PRODUCTION OF CARBON DOTS BY HYDROTHERMAL METHOD AND APPLICATIONS IN NANOFIBERS

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ABSTRACT

Master Thesis

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Wound management is a crucial component of healthcare, with wound dressings playing an essential role. These dressings protect wounds from external contaminants, promote healing, and enhance patient comfort. There is a wide variety of wound dressings available, ranging from basic gauze pads to advanced dressings that incorporate technologies such as antimicrobial agents, hydrogels, and foams. The selection of the appropriate wound dressing is influenced by several factors, including the type and severity of the wound, the amount of exudate, the presence of infection, and the stage of the healing process. Choosing the right dressing based on these criteria is vital for optimizing the healing process and achieving favorable outcomes.

Recent years have witnessed significant advancements in wound dressing technology, leading to the development of innovative materials and designs that offer

improved healing outcomes and patient comfort. This progress has resulted in a more personalized approach to wound care, where dressings are tailored to meet the specific needs of individual patients and wound types.

Nanofibrous dressings, compared to traditional dressings, offer higher porosity, better permeability, and enhanced hemostasis. They protect against infection, offer better conformability, and enable efficient drug loading. They show promise for advanced, biologically active dressings, leading to extensive research efforts. Nanofiber-based wound dressings offer advantages over conventional materials like gauze, hydrogels, foams, and sponges. They can promote hemostasis, maintain a moist wound environment, protect against bacterial penetration, and be easily functionalized with therapeutic compounds. Various materials, including collagen, gelatin, fibrinogen, chitosan, PU, PLA, and PVA, have been electrospun and evaluated for their wound-healing properties. Functional compounds like antibiotic agents and growth factors can be integrated into nanofiber mats to further enhance wound healing. The use of nanofibers in wound dressing holds great promise for facilitating wound healing and skin regeneration, offering a versatile and effective approach to wound care.

Polyvinyl alcohol (PVA) is widely used in wound dressing applications, serving as a key component that enhances dressing functionality and therapeutic effectiveness when combined with various polymers. To enhance the characteristics of PVA, blending it with different polymers and materials is extensively explored to overcome its limitations, hence enhancing its applicability as wound dressing materials. In this research, we utilized the addition of carbon dots (CDs) to PVA aiming to enhance the properties of polyvinyl alcohol (PVA) nanofibers. Carbon dots were chosen for their excellent properties, including mechanical properties, biocompatibility, and antimicrobial properties. These CDs were synthesized through a green and environmentally friendly hydrothermal method, using Consolida flower extract as a source.

The general objectives of this study emphasize the importance of wound dressings in modern wound care, focusing on wound healing, infection prevention, and patient comfort. The specific objectives include evaluating the physical, mechanical, and

antimicrobial properties of PVA-based wound dressings and improving these properties through the incorporation of CDs and a pH-responsive agent.

Comprehensive characterization techniques such as Scanning Electron Microscopy (SEM), Fourier-transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), Thermogravimetric analysis (TGA), water contact angle measurements, air permeability tests, mechanical properties evaluation, and antimicrobial activity tests were employed to analyze the properties of PVA nanofibers and their enhanced version, PVA/Co-CDs/CoA nanofibers. The incorporation of CDs into PVA nanofibers resulted in improved antimicrobial efficacy against both Gram-positive and Gram-negative bacteria, without compromising mechanical integrity. The enhanced hydrophilicity, modified crystalline structure, and improved thermal degradation properties of PVA/Co-CDs/CoA nanofibers further highlight their potential in wound care applications.

This research demonstrates that the electrospun PVA/PVA/Co-CDs/CoA nanofibers offer significant advantages such as antimicrobial properties and hydrophilicity, presenting a promising candidate for advanced wound dressings. By effectively addressing critical challenges in infection control and promoting accelerated wound healing, these innovative materials hold promise for enhancing patient outcomes in wound management. This study significantly contributes to expanding the body of knowledge on nanofiber technologies, paving the way for improved therapeutic strategies and outcomes in clinical settings.

Key Words **:** Nanofibers, Polyvinyl Alcohol, Electroblowing, Carbon dots, Consolida, wound dressing.

Science Code **:** 92503

ÖZET

Yüksek Lisans Tezi

HİDROTERMAL YÖNTEMLE KARBON NOKTALARIN ÜRETİMİ VE NANOLİFLERDE UYGULAMALARI

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Yara yönetimi, yara örtülerinin bu süreçte hayati bir rol oynadığı sağlık hizmetlerinin kritik bir bileşenidir. Yara örtüleri, yarayı dış kontaminantlardan koruma, iyileşmeyi teşvik etme ve hasta konforunu artırma gibi birçok amaca hizmet eder. Temel gazlı bez pedlerinden antimikrobiyal ajanlar, hidrojeller ve köpükler gibi teknolojileri içeren ileri düzey örtülere kadar geniş bir yara örtüsü yelpazesi bulunmaktadır. Uygun yara örtüsünün seçimi, yaranın türü ve ciddiyeti, üretilen eksüda miktarı, enfeksiyon varlığı ve iyileşme sürecinin aşaması gibi çeşitli faktörlerden etkilenir. Bu spesifik kriterlere uygun örtünün seçilmesi, iyileşme sürecini optimize etmek ve olumlu sonuçlar elde etmek için esastır.

Son yıllarda yara örtüsü teknolojisinde önemli ilerlemeler kaydedilmiş, iyileşme sonuçlarını ve hasta konforunu artıran yenilikçi malzemeler ve tasarımlar

geliştirilmiştir. Bu ilerlemeler, bireysel hastaların ve yara türlerinin spesifik ihtiyaçlarını karşılamak üzere daha kişiselleştirilmiş bir yara bakımına yol açmıştır.

Nanofiber örtüler, geleneksel örtülere kıyasla daha yüksek gözeneklilik, daha iyi geçirgenlik ve gelişmiş hemostaz sunar. Enfeksiyona karşı koruma sağlar, daha iyi uyum gösterir ve etkili ilaç yüklemesine olanak tanır. Gelişmiş, biyolojik olarak aktif örtüler için umut vaat ederler ve bu nedenle geniş araştırma çabalarına yol açarlar. Nanofiber bazlı yara örtüleri, gazlı bez, hidrojel, köpük ve sünger gibi geleneksel malzemelere kıyasla birçok avantaj sunar. Hemostazı teşvik edebilir, nemli bir yara ortamını koruyabilir, bakteriyel penetrasyona karşı koruyabilir ve tedavi edici bileşiklerle kolayca işlevselleştirilebilir. Kollajen, jelatin, fibrinojen, kitosan, PU, PLA ve PVA gibi çeşitli malzemeler elektrospun yöntemle üretilmiş ve yara iyileştirici özellikleri açısından değerlendirilmiştir. Antibiyotik ajanlar ve büyüme faktörleri gibi işlevsel bileşikler, yara iyileşmesini daha da artırmak için nanofiber matlara entegre edilebilir. Nanofiberlerin yara örtüsünde kullanımı, yara iyileşmesini ve cilt rejenerasyonunu kolaylaştırmak için büyük umut vaat etmekte olup, yara bakımına yönelik çok yönlü ve etkili bir yaklaşım sunmaktadır.

Polivinil alkol (PVA), çeşitli polimerlerle birleştirildiğinde yara örtüsünün işlevselliğini ve terapötik etkinliğini artıran temel bir bileşen olarak yara örtüsü uygulamalarında yaygın olarak kullanılmaktadır. PVA'nın özelliklerini iyileştirmek için farklı polimerler ve malzemelerle harmanlanması, sınırlamalarını aşmak ve dolayısıyla yara örtüsü malzemeleri olarak uygulanabilirliğini artırmak amacıyla kapsamlı bir şekilde araştırılmıştır. Bu araştırmada, polivinil alkol (PVA) nanofiberlerinin özelliklerini geliştirmek amacıyla karbon noktaların (CD'ler) eklenmesi kullanılmıştır. Karbon noktalar, mükemmel özellikleri, mekanik özellikleri, biyouyumluluğu ve antimikrobiyal özellikleri nedeniyle seçilmiştir. Bu CD'ler, çevre dostu ve yeşil bir hidrotermal yöntemle, Consolida çiçek özütü kullanılarak sentezlenmiştir.

Bu çalışmanın genel hedefleri, modern yara bakımında yara örtülerinin önemini vurgulamakta olup, yara iyileşmesi, enfeksiyon önleme ve hasta konforuna odaklanmaktadır. Spesifik hedefler arasında PVA bazlı yara örtülerinin fiziksel,

mekanik ve antimikrobiyal özelliklerini değerlendirmek ve bu özellikleri CD'ler ve pH duyarlı bir ajan ekleyerek iyileştirmek yer almaktadır.

Taramalı Elektron Mikroskobu (SEM), Fourier Dönüşümlü Kızılötesi Spektroskopisi (FTIR), X-ışını Kırınımı (XRD), Termogravimetrik Analiz (TGA), su temas açısı ölçümleri, hava geçirgenliği testleri, mekanik özellik değerlendirmesi ve antimikrobiyal aktivite testleri gibi kapsamlı karakterizasyon teknikleri, PVA nanofiberlerin ve geliştirilmiş versiyonu olan PVA/Co-CD'ler/CoA nanofiberlerin özelliklerini analiz etmek için kullanılmıştır. CD'lerin PVA nanofiberlere eklenmesi, mekanik bütünlüğü bozmadan Gram-pozitif ve Gram-negatif bakterilere karşı antimikrobiyal etkinliği artırmıştır. PVA/Co-CD'ler/CoA nanofiberlerinin artırılmış hidrofiliği, değiştirilmiş kristal yapısı ve iyileştirilmiş termal bozunma özellikleri, yara bakım uygulamaları için potansiyellerini daha da vurgulamaktadır.

Bu araştırma, elektroeğirme yöntemiyle üretilen PVA/PVA/Co-CD'ler/CoA nanofiberlerin, antimikrobiyal özellikler ve hidrofili gibi önemli avantajlar sunduğunu göstermektedir ve gelişmiş yara örtüleri için umut vaat eden bir aday olarak sunulmaktadır. Enfeksiyon kontrolündeki kritik zorlukları etkili bir şekilde ele alarak ve hızlandırılmış yara iyileşmesini teşvik ederek, bu yenilikçi malzemeler yara yönetiminde hasta sonuçlarını iyileştirme vaadi taşımaktadır. Bu çalışma, nanofiber teknolojileri konusundaki bilgi birikimini önemli ölçüde artırarak, klinik ortamlarda iyileştirilmiş terapötik stratejiler ve sonuçlar için yolu açmaktadır.

Anahtar Sözcükler : Nanofiberler, Polivinil Alkol, Elektroblowing, Karbon noktalar, Consolida, yara pansumanı.

Bilim Kodu **:** 92503

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SYMBOLS AND ABBREVIATIONS INDEXD

SYMBOLS

μm	: Micrometre
nm	: Nanometers
mm	: Millimeter
cm	: Centimeter
mm/s	: Millimeters per second
°C	: Degrees Celsius
Pa	: Pascal
MPa	: Megapascal
CFU/Ml	: Colony-forming units per milliliter
μL	: Microliter
mL/min	: Milliliter per minute
ml\hr	: Milliliter per hour
g/cm3	: Gram per cubic centimeter
meq/gr	: Milliequivalent per gram
g/mol	: Grams per mol
hPa	: Hectopascal
wt.%	: Weight precent
rpm	: Round per minute
kV	: Kilovolt
%	: Precentage

ABBREVIATIONS

PVA	: Polyvinyl Alcohol
CDs	: Carbon dots
CNDs	: Carbon nanodots
CQDs	: Carbon quantum dots
GQDs	: Graphene quantum dots
PU	: Polyurethane
PLA	: Poly (lactic acid)
PCL	: Poly(caprolactone)
PLGA	: Poly (lactic-co-glycolic acid)
PNIPAM	: Poly(N-isopropylacrylamide)
PEG	: Polyethylene glycol
PVP	: Polyvinylpyrrolidone
HA	: Hyaluronic acid
PVD	: Physical vapor deposition
CVD	: Chemical vapor deposition
ALD	: Atomic layer deposition
MBE	: Molecular beam epitaxy
CVD	: Chemical vapor deposition
VLS	: Vapor-liquid-solid) method
TMOs	: Transition metal oxides
CLSD	: Carbon dioxide laser supersonic drawing
CFD	: Computational fluid dynamics
UV	: Ultraviolet
PDT	: Photodynamic therapy
PTT	: Photothermal therapy
SBS	: Solution Blow Spinning
EBS	: Electroblowing
SEM	: Scanning Electron Microscope
FTIR	: Fourier Transformed Infrared
TGA	: Thermogravimetric Analysis
XRD	: X-ray diffraction

CHAPTER 1

INTRODUCTION

1.1. PREFACE

The management of wounds is a critical aspect of healthcare, with wound dressing playing a pivotal role in this process. Wound dressings serve multiple purposes, including protecting the wound from external contaminants, promoting healing, and enhancing patient comfort. The wide range of wound dressings available, from basic gauze pads to advanced dressings incorporating technologies such as antimicrobial agents, hydrogels, and foams, reflects the diverse approaches to wound care. The appropriate selection of a wound dressing is influenced by several factors, including the type and severity of the wound, the amount of exudate produced the presence of infection, and the stage of the healing process. Matching the dressing to these specific criteria is essential for optimizing the healing process and achieving favorable outcomes. Recent years have witnessed significant advancements in wound dressing technology, leading to the development of innovative materials and designs that offer improved healing outcomes and patient comfort. This progress has resulted in a more personalized approach to wound care, where dressings are tailored to meet the specific needs of individual patients and wound types [1].

Wound healing is a difficult procedure. The appropriate wound dressing may offer moisture and occlusion, guard against infection and contamination, be easy to apply and remove and be biocompatible, depending on the severity of the wound. Furthermore, wound dressings play a crucial part in wound healing, removing excess fluid from the wound, and speeding up the healing process [2]. The treatment of certain types of open wounds requires an ideal wound dressing material. Such a material should facilitate gas exchange, maintain a moist environment at the wound interface, and be easily removable without causing trauma. It should also act as a

barrier against bacteria and allow excess fluids to escape. Furthermore, the material must be antibacterial, non-toxic, biocompatible, and biodegradable. Bandages are often prone to becoming breeding grounds for microorganisms in the wound area. Therefore, developing new wound dressing materials is critical to shorten the healing process, reduce pain, and aid in the regeneration of the skin's structure and function in a short period. To create an effective wound dressing material that meets all these criteria, it must be structurally adaptable with controllable properties[3].

The ideal wound dressing possesses several key properties to facilitate optimal wound healing. It should maintain a balanced moisture level, allow for gas exchange, be biocompatible and biodegradable, exhibit proper adhesive properties, offer sufficient mechanical strength, and possess antimicrobial activity. Additionally, it should be transparent to enable wound inspection without removal. Wound dressings are classified into traditional and advanced types. Traditional dressings include gauze, cotton, and lint, while advanced dressings encompass hydrocolloid, hydrogel, alginate, foam, and transparent film dressings, as well as composite dressings. These advanced dressings provide various benefits, such as maintaining a moist environment, absorbing exudate, and forming a protective barrier against bacteria. Future advancements in wound dressing technology are focused on developing smart dressings with sensing capabilities and utilizing nanotechnology for controlled drug release to enhance wound healing processes [4].

Nanofibrous dressings, compared to traditional dressings, offer higher porosity, better permeability, and enhanced hemostasis. They protect against infection, offer better conformability, and enable efficient drug loading. They show promise for advanced, biologically active dressings, leading to extensive research efforts. Nanofiber-based wound dressings offer advantages over conventional materials like gauze, hydrogels, foams, and sponges. They can promote hemostasis, maintain a moist wound environment, protect against bacterial penetration, and be easily functionalized with therapeutic compounds. Various materials, including collagen, gelatin, fibrinogen, chitosan, PU, PLA, and PVA, have been electrospun and evaluated for their wound-healing properties. Functional compounds like antibiotic agents and growth factors can be integrated into nanofiber mats to further enhance wound healing. The use of

nanofibers in wound dressing holds great promise for facilitating wound healing and skin regeneration, offering a versatile and effective approach to wound care [2,5].

Polyvinyl alcohol (PVA) is widely used in wound dressing applications, serving as a key component that enhances dressing functionality and therapeutic effectiveness when combined with various polymers[6–8]. To enhance the characteristics of PVA material blending it with different polymers and materials is extensively explored to overcome its limitations, hence enhancing their applicability as wound dressing materials[9]. In this research we utilized the addition of carbon dots (CDs) to PVA aiming to enhance the properties of polyvinyl alcohol (PVA) nanofibers. Carbon dots were chosen for their excellent properties, including mechanical properties, biocompatibility, and antimicrobial properties[10]. These CDs were synthesized through a green and environmentally friendly hydrothermal method, using Consolida flower extract as a source. The green synthesis of carbon dots (CDs) involves using renewable and environmentally benign sources, such as fruits, vegetables, and plant derivatives. Techniques like the hydrothermal method are commonly used due to their cost-effectiveness and simplicity[11]. Hydrothermal synthesis for producing carbon dots (CDs), attributes its popularity to its environmentally friendly nature, simplicity, and mild reaction conditions[12].

1.2. OBJECTIVES

1.2.1. General Objectives

To evaluate the effectiveness and significance of wound dressings in modern wound care practices. This study aims to explore the various roles of wound dressings in promoting wound healing, managing exudate, preventing infections, and enhancing patient comfort. By examining the diverse range of wound dressing options available, this research seeks to highlight the importance of selecting the most appropriate dressing for different types of wounds and patient needs. Ultimately, this thesis aims to contribute to the understanding and optimization of wound care strategies, leading to improved outcomes for patients with acute and chronic wounds.

1.2.2. Specific Objectives

To investigate the potential of Polyvinyl alcohol (PVA) as a material for wound dressing applications, and to evaluate the physical, mechanical, and biological properties of PVA-based wound dressings. And enhancing its efficacy and biocompatibility. the study will explore enhancing the properties of PVA by incorporating carbon dots and a pH-responsive agent, with the goal of improving functionality and responsiveness to wound conditions. Through this investigation, the goal is to establish PVA as a viable and effective material for use in wound care, offering a novel approach to improving outcomes for patients with acute and chronic wounds.

CHAPTER 2

WOUNDS AND WOUND DRESSING

2.1. ANATOMY of the SKIN

The human skin is the body's largest organ and comprises three primary layers: the epidermis, dermis, and hypodermis as shown in Figure (1). The epidermis further divided into five sub-layers (stratum corneum, stratum lucidum, stratum granulosum, stratum spinosum, and stratum germinativum), is composed of keratinocytes, melanocytes, Langerhans cells, and Merkel cells, which collectively regulate body temperature. The dermis, categorized into the papillary and reticular regions based on proximity to the epidermis, houses structures such as hair follicles, sweat glands, sebaceous glands, apocrine glands, and lymphatic and blood vessels. It is primarily made up of connective tissue, providing resilience against external stressors. The hypodermis, though not technically part of the skin, is a subcutaneous layer beneath the dermis, consisting of fibroblasts, macrophages, and adipocytes. It plays a role in connecting the dermis to the underlying bone and muscles. The skin's bacterial composition varies across regions, with the upper layers commonly hosting non-harmful Staphylococci species, while gram-negative bacteria, if present in higher quantities, can lead to wound infections, particularly in compromised skin [13].

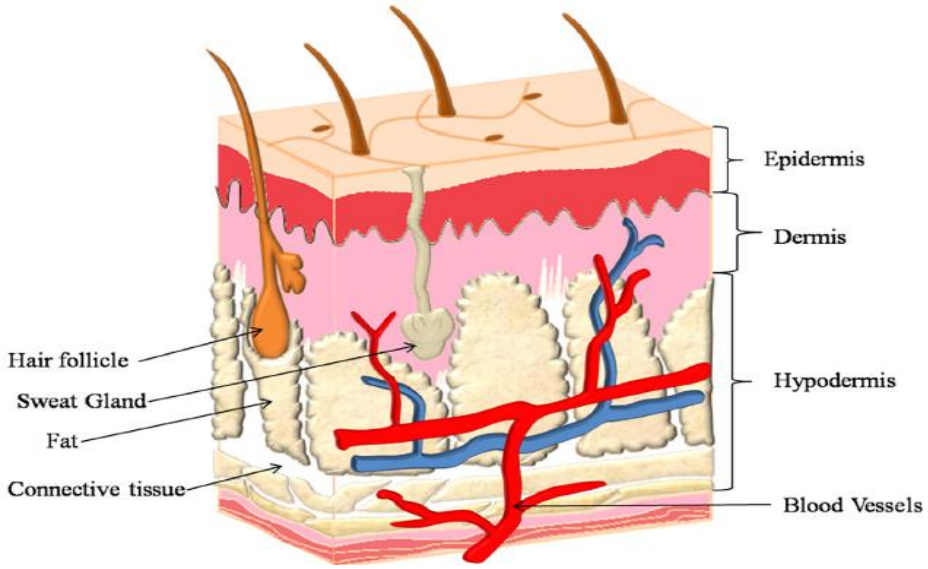

Figure 2.1 Structure of the skin layers [13].

2.2. WOUNDS

Wounds are disruptions of the normal anatomical structure and function of the skin, caused by thermal, physical, mechanical, or electrical damage. They can range from simple to severe breaks in the skin. They may extend beyond to other tissues and structures, including subcutaneous tissue, muscles, tendons, nerves, vessels, and even bone. The damage can manifest as superficial wounds, affecting layers above the sub-dermis, or deep wounds, impacting the dermis, epidermis, hypodermis, and sometimes sweat glands, hair follicles, and blood vessels. As the body's most exposed and easily damaged tissue, the skin is particularly susceptible to injuries such as abrasions and burns from trauma or surgery. Prompt restoration of physiological conditions is crucial for proper healing; delayed or incorrect healing can lead to severe consequences, including tissue loss, infection, skin diseases, circulatory system injuries, and even tissue death [1,13].

2.2.1. Classification of Wounds

Wounds are broadly categorized as acute or chronic. Acute wounds result from external damage to intact skin, such as surgical wounds, bites, burns, and traumatic injuries. They are expected to heal within a predictable timeframe, with treatment varying based on the wound's type, size, and depth. For example, surgical wounds may

require minimal intervention, while severe injuries like burns or gunshot wounds may need surgical debridement and antimicrobial therapy. Chronic wounds, on the other hand, are often caused by underlying conditions that compromise skin integrity, such as peripheral vascular disease, venous hypertension, diabetes mellitus, or pressure ulcers [7]. It is classified based on several criteria, including healing time, depth, complexity, cause, contamination, and mode of injury. Acute wounds heal without external support and in a minimal amount of time, while chronic wounds, like diabetic ulcers, take longer to heal and do not follow the typical stages of wound healing. Depth classification includes superficial wounds, which heal without scarring within 10 days, partial thickness wounds that heal within 10-21 days through scar formation, and full-thickness wounds that require more than 21 days to heal. Wounds can also be categorized based on complexity, with simple wounds involving only skin tissue, complex wounds involving significant tissue loss, and complicated wounds involving infection or other complications. Additionally, wounds can be classified by cause, including traumatic, iatrogenic, or burn-related wounds. Contamination classification includes clean wounds (Class I), clean/contaminated wounds (Class II), contaminated wounds (Class III), and dirty wounds (Class IV). Finally, wounds can be categorized by mode of injury, such as abrasions, ulcerations, incisions, lacerations, or degloving injuries. Each classification provides valuable insights for appropriate wound management and treatment strategies. These wounds heal slowly and unpredictably due to pathophysiological abnormalities and factors like age, obesity, smoking, poor nutrition, and immunosuppression. Pressure ulcers, caused by sustained external pressure, also contribute to chronicity and require specialized care [13,14].

2.2.2. Wound Healing Process

Wound healing is a complex and crucial process in human life, involving various components such as extracellular matrix molecules, mediators, fibroblasts, keratinocytes, and leukocyte subtypes. There are factors contributing to delayed wound healing, such as chronic wounds, including venous, ischemic, traumatic leg ulcers, diabetic foot ulcers, pressure ulcers, and other hard-to-heal acute wounds. Recent reports also highlight serious chronic wounds like buruli ulcers, caused by bacterial infection and involving significant skin tissue loss. The process of healing

consists of three stages: inflammation, proliferation, and maturation. Initially, platelets aggregate to control bleeding, followed by phagocytes clearing debris. Fibroblast cells then lay down collagen fibers around new blood vessels, and finally, collagen maturation occurs, which can take years to complete. Local factors like radiation, infection, and tissue oxygen tension, as well as systemic factors like overall health status, nutrition, and age, can influence the wound healing process. These factors can either facilitate or prolong the healing duration [1,4].

2.2.3. Stages of Wound Healing Process

The wound healing process is a complex series of events involving four distinct stages: hemostasis, inflammation, proliferation, and remodeling. Hemostasis is the initial response to injury, aiming to halt bleeding and create a temporary scaffold plug. This phase involves vasoconstriction to minimize blood loss and the accumulation of thrombocytes and inflammatory cells, which release various proteins and growth factors to stimulate clotting and create a conducive environment for subsequent stages. Inflammation follows, lasting approximately 24-48 hours post-injury, and is characterized by the attraction of leukocytes to the wound site. Mast cells release histamine, causing vasodilation and facilitating the migration of neutrophils to the injury site. Neutrophils play a crucial role in eliminating pathogens and debris through phagocytosis. Additionally, inflammatory cells release cytokines, growth factors, and chemokines that stimulate the migration and differentiation of monocytes into macrophages. Macrophages then phagocytose remaining pathogens and debris, initiating the formation of granulation tissue. The proliferation stage, which typically begins around day three and can last up to several weeks, is marked by the conversion of the temporary scaffold plug into permanent tissue. Fibroblasts, attracted by growth factors like TGF-β and PDGF, migrate to the wound site and produce extracellular matrix components, such as collagen, essential for tissue repair. Angiogenesis, the formation of new blood vessels, occurs to supply nutrients and oxygen to the wound bed, facilitating granulation tissue formation and re-epithelialization. The final stage, remodeling, begins around two weeks post-injury and can continue for over a year. During this phase, the newly formed tissue undergoes remodeling, with type III collagen being replaced by type I collagen, which is arranged in a more organized

manner to increase tensile strength. However, the repaired tissue typically only achieves about 80% of the original tissue's strength. The wound is ultimately repaired through the apoptosis and migration of cells from the wound site and the degradation of extracellular matrix components. Scar formation may occur due to the imperfect restoration of the epidermis and dermis connection, but maintaining a proper balance between collagen synthesis and degradation can help minimize scarring [13].

2.3. WOUND DRESSING

A wound dressing serves as a crucial element in wound care, providing a protective barrier that directly interacts with the wound environment to facilitate healing. Defined as a protective barrier applied directly to the wound, its primary function is to prevent further damage and promote the natural healing process. The classification of wound dressings can be approached from various perspectives, including their composition, intended use, and mechanism of action. One common classification divides wound dressings into passive products, such as gauze and tulle, and interactive materials, which may include polymeric films and foams. Passive dressings act as simple covers for wounds, allowing them to heal underneath, while interactive materials offer additional features, such as transparency and permeability to water vapor and atmospheric oxygen. These interactive dressings create a microenvironment conducive to healing, aiding in the removal of excess exudate and providing a barrier against external contaminants. The choice of dressing depends on various factors, including the type and severity of the wound, the presence of infection, and the desired healing outcomes. Overall, wound dressings play a critical role in wound management, contributing significantly to the overall success of the healing process [5]. The choice of dressing depends on various factors, including the type, depth, and location of the wound, the amount of discharge, the presence of infection, and the likelihood of the dressing adhering to the wound bed. While traditional dressings such as cotton gauze can lead to wound drying, slowing healing and causing discomfort during removal, modern polymer-based dressings provide an ideal environment for wound healing [4]. Wound dressings are crucial for the healing process as they protect wounds from external microorganisms and help manage pain. Careful selection of a wound dressing is important to prevent secondary trauma during dressing changes. Additionally,

wound dressings are used to absorb exudate in burns and chronic wounds, and maintaining a moist wound environment has been shown to promote more efficient healing compared to dry wounds. It is essential for wound dressings to be breathable to allow oxygen to reach the wound, which is necessary for all stages of wound healing. With a wide range of wound dressings available, choosing the right one is vital for promoting fibroblast proliferation and facilitating re-epithelialization. Dressings also play a role in stopping bleeding in full-thickness wounds and providing structural support to the skin in degloving injuries [13].

2.3.1. Classification of Wound Dressing

Wound dressings are classified into four types based on their interaction with the wound: passive, interactive, advanced, and smart dressings. Passive dressings create a conducive environment for wound healing by providing oxygen permeability through their porous structure. They can be made from natural or synthetic polymers and are popular for wounds requiring protection from mechanical damage. Interactive dressings not only provide a suitable environment but also help control bacterial growth. These dressings combine non-biological synthetic polymers with biological molecules to achieve ease of processing, antibacterial properties, and wound site affinity. Advanced dressings include drug-loaded nanofibers, which are capable of treating bacterial infections. These nanofibers can be fabricated using uni-axial, biaxial, or tri-axial electrospinning techniques. Coaxial electrospinning, in particular, is commonly used to fabricate drug-loaded nanofibers with a core containing the drug and a shell containing a polymer matrix. The drug release profile of these nanofibers depends on various factors such as shell thickness, polymer and drug wettability, and matrix biodegradability. Smart dressings are designed to perform multiple functions and can include sensors for real-time monitoring of wound healing status. These dressings have the potential to revolutionize wound care by providing personalized and responsive treatment options[13].

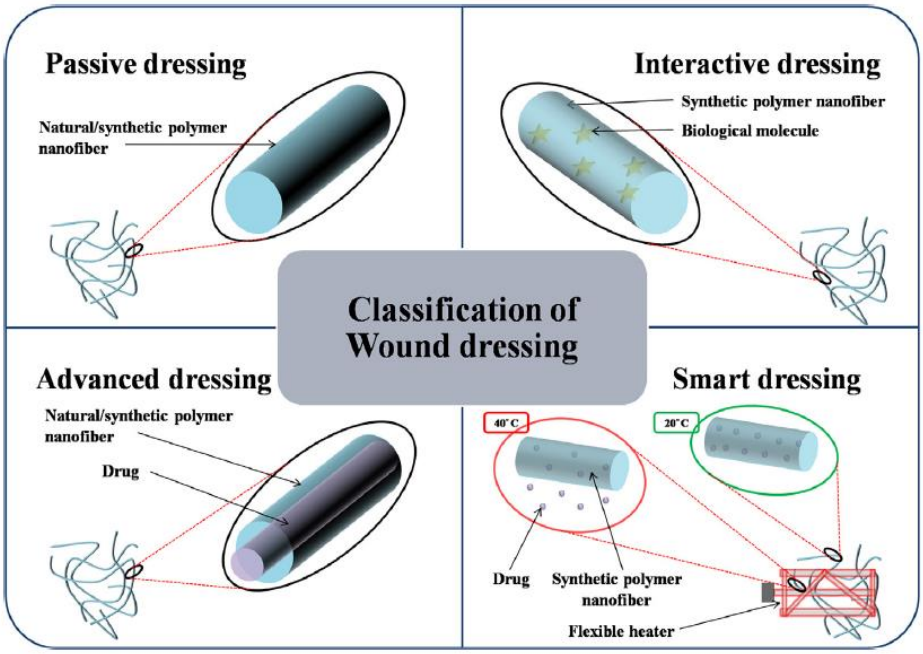

Figure 2.2. Classification of wound dressing [13].

2.3.2. Limitations of the Conventional Wound Dressings

Despite the development and commercialization of various wound dressings over the past few decades, challenges and limitations persist in their efficacy. While most wound dressings provide basic protection for wounds, few actively promote wound closure and healing. Wound healing is a complex process involving distinct molecular and physiological stages, each with specific requirements for optimal healing. Current wound dressings are often applied uniformly across all stages of wound healing, lacking responsiveness to the changing wound environment. Any abnormalities in the healing process can lead to stalled wound healing and the development of chronic wounds. Wound dressings that can monitor and even correct these abnormalities would be beneficial in wound management, providing timely guidance on treatment. However, current wound dressings fall short in this aspect. The emergence of smart wound dressings offers promise in addressing these challenges, as they can reflect the wound status and potentially offer corrective measures to support optimal wound healing [15].

2.3.3. Wound Dressing Development

Traditional wound dressings aim to establish a dry, protective barrier to prevent bacterial contamination and absorb exudate. They are typically used to shield the wound from contamination, but wound dressings can also function as platforms for delivering bioactive molecules to the wound site. Topical bioactive agents in solutions, creams, and ointments are often ineffective for wound drug delivery due to rapid absorption and loss of rheological characteristics, making solid wound dressings preferable for exudative wounds. Wound dressings have evolved to actively facilitate wound healing rather than merely covering the wound. These advanced dressings are designed to prevent dehydration of the wound and promote the healing process. Inhibiting the formation of a dry scab on a wound helps maintain a moist environment, which is crucial for encouraging the proliferation, migration, and differentiation of keratinocytes. These processes are essential for effective wound healing. [1,16]. With a wide array of products available in the market, selecting the appropriate dressing can be challenging. Modern wound dressings are predominantly made from synthetic polymers and are classified into passive, interactive, and bioactive categories. Passive dressings, such as gauze and tulle dressings, are non-occlusive and simply cover the wound, allowing it to heal underneath. Interactive dressings, in contrast, are semi-occlusive or occlusive and come in various forms, including films, foams, hydrogels, and hydrocolloids. These interactive dressings serve as barriers against bacterial penetration into the wound environment. [17].

2.3.4. Ideal Wound Dressing

Wet dressings have been found to accelerate wound healing compared to dry dressings, as they create an environment conducive to skin renewal without causing inflammation or eschar formation. Consequently, wet dressings are regarded as suitable for wound management. An ideal wound dressing should control moisture, allow gas transmission, absorb excess exudate, protect against infections, reduce surface necrosis, provide mechanical protection, be easily changed, biocompatible, biodegradable, elastic, non-toxic, relieve wound pain, and be cost-effective. [4]. Dressing selection should consider the wound type and its ability to maintain a moist

environment, enhance epidermal migration, promote angiogenesis and connective tissue synthesis, allow gas exchange, maintain appropriate tissue temperature, and protect against bacterial infection. Additionally, it should be non-adherent and easy to remove. Characteristics of an ideal dressing include maintaining high humidity, removing excess exudate, being free of toxic contaminants, and being non-toxic and non-allergenic, protecting against trauma, allowing gaseous exchange, being comfortable, requiring infrequent changes, being cost-effective, and having a long shelf life[17,18]. A dressing should also maintain a physiological wound environment by keeping the wound moist, absorbing excess exudate, providing thermal insulation, eliminating dead space, avoiding trauma and pain during dressing changes, minimizing scar tissue formation, being minimally toxic, supporting non-viable tissue debridement, and maintaining gas exchange. However, complications such as maceration and surgical site infections can arise if the balance of moisture is not maintained properly [16].

Table 2.1. Characteristics of an Ideal Wound Dressing.

Characteristics	Additional Details
Controls moisture	Maintains high humidity, Absorbs excess exudate
Allows gas transmission	Allows gaseous exchange
Protects against infections	Free of toxic contaminants, Non-allergenic
Reduces surface necrosis	Protects against trauma
Provides mechanical protection	Comfortable, Prevents surgical site infections
Easily changed	Requires infrequent changes, Long shelf life
Biocompatible	Nontoxic
Maintains physiological wound environment	Provides thermal insulation, Eliminates dead space, Minimizes scar tissue formation, Supports non-viable tissue debridement, Maintains gas exchange, Minimizes risk of maceration

2.3.5. Wound Dressing Types

2.3.5.1. Low adherent dressings

Readily accessible and cost-effective, it primarily functions to facilitate the passage of exudate into a secondary dressing while maintaining a moist wound environment. Typically available in the form of tulles, textiles, or multilayered/perforated plastic films, these dressings are designed to minimize adherence to the wound bed, making them especially beneficial for patients with sensitive or fragile skin [18].

2.3.5.2. Semipermeable films

These films are composed of sterile polyurethane sheets coated with hypoallergenic acrylic adhesive, serving primarily as transparent primary wound covers. While impermeable to fluids and bacteria, they allow for the exchange of air and water vapor, creating a controlled moist environment crucial for wound healing. Their flexibility makes them ideal for challenging anatomical sites, such as joints. However, they are not suitable for managing high levels of exudate and can potentially lead to maceration of the surrounding skin if used improperly [18].

2.3.5.3. Hydrocolloid dressings

Composed of gel-forming agents like sodium carboxymethyl cellulose, gelatins, and pectin, along with elastomers and adhesives, are widely used for wound management. These dressings create a moist environment that promotes healing by forming a gel on the wound surface. They are impermeable to bacteria and water vapor but permeable to exudate, aiding in the rehydration of dry necrotic tissue and promoting autolytic debridement. While they reduce wound pain and allow for normal daily activities, caution is advised for wounds requiring frequent inspection. Hydrocolloids are suitable for light to moderately exudating wounds, such as pressure sores and minor burns, and are also recommended for pediatric wound care due to their painless removal. However, they are not recommended for neuropathic ulcers or highly exudating wounds and are primarily used as secondary dressings [17,18].

2.3.5.4. Hydrogels dressings

Hydrogels, which consist of insoluble polymers with up to 96% water content, play a crucial role in maintaining a moist wound environment and promoting wound healing. They absorb wound exudate to varying degrees, depending on the brand, and are permeable to moisture vapor and oxygen. Hydrogels aid in wound debridement by rehydrating non-viable tissue, facilitating natural autolysis. While they are standard for managing sloughy or necrotic wounds, they are not suitable for highly exuding wounds or those with gangrenous tissue [16,18]. Hydrogel dressings, composed of insoluble polymers with high water content, facilitate autolytic debridement of necrosis and slough, making them ideal for dry and minimally exuding wounds. These dressings form a gel on the wound surface, promoting moist wound healing and protecting granulation tissue by absorbing and retaining exudates. Hydrogels are also used for chronic leg ulcers, although they may lead to exudate accumulation, maceration, and bacterial proliferation, necessitating careful management [17]. Hydrogels are a focus of wound dressing research due to their capacity to maintain moisture at the wound site and absorb exudate, thereby promoting fibroblast proliferation and keratinocyte migration, which are crucial for wound healing. Various hydrogel dressings with different properties have been developed, including injectability, adhesive properties, self-healing capability, antibacterial ability, antioxidant capacity, and drug release properties. Despite their widespread use, hydrogel dressings face challenges due to their limited mechanical property, which limits their application to mobile wounds [15]. Hydrogel dressings, made from hydrophilic, inflatable, and insoluble materials, contain 70–90% water, allowing them to absorb a large amount of exudate and create a damp environment that aids in autolytic debridement of necrotic tissue. They are suitable for surface wounds and are transparent, allowing easy observation of the wound without the removal of the dressing. Hydrogel dressings are particularly effective for wounds with low to controlled exudate, such as burns, surgical wounds, skin tears, and pressure ulcers. They are also used for painful wounds, with examples including sheet hydrogels, amorphous gels, and impregnated gauze [4].

2.3.5.5. Alginate dressings

Derived from seaweed and containing either calcium or sodium alginate, creates a hydrophilic gel upon contact with wound exudates, aiding in easier dressing removal. They are recommended for moderate to heavily exuding wounds, with the calcium component acting as a hemostat, beneficial for bleeding wounds. Alginate ribbon and rope variants are particularly useful for packing wound cavities [16]. These dressings are rich in either mannuronic or guluronic acid, which influences their absorbency and shape retention. Upon contact with wound fluid, they partially dissolve, forming a gel due to the exchange of sodium ions in the wound fluid for calcium ions in the dressing. Alginates can absorb 15 to 20 times their weight in fluid, making them suitable for highly exuding wounds. However, they should not be used on wounds with minimal exudate to avoid adherence to the healing wound surface, which can cause pain and damage to healthy tissue upon removal. [18]. Alginate dressings, made from sodium and calcium salts of mannuronic and guluronic acid units, are absorbent and biodegradable. They form a strong hydrophilic gel that controls wound exudates and reduces bacterial contamination. While alginate dressings have been reported to inhibit keratinocyte migration, studies suggest they accelerate healing by activating macrophages to produce TNF-α, initiating inflammatory signals. Suitable for moderate to heavily draining wounds, alginate dressings are not recommended for dry wounds, third-degree burns, or severe wounds with exposed bone. They require secondary dressings to prevent wound dehydration, which can delay healing. Commercially available alginate dressings include Sorbsan™, Kaltostat™, and Algisite™[17].

2.3.5.6. Foam dressings

Foam dressings, available in polyurethane and silicone variants, offer numerous benefits for wound care. Polyurethane foams, with their hydrophilic wound contact layer and hydrophobic backing, provide excellent absorbency and leakage prevention. They also come as cavity dressings, which include hydrophilic polyurethane foam chips within a perforated polymeric film membrane. Silicone foams, crafted from a silicone elastomer polymer, adapt to the wound shape, providing a soft, open-cell foam dressing that conforms to the wound [18]. These dressings facilitate moisture vapor

and oxygen transmission, offer thermal insulation, and effectively manage exudate while safeguarding the surrounding area from further harm. Foam and sponge materials, renowned for their porous structure, aid in wound healing and hemostasis. Polyurethane foams possess antibacterial and anti-inflammatory properties, promoting re-epithelialization. Sponges, with their interconnected porous structure, efficiently absorb blood and exudate. However, clot formation within the sponge due to absorbed blood and exudate can complicate and cause discomfort during dressing removal. Foam dressings, suitable for wounds with moderate to high exudate levels, come in various thicknesses and formulations, including adhesive and non-adhesive options. They are beneficial for reducing over-granulation, absorbing exudate, preventing pooling and skin leakage, and ensuring low adherence for painless, straightforward removal, making them effective as cavity fillers and primary dressings[15,16].

2.3.5.7. Antimicrobial dressings

Antimicrobial dressings play a crucial role in minimizing microbial growth in wounds, especially in cases of colonization or infection. Silver, available in ionic or nanocrystalline forms, has been widely used for its antimicrobial properties. Recent advancements have enabled its integration into dressings for different types of wounds. Iodine, another effective antimicrobial agent, is commonly used as povidone-iodine or cadexomer iodine, both with unique mechanisms of action. Cadexomer iodine, for instance, not only absorbs fluids but also releases iodine gradually, reducing bacterial load and facilitating debris debridement. However, caution is advised in patients with thyroid diseases due to possible systemic iodine uptake. Metronidazole gel is often employed to control odors caused by anaerobic bacteria, especially in fungating malignant wounds. The use of antimicrobial dressings has increased due to concerns over antibiotic-resistant bacteria, though their routine use is not universally recommended due to limited clinical evidence supporting their efficacy [16,18].

2.4. NANOFIBERS and FABRICATION METHOD

Nanofibers, defined as fibers with diameters typically ranging from 50 to 300 nanometers, encompass a realm where the prefix "nano-" denotes dimensions on the

order of one billionth of a meter, while "fiber" denotes slim, elongated structures that can be either natural or synthetic filaments. This amalgamation of dimensions and material characteristics has positioned nanofibers as intriguing one-dimensional nanomaterials. Offering unique mechanical, thermal, biological, optical, magnetic, and electrical properties, nanofibers have garnered attention for a diverse array of applications. Their importance stems from the diverse range of materials that can be used in their production, including natural and synthetic polymers, metals, metal oxides, carbon-based materials, and composites. Moreover, nanofiber properties can be tailored through the surface and bulk modifications to accommodate various functionalities, expanding their potential applications [19,20]. Notably, nanofibers, with diameters of 100 nanometers or less, possess exceptional characteristics such as a high surface-area-to-volume ratio and superior mechanical properties, making them suitable for applications ranging from filtration and battery separators to tissue engineering and electrochemical sensing [21]. Nanotechnology, exploring materials within the 0.1–100 nm range, holds immense promise for scientific advancement and economic competitiveness. However, challenges such as large-scale fabrication, environmental concerns, and flexibility limitations need addressing, with nanofibers emerging as a promising solution to meet these demands [22]. It has attracted considerable interest due to its outstanding physical, chemical, and mechanical properties, rendering it highly useful for a variety of industrial and domestic applications. These nanostructures boast a remarkable surface area, tensile strength, and aspect ratio, along with a porous structure and the potential for functionalization, which enhances their versatility. Among the different types of nanomaterials, nanofibers are particularly notable for their broad diameter range and adjustable pore size, especially in their polymeric form [23].

2.4.1. Nanofiber Fabrication Methods

Nanofiber fabrication techniques encompass two primary approaches: top-down and bottom-up methodologies. In top-down methods, such as chemical and mechanical treatment of materials like wood pulp, bulk substances are disintegrated into nanofibers, commonly utilized for producing cellulose nanofibers (CNF). Conversely, bottom-up techniques involve the fabrication of nanofibers from constituent molecules

and include methods like electrospinning, drawing, template synthesis, self-assembly, and phase separation. Electrospinning, in particular, stands out as the most prevalent bottom-up method due to its simplicity, cost-effectiveness, scalability, and ability to tailor nanofiber properties such as composition, diameter, and orientation to specific applications. These techniques can further be categorized into physical, chemical, and biological methods, each offering unique advantages and considerations. Physical methods involve the application of mechanical energy or high-energy radiation, while chemical methods facilitate the merging of atoms or ions to form nanoparticles. Biological techniques, on the other hand, leverage microorganisms or enzymatic treatments to produce nanofibers in an eco-friendly manner. By understanding and refining these fabrication techniques, researchers can unlock the full potential of nanofibers for various applications, contributing to advancements in materials science and engineering. Numerous techniques for fabricating nanofibers have been extensively documented in the literature, and categorized under various names and classifications. Generally, nanofiber fabrication methods are divided into bottom-up and top-down approaches. Bottom-up techniques include mechanical grinding, physical vapor deposition (PVD), chemical vapor deposition (CVD), solution blowing, centrifugal spinning, drawing techniques, template synthesis, self-assembly, phase separation, freeze-drying synthesis, interfacial polymerization, and electrospinning. In contrast, top-down approaches involve processes such as grinding, refining, sequential cutting, or milling of larger bulk materials. These techniques are further classified into physical, chemical, and biological fabrication methods, as well as spinning and non-spinning techniques. Spinning techniques are further categorized into electrospinning approaches utilizing electric voltage to control fiber morphology and other spinning approaches employing forces like pressurized air and centrifugal forces [19,22].

Table 2.2. Nanofibers fabrication methods.

Top-down techniques	Bottom-up techniques
1. Electrospinning	1. Template-assisted synthesis
2. Centrifugal spinning	2. Atomic layer deposition (ALD)
3. Melt blowing	3. Self-assembly
4. Phase separation	4. Molecular self-assembly
5. Drawing	5. Molecular beam epitaxy (MBE)
6. Template synthesis	6. Chemical vapor deposition (CVD)
	7. Vapor-liquid-solid (VLS) method
	8. Solution-phase synthesis
	9. Hydrothermal synthesis
	10. Electrochemical deposition
	11. Layer-by-layer assembly
	12. Emulsion templating

2.4.1.1. Self-Assembly

elf-assembly, as a bottom-up approach, entails the aggregation of small materials to create precise molecular structures like nanofibers. This mechanism depends on intermolecular forces like weak covalent bonds, hydrogen bonds, or van der Waals interactions. While self-assembly shows potential for creating thinner and multifunctional nanofibers, it is challenged by low production rates and complex manufacturing processes. Convergent synthesis, a chemical process utilized in self-assembly, synthesizes molecules necessary for this method. The morphology and properties of the resulting nanofibers are dictated by the interactions between these molecules. Studies have demonstrated the diverse applications of self-assembled nanofibers, ranging from anticorrosive coatings to antimicrobial materials and cancer theranostics. By controlling the chirality and structure of materials, self-assembly can yield promising nanostructured products, influencing properties such as antibacterial activity. Moreover, self-assembled nanofibers hold potential in areas such as ion exchange membranes, regenerative medicine, and various antimicrobial applications. Combining self-assembly with other bio-fabrication methods can enhance hierarchical biological control, leveraging the advantages of each technique to overcome limitations [21,22].

2.4.1.2. Phase Separation

Phase separation is an effective method for nanofiber fabrication. In this process, a homogeneous polymer solution is created by dissolving a polymer in a solvent. The solution then undergoes phase separation into two distinct phases due to physical inconsistency, leading to gelation. Gelation can be triggered by adding a nonsolvent or through thermal treatment. This step is crucial for maintaining the polymer's porosity and size, which ultimately shapes the nanofiber structure. After gelation, the polymer gel is freeze-dried to remove the solvent. The structure formation can be further modified by using different solvents and adjusting the temperature and polymer concentration. Known as solid-liquid phase separation or ice segregation-induced self-assembly, this technique produces scaffolds and membranes useful for bioreactors, artificial organ transplants, and drug delivery applications. However, limitations include higher polymer usage, impracticality for scale-up processes, and time-consuming procedures. Moreover, phase separation involves a straightforward process, where a polymer gel is formed from a homogeneous polymer solution stored at a designated gelation temperature. The gel undergoes solvent exchange by immersion in distilled water, followed by freeze-drying to obtain a nanofiber matrix. While this method is simple, it is primarily limited to laboratory-scale applications [21,22].

2.4.1.3. Template Synthesis

Template synthesis is a prominent technique for fabricating various nanomaterials such as tubes, fibers, and rods, providing versatility in producing a wide range of materials including semiconductors, metals, electroconductive polymers, and carbon nanotubes. Similar to DNA replication, template-assisted synthesis relies on templates or molds to achieve the desired nanomaterials, either independently or in combination with methods like chemical vapor deposition and sol-gel. This approach offers advantages over traditional spinning techniques by enabling the creation of flexible materials with customizable lengths. Two types of templates, hard and soft, are employed for producing nanotubes or rods and wire-like structures, respectively. However, removing the template after synthesis poses challenges, requiring physical

and chemical processes such as dissolution and calcination. Efforts to enhance the electrochemical performance of metal oxide electrode materials have led to the strategic development of novel hierarchical nanofibers using a multi-step self-templating method. Transition metal oxides (TMOs) have attracted considerable interest for their potential applications in various industries. Template-assisted synthesis has emerged as a preferred strategy for tailoring the morphology and physicochemical properties of TMOs. Soft templates, such as block copolymers and biological substances, are increasingly used in TMO synthesis, avoiding the labor-intensive process of template removal often associated with hard-template methods. Moreover, template synthesis methods have shown promise in fabricating porous carbons for supercapacitor applications, offering tunable pore size distribution and acceptable shapes [22].

2.4.1.4. Drawing

Drawing, a method similar to dry spinning, is used to create single nanofibers of considerable length. In this process, a droplet of the polymer intended for nanofiber fabrication is placed onto a SiO2 surface. Then, a glass rod or micropipette tip makes contact with the droplet and is slowly withdrawn, encouraging the formation of longer nanofibers. The withdrawal rate is adjusted according to the viscoelastic properties of the polymer to ensure it can withstand the stresses generated during pulling and undergo significant deformations. As the solvent evaporates during drawing, the polymer solution transforms into a dry solid nanofiber. However, this method has limitations, including its feasibility only on a laboratory scale, material selection constraints, and the effect of solvent evaporation on droplet viscosity and fiber diameter [21]. Improvements to the drawing-based method include track spinning, which utilizes two rotating tracks with opposing angles to enable continuous production, thus increasing production speed and offering improved control over fiber placement. Additionally, Carbon dioxide laser supersonic drawing (CLSD) simplifies the production of polymeric nanofibers with enhanced mechanical properties, ideal for applications in desalination and water treatment [22]. The drawing process involves depositing a millimetric droplet of solution onto a SiO2 surface, where evaporation causes concentration at the droplet edge, facilitating nanofiber formation upon

withdrawal of a micropipette at a controlled speed. This process is particularly suited for viscoelastic materials capable of enduring strong deformations during pulling, although it remains limited to laboratory-scale production [21].

2.4.1.5. Centrifugal Spinning

Also referred to as force spinning, this technique presents a promising alternative to electrospinning for nanofiber production, offering benefits in terms of safety, speed, and increased production rates. Similar to the principles employed in cotton candy manufacturing, centrifugal spinning uses centrifugal force to create a wide variety of nanofibers, including polymer, ceramic, metal, and carbon nanofibers, in a faster and safer manner. The process begins with ejecting a polymer solution from a spinneret with multiple orifices, driven by centrifugal force. This is followed by jet stretching to increase the surface area of the polymer material upon deposition onto a collector. The subsequent evaporation of the polymer solution causes the jet to solidify and contract, leading to nanofiber formation. Important parameters affecting nanofiber morphology in centrifugal spinning include polymer viscoelasticity, solvent type and evaporation rate, spinneret angular velocity, surface tension, solution concentration, temperature, orifice diameter, and distance between orifice and collector. Research has demonstrated the effectiveness of centrifugally spun nanofibers, such as Lignin Amine/Cellulose Acetate nanofibers, in selective metal adsorption. These nanofibers find applications in tissue engineering, pharmaceutical drug delivery, energy production, composites, protective textiles, filtration, and semiconductors. To combine the advantages of both centrifugal and electrospinning technologies, the electro-centrifugal spinning technique has recently been developed [22].

2.4.1.6. Electrospinning

Electrospinning stands as a pivotal method in the production of nanofibers, renowned for its simplicity, cost-effectiveness, and precise control over fiber characteristics such as diameter, alignment, and porosity [23]. This versatile technique finds its roots in Formhals' 1934 patent, which explored the production of artificial filaments using high electric fields, marking the inception of electrospinning as a viable process for nanofiber fabrication. The electrospinning setup as shown in Figure (3) typically

comprises essential components such as a syringe pump for precise polymer solution delivery, a power supply to generate the necessary electric field, and a grounded collector for nanofiber accumulation [21,22].

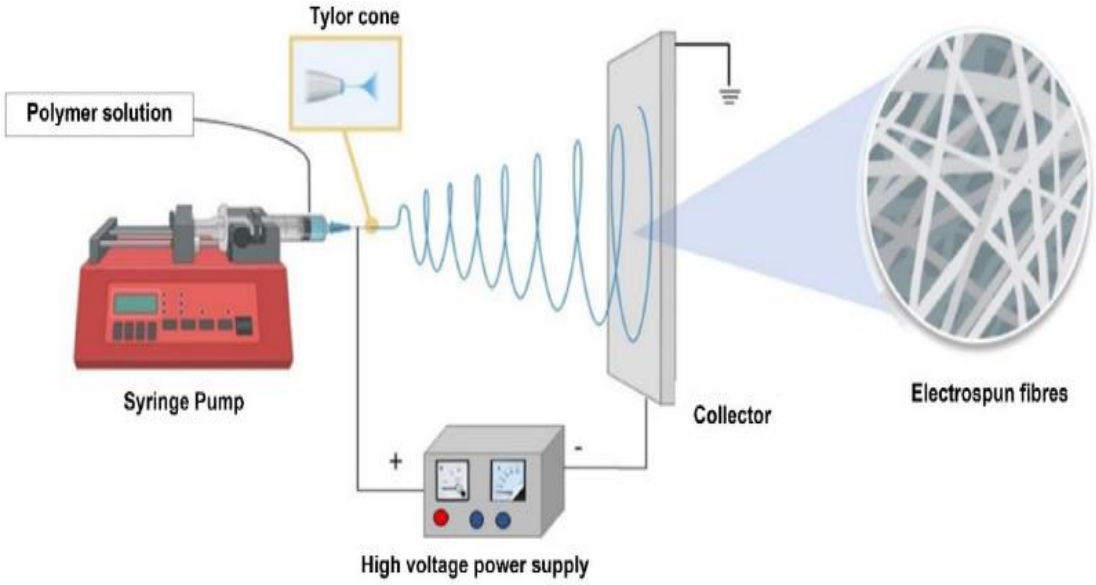

Figure 2.3. Electrospinning setup [23].

The electrospinning process commences with the electrification of a polymer solution, leading to the formation of a stretched jet known as the "Taylor cone." Subsequently, this jet travels towards the collector, where solvent evaporation facilitates nanofiber deposition, resulting in the formation of nonwoven webs. Various parameters, including polymer concentration, viscosity, and electric field strength, play crucial roles in determining the quality and morphology of electrospun nanofibers. Despite its numerous advantages, such as high surface area and porosity, electrospinning encounters challenges such as high voltage usage and limited scalability[23,24]. Over time, researchers have developed and refined various electrospinning techniques to address these challenges, including solution electrospinning, melt electrospinning, and coaxial electrospinning, each offering unique advantages and applications[21]. Recent advancements in electrospinning aim to enhance the properties and applications of nanofibers, with innovations such as the integration of nanoparticles to improve sensor performance and membrane functionality. Despite these challenges, electrospinning remains a versatile and accessible technique with diverse applications in fields such as tissue engineering, filtration, renewable energy, and biomedical devices[23,25]. As

research in this field continues to evolve, further advancements in electrospinning technology hold the promise of revolutionizing nanofiber production and its myriad applications in various industries.

Table 2.3. Advantages and disadvantages of nanofibers fabrication methods[22,26].

Method	Advantages	Disadvantages
Self-assembly	A straightforward method for making multifunctional nanofibers.	Complex process; High cost; Low productivity.
Phase separation	Controlled pore size and structure; minimum equipment requirement. Consistent for batch-to-batch production, can adjust props by varying concentration.	Limited to specific polymers; cannot produce long continuous fibers.
Template synthesis	Different templates can be used to create fibers of various diameters. Moderately easy.	Difficulty in the removal of the template. Applicable for few Polymers.
Drawing	Minimal requirement of equipment. Easy processing.	Difficult to obtain fibers less than 100 nm in diameter; discontinuous process. Discontinuous, fibers generated sequentially
Centrifugal spinning	High production rate; simple and low-cost process.	Difficulty in collecting.
Electrospinning	Simple, uses various polymers, produces long continuous nanofibers, feasible to generate aligned nanofibers. Fibers with sizes ranging from a few nanometers to a few microns; low-cost technology; high aspect ratio; and improved mechanical characteristics. Moderately easy.	Instability of the jet; limited pore size control; requirement of toxic chemicals. Low productivity.

2.5. ELECTROSPINNING and ELECTROBLO-BLOWING

2.5.1. Parameters Affecting the Electrospinning Process

The electrospinning process is influenced by various factors categorized into three main groups: solution parameters, process parameters, and environmental parameters. Smooth fiber production, devoid of beads, hinges on a comprehensive understanding of these

factors. In terms of solution parameters, polymer concentration significantly impacts fiber morphology, with low concentrations leading to bead formation and higher concentrations yielding pure fibers. Solution viscosity, surface tension, conductivity, molecular weight, and solvent selection also play crucial roles. Process parameters such as applied voltage, flow rate, collecting electrode type, needle tip to collector distance, and needle diameter affect fiber diameter and morphology. Environmental factors like temperature and humidity further influence solvent evaporation rates and fiber characteristics. Understanding and controlling these parameters are essential for achieving desired nanofiber properties in electrospinning processes [24,26].

Table 2.4 . Parameters affecting the Electrospinning process.

Parameters	Effects on Electrospinning Process
Polymer Concentration	Low concentrations may lead to bead formation, while higher concentrations yield pure fibers.
Solvent Choice	Evaporation rate, boiling point, and compatibility with the polymer influence fiber morphology.
Applied Voltage	Dictates electric field strength, influencing polymer jet stretching and fiber diameter.
Feed Rate	Controls solution jet intensity, with higher rates resulting in larger fiber diameters due to reduced solvent evaporation time.
Distance	Between tip and collector influences fiber drying time, ensuring uniform morphology and minimizing bead formation.
Temperature	Affects solution viscosity, with higher temperatures leading to decreased viscosity and smaller fiber diameters.
Humidity	Impacts fiber surface morphology, with elevated humidity promoting pore formation on the fiber surface.
Air Flow Velocity	Influences solvent evaporation rates, consequently affecting fiber diameter and morphology.
Electrical Conductivity	Determines charge density, impacting fiber diameter and uniformity.
Viscosity	Impacts solution flow and jet formation, crucial for controlling fiber diameter.
Molecular Weight	Affects viscosity, conductivity, and surface tension, influencing fiber diameter and morphology.

2.5.2. Solution Blowing

The solution Blow Spinning (SBS) process utilizes pressurized gas to synthesize continuous nanofibers; it has emerged as a maturing spinning technique. This method employs a concentric nozzle configuration, directing two parallel streams of polymer solution enveloped by a gas flow to form a dispersed jet. The physical principle behind

the SBS process is in line with Bernoulli's equation, where pressure differences are transformed into kinetic energy. At the nozzle's end, the shift from high-pressure gas to atmospheric pressure creates a shearing force at the gas/solution interface. Increasing gas pressure strengthens this shearing force, overcoming the polymer's surface tension and driving the solution jet into the gas stream. The SBS process has garnered significant interest due to its safety, simplicity, and scalability, making it suitable for industrial applications. However, inherent limitations such as uncontrolled fiber deposition, nozzle clogging, and jet instability persist. Bead formation in SBS alumina nanofibers has been attributed to jet instability and nozzle tip blockage, while disturbances in jet production and fiber continuity have been linked to nozzle protrusion length. To tackle these challenges, several strategies have been suggested. These include the creation of a hollow vacuum-connected drum with a metallic mesh surface to reduce the wastage of nanofibers and investigations into the effects of nozzle design on nanofiber morphology. Computational fluid dynamics (CFD) simulations have helped understand how nozzle diameter and needle protrusion length affect fiber diameter, while analyses using turbulence models have shed light on the relationship between process temperature, air density, and jet stability. Experimental studies have confirmed the impact of higher gas pressure on the morphological structure of nanofibers, showing tendencies for fiber overlap and bundle formation [23,27].

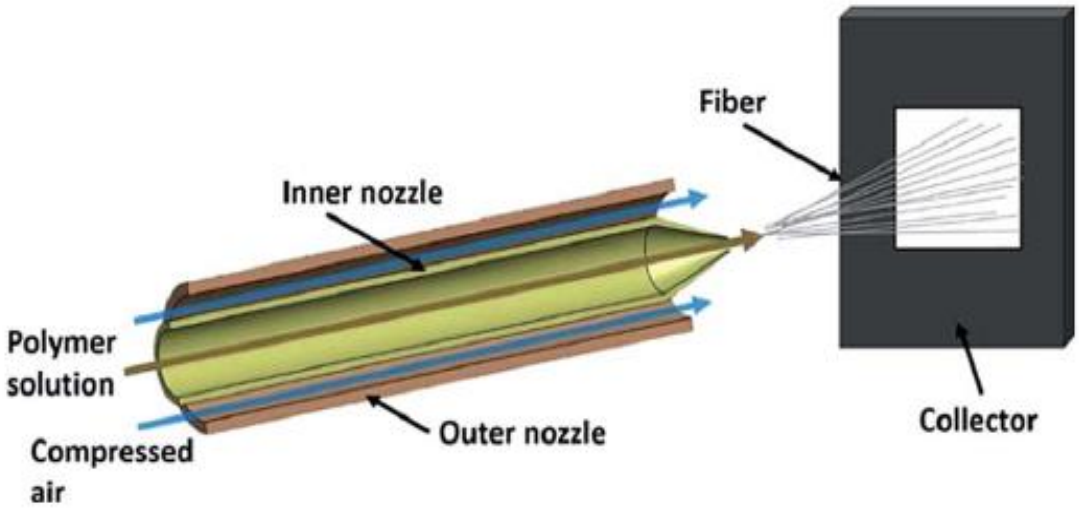

Figure 2.4. Solution-blowing system[27].

2.5.3. Electroblowing

Electro-blowing is an innovative technique that combines air blowing with electrospinning processes to produce polymeric nanofibers from both solutions and melts, thus integrating the advantages of both electrospinning and melt-blowing. In this method, a polymer is first dissolved in a solvent to create a polymer solution, which is then passed through a spinning nozzle. High voltage is applied to the system, and compressed air is injected through the end of the nozzle, resulting in the formation of a web of fibers on a grounded collector. Unlike melt-blowing, which relies solely on the drawing force from the gas jet, electro-blowing utilizes electrostatic repulsion to stretch the fibers, with the gas jet assisting in solution drawing during the initial phase. This approach involves the interaction of two forces: an electrical force and an air-blowing shear force, leading to the creation of nanofibers from the polymeric fluid. Notably, electro-blowing offers a straightforward process with high production rates, enabling the production of nanofibers from a wide range of materials with diameters below 100 nm, including aqueous hyaluronic acid, which may not be efficiently electrospun using traditional methods[28]. Moreover, electroblowing enhances productivity and fiber quality by introducing a high-speed air or gas stream, which aids in stretching the fibers and accelerating solvent evaporation, thus overcoming the high surface tension of the polymer solution. By adjusting parameters such as air-blowing pressure and applied voltage, control over the deposition amount and diameter distribution of the nanofibers can be achieved, offering versatility and enhancing the final product's properties [29]. The electroblowing process utilizes a spinneret consisting of two coaxial needles, with the inner needle delivering the polymer solution and the outer needle delivering the gas stream, thereby facilitating increased fiber productivity and deposition speed. This integrated approach holds promise for the mass production of nanofibers with improved functionality, addressing the demand for scalable nanofiber manufacturing solutions in various industrial applications [29,30].

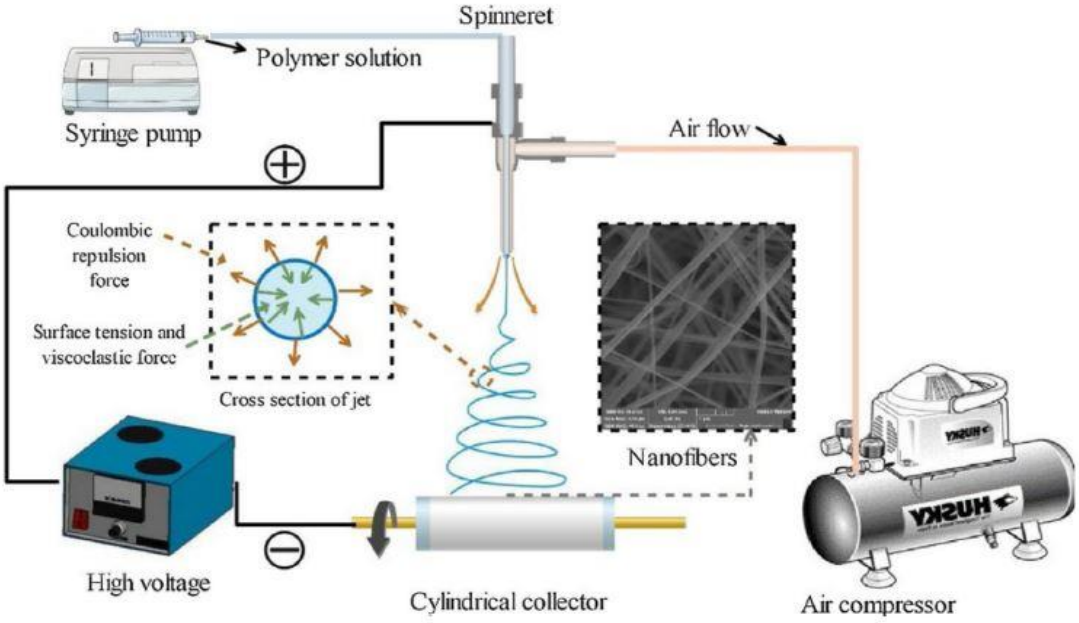

Figure 2.5. Electroblowing Setup[23].

2.5.4. Parameters Affecting the Electroblowing Process

Several factors are crucial in determining the diameter and morphological features of electro-blown nanofibers. These factors can be classified into three main groups: (1) polymer solution properties, (2) process parameters, and (3) ambient conditions. Polymer solution properties, including polymer concentration, viscosity, surface tension, and solvent evaporation rate, have a significant impact on nanofiber diameter and distribution. Studies have demonstrated a direct relationship between polymer concentration and nanofiber diameter, where higher concentrations lead to increased diameters due to elevated solution viscosity and surface tension. Additionally, variations in the composition of polymer solutions can affect viscosity and subsequently impact nanofiber diameter. When it comes to process parameters, factors such as gas pressure, electric field strength, injection rate, and nozzle-to-collector distance are critical in determining nanofiber diameter. Higher gas pressures can decrease fiber diameters due to increased shearing forces and faster solvent evaporation. Similarly, modifying the electric field strength can lead to finer and more uniform fiber diameters, although exceeding certain limits can be hazardous. Important process parameters like polymer feeding rate and nozzle-to-collector distance also affect nanofiber diameter. Optimal feeding rates prevent jamming of the

needle and ensure uniform fiber production, while appropriate nozzle-to-collector distances facilitate solvent evaporation and prevent random deposition. Lastly ambient parameters, such as humidity and air temperature, further impact nanofiber diameter. Higher humidity levels can inhibit solvent evaporation, resulting in thinner fibers, while elevated air temperatures can increase nanofiber production rates by lowering solution viscosity. Understanding and controlling these parameters are essential for tailoring the electro-blown nanofiber fabrication process to achieve desired morphological characteristics, making it a multidimensional optimization challenge in nanofiber production[23].

Table 2.5. Parameters affecting the Electroblowing process.

Parameters	Effects on the Electroblowing Process
Polymer concentration	Directly affects nanofiber diameter. Higher concentration leads to larger diameter.
Viscosity	Influences fiber morphology and diameter. Higher viscosity can lead to thicker fibers.
Surface tension	Affects jet stability and uniformity of nanofibers. Lower surface tension promotes uniform fiber formation.
Solvent evaporation rate	Influences fiber diameter and morphology. A faster evaporation rate leads to smaller diameter fibers.
Gas pressure	Impacts nanofiber diameter and deposition pattern. Higher pressure can reduce diameter and improve alignment.
Electric field strength	Controls fiber diameter and alignment. Stronger electric field results in finer and more aligned fibers.
Injection rate	Affects fiber diameter and jet stability. Higher rates can lead to thicker fibers and jet instability.
Nozzle-to-collector distance	Influences fiber alignment and deposition pattern. Optimal distance ensures uniform deposition.
Humidity	Impacts solvent evaporation rate and fiber diameter. Higher humidity can result in larger diameter fibers due to slower evaporation.
Air temperature	Affects polymer solution viscosity and jet stability. Higher temperatures can decrease viscosity and improve jet stability.

2.5.5. Difference Between the Electrospinning and Electroblowing Process

Electroblowing and electrospinning are two techniques employed for nanofiber production, each presenting distinct advantages and challenges. Electroblowing boasts significantly higher production rates, facilitated by gas flow assistance during the spinning process, making it particularly suitable for high-throughput fiber manufacturing. Its simplified setup compared to electrospinning enhances its appeal for industrial-scale production. However, electroblowing tends to yield fibers with higher porosities and more bundled structures due to the influence of gas flow. In contrast, electrospinning offers finer control over fiber morphology, resulting in more uniform and well-defined fibers. While electrospinning may be more complex in terms of setup and typically yields slower production rates, it excels in producing fibers with specific characteristics and is well-suited for laboratory-scale research. Material compatibility also differs between the two techniques, with electroblowing being compatible with a broader range of materials, including those difficult to electrospin. Ultimately, the choice between electroblowing and electrospinning depends on factors such as desired fiber properties, scalability requirements, and material characteristics, each technique offering unique benefits to researchers and manufacturers alike[31].

Table 2.6. Comparison between Electroblowing and Electrospinning processes.

Aspect	Electroblowing	Electrospinning
Production Rate	Higher production rates due to gas flow assistance	Generally slower production rates
Setup Complexity	Simplified setup compared to electrospinning	More complex setup requirements
Fiber Morphology	Fibers tend to have higher porosities and bundling	Offers finer control over fiber morphology
Material Compatibility	Compatible with a wide range of materials	Some materials may be challenging to process
Scalability	Well-suited for industrial production	May face challenges when scaling up to industrial levels

CHAPTER 3

PVA NANOFIBERS FOR WOUND DRESSING

3.1. NANOFIBERS for WOUND DRESSING

Nanofibers typically exhibit unique features attributed to their nano-scale dimensions. These one-dimensional nanomaterials provide high surface area, adjustable porosity, versatile surface functionalities, and enhanced mechanical properties, which make them suitable for a wide range of biomedical applications [19,20]. In wound care specifically, nanofibers have garnered attention due to their ability to mimic the extracellular matrix structure, promoting cell adhesion, proliferation, and wound healing. Electrospun nanofibers, classified into different types based on their composition and cladding, offer versatility and control over properties essential for wound dressing materials. These materials present several advantages over conventional wound dressings, including enhanced hemostasis, moisture retention, bacterial resistance, and ease of functionalization with therapeutic compounds. Nanofibers manufactured through electrospinning have shown antibacterial properties and effective drug delivery capabilities, indicating their potential for wound dressing applications [5,13]. Moreover, nanofibrous scaffolds create a favorable environment for wound healing by facilitating cell migration, oxygen exchange, and tissue regeneration. Natural and synthetic polymers electrospun into nanofibrous scaffolds offer a biomimetic approach to wound dressing, with materials such as collagen, chitosan, polylactic acid, polyurethane, polyvinyl alcohol, and their blends showing particular promise [6]. Poly(lactic acid) (PLA), poly(caprolactone) (PCL), and poly(lactic-co-glycolic acid) (PLGA) ,polyvinyl alcohol (PVA) which we focus on in this study , are among the commonly used synthetic polymers for wound dressing applications, offering advantageous mechanical and biodegradable characteristics[26]. While progress has been achieved, further enhancements are necessary in the biological compatibility and mechanical

properties of electrospun nanofibers to maximize their effectiveness in wound healing and tissue regeneration[5].

3.2. POLYVINYL ALCOHOL (PVA)

Polyvinyl alcohol (PVA) stands out as a versatile polymer renowned for its favorable characteristics in biomedical applications. Recognized for its high water solubility, biocompatibility, solubility, non-toxicity, and impressive mechanical properties.[32–34], PVA has garnered significant attention from researchers. As a water-soluble synthetic polymer, PVA boasts unique attributes, including a high degree of polymerization ranging from 200 to 3000, elasticity, substantial swelling capacity, and chemical stability. These properties render PVA an ideal candidate for various medical uses, such as wound dressing, bone fracture regeneration, dentistry, and skin tissue repair, and it serves as an effective component in adhesive films, textiles, and coatings, offering convenience and versatility in application [33–35]. Notably, PVA-based wound dressings maintain a moist wound environment and effectively absorb exudates, facilitating the healing process. Despite its drawbacks, such as limited biological activities and mechanical weaknesses, PVA remains a promising option for wound dressing applications[33]. Its synthesis involves the hydrolysis of poly(vinyl acetate), yielding a polymer with diverse characteristics depending on factors like degree of hydrolysis and molecular weight[35]. PVA hydrogels have gained traction in tissue engineering endeavors, serving as scaffolds for tissue and organ regeneration[36]. While inherently non-biodegradable, PVA demonstrates biodegradability under specific environmental conditions, influenced by factors like hydroxyl group presence and hydrolysis degree. Additionally, PVA exhibits favorable water affinity and crystallinity, impacting properties like solubility, mechanical strength, and thermal behavior[37]. Its versatility extends to easy preparation, excellent film-forming capacity, adhesive and emulsifying properties, and resistance to chemicals and odors[9].

PVA nanofibers boast diverse applications across various domains. In industrial filtration, they bolster air and water filtration systems, enhancing efficiency and membrane thickness. Amidst the COVID-19 pandemic, PVA nanofibers play a crucial

role in advanced personal protective equipment, providing superior protection with antibacterial and antiviral properties. In sensing technologies, they enable enhanced gas and biosensor capabilities, ensuring prompt and precise detection. In cancer therapy, PVA nanofibers facilitate targeted drug delivery, impeding tumor growth and augmenting treatment effectiveness[37].

Table 3.1. General PVA applications.

Application	Description
Industrial Filtration	PVA nanofibers enhance efficiency in air and water filtration systems, contributing to improved filtration performance and membrane thickness
Personal Protective Equipment	PVA nanofibers are integrated into advanced PPE, providing superior protection against pathogens, including antibacterial and antiviral properties, crucial during the COVID-19 pandemic.
Sensing Technologies	PVA nanofibers serve as key components in gas sensors and biosensors, enabling enhanced detection capabilities and rapid sensing responses.
Tissue Engineering	Electrospun PVA nanofibers play a crucial role in scaffolding for tissue regeneration, promoting cell attachment, proliferation, and differentiation, thereby facilitating wound healing and tissue engineering applications.
Drug Delivery	PVA nanofibers serve as drug delivery systems, facilitating controlled and targeted release of therapeutic agents for improved treatment outcomes in various biomedical applications.
Cancer Therapy	PVA nanofibers enable targeted drug delivery strategies in cancer therapy, contributing to the inhibition of tumor growth and proliferation, enhancing treatment efficacy.

3.3. PVA AS A BIOMATERIAL

Polyvinyl alcohol (PVA) stands out as a biomaterial due to its remarkable properties, including high biocompatibility, biodegradability, hydrophilicity, and fiber-forming ability. This versatility haled to its widespread use in various medical applications, often in combination with other polymers like chitosan, for its elasticity and tensile strength[38]. PVA finds extensive use in biomedical products such as surgical sutures, contact lenses, and wound dressings, and it's also explored for internal applications like artificial organ designs, including artificial kidney membranes and articular cartilage for orthopedic implants[37]. In the textile industry, PVA serves multiple roles, from a formulating agent to a coating material, water-soluble synthetic fiber, and microcapsule membrane material. Its fibers, known for their unique physicochemical and mechanical properties, find applications in various sectors, especially in geotextiles and biomedical devices[36]. Electrospinning emerged as a robust method

for manufacturing PVA nanofibers, offering versatility in fiber diameter and morphology control. This technique finds applications in various fields, including tissue engineering, drug delivery systems, and protective clothing[39]. Additionally, the synthesis of PVA hydrogels, either chemically or physically, offers further avenues for biomaterial development. Chemical crosslinking methods, employing agents like formaldehyde or glutaraldehyde, provide control over hydrogel properties but may raise concerns regarding cytotoxicity and degradation. Physical crosslinking methods, such as cryogenic gelation or electrospinning, offer alternatives with improved biocompatibility and mechanical properties, making them suitable for tissue engineering and drug delivery systems. In tissue engineering, PVA-based biomaterials play a crucial role, serving as scaffolds for tissue regeneration. Mimicking the natural extracellular matrix, these scaffolds support cell attachment, proliferation, and differentiation, making them promising candidates for various applications, including artificial pancreas, skin, and vascular devices[9].

Table 3.2. PVA applications as a biomaterial.

Application	Details
Medical Applications	Used in surgical sutures, contact lenses, and wound dressings. - Explored for internal applications like artificial organ designs, including artificial kidney membranes and articular cartilage for orthopedic implants.
Electrospinning	Robust method for manufacturing PVA nanofibers with control over fiber diameter and morphology. Applications in tissue engineering, drug delivery systems, and protective clothing.
PVA Hydrogels Synthesis	Chemical crosslinking methods using agents like formaldehyde or glutaraldehyde offer control over hydrogel properties but may raise concerns regarding cytotoxicity and degradation. - Physical crosslinking methods like cryogenic gelation or electrospinning offer alternatives with improved biocompatibility and mechanical properties.
Tissue Engineering	PVA-based biomaterials serve as scaffolds for tissue regeneration, mimicking the natural extracellular matrix. - Support cell attachment, proliferation, and differentiation, making them promising candidates for various applications, including artificial pancreas, skin, and vascular devices.

3.4. PVA FOR WOUND DRESSING

Polyvinyl alcohol (PVA) stands as a pivotal element in wound dressing applications, boasting a multifaceted role when combined with diverse polymers to bolster dressing functionality and therapeutic efficacy[6,8,32,39]. Notably, PVA pairs with chitosan, a compound celebrated for its antibacterial and hemostatic attributes, synergizing to promote wound healing while ensuring biocompatibility[8,32]. Alginate, renowned for its high-water swelling capacity and biodegradability, complements PVA, regulating the wound environment effectively. Moreover, hyaluronic acid (HA) merges with PVA, leveraging its hydrophilicity and interaction with growth factors to expedite tissue repair processes. Meanwhile, dextran collaborates with PVA, stimulating angiogenesis and facilitating rapid wound fundamental extracellular matrix constituent, works alongside PVA to stimulate fibroblasts and immune cells, thereby contributing to tissue repair. Gelatin, derived from collagen, exhibits inherent biological activity and reinforces PVA in wound dressing and tissue engineering realms. Furthermore, starch, with its biocompatibility, biodegradability, and affinity for water, augments PVA in wound dressings and drug delivery systems. Additionally, poly(N-isopropylacrylamide) (PNIPAM) and polyethylene glycol (PEG) confer thermoreversible properties and controlled drug delivery, enriching the functionality of PVA-based wound dressings. The amalgamation of these polymer combinations showcases promising pathways for advancing wound dressing materials, culminating in heightened therapeutic outcomes[8]. Moreover, the design of enhanced characteristics of PVA materials through blending with other polymers, clays, low molecules, silver, copolymerization, crosslinking, or grafting has been extensively explored to overcome limitations such as poor water stability and insufficient elasticity, enhancing their applicability as wound dressing materials[9]. Furthermore, PVP, in combination with PVA, has emerged as a valuable tool for preparing biomaterials, offering increased hydrophilicity and controlled drug release for various biomedical applications [6].

Table 3.3. Polymer materials commonly used in composite hydrogel dressings with PVA.

Polymer	Material Characteristics	Applications
Chitosan	Antibacterial, hemostatic, biocompatible	Wound dressings, drug delivery systems
Alginate	High-water swelling ability, biodegradable, biocompatible	Wound dressings, wound environment regulation
Hyaluronic Acid (HA)	Hydrophilic, biodegradable, interacts with growth factors	Wound dressings, tissue repair
Dextran	Enhances angiogenesis, rapid wound closure	Chronic wound healing
Collagen	Stimulates fibroblasts, immune cells, extracellular matrix component	Tissue repair, wound healing
Gelatin	Biologically active, derived from collagen	Wound dressings, tissue engineering
Starch	Biocompatible, biodegradable, water affinity	Wound dressings, drug delivery systems
Poly(N-isopropylacrylamide) (PNIPAM)	Thermoreversible, controlled drug delivery	Wound dressings, drug delivery systems
Polyethylene Glycol (PEG)	Biocompatible, water-soluble, transparent	Moist wound environment, controlled drug delivery

3.5. ADVANTAGES OF PVA WOUND DRESSINGS

Polyvinyl alcohol (PVA) offers many of advantageous properties conducive to wound healing. PVA-based dressings demonstrate outstanding biocompatibility, ensuring they are compatible with both the skin and wound bed. Particularly, PVA's capacity to retain moisture fosters an optimal environment for wound healing by preventing dehydration and encouraging tissue regeneration[40,41]. Moreover, PVA-based nanofibers possess remarkable mechanical strength, enabling them to withstand handling during application while conforming to irregular wound shapes without compromising integrity. The versatility of PVA allows for facile incorporation of

bioactive agents, facilitating controlled drug delivery to the wound site to accelerate healing processes[33,41]. Furthermore, PVA-based dressings can be engineered to exhibit antibacterial properties through the incorporation of nanomaterials such as graphene oxide and silver nanoparticles, thereby reducing the risk of wound infections and promoting optimal healing conditions[39,40]. These collective properties underscore the potential of PVA as a versatile and effective material for wound dressing applications, promising improved patient outcomes and enhanced wound healing.

Table 3.4. Properties of PVA.

Property	Description
Biocompatibility	PVA-based dressings exhibit excellent biocompatibility, ensuring compatibility with the skin and wound bed, minimizing the risk of adverse reactions and tissue irritation
Moisture Retention	The moisture-retaining capability of PVA fosters an environment conducive to wound healing by preventing dehydration, promoting tissue regeneration, and facilitating cellular migration.
Mechanical Strength	PVA-based nanofibers possess remarkable mechanical strength, enabling them to withstand handling during application while conforming to irregular wound shapes without compromising integrity.
Versatility	PVA-based dressings offer versatility in fabrication techniques and can be easily modified or functionalized to tailor their properties for specific wound care needs.
Antibacterial Properties	PVA-based dressings can be engineered to exhibit antibacterial properties through the incorporation of nanomaterials, reducing the risk of wound infections and promoting optimal healing conditions.
Drug Delivery	PVA's versatility allows for facile incorporation of bioactive agents, facilitating controlled drug delivery to the wound site to accelerate healing processes.

3.6. CARBON DOTS

Carbon dots (CDs) are an emerging class of zero-dimensional carbon-based nanomaterials typically smaller than 10 nm, first discovered during the purification of single-walled carbon nanotubes by Xu et al. in 2004 and later named by Sun et al. in 2006[42]. Carbon dots (CDs) are composed of sp2 and sp3 carbon atoms decorated with different functional groups like hydroxyl, carboxyl, and amino, providing exceptional water solubility and biocompatibility. These functional groups also facilitate surface passivation and functionalization, thereby enhancing their photoluminescent properties, although achieving a high quantum yield remains a challenge for practical applications in biological imaging and diagnosticsCarbon dots

(CDs) are commonly categorized into three groups: carbon nanodots (CNDs), carbon quantum dots (CQDs), and graphene quantum dots (GQDs), each with unique structural and optical characteristics. CNDs typically exhibit amorphous or graphite-like structures, CQDs consist of multiple graphene layers, and GQDs are composed of single or few-layer graphene with notable quantum confinement effects [43]. Carbon dots (CDs) have garnered considerable interest in nanotechnology and biomedical sectors because of their distinctive features, such as high photoluminescent quantum yield, fluorescence, resistance to photodecomposition, excellent biocompatibility, and low toxicity. Their abundant surface functional groups allow for easy functionalization, further expanding their potential applications across various fields [44].

3.7. PROPERTIES AND APPLICATIONS

The versatile properties of carbon dots (CDs) make them highly attractive for various biomedical applications. In terms of electrochemical properties, CDs exhibit superior charge transferability, high electrical conductivity, and abundant surface functional groups, allowing for efficient energy transformation and improved sensor performance. Additionally, heteroatom doping enhances their electronic properties, making CDs ideal for electrocatalytic reactions such as oxygen evolution and reduction. Moreover, CDs demonstrate long-term chemical stability and contain numerous defect sites and active centers, further enhancing their electrochemical performance. On the optical front, CDs possess strong UV absorbance and exhibit fluorescence properties that can be tuned for specific applications, including biosensing and bioimaging. Their resistance to photobleaching and ability to emit photons via chemical or electrical excitation make them valuable tools for sensitive detection methods. Overall, the unique combination of electrochemical and optical properties positions CDs as promising candidates for advancing various biomedical technologies [44].

Carbon dots (CDs) have found wide-ranging applications in biochemical sensors, fluorescent probes, biological imaging, photocatalytic technology, drug carriers, light emitting devices, and energy conversion/storage devices. Their low toxicity,

biocompatibility, cost-effectiveness, and chemical inertness make them advantageous over traditional semiconductor quantum dots, while still offering similar fluorescence properties. Particularly in the biomedical field, CDs have been extensively utilized for fluorescence sensing and imaging both in vitro and in vivo. Notably, in biotherapy, CDs play a significant role in photodynamic therapy (PDT) and photothermal therapy (PTT) owing to their unique optical properties, high water solubility, and photostability. However, challenges such as PDT resistance due to hypoxia have been addressed through innovative approaches like light-driven water decomposition using CDs modified nanocomposites. Moreover, CDs show promise in cancer theranostics, gene therapy, and drug delivery, offering targeted treatment and imaging capabilities. Their applications extend to biological imaging, where CDs serve as efficient fluorescent probes for cell labeling and tracking, demonstrating low cytotoxicity and high biocompatibility. Additionally, CDs have been utilized in biosensors for the sensitive detection of biomolecules, showcasing their potential for advancing diagnostic and therapeutic strategies in biomedical research and clinical practice[10].

Table 3.5. Carbon dots applications.

Application	Description
Biochemical Sensors	Used for detecting and analyzing biomolecules in various biological samples, offering a simple and reliable sensing platform.
Fluorescent Probes	Employed as fluorescent markers for labeling and tracking biological structures and processes in vitro and in vivo, facilitating visualization and analysis
Biological Imaging	Utilized in biomedical imaging for labeling cells and tissues, enabling real-time observation and analysis of biological specimens with high biocompatibility and low cytotoxicity.
PDT and PTT	Applied in photodynamic therapy (PDT) and photothermal therapy (PTT) for cancer treatment, leveraging their unique optical properties, high water solubility, and photostability to induce localized cell death through light-triggered mechanisms, with potential for minimizing side effects and drug resistance.
Drug Carriers	Used as carriers for delivering therapeutic agents to specific sites in the body, enhancing drug efficacy and reducing side effects through controlled release and targeted delivery.

Cancer Theranostics	Utilized for cancer diagnosis and treatment, combining imaging and therapy modalities to achieve personalized and targeted cancer management strategies, offering potential for improved treatment outcomes and patient care.
Gene Therapy	Employed in gene delivery for therapeutic purposes, facilitating the safe and effective delivery of nucleic acids to target cells for treating various genetic diseases, including cancer, cardiovascular diseases, and neurological disorders, showcasing potential for advancing gene therapy approaches.
Drug Delivery	Utilized in drug delivery systems for controlled release and targeted delivery of therapeutic agents to specific sites in the body, enhancing treatment efficacy while minimizing side effects, offering potential for improving patient outcomes in various disease treatments.
Biosensors	Utilized for detecting and quantifying biomolecules in biological samples, offering sensitive and selective detection platforms for diagnostic and research applications, with potential for advancing disease diagnosis and monitoring.
Photocatalytic Tech	Applied in photocatalytic processes for environmental remediation and energy conversion, harnessing their optical properties for catalyzing chemical reactions under light irradiation.
Light Emitting Devices	Incorporated into light-emitting devices for various applications such as displays, lighting, and optoelectronic devices, benefiting from their fluorescent properties and compatibility with device fabrication processes.
Energy Conversion/Storage	Employed in energy conversion and storage devices, contributing to advancements in energy harvesting, storage, and utilization technologies due to their efficient light absorption and conversion capabilities.

3.8. CONSOLIDA ORIENTALIS

Consolida orientalis (Gay) Schröd. is a medium to tall annual plant characterized by stickily-hairy stems that can reach lengths of 20-74 cm, and numerous linear-setaceous leaves. Its purplish-violet flowers, 18-26 mm in size, are borne in dense racemes with flower stalks shorter than the lower dissected bracts, and spurs 10-12 mm long. This species is commonly used in the cut flower trade, both as fresh and dried flowers, and in bedding plant designs [45]. The genus Consolida, is a part of the Ranunculaceae family, consists of approximately 50 species predominantly found in drought-prone regions of southern Europe, northern Africa, and western Asia, with a significant diversity in Anatolia.

Figure 3.1. Consolida Orientals.

These plants thrive in dry, stony slopes of steppes and semideserts and have been cultivated for ornamental purposes globally. Consolida species, often confused with the Delphinium genus, were distinguished as a separate genus by Gray in 1821. Consolida plants, including species like C. ambigua, C. regalis, and C. orientalis, are known for their high ornamental and medicinal value. They have been used for centuries in traditional medicine across regions such as Turkey and China to treat various ailments. The chemical constituents of Consolida, such as diterpenoid alkaloids and flavonoids, have been studied extensively, revealing a range of biologically active compounds that could be valuable for drug discovery. Consolida plant extracts and isolated compounds, particularly diterpenoid alkaloids (DAs) and flavanols, have demonstrated significant bioactivity, including insecticidal, antileishmanial, antimicrobial, antiviral, antitumor, and antioxidant properties. [46].

3.9. RELATED STUDIES

Ahlawat et al. investigated the potential of utilizing poly (vinyl alcohol) (PVA)-gelatin nanofibrous scaffolds loaded with Carica papaya extract for wound dressing applications. The study focused on the fabrication and characterization of nanofibrous scaffolds. Their findings suggested that the incorporation of Carica papaya extract into

the PVA-gelatin scaffold enhanced its biocompatibility and antimicrobial properties, making it a promising candidate for wound dressing materials. This study contributes valuable insights into the development of novel wound dressings utilizing PVA-based nanofibers and highlights the potential of natural additives for improving wound healing outcomes[3].

Sattariazar et al. aimed to enhance the properties of electrospun polyvinyl alcohol (PVA)/oxidized sodium alginate (OSA) nanofibers by integrating fluorescence carbon dots (CDs). Through detailed characterization using techniques such as scanning electron microscopy (SEM), Fourier-transform infrared spectroscopy (FTIR), and fluorescence spectroscopy, the researchers successfully fabricated nanofibers with embedded CDs. The inclusion of CDs offered additional enhancements. These enhancements include improved biocompatibility, potential antimicrobial activity, conferred fluorescence properties to the nanofibrous scaffold, as evidenced by fluorescence spectroscopy analysis, and tunable properties due to the inherent properties of CDs. It has broaden the potential applications of the nanofibers, particularly in biomedical fields like wound dressing. The study underscores the promising role of incorporating novel materials, like CDs, into PVA-based nanofibers, presenting opportunities for the development of multifunctional materials with improved properties and functionalities[40].

Norouzi et al. investigated the potential of PVA-based nanofibers containing chitosan modified with graphene oxide and carbon quantum dot-doped TiO2 for wound healing was explored, offering significant insights into wound care, the study utilized a rat model to assess the wound healing properties of the nanofibers. Through meticulous experimentation, the researchers demonstrated the enhanced wound healing efficacy of the nanofibers, attributed to their unique composition and properties. These findings underscore the potential of PVA-based nanofibers as promising wound dressing materials, particularly when modified with graphene oxide, carbon quantum dots, and TiO2[41].

Fangchao Cui et al. led an investigation that delves into the fabrication and application of carbon dots-incorporated nanofibers within hydrogel matrices for enhanced wound

healing capabilities. This novel composite system demonstrates remarkable attributes including antibacterial efficacy, superior biocompatibility, and notable fluorescence properties. By meticulously characterizing the structural and functional aspects of these materials, the study elucidates their potential as advanced wound dressings. Furthermore, the integration of carbon dots within the hydrogel framework offers additional advantages such as sustained release of therapeutic agents and improved mechanical properties. This comprehensive exploration underscores the significance of carbon dots-nanofiber-hydrogel composites as promising candidates for next-generation wound care materials, advocating for their further investigation and translation into clinical practice[47].

Another study led by Somaye Ebrahimi and Hamide Ehtesabi explores the development of an innovative double-layer alginate/carbon dot nanocomposite hydrogel for potential use in wound dressing applications. This innovative approach capitalizes on the synergistic properties of alginate and carbon dots to develop a multifunctional wound dressing material. The double-layer design allows for controlled release of therapeutic agents and enhances the mechanical integrity of the hydrogel. By leveraging the unique attributes of carbon dots, such as their fluorescence and antibacterial properties, the study demonstrates the potential of this nanocomposite hydrogel in promoting wound healing[48].

Rahmani et al. explored the development and characterization of pH-responsive polyvinyl alcohol (PVA)-based nanofibers incorporating graphene oxide (GO) modified with silver (Ag) nanoparticles. Their study involved a comprehensive physico-chemical analysis to assess the structural and functional properties of these nanofibers. The research demonstrated that the incorporation of Ag nanoparticles onto GO significantly enhanced the antimicrobial properties of the nanofibers, making them suitable for wound dressing applications. Additionally, the pH-responsive behavior of the nanofibers facilitated controlled drug release, presenting a promising approach for drug delivery systems. This work provides significant insights into the multifunctional capabilities of PVA-based nanofibers, particularly in the fields of biomedical applications and smart wound care solutions. The innovative integration of GO and

Ag nanoparticles in this study highlights the potential for advanced material design in healthcare technologies[33].

CHAPTER 4

METHODOLOGY

4.1. MATERIALS

The polymers used in this study were Polyvinyl alcohol (PVA), sourced from ZAG Kimya in Istanbul, Turkey, which boasts a purity of 87.8%, a density ranging from 0.4 to 0.6 g/cm3 at 20℃, and a melting point from 160 to 240 ℃. Ethanol meeting the specified criteria was procured from TEKKİM Chemicals in Istanbul, Turkey. The ethanol obtained adheres to the following specifications: purity > 95%, a molar mass of 46.07 g/mol, a density ranging between 0.801 and 0.805 g/cm³ at 20℃, acidity level below 0.0005 meq/gr, HS Code of 3402.90.10, and a vapor pressure of 59 hPa at 20℃. Ultra-distilled water was utilized as the solvent during the sample preparation process.

Figure 4. 1. Polyvinyl Alcohol.

4.2. OBTAINING ANTHOCYANINS (COA) AND CDOTS (CO-CDS) FROM CONSOLIDA ORIENTALIS.

The purple flowers of *Consolida orientalis*, which grows naturally at the coordinates of 39°12'09.4"N 35°15'40.3"E, were collected in mid-August. The collected flowers were spread in a thin layer on coarse filter paper and dried in the shade at room temperature for 10 days. Dried flowers separated from the stems were ground in Waring Blander to obtain. The flower powder was mixed 1:10 with water at 150 rpm at 25 °C for 24 hours. Then, it was filtered through coarse and Whatman No 1 filter papers, respectively. The supernatant was stored as CoA at +4 degrees. The pulp remaining on the coarse filter paper was dried at 60 degrees for 12 hours. Then, it was mixed with water at a ratio of 1:20 and placed in a 250 mL hydrothermal reactor with Teflon inner. After heat treatment at 200 °C for 10 hours, the reactor was cooled to room temperature. The brown reaction product was first filtered through Whatman no:1 filter paper, then the amber colored liquid passed through a 0.22 μm PTFE filter was stored as Co-CDs at +4 °C.

Figure 4.2. Grounded Consolida flowers.

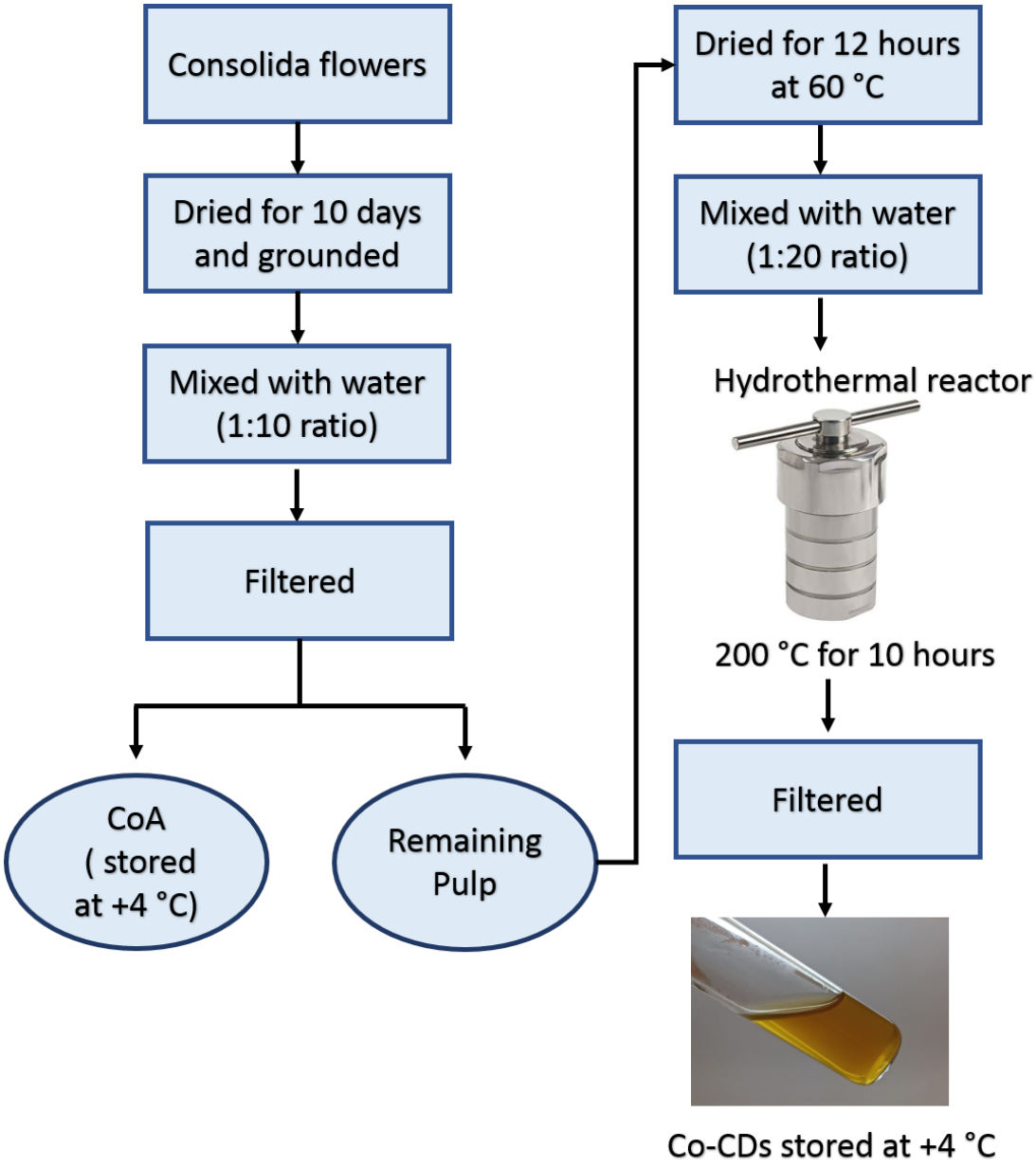

Figure 4.3. Schematic drawing of Co-CDs and CoA prepration process.

4.3. PREPARATION OF POLYMER SOLUTIONS

The PVA solution was prepared according to Table 4.1 by dissolving 10 wt.% of PVA with 36 wt.% of ethanol, and 54 wt.% of water, and stirred using a magnetic stirrer for 6 hours at the temperature of 90 °C. And the PVA/Co-CDs/CoA solution was prepared by dissolving 10 wt.% of PVA with 8wt.% of ethanol, 32wt.% of water, 15 wt.% CD solution, and 35wt.% of dye extract and stirred using a magnetic stirrer for 6 hours at the temperature of 90 °C.

Table 4.1. Polymer solutions.

Solution	PVA	Water	Ethanol	CD solution	Dye extract
PVA	10	54	36	0	0
PVA/Co-CDs/CoA	10	32	8	15	35

4.4. FABRICATION OF NANOFIBERS

In this research electroblowing method was employed to produce the nanofibers samples. This process parameters as shown in table 4.2 which combines air pressure and an electric field to propel the polymeric solution. The nozzle was situated 35 cm away from the rotating collector. A highly pressurized air supply of 1.5 bar was delivered by an air compressor. Simultaneously, an electric voltage of 20 kV was applied at the nozzle tip to enhance spin ability and minimize fiber bundle formation. As the solution traveled from the nozzle to the collector with a feeding rate of 15 ml\hr, the solvent evaporation occurred, resulting in nanofibers with varying morphologies and diameters. These disparities were attributed to the solution concentration. Our orchestrated electroblowing process successfully yielded nanofibers for both our samples.

Table 4.2. Parameters of EBS.

Parameters	Details
Nozzle distance	35cm
Air pressure	1.5 bar
Voltage	20kV
Feeding rate	15ml\hr

4.5. CHARACTERIZATION METHODS of NANOFIBER MATS

4.5.1. Scanning Electron Microscope (SEM)

To examine the fibrous mat structures, a Carl Zeiss Ultra Plus Field Emission Scanning Electron Microscope (FE-SEM) was utilized. SEM images were then analyzed using ImageJ software to determine the average diameter and distribution of the nanofibers. One hundred diameter measurements were collected from randomly selected images of each sample.

4.5.2. Fourier Transform Infrared Spectroscopy (FTIR)

The Fourier-transform infrared spectra (FTIR) of the fibrous mats were obtained using a Bruker ALPHA FTIR Spectrometer, covering 24 scans across the 400–4000 cm-1 wavelength range. This analysis aimed to examine the relationships among different components present.

4.5.3 XRD

X-ray diffraction (XRD) analysis was performed at room temperature over a Bragg angle range of 10–90°, utilizing a RIGAKU ULTRA IV XRD diffractometer. The X-ray tube was maintained at a constant current of 20 mA and a voltage of 30 kV, with a step width of 0.03.

4.5.4. Thermogravimetric Analysis (TGA)

To study the thermal degradation patterns of the nanofiber mat, a thermogravimetric analyzer (STA 7300, Hitachi, Japan) was used for thermogravimetric analysis (TGA). Samples were heated from room temperature to 450°C at a steady rate of 10°C per minute under a constant nitrogen gas flow of 2 mL/min**.**

4.5.5. Water Contact Angle

To evaluate the surface hydrophobic properties of each sample, contact angles were measured using the sessile drop technique with approximately 0.0085 mL of pure water at room temperature. Video contact angle measurement (Theta Lite) was used

for these evaluations. Samples were prepared in dimensions of 50 mm × 50 mm for this analysis.

4.5.6. Air Permeability

The air permeability of the PVA nanofiber mats was measured using the Prowhite Air Test II apparatus. Tests were performed at a temperature of 25 ℃ using 20 cm square samples. Each sample was exposed to a pressure of 100 Pa of air during testing.

4.5.7. Mechanical Properties Analysis

The mechanical properties, including tensile strength (TS), elongation, and maximum load-bearing capacity, of all nanofibers integrated with Consolida carbon dots (Co-CDs) were evaluated using the Shimadzu universal testing machine, with a loading capacity of 1 KN. Tensile testing was conducted at a crosshead speed of 1 mm/min.

4.5.8. Antimicrobial Activity

The antimicrobial properties of micro-nanofibers were evaluated against food-borne pathogens Escherichia coli (gram-negative) and Staphylococcus aureus (gram-positive). Initially, stock cultures were regenerated by transferring each microorganism into 5 mL of Mueller Hinton Broth (MHB) and incubating overnight at 35°C. The cultures were then diluted to 10^8 CFU/mL based on OD600 absorbance. Antimicrobial activity was tested using a modified agar disc diffusion method, following the technique by Dannenberg et al. (2017). A 100 µL aliquot of the diluted bacterial suspension was spread onto Mueller Hinton Agar Petri dishes using a sterile swab, and the media was allowed to absorb the fluid for 5 minutes. Micro-nanofibers were cut into 6 mm discs with a sterile leather punch tool and exposed to UV light for 2 hours (1 hour per side) in a laminar flow hood. The discs were placed on the agar, and the Petri dishes were incubated at 35°C for 24 hours. The diameters of the inhibition zones around the discs were measured with a caliper and recorded.

CHAPTER 5

RESULT AND DISCUSSION

5.1. SEM

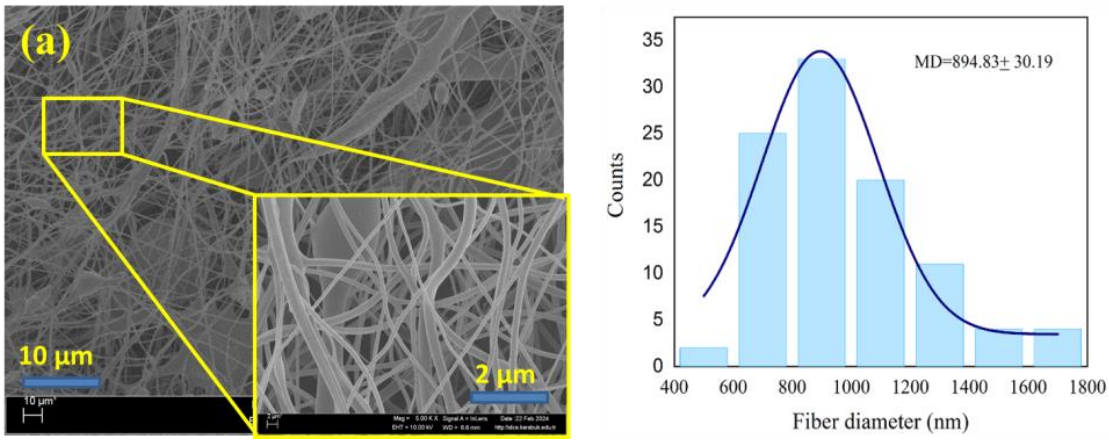

Figure 5.1. SEM images and fiber diameter distribution of PVA.

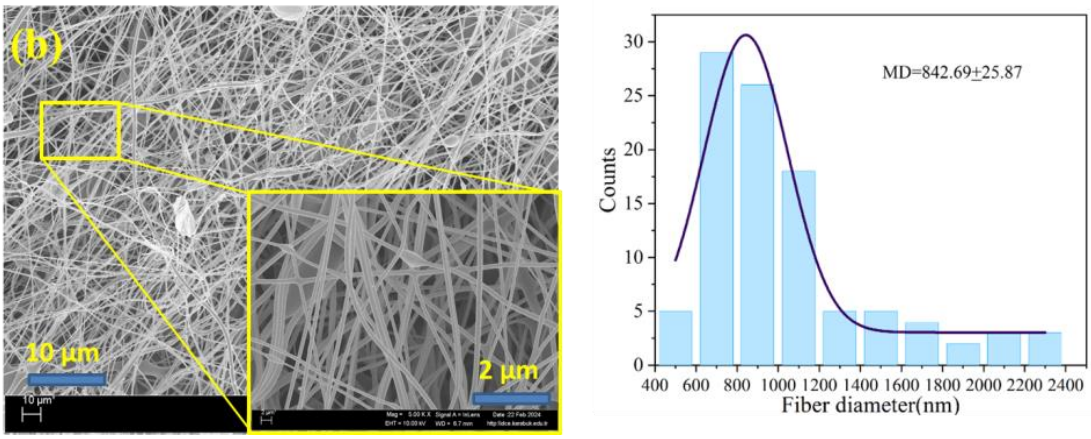

Figure 5.2. SEM images and fiber diameter distribution of PVA/Co-CDs/CoA.

The SEM analysis of both the PVA in picture (a), and PVA/Co-CDs/CoA (b) nanofiber samples unveiled heterogeneous diameter distributions, with an acceptable level of droplets. For the PVA nanofibers, the electroblowing technique yielded a

mean diameter (MD) of 894.83 nm, with a prevalent range spanning from 700 nm to 1300 nm. This diversity in diameter highlights the technique's efficacy in producing nanofibers with tailored size characteristics. Conversely, the PVA/Co-CDs/CoA nanofiber sample exhibited a 5.83% decrease ration with a slightly smaller mean diameter of 842.69 nm, with the majority of fibers falling within this range. While both samples displayed heterogeneous distributions, the subtle differences in mean diameter and diameter range. Conversely, the addition of carbon dots (CDs) led to a notable decrease in nanofiber diameter similar to the results obtained by Sattariazar et al., Rooholghodos et al., and lee et al.[40,49,50]. It is possible that incorporation of carbon dots might have increased both conductivity and viscosity as in the research conducted by Rooholghodos et al.[49].

5.2. FTIR ANALYSIS

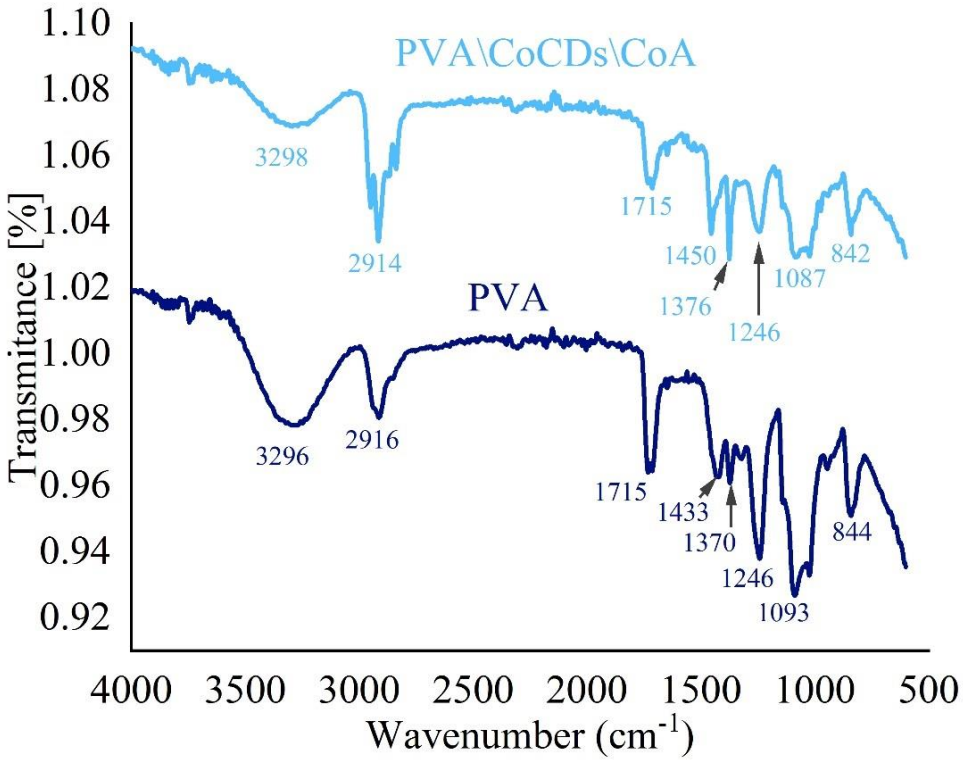

Figure 5.3. FTIR spectrum of PVA and PVA/Co-CDs/CoA nanofiber samples.

The Fourier-transform infrared spectroscopy (FTIR) analysis of polyvinyl alcohol (PVA) nanofiber samples and PVA nanofibers incorporated with Consolida flower carbon dots (PVA/Co-CDs/CoA) revealed distinct spectral features indicative of differences in molecular composition and structural properties. In the PVA sample, characteristic peaks corresponding to hydroxyl (OH) stretching (3296 cm^-1), aliphatic C-H stretching (2916 cm^-1), and carbonyl (C=O) stretching (1715 cm^-1) were observed similar to Gökmeşe, F.et al.[35], along with other functional group vibrations. Conversely, the PVA/Co-CDs/CoA sample exhibited similar peaks the addition of CDs to the PVA nanofiber did not significantly alter the absorption pattern[40], with slight variations in intensity and position. Notably, the OH stretching peak in PVA/Co-CDs/CoA showed a slightly higher transmission value compared to PVA, the peak around 3298 cm^-1, corresponding to the stretching vibration of OH groups[40,50,51], shows a slightly higher transmission value compared to PVA. Other peaks, such as those at (2914.6 cm^-1), (1450.1 cm^-1), (1376.7 cm^-1), and (1087.1 cm^-1), also show a slight differences in transmission values compared to the PVA sample.

5.3. XRD

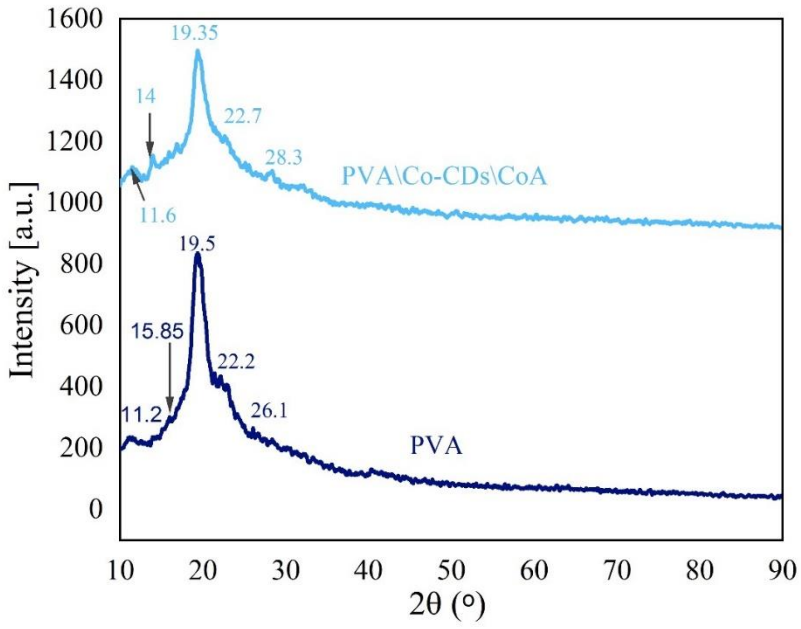

Figure 5.4. XRD analysis results of PVA and PVA/Co-CDs/CoA nanofiber samples.

The XRD analysis was performed on the two samples which showed that the PVA sample exhibited diffraction peaks at 11.2°, 15.85°, 19.5°, 22.2°, and 26.1°, which are characteristic of PVA's crystalline structure, the large peak at 19.5◦ corresponds to the crystal planes of the PVA semi-crystalline nature[49,51]. The PVA/Co-CDs/CoA sample showed diffraction peaks at 11.6°, 14°, 19.35°, 22.7°, and 28.3°. The shifts in peak positions and the appearance of a new peak at 28.3° in the PVA/Co-CDs/CoA sample suggest that the incorporation of carbon dots affects the crystalline structure of PVA. These changes imply that the addition of carbon dots, likely led to a decrease in crystallinity akin to Sattariazar et al., and Aziz et al. [40,51,52],caused by disruption of the regular arrangement of PVA molecules due to the introduction of irregularities and new phases within the polymer matrix[51,52]. This disruption indicates significant interactions between the PVA matrix and the carbon dots, the breakdown of hydrogen bonding between carbon dots' surface groups and the hydroxyl group in PVA polymer could explain these findings. which can modify the material's properties[51].

5.4. TGA

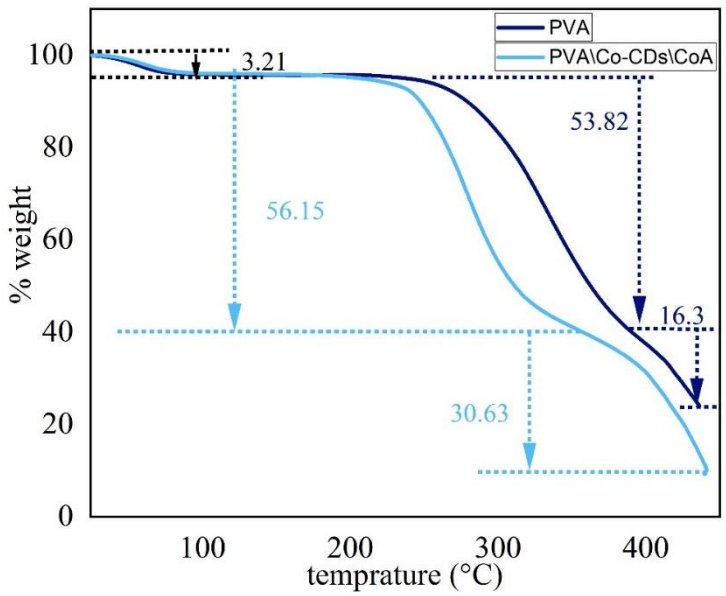

Figure 5.5. TGA analysis results of PVA and PVA/Co-CDs/CoA nanofiber samples.

The TGA analysis was conducted to evaluate the thermal stability and degradation behavior of the two samples: PVA and PVA/Co-CDs/CoA. The analysis, performed within the temperature range of 24 to 450°C, revealed three distinct degradation stages for each sample. Both samples exhibited three weight loss steps and an initial weight loss of 3.21%, likely due to the evaporation of absorbed moisture similar to fadil et al. [53]. In the main degradation stage, the PVA sample demonstrated a weight loss of 53.82%, whereas the PVA/Co-CDs/CoA sample exhibited a slightly higher weight loss of 56.15%. This indicates that the incorporation of carbon dots does not significantly alter the primary degradation temperature but may enhance the degradation process slightly. In the secondary degradation stage, the PVA sample lost 16.3% of its weight which also parallels the enhanced degradation seen in composite samples studied by fadil et al.[53], compared to a more substantial 30.63% weight loss observed in the PVA/Co-CDs/CoA sample. This discrepancy suggests that the carbon dots in the PVA/Co-CDs/CoA sample contribute to additional thermal degradation mechanisms. Consequently, the final residue was significantly lower for the PVA/Co-CDs/CoA sample at 9.17%, compared to 23.99% for the PVA sample, indicating more complete degradation in the presence of carbon dots. Overall, these results suggest that the PVA/Co-CDs/CoA nanofibers have a distinct thermal stability profile compared to PVA nanofibers, likely due to the influence of the carbon dots, which may have facilitate or enhanced the thermal degradation consistent to the study conducted by Date et al. and Wang et al.[54,55]. The decrease in thermal stability might also be due to the decrease of crystallinity in the PVA/Co-CDs/CoA sample as shown in our XRD results and consisted with studies conducted with Date et al., Sattariazar et al., and Aziz et al.[40,51,54].

5.5. WATER CONTACT ANGLE

The water contact angle test results provide valuable insights into the hydrophilicity of the nanofiber samples, essential for understanding their physicochemical properties.

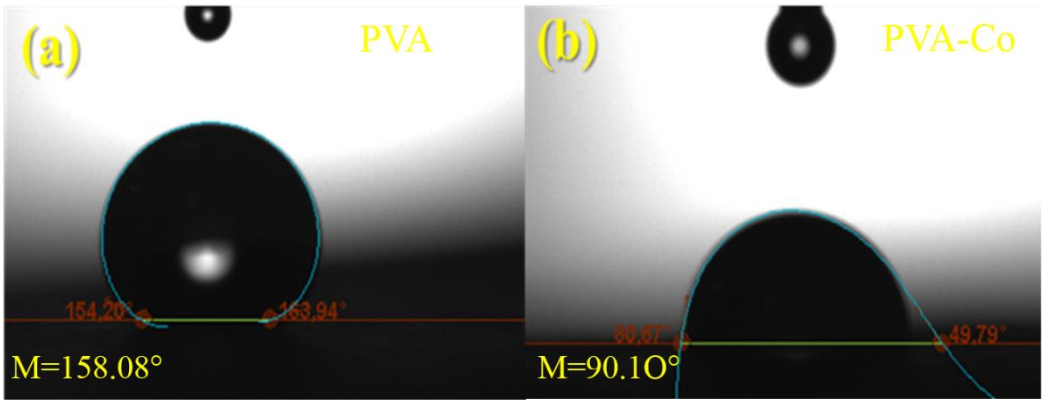

Figure 5.6. Water Contact Angel results for PVA and PVA/Co-CDs/CoA nanofiber samples.

The PVA nanofibers in picture (a) exhibited a mean contact angle of 158.08°, indicative of their intrinsic hydrophilic nature. In contrast, in picture (b) the PVA/Co-CDs/CoA nanofibers exhibited a mean contact angle of 90.10° demonstrated a significantly lower mean contact angle than the PVA sample similar to the results acquired by Xu et al. [56], suggesting that the addition of carbon dots caused an enhanced degree of hydrophilicity compared to PVA similar to Shakiba-Marani and Ehtesabi [57]. These observations highlight the distinct hydrophilic characteristics of the two samples formulation.

5.6. AIR PERMEABILITY

The air permeability test was conducted on the two nanofiber samples and was performed under a pressure of 100 Pa and at a temperature of 25°C, using a 20 cm square sample. Five measurements were taken for each sample to ensure accuracy. For the PVA sample, the mean for air permeability was 72.2 mm/s, with a standard deviation of ±3.83 cfm. For the PVA/Co-CDs/CoA sample with added carbon dots, the mean air permeability was 49.8 mm/s, with a standard deviation of ±4.08 mm/s. The PVA sample exhibited higher air permeability compared to the PVA/Co-CDs/CoA sample.

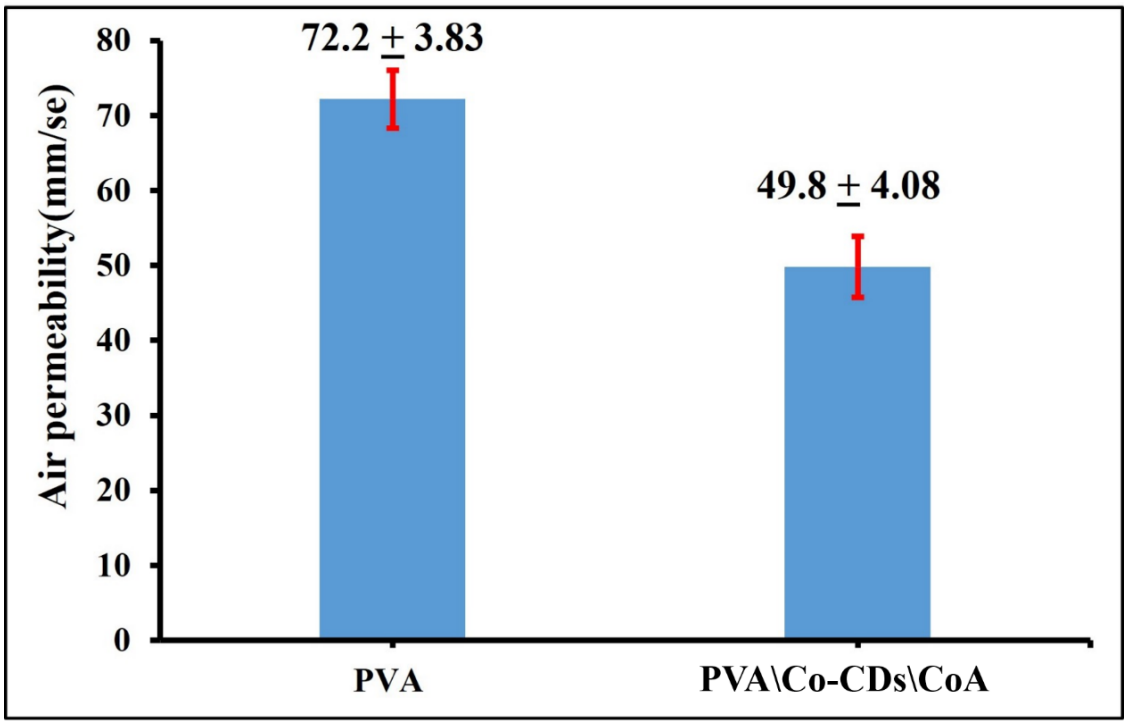

Figure 5.7. Air permeability test results for PVA and PVA/Co-CDs/CoA nanofiber samples.

The air permeability of nanofibrous membranes is influenced by factors such as membrane thickness, fiber diameter, surface density, and porosity[58], the reduction in air permeability for the PVA/Co-CDs/CoA sample suggests that the addition of carbon dots impacts the airflow through the nanofiber structure. This could be due to the changes in fiber morphology or pore structure introduced by the carbon dots as we observed in our SEM results. Typically, the presence of carbon dots can result in finer fibers and decrease the fibers diameter [40,49,50], which can decrease pore size and reduce air permeability. Reduced air permeability enhances particle capture and provides a better protection against bacteria and viruses[58].

5.7. MECHANICAL PROPERTIES

The mechanical performance analysis of PVA nanofibers and PVA/Co-CDs/CoA results shown in table 5.1 below revealed distinct characteristics in tensile strength and elongation at break. The average tensile strength of PVA nanofibers was determined to be 6.81 Mpa with a ±2.56 Mpa standard deviation, and marginal decrease observed

in PVA/Co-CDs/CoA nanofibers to 6.76 Mpa with a ±0.86 Mpa standard deviation. This slight reduction indicates a minor impact on tensile strength following the addition of carbon dots. Conversely, the elongation at break exhibited a notable disparity between the two samples. PVA nanofibers displayed an average elongation at break of 20.08% with a ±3.83% standard deviation, whereas PVA/Co-CDs/CoA nanofibers demonstrated a notable decrease with an average of 10.27% with a ±2.39 standard deviation. The incorporation of carbon dots into the PVA composite led to a decrease in the elongation at break as observed by Fan Li et al. and Alp et al.[59,60]. This notable decrease implies that the incorporation of carbon dots diminishes the flexibility of the nanofibers. Our XRD results demonstrated that adding carbon dots to the PVA matrix disrupts its crystalline structure[51,52], leading to decreased crystallinity[40,51,52]. This decrease in crystallinity might be reason for a marginal decrease in tensile strength but a significant reduction in elongation at break.

Table 5.1. Mechanical performance test results.

Nanofiber sample	Tensile strength (Mpa)	Elongation at break (%)
PVA	6.81 ± 2.56	20.08 ± 3.83
PVA/Co-CDS/CoA	6.76 ± 0.86	10.27 ± 2.39

5.8. ANTIMICROBIAL ACTIVITY

Based on the inhibition zone measurements obtained, the antimicrobial activity of PVA/Co-CDs/CoA nanofibers was evaluated against S. aureus and E. coli. The results revealed inhibition zones with diameters of 5.8921 mm for S. aureus and 7.88 mm for E. coli. These findings indicate moderate to good antimicrobial efficacy of PVA/Co-CDs/CoA against both Gram-positive and Gram-negative bacteria commonly associated with wound infections, due to the incorporation of carbon dots which exhibit antibacterial properties against both E. coli and S. aureus [49,61].

CHAPTER 6

CONCLUSION

In conclusion, this thesis has explored the prospective and promising aspects of Polyvinyl alcohol PVA nanofibers as advanced wound dressings, and enhancement through the incorporation of carbon dots. The study's general objectives underscored the pivotal role of wound dressings in modern wound care, emphasizing wound healing, exudate management, infection prevention, and patient comfort. Specific objectives centered on investigating PVA's suitability for wound dressings, exploring its physical, mechanical, and biological properties, and enhancing these properties through carbon dot integration and pH-responsive agents.

Through comprehensive characterization employing SEM, FTIR, XRD, TGA, water contact angle, air permeability, mechanical properties, and antimicrobial activity tests, this study elucidated distinct characteristics and functionalities of PVA nanofibers and their enhanced version, PVA nanofibers incorporated with carbon dots (PVA/CoCDS/CoA). Structural and molecular changes observed upon incorporating carbon dots positively influenced the antimicrobial efficacy of PVA/Co-CDs/CoA nanofibers against both Gram-positive and Gram-negative bacteria. These findings highlight the potential of PVA/Co-CDs/CoA nanofibers to effectively combat infections, which is crucial for improving wound healing outcomes.

Additionally, the inclusion of carbon dots did not compromise the mechanical integrity of PVA nanofibers. Enhanced hydrophilicity, modified crystalline structure, and improved thermal degradation properties were also demonstrated in PVA/Co-CDs/CoA nanofibers, promising advancements in wound care applications.

Ultimately, the development of PVA nanofibers incorporated with carbon dots offers substantial advantages in advancing wound care treatments. By effectively addressing critical challenges in infection control and promoting accelerated wound healing, these innovative materials hold promise for enhancing patient outcomes in wound management. This research significantly contributes to expanding the body of knowledge on nanofiber technologies, paving the way for improved therapeutic strategies and outcomes in clinical settings.

Future research should focus on conducting comprehensive in vivo studies to evaluate the long-term biocompatibility, efficacy, and degradation behavior of PVA/Co-CDs/CoA nanofibers in realistic biological environments. Additionally, thorough toxicity analysis is essential to assess potential effects. Detailed histopathological studies and comparative analyses with other nanomaterials will further elucidate the safety profile of PVA/Co-CDs/CoA nanofibers. These investigations will insights necessary for the clinical translation and regulatory approval of these advanced wound dressings.

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RESUME

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