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Silver-Nanoparticle-Loaded Polyurethane Composites for Antibacterial Medical Devices

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Abstract

Polyurethane (PU) polymer is widely used in biomedical application. In our study we have combined polyurethane with silver nanoparticles to develop a nanocomposite material for antibacterial medical applications. Such combination has antibacterial properties and control the toxicity too. In current research we have mixed the different sizes and types of silver nanoparticles into the polyurethane matrix. The result was their antibacterial activity, mechanical strength, and biocompatibility. The antibacterial performance of the prepared nanocomposites was evaluated against representative bacterial strains, while their mechanical and biocompatibility characteristics were also examined. The effect of silver nanoparticle incorporation on the structural, morphological, and functional properties of the polyurethane matrix was investigated. Particular emphasis was placed on understanding nanoparticle–polymer interactions and their contribution to the overall performance of the composite material. Although silver nanoparticles are generally toxic, embedding them within the polyurethane matrix reduces their toxicity and allows controlled release of silver ions. Various characterization techniques were used to analyze the structure of the material, including FESEM for surface morphology, FTIR for chemical bonding, and XRD for crystal structure analysis. These results confirmed that silver nanoparticles were uniformly dispersed within the polyurethane matrix and formed interactions with the polymer. Thus, polyurethane–silver nanoparticle composites have the antibacterial capabilities, making them suitable for use in medical devices – such as wound dressings – where infection control and material performance are critical.

Keywords: Polyurethane, sliver nanoparticles, antibacterial, polymer, medical devices, wound dressing

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INTRODUCTION

Polyurethane (PU) is a strong and flexible polymer that is widely used due to its biocompatibility. It has various applications such as coatings for surface protection, adhesives for bonding, foams as soft materials, and in rubber and composite materials. PU is biocompatible, meaning it is safe for use inside the human body [1, 2]. Therefore, it is also used in medical applications – such as implants and other devices – that are placed inside the body. Shape memory polyurethane (SMPU) has attracted considerable attention in recent years owing to its unique shape recovery behavior and potential for biomedical applications [3]. The aim of researchers is to improve the strength of the material while maintaining its elasticity. Polyurethane also exhibits good mechanical properties such as high tensile strength, suitable Young's modulus, and high elongation at break [4, 5].

Wound dressings are very important because they protect the wound from infection and further damage and also help in the healing of skin tissues [6]. Infectious diseases continue to impose a significant burden on healthcare systems in India, highlighting the importance of effective infection prevention strategies in clinical practice [7]. The demand for better wound dressings is increasing due to the rising number of cases of burns, diabetic ulcers, and venous ulcers [8]. An ideal wound dressing should possess properties – such as non-toxicity (so that it is not harmful to the body), biocompatibility (so that it is compatible with the body), strong mechanical properties (to ensure durability and strength), and suitable permeability – to allow the exchange of gases and moisture. Various natural materials – such as collagen and chitosan – are used to prepare wound dressings in the form of hydrogels, films, and foams, as they are biocompatible and biodegradable.

Silver nanoparticles represent one of the most widely studied nanomaterials in the biomedical field. Their antimicrobial potential and compatibility with a variety of material systems have encouraged their integration into wound dressings, implant coatings, polymer composites, and healthcare-related products aimed at reducing microbial contamination [9].

Thermoplastic polyurethane (TPU) is considered a good material for wound dressings due to its excellent chemical stability, which prevents damage from chemicals, and its strong mechanical properties, including strength and flexibility [10]. However, TPU lacks antibacterial properties, and since wounds are prone to infection, bacteria can damage the wound site. Therefore, the use of TPU in wound dressing applications is somewhat limited [11]. One possible solution to this problem is to incorporate antibiotics, such as amoxicillin, vancomycin, and gentamicin, into wound dressings. However, excessive use of antibiotics can lead to the development of drug-resistant bacteria, which reduces the effectiveness of antibiotics and poses a serious threat to public health. Therefore, researchers have explored alternative solutions and found that nano-silver is a promising option. The antimicrobial effectiveness of silver nanoparticles has been extensively investigated, with studies reporting activity against both conventional bacterial strains and antibiotic-resistant microorganisms [12]. Nano-silver damages bacteria through multiple mechanisms such as disrupting the cell membrane, inhibiting DNA replication, and interfering with the respiration process [13]. Due to these multiple modes of action, bacteria are less likely to develop resistance against nano-silver.

Although nano-silver can be toxic to human cells, studies have shown that toxicity occurs only at high concentrations. When nano-silver is incorporated into polyurethane, it is released slowly in a controlled manner, which reduces its toxicity and makes it safer for biomedical applications. Medical-grade TPU has been employed in a variety of biomedical devices due to its combination of elasticity, processability, and compatibility with biological environments [14].

Various methods have been used for the synthesis of nano-silver; however, these methods often face challenges as the processes are complex and may generate harmful and toxic by-products during preparation [15]. Therefore, such methods are not considered safe or desirable, especially for biomedical applications. Recently, researchers have introduced a new approach using polydopamine (PD). This material has gained significant attention in tissue engineering because it can modify almost any surface and can also reduce metal ions on its own. Thus, it serves a dual function by acting as both a coating material and a medium for nanoparticle formation. This concept is inspired by mussels, which can strongly adhere to almost any surface [16]. Studies have shown that dopamine exhibits similar behavior, and this phenomenon is known as mussel-inspired adhesion. When dopamine is placed in an alkaline (basic pH) environment, it undergoes self-polymerization to form polydopamine. This polydopamine can form a thin coating layer on various biomaterials. Polydopamine contains functional groups, such as amines and catechol's, which can directly reduce silver ions (Ag^{+}) into silver nanoparticles (AgNPs) [17]. This process occurs directly on the surface of the material. The use of polydopamine offers several advantages, including non-toxicity, a simple preparation process, absence of harmful by-products, eco-friendliness, and the ability to provide a strong and uniform coating [18].

The focus of this study is to develop a flexible antibacterial wound dressing using thermoplastic polyurethane (TPU) and nano-silver through a simple and eco-friendly method. A porous TPU membrane was prepared using two techniques: immersion precipitation and particle leaching. A polydopamine (PD) layer was coated onto the TPU surface, followed by the incorporation of silver nanoparticles [19]. This process is known as in situ coating, where nanoparticles are formed directly on the material surface. The morphology, molecular interactions, and crystalline structure of the nanocomposite were examined using SEM, ATR-FTIR, and XRD techniques [20]. The study hypothesizes that the developed nanocomposite will effectively kill bacteria while remaining safe for human cells.

MATERIALS AND METHODS

Material

Thermoplastic polyurethane (TPU) is the main polymer used for the preparation of wound dressings. N, N-dimethylformamide (DMF) is a chemical solvent used to dissolve TPU and to prepare the membrane [21]. Silver nitrate is used as a source of silver ions for the formation of silver nanoparticles. Dopamine is used to form a polydopamine coating on the surface of TPU. Sodium citrate is used in nanoparticle synthesis, where it acts as both a stabilizing and reducing agent.

Developing a TPU Porous Membrane

Two techniques, namely immersion precipitation and particle leaching, were used to prepare a porous TPU membrane, which is useful for wound dressing applications [11]. First, the required materials were taken: 12.5 g of TPU granules, 100 mL of DMF (solvent), and 25 g of sodium citrate. These components were thoroughly mixed to form a homogeneous mixture without any lumps. The mixture was then placed in a vacuum oven at 50°C for 2 hours to remove air bubbles and prevent defects in the membrane. To give the membrane a fixed shape, the mixture was cast into a polytetrafluoroethylene (PTFE) mould. When the mould was immersed in ethanol, the liquid mixture transformed into a solid membrane due to the immersion precipitation process [22]. The membrane was then washed with deionized water for 2 days to remove the sodium citrate particles. The removal of these particles created pores in the membrane, a process known as particle leaching. Finally, the membrane was dried at 45°C for 4 hours, resulting in the formation of a microporous TPU membrane.

TPU/NS Nanocomposite Synthesis

In this process, polydopamine and silver nanoparticles are incorporated onto the TPU membrane to develop an antibacterial nanocomposite. For this purpose, the TPU membrane was first immersed in a dopamine solution (2 mg/mL) and kept for 20 hours at room temperature under alkaline conditions (pH 8.5) [23]. During this time, dopamine undergoes self-polymerization to form a polydopamine (PD) layer on the membrane surface. The color of the membrane changes from pale white to brown, indicating the successful formation of the PD coating [24]. Subsequently, the PD-coated membrane was immersed in silver nitrate ($AgNO_3$) solutions of different concentrations (1 mM, 2.5 mM, and 5 mM) for 6 hours at 25°C, while being protected from light [25].

TPU/NS Nanocomposite Characterization

In this section, the structure of the membrane, the presence of silver nanoparticles, the pore characteristics, and surface properties were analyzed using different characterization techniques. Scanning electron microscopy (SEM) was used to observe the surface morphology, which helps to determine whether the membrane is smooth or rough, the size of the pores, and the presence of nanoparticles [26]. It also allowed comparison between the structures of pristine TPU and TPU/NS membranes. ImageJ software was used to measure pore size, porosity, and the size of silver nanoparticles from the SEM images [27]. X-ray diffraction (XRD) was used to analyze the crystal structure, helping to determine whether silver nanoparticles were properly formed and to identify their crystalline nature within a specific range. The chemical characteristics of the nanocomposite were investigated using ATR-FTIR spectroscopy to assess polymer–nanoparticle interactions and structural features [28].

Measurements of Mechanical Properties

Tensile testing was performed on dumbbell-shaped specimens to evaluate the mechanical performance of the prepared membrane. Measurements obtained during uniaxial deformation were used to characterize the material's tensile response [29, 30].

RESULT

Morphology and Characterization of TPU/NS Nanocomposites

SEM was used to study the surface structure of TPU and TPU–silver nanocomposite membranes. It helps to determine whether all membranes exhibit a similar microporous structure and whether the addition of polydopamine coating and silver nanoparticles affects the basic structural integrity of TPU. After treatment, silver nanoparticles were uniformly distributed on the membrane surface, indicating that the nanocomposite was successfully formed and that silver was present in the membrane. The porous structure of the membrane showed large pore size and high porosity, which helps in cell attachment, cell growth, and gas and fluid exchange. Therefore, this material is suitable for biomedical applications such as wound healing.

Mechanical Properties of TPU/NS Nanocomposites

When silver nanoparticles are incorporated into TPU, its elasticity and flexibility are maintained, allowing the membrane to easily cover the wound. At the same time, the addition of silver increases the stiffness of the material. The tensile strength of TPU/NS membranes increases significantly, and a higher concentration of silver leads to greater strength, which is referred to as dose-dependent behavior. All membranes showed an elongation at break in the range of 562–588%, indicating that the material can undergo high stretching while maintaining its flexibility. Overall, silver nanoparticles improved the strength of TPU while maintaining its flexibility, making it an ideal material for wound dressing applications.

Antibacterial Activity

The antibacterial activity of TPU/NS nanocomposites has been evaluated against different bacterial strains, including Gram-negative *Escherichia coli* and Gram-positive *Staphylococcus aureus*. In previous studies, a bacterial suspension assay was commonly used, where the OD600 value was measured after 24 hours of incubation. The OD600 value indicates bacterial growth, where a higher OD corresponds to greater bacterial proliferation, while a lower OD indicates reduced bacterial growth. It has been reported that TPU and TPU/DA showed bacterial growth, like the control group, indicating negligible antibacterial activity. In contrast, TPU/NS nanocomposites exhibited a significant reduction in OD600 values, and the antibacterial effect increased with increasing silver concentration (NS1 < NS2.5 < NS5), demonstrating dose-dependent behavior. The best antibacterial performance was observed at higher silver concentrations. Furthermore, Live/Dead staining assays revealed that live bacteria appear green, whereas dead bacteria appear red. A higher proportion of green (live) bacteria was observed in control, TPU, TPU/DA, and TPU/NS1 groups, while TPU/NS2.5 and TPU/NS5 groups showed predominantly red (dead) bacteria, confirming strong antibacterial activity. Overall, higher silver content resulted in enhanced antibacterial performance, which was also effective over extended durations.

CONCLUSION

In this study, a wound dressing was developed that is biocompatible, flexible, and antibacterial. This wound dressing was prepared by incorporating silver nanoparticles onto a thermoplastic polyurethane (TPU) membrane using polydopamine (PD). The fabrication method is simple and safe. The TPU/NS2.5 dressing exhibited strong mechanical strength and excellent flexibility, allowing it to easily bend and stretch. Characterization studies confirmed the successful incorporation of silver nanoparticles onto the TPU surface and provided insight into the structural features of the composite material. The combination of TPU, polydopamine, and silver nanoparticles resulted in a multifunctional dressing with properties desirable for wound care applications. The developed membrane represents a promising approach for designing advanced antibacterial wound dressings and may serve as a useful platform for further biomedical material development. Future studies may focus on optimizing the composition and evaluating long-term performance under physiological conditions.

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