nature but they have non-toxic properties, and possess antimicrobial activity, for eg. polyhexamet hylene biguanide, quaternary ammonium, triclosan, and polyethyleneimine. They are good for their antimicrobial nature and are environmentally friendly. The development of antimicrobial fabric through nanotechnology with the use of metal and metallic salt enhances the quality of finishing and creates a new approach to antimicrobial finishing. These agents play a vital role in maintaining the cleanliness and functionality of textiles across various applications ranging from healthcare and hospitality to sport and outdoor apparel.

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