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Evaluation of Antibacterial Activity and Controlled Drug Release Behaviour of Biodegradable Polymeric Nanofibres for Wound Dressing Applications

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Abstract--- The rise in chronic wound, surgical and skin infections has resulted in need for better wound dressing materials with antibacterial and drug delivery features. Traditionally, wound dressings have provided only physical protection but have been ineffective in maintaining localized drug concentration and bacterial inhibition. Biodegradable polymeric nanofibers have found their way as wound dressings due to high surface area-to-volume ratio, interconnected porosity, flexibility and controllable drug delivery capability. The innovative aspect of the research is the integration of antibacterial and drug delivery features into a biodegradable electrospun nanofibers system. The methodological aspect will include preparation of the solutions of the chosen biodegradable materials, addition of the selected antibacterial substance and fabrication of the nanofibers by electrospinning technique. The samples will be analyzed using scanning electron microscopy, Fourier transform infrared spectroscopy and water contact angle measurements. Antibacterial efficacy is tested against selected wound related bacterial species through suitable microbiological techniques. The drug release mechanism is studied under controlled physiological conditions at regular time intervals. Kinetics of drug release is analyzed by means of mathematical models such as zero order, first order, Higuchi and Korsmeyer-Peppas models. Additionally, swelling behavior, degradation and in vitro biocompatibility properties are also taken into account for evaluation of suitability of material. The current research work is anticipated to identify relationship between nanofiber morphology, antibacterial efficacy and drug release behavior. This study offers an approach to develop biodegradable wound dressing system for localized antibacterial therapy, sustained delivery and improved wound management without the requirement of frequent dressing changes.

Keywords--- Biodegradable Polymers, Polymeric Nanofibres, Electrospinning, Antibacterial Activity, Controlled Drug Release, Wound Healing, Drug Encapsulation, Biocompatibility.

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I. Introduction

The wound healing process includes several steps such as inflammation, tissue development, and remodeling. Yet, the presence of bacteria may impede this process, slowing down the restoration of the tissue and increasing the risk of developing complications. Traditional wound dressings include cotton gauze and adhesive bandages; they usually prevent physical contamination but are incapable of providing efficient control over microbial contamination and the proper environment for treatment. Therefore, the development of advanced wound dressing materials able to combine antibacterial activity, moisture control, and local delivery of medicines became an object of much interest among researchers (Sagitha et al., 2019; Nguyen et al., 2024). Biodegradable polymeric nanofibers have a number of advantages that make them suitable for use as wound dressings. The high surface-to-volume ratio, porous structure, and flexibility of these fibers allow fluid absorption, gas exchange, and interaction with the wound site. One of the ways of fabrication of nanosized fibers is electrospinning. Polycaprolactone (PCL), polylactic acid (PLA), gelatin, as well as biodegradable polymers containing polyvinyl alcohol, can be used for the development of nanofibrous wound dressings. Antibacterial additives can be added to them. This research work will explore the antibacterial effects and drug release from biodegradable nanofibers. This research work is targeted at developing an electrospun nanofibrous platform with appropriate physicochemical characteristics (Schneider et al., 2018; Sleinus et al.,

2025). Antibacterial performance will be determined by using the test bacterial strains and drug release studies will be done by simulating physiological environment (Moazzami Goudarzi et al., 2024; Afzal et al., 2023; Thakur et al., 2008). The morphological, chemical and physical characterization will be done through scanning electron microscopy, Fourier transform infrared and contact angle analysis.

The innovative aspect of this research work is in its dual approach of investigating the antibacterial performance and controlled drug release in a biodegradable nanofibrous wound dressing system. In addition, drug release kinetics, swelling behavior, degradation and biocompatibility will be studied for performance analysis. The objective of this research work is to create a design guide for biodegradable nanofibrous wound dressings for localized antibacterial treatment and sustained drug delivery.

Problem Statement

Most existing wound dressing materials provide only physical protection without having any antibacterial properties. Bacteria present in wounds might delay wound healing, cause inflammation, and make wound infections even worse, especially in chronic wounds. Even though bacteria may be killed using various antibacterial drugs, their uncontrollable release might lead to a fast depletion of antibacterial drugs that might not provide long enough treatment. Moreover, some non-degradable materials used for wound dressings should be replaced after being used, causing additional discomfort and waste. Biodegradable polymeric nanofibers appear to be another approach that may be considered, since they have high porosity and large surface area, which allows incorporation of drugs and their local release. Nevertheless, developing a material that will provide sufficient antimicrobial action, controlled release, structural stability, and biocompatibility is a difficult task. That is why this research deals with the development of biodegradable electrospun polymeric nanofibers containing an antibacterial drug.

Section Overview

The present manuscript is concerned with an examination of biodegradable polymeric nanofibres for use in antibacterial wound dressing and controlled drug release applications. In the introduction, the rationale for the study, problems associated with wound infections and benefits of using nanofibrous material are presented. The literature review deals with biodegradable polymers, electrospinning processes, antibacterial materials and drug release. The research gap describes existing deficiencies of current wound dressing systems. In the methodology, polymer preparation, antibacterial agent addition, electrospinning process and material characterization are described. The suggested system depicts the entire experimental procedure.

II. Literature Review

Degradable polymeric biomaterials have gained substantial attention as wound dressing substrates because of their ability to serve as temporary wound protectants that can undergo biodegradation in appropriate environmental conditions. Polymers like polycaprolactone, polylactic acid, gelatin, chitosan and blends of biodegradable polymers have been studied for biomedical applications (Ribeiro et al., 2021; Amiri et al., 2020). Physical, chemical and biological properties affect fiber formation, mechanical integrity, water uptake and cellular behavior. Natural and synthetic polymers have also been combined in order to optimize biological performance and mechanical strength (Elsner et al., 2010). Electrospinning is extensively studied for production of polymeric nanofibers due to its ability to generate continuous fibers with tunable morphology and high surface area. This technique consists of application of high voltage electric field to a solution or molten form of a polymer. Fibers are collected as a nonwoven membrane from a polymer jet. Fiber diameter, porosity, surface features and mechanical properties are determined by solution concentration, voltage, flow rate, distance between nozzle and collector as well as environmental conditions.

Introduction of antibacterial properties into nanofibrous materials can be accomplished through appropriate incorporation of antimicrobial agents (Parham et al., 2022; Wang et al., 2018). Various natural and synthetic antibacterial materials have been explored with an aim of reducing contamination by microorganisms as well as facilitating wound management. Encapsulation of drugs into the fibers enables modulation of the release rate as well as localization of the drug. The release characteristics depend on polymer degradation, drug diffusion, fiber diameter, polymer and drug interaction. For the studies on drug release, various physiological buffer solutions have been used in conjunction with specific temperatures. Evaluation of the release kinetics uses models such as zero order, first order, Higuchi and Korsmeyer-Peppas. For the determination of the antimicrobial effects, techniques used include agar diffusion, bacterial viability and counting. Characterization of materials is carried out using scanning electron microscope, Fourier-transform infrared spectrometry and

contact angle measurements. Factors considered for the evaluation of wound dressings include material biocompatibility, swelling, degradation and mechanical behavior. Despite the tremendous success in the area, optimization of the antibacterial effect, sustained drug release, degradation and biocompatibility is still challenging. The results obtained form a basis for further development of multifunctional biodegradable nanofibrous materials

Research Gap

From previous research studies, there have been clear possibilities shown about the use of biodegradable nanofibres in wound dressings and drug release. But there still exist some limitations to the integration of the antibacterial efficiency and the predictable and controlled release of drugs. The differences in the polymer structure, fibre diameter, drug loading and electrospinning parameters might have great effects on the characteristics of the material. Moreover, antibacterial efficiency and the release rate are normally studied separately, which will reduce the study of their integrated function. Inadequate study about degradation, swelling, mechanical property and biocompatibility will limit the application of wound dressings. This project aims to develop an integrated study platform involving all the above factors.

III. Methodology

The recommended methodology will employ an experimental approach for the synthesis of biodegradable polymer nanofibres and the determination of their antibacterial property and controlled drug release. The research study involves the selection of polymer materials, preparation of solutions, incorporation of antibacterial agents, electrospinning, material characterisation, antibacterial studies and drug release analysis.

Selection of Biodegradable Polymers and Antibacterial Agent

Biodegradable polymers such as polycaprolactone (PCL), gelatin, chitosan and polylactic acid (PLA) which have been chosen based on their structural, chemical and biological characteristics will be used for nanofibre fabrication. A combination of the biodegradable polymer materials will be done to achieve the required balance between the physical and biological properties such as mechanical strength, flexibility and biocompatibility. A suitable antibacterial agent will be selected based on its antimicrobial capability and its compatibility with the selected polymer blend. The concentration of the drug will be determined through formulation.

Preparation of Polymer Solution

The biodegradable polymers will be dissolved in appropriate solvents with stirring to form a homogeneous polymer solution. The solution concentration and viscosity will be varied to ensure the production of continuous fibre in electrospinning process. The antibacterial agent will be incorporated in the polymer solution.

Fabrication of Polymeric Nanofibres Using Electrospinning

Electrospinning is used to produce biodegradable polymeric nanofibers. The prepared polymer solution is fed to a syringe attached to a metal needle. An electrostatic field is created between the needle and the collector, leading to the formation of a charged polymer jet that gets stretched and solvent evaporated. The collected nanofibers form a nonwoven mat with the embedded antibacterial agent. Process parameters such as voltage applied, flow rate of the solution, distance of the collector, and polymer concentration are varied to obtain uniform fiber structure.

Physicochemical Characterization

The produced nanofibers undergo characterization for the evaluation of structural and surface properties.

- SEM: Fiber morphology, diameter, and surface homogeneity.
- FTIR: Detection of chemical functional groups and polymer-drug interaction.
- XRD: Determination of crystalline and amorphous structural features.
- Contact angle determination: Surface wettability.
- Swelling behavior: Evaluation of fluid absorbance.
- Tensile testing: Mechanical strength and flexibility.

Efficiency of drug entrapment can be quantified by comparing the amount of loaded drug to the initial amount of the drug.

Evaluation of Antibacterial Activity

The antibacterial efficacy is studied for the chosen wound-associated bacteria such as Staphylococcus aureus and Escherichia coli using proper lab methods. The agar diffusion test method can be employed for studying the inhibition zones for the nanofibre samples. Bacteria viability and count tests will give further data regarding the microbial killing efficiency.

The antibacterial effectiveness can be expressed in equation (1):

$$\text{Bacterial Reduction (\%)} = \frac{N_c - N_s}{N_c} \times 100 \quad (1)$$

Where:

- N_c = Bacterial count in the control group.
- N_s= Bacterial count in the treated sample group.

Controlled Drug Release Evaluation

The drug release profile is determined using a proper in vitro release setup that contains physiological buffer solution maintained at around 37°C. Nanofibre samples are dipped in the release medium, and samples are taken at certain time intervals. New medium is added to maintain the required volume. The drug concentration is measured by employing a suitable analytical method such as UV-Vis Spectroscopy or HPLC.

The cumulative drug release percentage is calculated in equation (2):

$$\text{Drug Release (\%)} = \frac{\text{Cumulative amount of drug released}}{\text{Initial amount of drug loaded}} \times 100 \quad (2)$$

Release kinetics are analyzed using:

- Zero-order model.
- First-order model.
- Higuchi model.
- Korsmeyer–Peppas model.

These models help identify the dominant release mechanism and understand the influence of polymer composition and fibre morphology.

Biocompatibility and Degradation Assessment

The fabricated nanofibers undergo assessment by conducting cytocompatibility assays in vitro on cell models associated with skin tissue, such as fibroblasts. Assessment is made by evaluating cell viability and morphology.

Degradation studies are done by means of controlled incubation and monitoring of mass loss, changes in morphology, and degradation. This will enable the assessment of properties of the fabricated nanofibers during their application as wound dressings.

Proposed Architecture

The suggested architecture will be considered as the experimental approach for the creation of antibacterial biodegradable polymeric nanofibres. First of all, biodegradable polymer and an appropriate antibacterial substance will be chosen and will be processed into a uniform solution. Then electrospinning will be carried out at specified fabrication conditions producing the drug-loaded nanofibrous membranes. After that, the prepared samples will be characterized physically and chemically to study their morphology, structure, and surface characteristics. Afterwards, antibacterial testing, drug release, swelling studies and biocompatibility testing will be carried out.

The figure 1 framework shows how the antibacterial biodegradable polymeric nanofibrous wound dressing is evaluated using four experimental parameters. The fibre diameter shows structural uniformity of the material, the drug loading shows how much of the antibacterial substance is present in the polymer, the antibacterial test shows the ability to inhibit bacteria, while the in vitro drug release shows how long it takes for the drugs to be released.

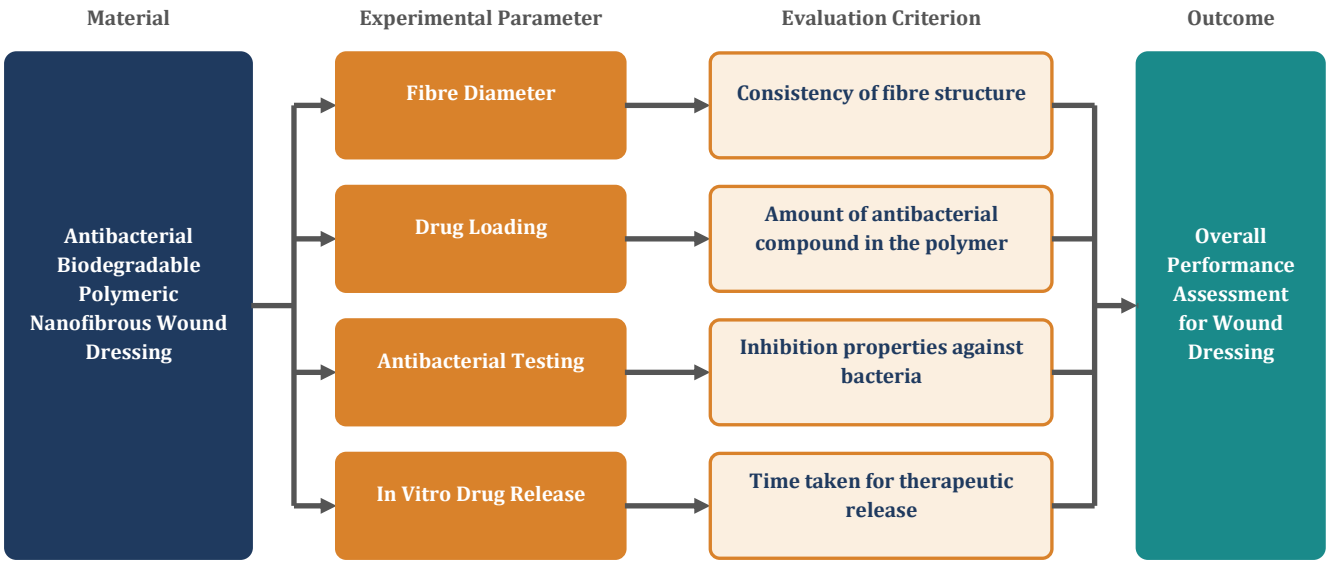


Figure 1: Proposed Experimental Architecture for Antibacterial Biodegradable Polymeric Nanofibres with Controlled Drug Release

Experimental Parameters and Evaluation Criteria

Table 1 shows the different properties that will be taken into consideration when assessing the performance of the artificial nanofibrous wound dressing material. The fiber diameter will give data on the consistency of the structure, while the drug loading will give the amount of antibacterial compound contained within the polymer material. Antibacterial tests will help determine the inhibition properties, while the in vitro release test will give details on the time it takes for therapeutic release.

Table 1: Experimental Parameters and Evaluation Methods for Biodegradable Polymeric Nanofibres

Parameter	Evaluation method	Research significance
Fibre diameter	SEM analysis	Determines fibre morphology
Drug loading	UV–Vis/HPLC	Measures incorporated drug
Antibacterial activity	Agar diffusion and CFU assay	Evaluates microbial inhibition
Drug release	In vitro release testing	Determines release behaviour
Swelling ratio	Gravimetric analysis	Evaluates fluid absorption
Biocompatibility	Cell viability assay	Examines cellular compatibility

IV. Technical Investigation of the Proposed System

Fabrication and Physicochemical Characterization of Biodegradable Polymeric Nanofibres

The process of preparing biodegradable polymer-based nanofibres is an essential part of the creation of the modern wound dressings with antibacterial and controllable drug delivery functionalities. Electrospinning technique allows for obtaining continuous nanofibres that have porous structure. The choice of appropriate biodegradable polymers influences greatly on the physical and biological properties of the final nanofibrous matrix. Polycaprolactone gives mechanical strength and slow degradation; gelatin and chitosan provide hydrophilicity and biological relevance. The use of blended polymers could be studied to optimize the properties of the dressing.

First, the chosen polymers are dissolved in appropriate solvents to obtain uniform solutions. An antibiotic is then included in the polymer solution through appropriate mixing procedures. The solution is put in the electrospinning syringe, where an electric field causes stretching of the polymer jet and generation of nano-scale fibers. Solvent evaporation takes place during the process of fiber formation, after which the nanofibers are collected on a grounded collector. Electrospinning parameters such as polymer concentration, voltage applied, flow rate of solution and distance between the needle and collector are optimized to ensure uniformity of the fibers and reduce structural irregularities. The fabricated membranes are then analyzed by scanning electron microscopy to ascertain fiber size distribution, surface structure and structural uniformity. Fourier-transform infrared spectroscopy is used to analyze the chemical functional groups and any interaction

between the polymer and antibacterial agent. X-ray diffraction provides information about the crystal properties of the developed material. Contact angles are measured to evaluate surface wettability, and swelling and mechanical tests assess the interaction between the membrane and aqueous medium and the physical stability of the material. Encapsulation efficiency of the drugs is another important aspect as it affects the quantity of the antibacterial agent that will be available for further release. The uniform distribution of the drug within the nanofibrous structure may facilitate the controlled drug delivery. Thus, the analysis of these parameters forms the basis of the assessment of the wound dressing system.

Evaluation of Antibacterial Activity and Controlled Drug Release Behaviour

The antibacterial properties and the drug release profile of biodegradable nanofibers are among the factors that play significant roles in the effectiveness of these materials in wound dressings. The presence of bacteria in wounds may affect the healing process and even cause infection-related complications. The incorporation of suitable antibacterial agents in the nanofiber-based matrices enables the realization of the local delivery of the antimicrobial agents while preserving the barrier properties of the wound dressings. Antimicrobial properties are tested using certain types of microorganisms, such as Staphylococcus aureus and Escherichia coli. The agar diffusion tests give information about the inhibitory effects of bacterial growth around the prepared nanofibers. However, since the diffusion process of the antibacterial agent may affect the inhibition zone results, the viability and colony forming unit tests will also be used. The release of drugs is studied under simulated physiological conditions with the help of an appropriate buffer solution kept at 37°C. Release data is obtained at selected intervals to construct a cumulative release profile. While the early release process may include diffusion from the surface bound drugs, the later release process could be controlled by diffusion and polymer degradation processes. The release rate is affected by the fibre diameter, drug loading, polymer composition, hydrophilicity and the interaction between drugs and polymers.

The mathematical models based on zero order, first order, Higuchi and Korsmeyer-Peppas equations give useful information regarding the nature of the release process. Comparison between the experimental results and model predictions gives useful information to choose the best fit mathematical model. The swelling and degradation studies provide further information about the effects of wound environment on release behavior.

In addition, biocompatibility assessment with relevant cells associated with the skin tissue should be considered to study any possible influence of the material and antibacterial agent released from it on neighboring tissues. Antibacterial activity, release kinetics, degradation and cell compatibility combine into an integrated evaluation approach, which helps in creating biodegradable nanofibrous wound dressings with appropriate antimicrobial properties.

V. Graphical Evaluation

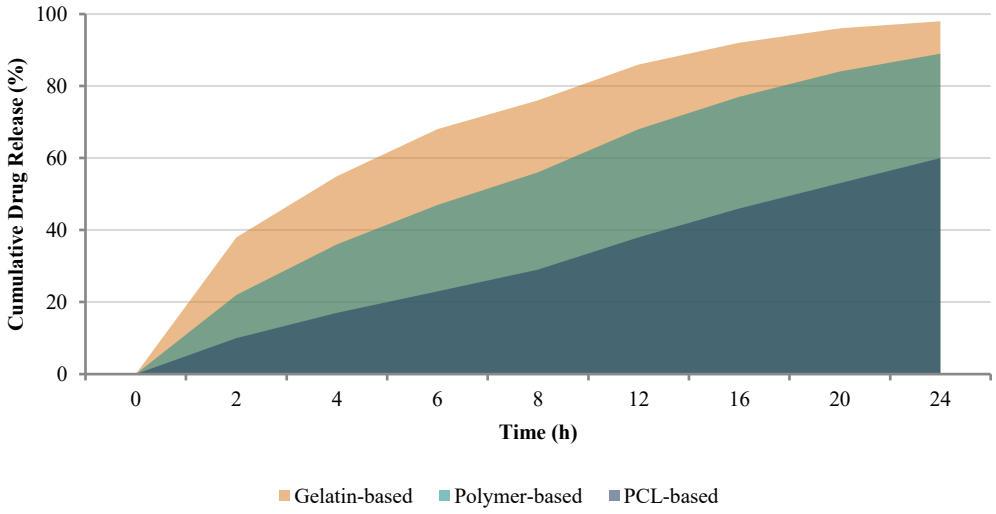


Figure 2: Illustrative Controlled Drug Release Profiles of Biodegradable Polymeric Nanofibres with Different Polymer Compositions

Figure 2 shows the area graph below, the drug release behavior of three biodegradable nanofibers is shown in 24 hours. The formulation using gelatin releases the fastest while the formulation based on PCL releases slowly and gradually. The other formulation based on polymer falls in between. This shows the effect of hydrophilicity of the polymer used on the drug release behavior.

VI. Discussion

The suggested study merges antibacterial properties and controlled drug delivery into biodegradable polymeric nanofibers for wound dressings. Electrospinning proves to be an efficient technique in fabricating membranes with customizable fibre properties. The antibacterial test helps to reveal the efficacy of the suggested material in inhibiting wound-associated bacteria; the release test will indicate the time and amount of drug released. Polymer type, fibre diameter, drug concentration and hydrophilicity are anticipated to affect the process of release. The suggested graphical analysis shows the differences in polymer types and stresses the importance of material choice. Moreover, swelling, degradation and biocompatibility tests give additional insight into wound dressing properties. Nevertheless, antibacterial performance alone is not enough to prove the effectiveness of the material. Additional studies on cytotoxicity, mechanical stability and sterility are needed.

Challenges in the Proposed Research

Challenges faced in the design of biodegradable polymeric nanofibres for wound dressings include issues related to polymer compatibility that could influence uniformity of the solutions and nanofibre fabrication, variations in electrospinning conditions resulting in uneven structures and bead formation, drug stability because drugs may be unstable during preparation. Sustained delivery of the drug without an initial burst release is another challenge, and finally, antibacterial activity of the wound dressings needs to be maintained. Biocompatibility of the dressings with regard to cell toxicity of the polymers, drugs and degradates is crucial, along with mechanical stability and controllable degradation. Another challenge posed by large-scale electrospinning is obtaining uniformly structured nanofibres and uniform drug dispersion within them.

Future Recommendations

Future research needs to pay attention to the creation of high-level biodegradable polymer blends for enhanced mechanical properties, flexibility and controllable degradation rate. Multi-functional antibacterial systems may also be considered in order to increase protection from bacteria while retaining compatibility with cells. Advanced methods of drug loading such as core-shell electrospinning and coaxial nanofibers synthesis can contribute to the control of drug release. Smart wound dressings including pH and moisture responsive substances may be developed for controlled drug release depending on wound conditions. Long-term drug release tests conducted under simulated wound conditions are required to evaluate the properties of the therapy. In addition, biological tests using fibroblasts, keratinocytes and wound model can demonstrate material compatibility. The sterilization method, manufacturability and shelf life are other issues that need to be studied in future. Machine learning and statistical optimization methods can be used in order to find correlations between electrospinning conditions, fibre structure, antibacterial properties and drug release characteristics.

VII. Conclusion

The aim of this research is to prepare biodegradable nanofibers with antibacterial activity and drug release for wound dressing applications. The study attempts to overcome the problems with traditional wound dressings, mainly regarding their limited antibacterial activity and inability to provide localized therapeutic effect. The uniqueness of this research lies in the combination of the inclusion of antibacterial agents into the formulation, biodegradable polymers and drug release ability within electrospun nanofibrous structure. The methods used in this research include the preparation of solutions of biodegradable polymers, inclusion of antibacterial agents and electrospinning of the obtained nanofibers. The obtained nanomaterials will be characterized with scanning electron microscopy, Fourier transform infrared spectroscopy, X-ray diffraction and contact angle measurements. Antibacterial properties of the prepared nanomaterials will be tested against certain bacterial species of wound origin, while drug release behavior will be studied under physiological conditions. Expected results include the determination of appropriate polymer compositions with favourable fibre formation, antibacterial properties, and sustained release of drugs. In addition, the comparative analysis of different polymer compositions will allow us to determine the impact of material properties on the delivery

of therapy. In addition, biological compatibility and degradation studies will give us significant information about the potential use of wound dressings. However, the effectiveness of our materials should be confirmed experimentally. Further researches should consider advanced methods of drug encapsulation, responsive polymers, long-term antibacterial effect, and scalable production of the material. In general, the suggested study will give a research basis for the development of multifunctional biodegradable nanofibres which will be used as wound dressings.

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