Comprehensive Review of Antibacterial Properties of Lyocell Fiber with Silver Nanoparticles: Mechanisms, Functionalization Methods, And Potential Applications

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Abstract — Lyocell, a regenerated cellulose fiber produced through eco-friendly processes using renewable resources such as trees, bamboo, and straw, has gained significant attention since its commercialization in 1988. Renowned for its smooth texture, comfort, and excellent physical properties compared to viscose fiber. Lyocell is widely used in textiles, nonwoven materials, and medical applications. However, its lack of inherent antimicrobial properties limits its potential in medical fields. This review explores various strategies, including physical blending, chemical modification, and post-treatment methods, to enhance the antibacterial characteristics of Lyocell fibers. Incorporating antimicrobial agents like silver nanoparticles has proven effective in improving bacterial resistance. The discussion emphasizes the mechanism challenge aspect of the future of these approaches, showcasing their potential to develop advanced antibacterial Lyocell fibers for diverse applications.

Keywords: Lyocell, N-Methylmorpholine Oxide (NMMO), Antibacterial Lyocell Fiber, Silver Nanoparticles

I. INTRODUCTION

Lyocell is a regenerated cellulose fiber, developed in the 1990s, utilizing renewable materials such as bamboo and other trees. These materials are processed into thin sheets of various sizes, which are then dissolved in non-toxic, N-methyl morpholine oxide (NMMO) and They include various steps and then fiber produced through using the dry-jet wet spinning process. (Fink et al., 2001) Lyocell was first developed in 1984, with large-scale production commencing in 1988. It is used to produce a variety of textiles that are not only soft and pleasant to wear but also exhibit excellent strength and durability compared to viscose Fiber. Its high absorbency and robust performance also make it suitable for creating nonwoven materials and paper products. These fibers, obtained through direct cellulose dissolution, are categorized under the generic term Lyocell. As cellulose is one of the most plentiful natural resources on the planet, it has been the focus of extensive studies for its applications in creating films, plastics, and fibers. (Periyasamy, 2021). Traditional regenerated cellulose fibers, such as viscose, often rely on processes involving hazardous chemicals like CS2, HCl, and caustic solutions. In contrast, the production of Lyocell fiber is more eco-friendly, utilizing a non-toxic solvent, NMMO, for pulp dissolution. This innovation eliminates the release of harmful gases, supports sustainability, and enables recycling. Additionally, Lyocell fibers offer a soft texture, exceptional comfort, straightforward dyeing, and high color retention, making them a superior alternative. (Sarkar and Vora, 2011), at the same time, the product also can achieve microbial degradation in the natural environment, which is expected to fundamentally solve the major problems of sustainable development of the textile industry (Jiang et al., 2020; Parajuli et al., 2021).

II. MANUFACTURING PROCESSES

The lyocell manufacturing process is different from viscose fiber, In lyocell fiber cellulose and NMMO use as a raw material,The lyocell manufacturing process (Fig. 1) mainly consists of Six steps (Fink et al. 2001)

1) Dope Formation: This step includes the disintegration of the pulp fibers sheet and mixing with the solvent of nontoxic NMMO at high temperature. Cellulose is dissolved in an aqueous system containing NMMO to form a dope of high viscosity by evaporation of excess water. The pulp dissolution step in the Lyocell process is far more straightforward compared to the viscose method. In the viscose process, the dissolving pulp undergoes several complex stages, including soaking in sodium hydroxide (mercerization), a period of controlled aging, and a chemical reaction with carbon disulfide during the xanthation phase.
2) Dope Filtration: The formed dope is filtered to remove coarse components. In comparison, the purification of the viscose process includes ripening, filtering, and degassing.
3) Dry Jet Spinning: The dope is extruded through an orifice spinneret into an air gap, and then regenerated in a coagulation bath and Required air through jet hole to quench the high temperature dope. In contrast to this, the production of viscose rayon requires a wet spinning process in an acid bath.
4) NMMO Washing & Recovery: The resulting lyocell fibers are washed and the residual NMMO is recovered and recycled and its washing done in multiple to full recovery of NMMO; while the viscose fibers are also washed for removal of the residual CS2, the high volatility of CS2 may lead to its loss via evaporation, causing a negative environmental impact for the viscose process.
5) Finishing: This step involves post-treatment of the fibers, including bleaching with Hypo, and soft finish with GA & MGR.
6) Drying: This step involves drying fiber with hot air

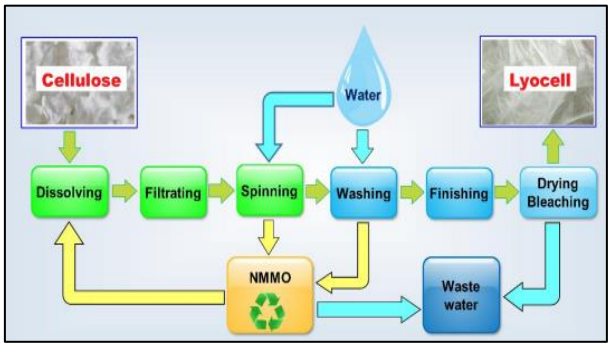

Fig. 1. Lyocell manufacturing process (Zhang et al., 2018)

III. PREPARATION METHODS OF ANTIBACTERIAL LYOCELL FIBER

Cellulosic fibre-based textile materials create an ideal environment for the growth, multiplication, and spread of harmful microorganisms, such as bacteria, fungi, and yeast, when appropriate levels of nutrients, moisture, and temperature are available. This microbial growth can result in staining, unpleasant odors, discoloration, reduced mechanical strength, and various health hazards. Additionally, during the use of fiber products, they frequently come into contact with microorganisms like bacteria and molds. Under favorable external conditions, these microorganisms can rapidly proliferate, causing unpleasant odors and increasing the risk of disease transmission. (Wang et al., 2017). However, the fact that Lyocell fiber itself does not possess antibacterial properties limits its development and high-end application in medical- and health-related fields.

Lyocell fiber is a useful substrate for antibacterial garments due to its biodegradability, low toxicity, comfort, and other strong physical properties (Ristić et al., 2011). In recent years, there have been many reports on the properties and anti-microbial efficacy of antibacterial Lyocell fibers prepared using various antibacterial agents, and by different methods. In order to achieve the greatest antimicrobial activity, an ideal agent used in the modification of Lyocell fiber should satisfy a number of requirements. First, the antimicrobial agent should be effective against the spectrum of bacterial and fungal species abroad; and it should exhibit low toxicity to consumers, e.g. not cause dermal toxicity, allergy, or irritation to the user. Then, the antimicrobial treatment process should not negatively affect quality (e.g. physical strength, feel) or appearance of the fiber.There are three different ways to prepare antibacterial Lyocell fibers: physical blending, chemical reaction, and post-treatment (Fig. 1).

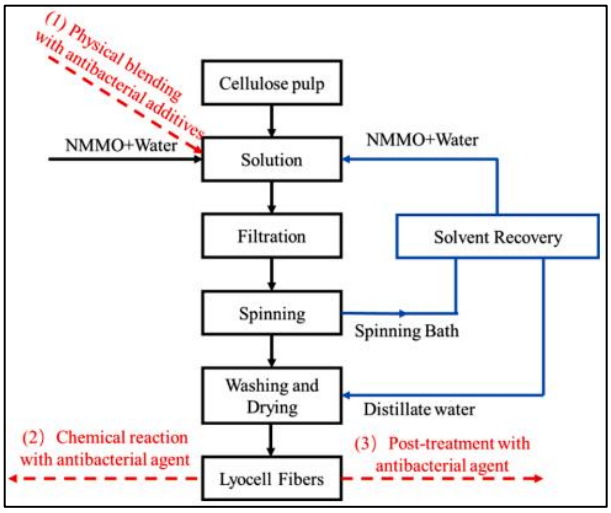

Fig. 2: Three categories of preparation methods of antibacterial Lyocell fiber (Edgar and Zhang, 2020)

1) Physical blending methods for antibacterial modifation of Lyocell fiber: Physical blending is a prevalent method for imparting antibacterial properties to Lyocell fibers by incorporating agents directly into the NMMO spinning solution This technique is favoured for its simplicity and cost-effectiveness (Edgar & Zhang, 2020).

   Silver nanoparticles are commonly used antibacterial agents in this process. For instance, silver ions embedded in a phosphate glass matrix have been introduced into Lyocell fibers, resulting in effective antimicrobial activity (GB2412083A, 2005).

   Chitosan, a biodegradable polysaccharide with inherent antibacterial properties, is another additive used in physical blending. However, its limited solubility above pH 6.5 poses challenges for incorporation into the alkaline NMMO solution (Islam & Butola, 2019) To address this, chitosan derivatives with enhanced solubility across a broader pH range have been developed. These derivatives can be directly dissolved into the cellulose/NMMO spinning dope, facilitating the production of antibacterial Lyocell fibers (Islam & Butola, 2019).

   Other antibacterial agents, such as quaternary ammonium compounds, have also been explored. For example, incorporating dimethyl octadecyl [3-(trimethoxysilyl) propyl] ammonium chloride into the spinning solution has yielded fibers with significant antibacterial activity against *Escherichia coli* and *Staphylococcus aureus* (Edgar & Zhang, 2020).

   The success of physical blending depends on the compatibility of the antibacterial agent with cellulose and NMMO, as well as the agent's thermal stability during the high-temperature spinning process (Edgar & Zhang, 2020). When these conditions are met, physical blending effectively produces antibacterial Lyocell fibers suitable for medical and hygienic applications.

2) Chemical reaction methods for antibacterial modification of Lyocell fiber: Chemical reaction methods enhance Lyocell fibers' antibacterial properties by covalently bonding antimicrobial agents to cellulose hydroxyl groups, ensuring durability through multiple

washes However, the linear, ribbon-like structure of cellulose limits the accessibility and reactivity of these hydroxyl groups, especially in Lyocell fibers with high crystallinity and orientation (Edgar & Zhang, 2020).

Oxidation techniques increase fiber reactivity. Oxidizing primary hydroxyl to carboxyl groups creates sites for attaching antibacterial agents via ester, amide, or hydrazide linkages (Gao & Edgar, 2018). Periodate oxidation cleaves the C2–C3 bond in cellulose, forming 2,3-dialdehyde groups that can react with amine-containing antibacterials through Schiff base reactions, introducing imine linkages (Potthast et al., 2006)

Fadavi et al. developed photodynamic antimicrobial Lyocell fibers using azide-alkyne click chemistry. They first functionalized the fibers with an azide-substituted alkoxysilane, then grafted a protoporphyrin IX derivative onto the surface via copper-catalyzed cycloaddition. The modified fibers exhibited significant photo-antibacterial activity against *Bacillus subtilis* and *Staphylococcus aureus* (Fadavi et al., 2019).

Similarly, Lyocell fibers modified with Schiff base-Cu(II) complexes demonstrated excellent antimicrobial properties. The fibers were first oxidized to introduce aldehyde groups, which then formed Schiff bases with amine-containing compounds, followed by coordination with copper ions. This modification imparted significant antibacterial activity to the fibers (Li et al., 2011).

While chemical grafting offers durable antimicrobial properties, it involves complex and costly processes that may require extended processing times (Edgar & Zhang, 2020). Additionally, oxidation can reduce cellulose molecular weight and introduce unwanted reactivity, potentially affecting fiber properties (Potthast et al., 2006).

3) Post-treatment methods for antibacterial modification of Lyocell fiber: Post-treatment methods enhance Lyocell fiber antibacterial properties by applying antimicrobial agents through coating, padding, or impregnation processes (Borsa, 2012; Liu et al., 2018;). These methods are cost-effective and flexible but may face durability issues due to washing (Borsa, 2012).

In Fiber Impregnation antibacterial Lyocell can be prepared by impregnating the fibers in a solution containing antibacterial agents alone or combined with other functional additives (Sarkar & Vora, 2011; Zemljic, Sauperl, Kreze, & Strnad, 2013). The fibers are then rinsed and air-dried. This simple method minimizes waste and maximizes yield. Durability can be enhanced by using water-insoluble agents dissolved in suitable solvents, followed by evaporation or dilution with a poor solvent like water (Sarkar & Vora, 2011).

TEMPO-mediated oxidation improves Lyocell fibers' ability to absorb cationic agents, such as chitosan, by increasing surface polarity and introducing anionic groups (Milanović et al., 2013). This regioselective oxidation confines functionalization to the surface without affecting bulk fiber properties, making it ideal for antibacterial modification (Saito, Okita, Nge, Sugiyama, & Isogai, 2006).

Plasma treatment modifies fiber surfaces using oxygen, nitrogen, or argon gas, enhancing the fiber's polarity and affinity for antibacterial agents (Karahan & Özdoğan, 2008; Abdel-Aziz et al., 2014). Silver nanoparticle-treated plasma-modified fibers exhibit strong antibacterial activity against Gram-positive and Gram-negative bacteria, with durability retained after multiple washes (Ibrahim et al., 2017; Peran et al., 2017).

Deposition Methods-Zero-valent metal particles like silver or copper can be deposited onto fibers to impart antibacterial properties. Impregnating fibers with metal salts, followed by reduction, creates nanoparticles that adhere to the fiber surface (Emam & El-Bisi, 2014; Vainio et al., 2007). Alternatively, colloidal solutions of metal oxides can be deposited for similar effects (Abramov et al., 2009). These methods effectively tailor Lyocell fibers for hygienic and medical applications.

IV. Antibacterial Applications of Silver Nanoparticles in Lyocell Fibers

Silver nanoparticles (AgNPs) possess versatile properties, making them valuable for various biomedical applications. They have demonstrated strong antimicrobial efficacy against bacteria like *E. coli*, *N. gonorrhea*, *C. trachomatis*, and viruses, Silver nanoparticles are often incorporated into Lyocell fibers due to their broad-spectrum antibacterial properties. They are effective at eliminating various types of bacteria and are generally considered safe for contact with human skin.(Marin et al., 2015; Tran et al., 2013) Researchers have developed antibacterial Lyocell fibers by incorporating silver nanoparticles during the NMMO spinning process. For instance, one method involves depositing silver chloride onto titanium dioxide, which acts as a porous carrier, and integrating this composite into the fibers. (Vegad & Hayhurst, 2007). The fibers produced through this technique retained their antibacterial efficacy even after undergoing cleaning, washing, and drying. However, a notable drawback is their tendency to discolor upon light exposure; the silver-treated Lyocell fibers often shift from white to grey due to redox reactions involving silver and its salts under UV light.

Typically, silver nanoparticle-modified Lyocell fibers are prepared by introducing an aqueous silver nitrate solution into the cellulose/NMMO mixture. The reduction of silver salts to zero-valent nanoparticles within NMMO is affected by various factors. Lyocell fibers containing approximately 100 ppm of silver nanoparticles exhibit significant bacteriostatic and bactericidal effects against *E. coli*, while those with 500 ppm demonstrate additional antimicrobial activity against *S. aureus* (Kulpinski, 2007).

It's worth noting that the reduction of silver ions can be triggered by ultraviolet radiation, elevated temperatures, or reducing agents (Shankar and Rai, 2004. Additionally, the incorporation of silver nanoparticles into textiles can be achieved through in-situ synthesis methods, which have been shown to produce fibers with excellent antibacterial properties (Song et al., 2009).

However, the durability of the antimicrobial treatment depends on the strength of the bonds between the textile and silver nanoparticles. Strong bonds are required to

ensure long-term efficacy, and the type of treatment is a major determinant in the retention of silver on textiles (Perelshtein et al., 2008).

Furthermore, the size of the silver nanoparticles plays a crucial role in their effectiveness. Smaller nanoparticles have a greater specific surface area, which can lead to increased release of silver ions and enhanced antimicrobial properties (Perelshtein et al., 2008). The best reported method, permitting generation of silver nanoparticles with the smallest diameter (12 nm) and the smallest agglomerates (665 nm), was exposure of cellulose pulp to $AgNO_3$ in a darkroom for 24 h (Smiechowicz et al., 2011).

V. Antibacterial Mechanisms of AgNPs

The antibacterial efficacy of AgNPs is attributed to several mechanisms:

1) Disruption of Cell Membranes: AgNPs can attach to bacterial cell membranes, increasing permeability and leading to cell lysis. The interaction of silver with cell wall proteins results in membrane disruption and cell death (Rai et al., 2009).
2) Generation of Reactive Oxygen Species (ROS): AgNPs can induce the production of reactive oxygen species within bacterial cells, causing oxidative stress and damage to cellular components. This oxidative stress can lead to cell death (Marambio-Jones and Hoek, 2010).
3) Interaction with DNA and Proteins: AgNPs can penetrate bacterial cells and interact with DNA and proteins, inhibiting replication and essential enzymatic functions, ultimately leading to cell death (Feng et al., 2000).

VI. Antibacterial Efficacy in Lyocell Fibers

The integration of silver nanoparticles (AgNPs) into Lyocell fibers has been shown to impart significant antibacterial properties. Studies have demonstrated that these modified fibers exhibit antibacterial activity against various pathogens, including *Staphylococcus aureus* and *Escherichia coli*. The treated fibers maintain their antimicrobial properties even after multiple laundering cycles, indicating the durability of the AgNP integration (Zhang et al., 2020).

VII. Safety and Environmental Considerations

While AgNPs offer substantial antibacterial benefits, their potential cytotoxicity and environmental impact require careful consideration. Ensuring that the nanoparticles are securely embedded within the fiber matrix can mitigate the risk of nanoparticle release during use and washing. Additionally, evaluating the long-term effects of AgNP exposure on human health and the environment is crucial for the sustainable application of these materials (Marambio-Jones and Hoek, 2010).

VIII. Challenges and Future Prospects

Despite the promising antibacterial properties of AgNP-integrated Lyocell fibers, several challenges remain:

1) Cost and Scalability: The cost of silver and the complexity of nanoparticle synthesis can hinder large-scale production. Developing cost-effective and scalable methods for AgNP integration is essential for commercial viability.
2) Durability and Wash Fastness: Ensuring that AgNPs remain attached to fibers after repeated washing is crucial for maintaining antibacterial efficacy. Research into enhancing the durability of nanoparticle attachment is ongoing.
3) Regulatory and Environmental Concerns: Regulatory guidelines regarding the use of nanoparticles in consumer products are evolving. Complying with these regulations and addressing environmental concerns related to nanoparticle release are critical for the acceptance of AgNP-integrated textiles.

IX. Conclusion

The development of antibacterial Lyocell fibers has significant potential for expanding the use of this sustainable material in health and medical industries. Methods such as physical blending, chemical grafting, and post-treatment offer viable pathways for modifying Lyocell fibers with antimicrobial agents. Among these, the incorporation of silver nanoparticles has shown promising results in enhancing antibacterial activity while maintaining the fiber's desirable properties.

However, challenges such as the durability of antibacterial properties and the cost and complexity of certain methods remain. Future research should focus on optimizing these processes, improving the stability of antibacterial treatments, and exploring alternative eco-friendly antimicrobial agents to ensure the long-term efficacy and commercial viability of antibacterial Lyocell fibers. . Through various synthesis methods, AgNPs can be effectively integrated into the fiber matrix, providing durable antimicrobial functionality. However, addressing safety, environmental, and scalability concerns is essential to fully realize the potential of AgNP-enhanced Lyocell fibers in commercial textile applications.

Reference

[1] Adams, J. G., & Walls, R. M. (2020). Supporting the health care workforce during the COVID-19 global epidemic. *jama*, *323*(15), 1439-1440.
[2] Abramov, O. V., Gedanken, A., Koltypin, Y., Perkas, N., Perelshtein, I., Joyce, E., et al. (2009). Pilot scale sonochemical coating of nanoparticles onto textiles to produce biocidal fabrics. *Surface & Coatings Technology*, *204*(5), 718–722.
[3] Borsa, J. (2012). Antimicrobial natural fibres. In *Handbook of natural fibres* (pp. 653-687). Woodhead Publishing.
[4] Edgar, K. J., & Zhang, H. (2020). Antibacterial modification of Lyocell fiber: A review. *Carbohydrate polymers*, *250*, 116932.
[5] Emam, H. E., & El-Bisi, M. K. (2014). Merely Ag nanoparticles using different cellulose fibers as removable reductants. *Cellulose*, *21*, 4219-4230.
[6] Fadavi, F., Abdulkhani, A., Hamzeh, Y., Bacher, M., Gorfer, M., Bandian, D., ... & Hettegger, H. (2019).

Photodynamic antimicrobial cellulosic material through covalent linkage of protoporphyrin IX onto Lyocell fibers. *Journal of Wood Chemistry and Technology*, *39*(1), 57-74.

[7] Fink, H. P., Weigel, P., Purz, H. J., & Ganster, J. (2001). Structure formation of regenerated cellulose materials from NMMO-solutions. *Progress in Polymer Science*, *26*(9), 1473-1524.

[8] Feng, Q.L., Wu, J., Chen, G.Q., Cui, F.Z., Kim, T.N., & Kim, J.O. (2000). A mechanistic study of the antibacterial effect of silver ions on *Escherichia coli* and *Staphylococcus aureus*. *Journal of Biomedical Materials Research*, 52(4), 662-668.

[9] Gao, C., & Edgar, K. J. (2018). Efficient synthesis of glycosaminoglycan analogs. *Biomacromolecules*, *20*(2), 608-617.

[10] GB2412083A. (2005). Making anti-microbial lyocell fibres containing silver and phosphate Sources.

[11] Ibrahim, N. A., Eid, B. M., & Abdel-Aziz, M. S. (2017). Effect of plasma superficial treatments on antibacterial functionalization and coloration of cellulosic fabrics. *Applied Surface Science*, *392*, 1126-1133.

[12] Islam, S., & Butola, B. S. (2019). Recent advances in chitosan polysaccharide and its derivatives in antimicrobial modification of textile materials. *International Journal of Biological Macromolecules*, 121, 905-912.

[13] Jiang, X., Bai, Y., Chen, X., & Liu, W. (2020). A review on raw materials, commercial production and properties of lyocell fiber. *Journal of Bioresources and Bioproducts*, *5*(1), 16-25.

[14] Karahan, H. A., & Özdoğan, E. S. E. N. (2008). Improvements of surface functionality of cotton fibers by atmospheric plasma treatment. *Fibers and polymers*, *9*, 21-26.

[15] Kulpinski, P. (2007). Bioactive cellulose fibres with silver nanoparticles. *E-Polymers*, *7*(1), 068.

[16] Liu, X. H., Zhang, Q. Y., CheONg, B. W., Ren, Y. L., Zhang, Y. G., & Ding, C. (2018). Durable flame retardant cellulosic fibers modified with novel, facile and efficient phytic acid-based finishing agent. *Cellulose*, *25*, 799-811.

[17] Marin, S., Mihail Vlasceanu, G., Elena Tiplea, R., Raluca Bucur, I., Lemnaru, M., Minodora Marin, M., & Mihai Grumezescu, A. (2015). Applications and toxicity of silver nanoparticles: a recent review. *Current topics in medicinal chemistry*, *15*(16), 1596-1604.

[18] Milanović, J., Kostić, M., Dimitrijević, S., Popović, K., & Škundrić, P. (2013). Antibacterial activity of selectively oxidized Lyocell fibers. *Contemporary Materials*, *4*(1), 39-45.

[19] Periyasamy, A. P. (2021). Processing and Application of Lyocell–An Overview.

[20] Potthast, A., Rosenau, T., & Kosma, P. (2006). Analysis of oxidized functionalities in cellulose. *Polysaccharides ii*, 1-48.

[21] Ristić, T., Zemljič, L. F., Novak, M., Kunčič, M. K., Sonjak, S., Cimerman, N. G., & Strnad, S. (2011). Antimicrobial efficiency of functionalized cellulose fibres as potential medical textiles. *Science against microbial pathogens: communicating current research and technological advances*, *6*, 36-51.

[22] Saito, T., Okita, Y., Nge, T. T., Sugiyama, J., & Isogai, A. (2006). TEMPO-mediated oxidation of native cellulose: Microscopic analysis of fibrous fractions in the oxidized products. *Carbohydrate polymers*, *65*(4), 435-440.

[23] Sarkar, A. K., & Vora, G. (2011). Imparting protective properties to Lyocell via finishing treatments. *Autex Research Journal*, *11*(3), 89-92.

[24] Smiechowicz, E., Kulpinski, P., Niekraszewicz, B., & Bacciarelli, A. (2011). Cellulose fibers modified with silver nanoparticles. *Cellulose*, *18*, 975-985.

[25] Vegad, H., & Hayhurst, M. (2007). *U.S. Patent Application No. 11/573,129*.

[26] W. Wang, w.u. xiao-song, y.y. chen, w. Sun, w. Zhang. (2017). Study on antibacterial properties of an antibacterial fabric chinese. J. Disinfection, 12, pp. 1105-1107

[27] Wang, Z. M., Shao, H. L., Hu, X. C., & Shen, Y. Y. (2003). A study on antibacterial Lyocell fibers. *Journal of Donghua University*, *29*(1), 71-76.

[28] Tran, Q. H., Nguyen, V. Q., & Le, A. T. (2013). Silver nanoparticles: Synthesis, properties, toxicology, applications and perspectives. Advances in Natural Sciences: Nanoscience and Nanotechnology, 4(3), 033001.

[29] Kulpinski, P. (2007). Silver nanoparticle-modified Lyocell fibers with antimicrobial properties. Journal of Applied Polymer Science, 106(1), 321–326.

[30] Shankar, S. S., & Rai, A. (2004). Factors influencing silver ion reduction and nanoparticle formation. Materials Chemistry and Physics, 85(2-3), 194–198.

[31] Song, J., Kong, H., Jang, J. (2009). Antibacterial properties of in-situ synthesized silver nanoparticles on cotton textiles. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 341(1-3), 79–83.

[32] Perelshtein, I., Applerot, G., Perkas, N., Wehrschuetz-Sigl, E., Hasmann, A., Guebitz, G. M., & Gedanken, A. (2008). Antibacterial properties of silver nanoparticles deposited onto textile fabrics. Nanotechnology, 19(24), 245705.

[33] Rai, M., Yadav, A., & Gade, A. (2009). Silver nanoparticles as a new generation of antimicrobials. Biotechnology Advances, 27(1), 76–83.

[34] Marambio-Jones, C., & Hoek, E. M. V. (2010). A review of the antibacterial effects of silver nanoparticles and potential implications for human health and the environment. Journal of Nanoparticle Research, 12(5), 1531–1551.

