

**Self-Healing and Antibacterial Specialty Yarn: Future Frontier in Protective and Medical Textile**

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**ABSTRACT**

*The healthcare industry as well as the personal safety industry is undergoing a revolution due to recent innovations in the field of special yarns and smart textiles. The current paper will focus on how future medical and protective fabrics become a part of living. In particular, it will discuss how such fabrics are capable of healing themselves, neutralizing microorganisms, and enhancing the recovery process. Self-healing textiles based on bacterial biofilm and composites is one of the latest frontiers that have emerged. Such textiles are capable of repairing themselves. Hence, extending the service period and increasing security levels. Another innovation includes antibacterial and anti-inflammatory surface treatments for cotton, among other types of fabrics. In addition to this, we discuss the revival of plant and insect based colorants and the possibilities for chemical free dyeing with additional health advantages. On the other hand, nanotechnology is creating niche markets for textiles with properties such as fire resistance, dirt repellency, and microbe killing simultaneously. In the case of PPEs, there have been not able advancements*

*towards developing lightweight, resilient, and reusable fabrics that can detect hazardous elements. One of the most promising developments is the closed loop intelligent system in personal healthcare management. In this technology, wearables will be capable of monitoring the skin condition or wound and subsequently deliver medicine or regulate temperature on their own without any human intervention. Last but not least, we connect everything to sustainability. This would be possible through the implementation of artificial intelligence, energy recovery, and economic stability in such a way that would allow for better waste management while creating high quality materials at the same time. In conclusion, the future of medical and protective fabrics lies in biology and nanotechnology being implemented into smart fabrics clothes that can heal and protect on their own.*

**Keywords:** *Self-healing yarn, Antibacterial textile coatings, Nanostructured fabrics, Bacterial biofilm composites, Smart healthcare clothing, Personal Protective Equipment (PPE) materials, Natural colorants, Shear Thickening Fluids (STFs) and Shear Thickening Gels (STGs) materials, Microbe based wound management, Closed loop wearable systems, Sustainable waste management in textiles, Flame resistant and self cleaning finishes.*

## **INTRODUCTION**

The fabric production industry constitutes one of the most massive and fast developing industries of the global economy. Millions of tons of clothes and materials are being produced, used, and eventually disposed of yearly. A significant proportion of such material finds its place in landfills since they may be torn, stained, or deteriorate their qualities. It makes a real threat to the environment. Meanwhile, there is an increasing demand for protective and medical textiles which would ensure safety from pathogens and toxic substances among healthcare professionals and patients. It became very clear during the COVID-19 pandemic that effective protective clothing was essential. Medical personnel such as doctors and nurses require protective equipment like masks, gowns, and gloves which can resist viruses and bacteria. However, the major part of such items is single use and then disposed of. This results in a significant amount of waste being generated. Thus, it has become necessary to develop reusable medical textiles and also self repairing medical textiles. The concept of self-healing materials is not a novel one in scientific research. Many scientists have been exploring the self-healing capability of plastics and coatings for decades now. The problem arises when it comes to making fabrics that can self-heal. Textiles are flexible and are put through tremendous amounts of stress in the course of their use and even washing. The other probable solution would be getting an idea from nature. Some types of bacteria, including *E. coli*, naturally create biofilms. The biofilm is made up of proteins referred to as curli fibers that naturally self-heal when they come into contact with water by joining up and healing any cracks that may be present. Scientists have found out how to apply the biofilms on regular cotton fabrics to develop self-healing clothes that heal any damage when exposed to water [1].

However, there have also been great developments in antibacterial fabrics. Infections are always a matter of concern for hospitals. Whenever a patient has a wound or a surgical opening, there is a chance for bacteria to penetrate into the body. Traditionally, patients had simple bandages wrapped around the affected part. However, there are new 'smart' bandages today that kill bacteria and reduce swelling. While some of these 'bandages' consist of silver nanoparticles that are very effective at killing bacteria, others use unique coating technology that releases medication in case of an infection [2, 6].

Another development that looks quite promising involves using natural sources. For many centuries, people used extracts from nature to dye their clothes. Natural dyes have recently come back into fashion due to their safety and therapeutic properties. There are cases where some plant extracts can not only help in

coloring the fabric, but also destroy bacteria or reduce swelling. Therefore, future medical fabrics may be dyed naturally [6].

Nanotechnology is another area that is revolutionizing the industry. Nanoparticles are microscopic particles thousands of times smaller than a human hair. The use of nanoparticles in coatings on fabric gives it incredible features. Zinc oxide nanoparticles, for instance, can make a fabric anti-bacterial, UV-resistant, and self cleaning under sunlight [3, 7]. The cotton material coated with such nanoparticles maintains its effectiveness through repeated washing.

The development of personal protective equipment (PPE) requires materials that are light, durable, and reusable. Today's PPE, such as hazmat suits, are bulky and uncomfortable. An employee cannot work for extended hours wearing them. Shear Thickening Fluids (STFs) and Shear Thickening Gels (STGs) make up novel materials that are soft and flexible until impacted by something. These materials are ideal for use in bullet proof vests and cut proof gloves [14].

Additionally, AI is now finding applications in the textile industry. Through the use of AI, it is possible to develop more efficient textiles, predict the lifespan of such textiles, and categorize worn out clothes for recycling. Additionally, this relates to our theme of sustainability, in which it becomes necessary to invent textiles that are durable, capable of self repairing, and recyclable at the end of their lifespan [5, 9].

## **REVIEW OF LITERATURE**

### **Importance of Protective and Medical Textiles in Modern Healthcare**

In modern medicine, the use of protective and medical textiles is indispensable. Examples of such textiles may be surgical gowns, face masks, bandages, hospital bed linen, and wound dressings. The primary purpose of using these products lies in preventing infections. In other words, when a medical worker wears a surgical gown, he/she becomes immune to bacteria and viruses which cannot get onto his/her skin and clothes. In addition, by applying a wound dressing, patients can recover sooner.

The demand for high end medical textiles rose greatly during the time when the coronavirus disease started spreading worldwide. In all the hospitals, there was a lack of masks and gowns due to the pandemic. As a result, the current practice of using single use and disposable textiles cannot be continued and there arises the need to introduce reusable textiles [7].

Moreover, the textile material must be comfortable enough. When the textile material is rough or too thick and thus difficult to permeate, then it will surely become hot and uncomfortable to wear. The doctors and nurses work under great difficulty and they certainly do not deserve such additional difficulties due to what they wear. Thus, today's textiles need to ensure safety as well as convenience. Cost is another critical issue. Most hospitals operate in developing nations or rural regions. They cannot pay for costly technical fibers. The new medical textiles should be available at affordable prices. That is why researchers have been exploring cost effective technologies, such as bacterial biofilms and natural dyes [1].

### **Self-Healing Specialty Yarn: Concept and Working Mechanism**

The other crucial issue is price. Most hospitals work in developing nations or rural settings where high cost hi-tech fabrics would not be feasible. Therefore, any innovation in medical textiles needs to be economically viable so that all hospitals can afford it. That is why researchers focus on economical methods such as biofilms made by bacteria and organic dyes. Self-healing materials mean exactly what they imply. Self-healing refers to a type of material which can heal itself after sustaining an injury without any external aid.

Self-healing in textiles occurs when the fabric repairs the damage on its own. There are two main techniques of producing self-healing medical textiles. First, one could coat the fabric with a self-healing material. Second, one could produce self-healing fibers [1, 4].

The coating process is easier to implement with existing manufacturing machinery. First, you select any typical fabric, such as cotton or polyester, and immerse it in the solution. This liquid will be composed of compounds capable of regeneration. The resulting textile will then develop a film layer on its surface. In case of injury to the coating layer, it will be able to regenerate itself under the influence of heat, light, and moisture [1, 8].

However, this approach has one drawback. The healing layer is located solely on the surface. Thus, when an injury extends beyond the coating to affect the base fabric, self repair may fail. In addition, there is always a risk of wearing out the coating layer after prolonged use and cleaning [1].

The second method is focused on making self-healing yarns. In the case of this approach, the yarn fibers will be made with self-healing abilities. The yarns would not only recover from minor damage but could heal even if the whole material was completely punctured. It is more difficult to develop such yarns compared to the previous one [4].

What makes self-healing possible on a molecular level? Usually, self-healing materials have chemical bonds that will break if the material is damaged. However, they will reform again once a certain factor (such as water or heat) will be introduced into the process. Consequently, the material returns to its initial state. A new advance was found out while conducting experiments related to biofilms formed by bacteria. One of such bacterial species is *E. coli*, which produces a protein CsgA. The protein forms large fibrils called curli fibers, which are rather strong and have one unique characteristic they are capable of self-healing in contact with water. The principle behind the healing of the curli fibers is their structure. The curli fibers contain several hydrogen bonds, which are rather weak connections between molecules. In case any part of the fiber is cut, the hydrogen bonds get destroyed. Nevertheless, after adding water to it, the fiber swells up absorbing water molecules, and its two parts come together. Thus, new hydrogen bonds appear, which heal the damage made [1, 10].

Researchers from the University of Montreal, Canada, found out the way to cover common cotton fabric with *E. coli* biofilms. They used three methods for doing that: adsorption, doctor blading, and vacuum filtration. As a result, all three methods showed high efficacy since a piece of the healed fabric can restore even several centimeter cuts within several minutes of contact with water. Along with measuring the efficiency of healing, researchers examined the strength of the healed material. It was found out that its quality increased dramatically because of the strong bond formed between the fabric and biofilm. Therefore, the two sides of the cut material could join together as a result of the biofilm flow [1].

### **Antibacterial Functionality and Microbial Protection**

Antibacterial textiles refer to any type of fabric which is able to either destroy bacteria or suppress their multiplication. This feature is especially important for application within medicine. If a person is injured, bacteria may penetrate through the wound and cause infections, which will extend recovery period and sometimes even result in death [2, 6].

Several ways exist in order to make a fabric antibacterial. First of all, we can use chemicals that kill bacteria by applying them on the textile. They may include metals like silver, copper, zinc. Furthermore, there exist plants that have antibacterial features [6, 7].

Silver is especially popular antibacterial material. Long before, it was applied for purification of water and other consumables. Silver kills bacteria in several ways. It destroys cells' walls, interferes with bacteria metabolism and prevents reproduction. However, silver nanoparticles have some downsides. To begin with, they can prove to be rather expensive. Secondly, it has been noted that the excessive use of silver could lead to bacteria becoming resistant to it, similarly to antibiotics. Lastly, some researchers cast doubts about the safety of silver nanoparticles for both humans and the environment [6].

Zn O (zinc oxide) nanoparticles could also be considered. First and foremost, zinc, in comparison with silver, is cheaper and safe for people. Moreover, Zn O nanoparticles are able to kill different bacteria; namely, Gram positive and Gram negative. They are also able to protect against ultraviolet (UV) radiation [3, 7].

According to the latest study conducted by researchers and published in Scientific Reports in 2026, Zn O nanoparticles were proved to have outstanding antibacterial properties when applied to cotton textiles. Moreover, such treatment helped increase the UV resistance of the fabrics. It should also be mentioned that such antibacterial properties remained intact even after five washes [7].

The second innovation is based on silica nanoparticles. There are two types of medicines, which may be introduced into the body using silica nanoparticles. Specifically, an antibiotic and anti-inflammatory medicines can be delivered using silica nanoparticles simultaneously. The first medicine is used externally on the surface of the cotton bandages [6].

One of the main advantages of the invention is selective medicine delivery. This means that drugs are attached to nanoparticles using specific bonds, which are broken due to the action of enzymes. As soon as infection takes place, the body produces enzymes responsible for breaking the bonds between drugs and silica nanoparticles. Consequently, the amount of drug delivered is significantly reduced, ensuring that there is almost no chance of experiencing an adverse reaction. Those people who are more likely to become infected are those who have long lasting injuries such as diabetic ulcers and bedsores. One would normally need to take some kind of antibiotics to prevent infections. However, this may contribute to developing antibiotic resistance.

### **Advanced Materials Used in Specialty Yarn Development**

Materials are extremely advanced in the case when we talk about producing special types of threads needed for protective and medical fabrics. First of all, it should be emphasized that the materials necessary to produce such goods have to possess the following properties: mechanical strength, flexibility, biocompatibility (absence of harm for living organisms), and biodegradability [1, 4].

**Bacterial Biofilms:** It is known that development of bacterial biofilm is one of the most important scientific achievements. In fact, curli fibers composing such biofilm are made of proteins having mechanical properties comparable with those of the polymers. Besides, curli fibers possess mechanical strength, self repairing capabilities, they are biodegradable, and not toxic. It is easy to produce bacteria capable of producing such a type of biofilms as cultivation in inexpensive culture media can be performed [1, 10].

What is more, Young's modulus of curli fibers lies between 3 and 20 GPa. Hence, it means that such fibers are mechanically strong enough to compete with artificial plastic materials. Additionally, there are possibilities for genetic modification of the bacteria. Namely, they can be altered in such a way that they will produce curli fibers possessing additional properties. One of them can be binding nanoparticles of various metals or luminescent groups [1].

**Shear Thickening Materials (STF and STG):** STFs are fluids that harden under sudden pressure, i.e., under impacts. Under normal conditions, they behave like regular fluids. When impacted, however, STFs suddenly harden and become similar to solids. These materials are excellent for body armor and bulletproof vests. The key to STF properties is the nature of interaction between particles within them. As a rule, STFs contain numerous solid particles suspended in a fluid. In case of low speed of liquid movement, particles can freely slide over one another. However, upon impact, they jam and prevent the motion of neighboring particles. Furthermore, the same principle of STF is applicable to STG. Herein, however, the STG will always be highly viscous. Both STF and STG can be included in the clothing material, leading to production of elastic material that becomes harder on hitting by blades and bullets [4].

**Nanoparticles:** The three types of nanoparticles are zinc oxide, silver, and silica. They are proposed for inclusion in clothing due to their antibacterial properties. The reason why such nanoparticles are used is that there are billions of them in a single fiber of cotton due to their very tiny sizes. This makes them have certain characteristics that cannot be found in other materials with larger sizes. For instance, nanoparticles of zinc oxide are able to absorb ultraviolet rays and convert them into heat energy in order to shield individuals from ultraviolet rays. In addition, once these nanoparticles are activated using light, they can release reactive oxygen species that are highly potent in killing cells due to their ability to penetrate cellular membranes [3, 7].

**Natural Polymers:** The first one is known as chitosan. It is a type of polymer which can be obtained through shrimps and crab shells. This polymer is completely natural and has properties like biodegradability and antibacterial effects. Nanofibers can be prepared using chitosan and can be coated on the surface of the cotton fabrics. The studies showed that this approach helped accelerate the wound healing process and scar formation. Another type of natural polymer is known as cyclodextrin. It is a product of starch and has a ring shape, and both its outer surface and inner surface are characterized by hydrophobic and hydrophilic features respectively. This means that cyclodextrins can carry molecules in their rings. Regarding textiles, cyclodextrins can help capture odorants or slowly release drugs [2].

### **Role of Nanotechnology in Antibacterial Textile Fibers**

This concept indicates that manipulation takes place at the nanometer level (1-100 nanometers). To get a grasp of the scale, take into account that a human hair strand is 80,000 nanometers in diameter. Since nanoparticles are very tiny, they acquire physical characteristics that differ from those possessed by larger objects. Physical characteristics, such as optical, mechanical, and chemical ones, can differ [7].

Nanotechnology applications in the textile sector refer to the introduction of new features to textile fibers. The first application of nanotechnology within the textile sphere concerns an antibacterial treatment of fabrics. Nanoparticles of silver, zinc oxide, copper, and titanium dioxide are used in this procedure [3, 7].

There is a problem with the stability of nanoparticles when washing fabric. It means that nanoparticles must be strongly bound to fiber surfaces since they can become detached from textile material. Several methods have been proposed for improving the stability of nanoparticles. The first way is to use enzymes in order to treat the surface of the fabric, after which nanoparticles can be introduced. Enzyme cellulases usually are used to soften cotton fabrics. It has been discovered, however, that cellulases increase the number of carboxyl and hydroxyl groups in cotton fibers. Those groups work as anchors to nanoparticles. A 2026 research investigated this concept. They soaked cotton and cotton polyester mixed fabrics in cellulase enzyme solution and applied zinc oxide nanoparticles to them. This treatment improved the binding ability between nanoparticles and fabric as well as their durability. After five washes, they destroyed about 99 percent of bacteria [7].

Another alternative is the use of chemicals for attaching nanoparticles to the fabric. For example, the addition of diethylenetriamine (DETA), which contains two amino groups, on nanoparticles improved their attraction to the fiber composition of the fabric. Applying the BN, Zn, O nanoparticles with DETA enhanced their stability. After immersing the particles in water for 24 hours, 92.6% of the nanoparticles were retained in contrast to the bare particles which showed 63.6%. Aside from super hydrophobicity, the nanoparticles provided the fabric with self cleaning property by degrading the contaminants when the fabric is irradiated by UV light. Moreover, the fabric is resistant to ink, soy sauce, and tomato juice stains. This could be utilized in hospital gowns that require hydrophobic, self cleaning, and antibacterial fabric qualities. When working with nanoparticles, one has to take into account that there might be risks involved. The fact is that because the size of nanoparticles is so small, they can pass through inhalation or through the skin. Yet, no studies have found any cases where irritation or inflammation has appeared from exposure to zinc oxide nanoparticles. Histologically, normal skin structures have been observed. There may be need for further investigations, but presently, there does not seem to be any adverse effect [3].

### **Applications of Self-Healing Yarn in Medical Textiles**

Self-healing yarns have various applications in medicine. One of the simplest uses for such technology is wound dressings and bandages. A wound dressing made from such materials would have a higher shelf life and provide more protection. In case such material becomes damaged through a tear, it would mend itself without requiring replacement. Another useful application for such technology would be the use of surgical gowns and drapes. During surgery, the gown may accidentally become punctured or torn. Any tears in the surgical gown will allow bacteria to contaminate either the patient or the surgical team. By creating a surgical gown using such materials, it will seal itself instantly. Finally, medical tents set up during disasters or at military bases could benefit from such technology. Tents need to be erected on short notice within hazardous environments and thus might be damaged. This may happen through exposure to wind, sharp objects, and rough treatment. Such tents made from self-healing materials will automatically repair themselves [4].

The research scientists who created the biofilm coating on the bacteria then tried out its use in repairing large holes in the material. Patching was done by placing the biofilm coated fabric piece onto a hole in the fabric. Water was then poured. The biofilm on the patched part fused with the existing biofilm thus welding the patch in place. Also welding two pieces of fabrics together edge to edge was attempted. This was done by putting two pieces of biofilm coated fabrics together with a tiny gap between them. A drop of concentrated biofilm solution was put on the gap before pouring water. Welding was achieved since the new and existing biofilms joined, closing the gap and making the pieces join as one piece. This welding technology is very important especially in the medical industry. For instance, a physician in the bush could repair a torn surgical cloth by just applying a patch with water. This process would not require any extra effort [1].

### **Use in Personal Protective Equipment (PPE)**

Personal Protective Equipment (PPE) comprises hazmat suits, chemical protection suits, bulletproof vests, and fire suits. Such materials should be highly durable and protective. Self-healing and antimicrobial functions will enhance such products [1, 4].

In hazmat suits, one tiny pinhole can cause serious problems. Toxic agents or virus particles can enter through this pinhole. Today's hazmat suits are disposable since they cannot be fixed permanently. However, the self-healing hazmat suit will operate differently. If there is a tear in the suit, the user can heal it by applying water. This process will make the suit impermeable again [1].

At Penn State University, scientists developed another kind of self-healing coating for PPE. It uses bio inspired polymers that were based on proteins in squid ring teeth. Those proteins are known for their strength and ability to heal themselves with the help of water. To this kind of polymer coating, scientists added enzymes that would be able to degrade toxins, including organophosphates (which is one of the kinds of nerve agents). Therefore, if a worker wearing such coated suit faced a chemical weapon attack, two effects would take place. First, a barrier will form. Second, the enzymes would start decomposing the toxic molecules. And if the protective coating becomes damaged, it would be able to self-heal through exposure to moisture from sweat or decontamination solutions [8].

In relation to bulletproof vests, self-healing is not concerned with the prevention of bullets. Instead, it involves maintaining the efficacy of the vests despite prolonged wear. Bulletproof vests consist of many layers of tough fibers. In a case where a bullet strikes the vest, some fibers will be stretched or broken. With time, due to many impacts on the vest, its effectiveness will deteriorate. Therefore, a self-healing fiber would help to extend the lifespan of the vest. STFs can be integrated into personal protective equipment. STFs are currently being used in making cut resistant gloves for factory workers. These gloves remain soft during normal activities but get hard upon contact with any sharp object. As such, they offer cut resistance while still allowing finger movement [4, 14].

Nanotechnology can be integrated into firefighter equipment. Zinc oxide nanoparticles are capable of destroying harmful bacteria in addition to being a barrier to both ultraviolet radiation and moisture. Firefighters are usually exposed to many dangers, among which is exposure to high temperature, harmful chemicals, and bacteria [3].

### **Advantages of Self-Healing and Antibacterial Yarns**

The combination of self-healing and antibacterial properties in a single yarn offers several important advantages.

**Extended Life Span:** Materials that have self-repair capabilities have increased life spans. Any tiny cuts and tears that might spoil a fabric can be fixed easily. It reduces replacement needs. This factor is particularly critical for medical textiles. Hospital bed sheets and surgical gowns need to be frequently changed. If they were self-healing, their usage period would increase [1, 4].

**Improved Safety:** Damaged protective clothing is not only unsightly but also risky. A minor puncture in protective hazmat suits and gowns can cause leakage of toxic material. Self-healing materials repair such damage immediately without any human intervention [1, 4].

**Low Chance of Infection:** The antibacterial finish eliminates bacteria that might get on the surface of the clothing. Hence, this feature minimizes the risk of infection in medical facilities. The case is different for wounds; the antibacterial function ensures quicker healing by eliminating bacteria directly from the wound [2, 6].

**Decreased Usage of Antibiotics:** Advanced wound dressings that administer antibiotics only when necessary may help prevent the overuse of antibiotics, which is becoming a worldwide concern. The appropriate use of antibiotics will minimize the formation of antibiotic resistant bacteria [6].

**Sustainability:** Durability of fabric implies reduced production of waste that goes into the landfills. Since the material is biodegradable, for instance, through bacterial biofilm or natural polymers, there will be no problem at all when it decomposes once it is discarded. The use of environmentally friendly production techniques, such as enzymes, minimizes pollution [1, 7]

**Cost Efficiency:** While the self-healing materials and the antibacterial materials could be costly initially, they are in fact cost efficient in the long run. Hospitals will incur lower costs in purchasing hospital wear and bandages. The workers will need to purchase their protective gears less frequently. Hospital stays for the patients will become shorter because their wounds heal faster [6, 7].

### **MANUFACTURING CHALLENGES AND COMMERCIALIZATION OPPORTUNITIES**

Even with all these promising findings, several issues need to be addressed before self-healing and antibacterial textiles can become widely available.

**Scalability:** Almost all the techniques discussed in this paper have only been implemented under laboratory conditions. Translating them into an industrial context is far from easy. For instance, the growth of bacterial biofilms on a large scale would involve stringent regulation of environmental conditions, such as temperature and nutrition levels. This is by no means an easy task [1].

**Cost:** The raw materials employed for production of these next generation textiles are often costly. Silver nanoparticles are substantially more expensive than standard cotton. Even biofilm produced by bacteria using inexpensive raw materials requires special equipment and trained personnel to manufacture. As long as they remain expensive, these textiles will only be available for premium purposes [1].

**Durability:** These fibers undergo considerable stress when subjected to washing and everyday use. Protective coatings may wear away. Individual fibers can deteriorate. Self-healing coatings may function effectively during their initial days of use but become dysfunctional after ten washings. Further research needs to be conducted to improve the durability of these innovations [1, 7].

**Regulation and Safety:** Medical textiles are usually classified as medical devices. To become available on the market, they must undergo numerous tests that show their efficiency and safety. This may take several years and costs millions of dollars. Nanoparticle containing materials raise other questions regarding the possibility of penetration of nanoparticles into the body [3].

**Standardization:** Self-healing textile products do not have standardized tests that determine their healing effectiveness and number of healing cycles. It is difficult to compare one self-healing material with another without established standards [4].

**Consumer Acceptance:** Even though this technology is effective, will customers want to use it? Wearing a textile product covered with bacteria even if dead, does not seem too appealing. Clear communication about the advantages of this invention should help overcome this problem [1].

Nevertheless, there are plenty of commercial applications. First of all, it involves the healthcare industry. Hospitals constantly strive to find new ways to decrease both infections and expenses. In case an antibacterial self-healing gown requires higher initial expenditure but at the same time provides hospitals with the ability to decrease their budget by 50% as well as to cut down infections, then they will definitely purchase the product [4].

Another industry is related to the military forces. They are constantly searching for the materials that could withstand tough environmental conditions. Moreover, it would mean that soldiers would have a chance to fix tears in uniforms and even gas masks with plain water. Also, military expenditures provide sufficient funding for innovative projects [8].

Additionally, outdoorsmen or any other athletes can take benefit from the invention. All the clothes they use tend to become dirty or torn easily. Therefore, they can also become self-healing and antibacterial [4].

### **Sustainable and Eco-Friendly Innovations in Smart Textiles**

The topic of sustainability has become a hot topic in textile research. The fashion sector is one of the dirtiest industrial sectors globally. It consumes immense quantities of water, energy, and chemicals. Moreover, it produces a substantial amount of waste. Intelligent textiles provide an approach to decrease this negative impact on the environment [1, 5].

**Biodegradable Materials:** One of the main benefits of utilizing bacterial biofilms lies in their complete degradability. Once biofilm impregnated material has reached its end of life and has been discarded, biofilm begins degrading. Cotton fabric that is coated with biofilm also starts breaking down. In other words, there are no toxic leftovers. In contrast, materials such as polyester degrade only after hundreds of years [1].

**Enzyme-Based Processing:** The conventional textile finishing process involves the use of strong chemicals such as acids, bases, and organic solvents. Such chemicals may be harmful to the environment and may even pose dangers to employees. In contrast, the more recent methods employ the use of enzymes. Enzymes are biological catalysts, which operate at gentle conditions. In the study conducted in 2026, cellulase enzymes were used to treat fabric surfaces for the activation of Zn O nanoparticles. As a result, no harmful substances such as poly carboxylic acids were needed during treatment; thus, the procedure was environmentally friendly and safe for employees [7].

**Artificial Intelligence in Textile Recycling** Artificial intelligence is currently used to facilitate the process of recycling clothes. The problem with textile recycling is that the items often contain various accessories and consist of different materials. Manual sorting of garments and their components takes a lot of time and money. However, with the help of cameras and sensors, as well as artificial intelligence algorithms, robots can scan each item and automatically identify the material and components. After that, they can cut out all the necessary details and separate them according to the type of material. Such an approach would greatly facilitate the process [5, 9].

The European Union is now supporting the research of a project called Flex Cycle. Its goal is to create a fully automatic robotic system for flexible material processing. This would significantly increase the effectiveness of textile recycling [9].

**Energy Recovery:** It may happen that some fabrics cannot be recycled due to the extent of damage or contamination they undergo. In this case, the method of energy recovery is a good choice. It involves burning textile waste in specific installations to recover energy to produce electricity or heat. Even though burning does not equal recycling, it is still preferable to disposal because it results in the recovery of energy [5, 9].

**Natural Colorants:** Natural plant and insect derived dyes have gained popularity recently. They are renewable and eco friendly and have additional benefits such as antimicrobial or anti-inflammatory properties. Turmeric, indigo, and madder root based dyes, for instance, can suppress the growth of some bacteria. Hence, in addition to aesthetic functions, coloration contributes to other beneficial effects [6, 11].

### **FUTURE TRENDS AND EMERGING DEVELOPMENTS**

In terms of the future, many interesting developments could impact the field of self-repairing and antimicrobial fabrics.

**Genetic Engineering of Biofilms:** Biofilm curli fibers found in E.coli bacteria are proteins known as CsgA. It is possible to genetically modify the DNA sequence that codes for such proteins. New functionalities can be introduced through genetic modification using other proteins. For instance, a metal binding domain can be incorporated into the fiber, which would result in a pollution absorbing fabric. These engineers might also use the domain that reacts to pH levels and temperature changes. This way, the smart bandages will change colors when the wounds get infected (since infections alter the pH levels of wound secretions). They can use the same reaction to deliver medicines into the wound site [1].

**Living Textiles:** While the present day self-repairing materials are made of dead bacteria (as the biofilm is harvested and then dried), why not think about creating live bacteria based materials? The fabric with live bacteria on its surface would be able to produce new curli fibers endlessly, as well as monitor the surrounding conditions and react to them.

**Multi-Functional Coatings:** There is an increasing tendency towards coatings that perform multiple tasks. A coating can act as self-healing, antibacterial, anti-inflammatory, water repellent, ultraviolet (UV) resistant, and fire retardant. Using several layers would be costly and could result in stiffness of the fabric. An example is the B N Zn O, DETA coating that we have seen previously. It had seven different functionalities: self cleaning, UV resistance, water resistance, stain resistance, antibacterial effect, skin safety, and washability [3, 6].

**Closed Loop Healthcare Systems:** The use of smart textiles would be incorporated into large health care networks. An intelligent sensor could record vital signs of a patient and forward the information to his doctor. The clothing item could release medication on demand. This process is known as a closed loop process, because it involves sensing, decision making, and acting [4, 15].

**Personalized Textiles:** The more flexible manufacturing becomes, the more capable we become of making personalized textiles. A wound dressing can be printed out precisely to match the dimensions of that individual's injury and tailored specifically to deliver the right medicines in the necessary amounts.

## CONCLUSION

In conclusion, the recent development in the production of self-healing and antibacterial specialty yarns for medical and protective purposes has been evaluated in this paper. It should be noted that this sphere progresses rather rapidly owing to the demand for innovative and more secure textile products. The scientific evidence indicates that the era of self-healing fabrics is coming true. Scientists managed to design cotton fabrics that are capable of healing even cuts on a centimeter scale just by means of water. The principle of action involves the reconstruction of hydrogen bonds in the protein structure. After healing, the fabric remains nearly as strong as it was before. Three scalable techniques were developed: adsorption, doctor blading, and vacuum filtration, each resulting in specific composite materials [1].

However, the antibacterial textile industry has made great progress. It has become possible to attach nanoparticles of silver, zinc oxide, and other substances to the surface of fabric, thus destroying bacteria. Novel technology relies on silica nanoparticles capable of delivering antibiotics and anti-inflammatory drugs precisely to target places. Enzymatic treatment of the surface of fabrics promotes better adhesion of nanoparticles and increases their stability during washes [2, 3, 6, 7].

The integration of both self-healing and antibacterial capability in one material brings numerous benefits. The protection offered by protective gear is improved due to the automatic fixing of any damage. The safety of medical textiles is increased by destroying the bacteria instantly. Both kinds of textiles are more durable and cost effective [1, 4].

It is necessary to scale up from lab results to industry application. Production costs should be reduced. The long term weariness resistance through numerous washings should be proved. Also, it is required to conduct safety tests for nanoparticles and bacteria [1, 3, 7].

In terms of future advancements, integration of different technologies holds the most promise. One type of fabric may include a bacterial film for self-repairing capabilities, nanoparticles to create antibacterial effects, organic pigments for the dying process, and AI designed architecture to ensure the best results. These will be included in closed loop healthcare systems, which automatically detect, analyze, diagnose, and treat [1, 4, 6]. The need to develop sustainable solutions will be at the core of this revolution. Materials will have to be biodegradable and enzymes, AI, and energy harvesting techniques applied in processing [1, 5, 7, 9].

Conclusively, self-healing and antibacterial yarns are one of the latest innovations in the textile industry. These yarns offer the possibility of revolutionizing medical as well as protective clothing by making them not only passive but proactive by providing protection, healing capabilities as well as repairing abilities. Though many advancements have yet to be achieved, the foundation for such innovations has been created.

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