Bulletin of Electrical Engineering and Informatics
Vol. 14, No. 1, February 2025, pp. 409~420
ISSN: 2302-9285, DOI: 10.11591/eei.v14i1.7315

Progression of polymeric nanostructured fibres for pharmaceutical applications

Hamza Abu Owida[1], Jamal I. Al-Nabulsi[1], Nidal M. Turab[2], Muhammad Al-Ayyad[1], Raed Alazaidah[3], Nawaf Alshdaifat[4]
[1]Department of Medical Engineering, Faculty of Engineering, Al-Ahliyya Amman University, Amman, Jordan
[2]Department of Networks and Cyber Security, Faculty of Information Technology, Al-Ahliyya Amman University, Amman, Jordan
[3]Department of Computer Science, Faculty of Information Technology, Zarqa University, Zarqa, Jordan
[4]Department of Computer Science, Faculty of Information Technology, Applied Science Private University, Amman, Jordan

Article Info

Article history:

Received Aug 3, 2023
Revised Aug 24, 2024
Accepted Sep 4, 2024

Keywords:

Drug delivery
Electrospinning
Electrospun nanofibers
Kinetic releasing
Nanofibers

ABSTRACT

Electrospinning has emerged as a simple and cost-effective technique for producing polymer nanofibers, offering a versatile approach for creating nanostructured fibers from a wide range of polymer materials. The pharmaceutical field has particularly welcomed the advent of electrospun nanofibers, as they hold immense potential for revolutionizing drug delivery systems. The recent surge of interest in electrospun nanofibers can be attributed to their unique characteristics, including elasticity and biocompatibility, which make them highly suitable for various biomedical applications. By incorporating functional ingredients into blends of nanostructured fibers, the capabilities and reliability of drug delivery devices have been significantly enhanced. This review aims to provide a comprehensive summary of recent research endeavors focusing on the concept of nanofibrous mesh and its multifaceted applications. With an emphasis on the simplicity of fabrication and the virtually limitless combinations of materials achievable through this approach, nanofibrous meshes hold the promise of transforming specific treatment modalities. By streamlining the delivery of therapeutic agents and offering enhanced control over drug release kinetics, nanofibrous meshes may herald a new era in targeted and personalized medicine.

Corresponding Author:

Nidal Turab
Department of Networks and Cyber Security, Faculty of Information Technology
Al-Ahliyya Amman University
Amman-19328, Jordan
Email: n.turab@ammanu.edu.jo

1. INTRODUCTION

The exploration of novel pharmaceuticals presents a significant challenge for both academic institutions and industry [1]. According to available data, the global pharmaceutical industry allocated an estimated sum of 83 billion dollars towards research and development activities for the creation of novel pharmaceutical products in the year 2019 [2]. Clinical trials are a critical stage in the drug development process, wherein a significant number of drug candidates experience failure due to either unanticipated toxic effects or insufficient efficacy in addressing the specific medical condition under investigation [3]. The therapeutic efficacy of a drug is profoundly influenced by it is mode of delivery, as evidenced by scientific research conducted in recent decades [4]. Nanotechnology-based novel drug delivery approaches have recently emerged as a promising and innovative tool within the pharmaceutical industry [5].

The delivery of drugs is considered a highly promising application of nanotechnology. Electrospinning emerges as an appealing drug delivery technology due to its notable attributes, including a substantial loading capacity, efficient encapsulation, capability to administer multiple therapies concurrently, straightforward operational procedures, and cost-effectiveness. The potential applications of electrospun fibres as drug carriers in the field of biomedicine hold great promise for the future [6]–[8].

Over the years, electrospinning has emerged as a highly efficient, convenient, and versatile method for fabricating nanostructured fibres [9]. The versatility, efficiency, and unique physical and chemical characteristics of nanofibers made from biodegradable and biocompatible polymers have led to their widespread use. These characteristics include a porous structure and a large surface area relative to their ultra-fine diameter [6], [9]. Nanofibrous scaffolds have the potential to be utilised in situ for drug delivery, thereby mitigating the adverse consequences associated with the structural administration of free drugs or alternative drug administration techniques. This approach offers the advantage of enhancing pharmaceutical drug efficacy by facilitating a controlled and gradual release of the drug at the targeted site [10]. The resemblance of the fibbers to the natural fibrils of the extracellular matrix offers a significant advantage for medical applications, as it promotes adhesion and proliferation [11]. The integration of biological molecules into electrospun fibres has been successfully achieved [12]. Devices that possess greater levels of complexity are also capable of administering different drugs with bioactive interactions or adjusting the release of the enclosed drug in response to a stimulus [13]. The present discourse aims to elucidate the various methodologies and field implementations of electrospinning in the context of drug delivery, thereby enhancing the readers' comprehension on this subject matter.

2. ELECTROSPINNING SETUPS AND PROCESS

Nanostructured fibres are produced through the utilisation of a high-voltage electrostatic potential in the process known as electrospinning. The schematic of the electrospinning setup is depicted in Figure 1, consisting of three primary components: a high-voltage supplysyringe pump, and a collector [14]. The fundamental principle underlying the process of electrospinning is the application of a high-intensity electric field. The polymer solution is extracted and dispensed through a syringe. When a high voltage is applied to the polymer solution droplet, it will undergo a significant electrification process, resulting in the dispersion of charges across the entire surface of the droplet. Taylor cones refer to the geometrically spherical structures that emerge when liquid droplets undergo deformation under the influence of an electric field. When the magnitude of the voltage surpasses a certain threshold, the magnitude of the electric force becomes sufficiently robust to surpass the cohesive forces at the surface of the droplet. Consequently, one or more charged streams of solvent are emitted from the tip of the droplet. As the jet nears a metal screen used for collection referred to as the counter electrode, the solvent undergoes evaporation, resulting in the formation of a nonwoven fabric mat as indicated by references [6], [9], [11]. Several factors influence the process, including the magnitude of the electric field, the rate at which the solution flows, the concentration of the solution, the viscosity and conductivity of the solution, the surface tension of the solution, the distance between the syringe and the collector, and the prevailing environmental conditions [6], [10].

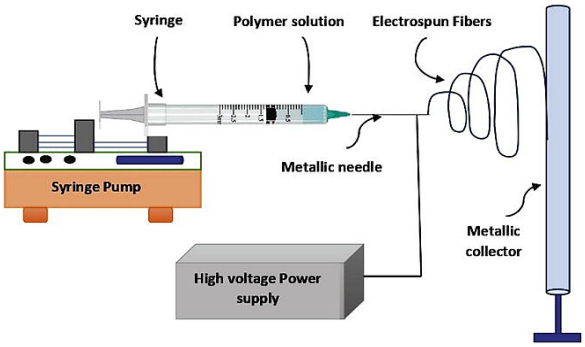


Figure 1. Schematic of general electrospinning setup

3. MECHANISM OF KINETIC RELEASING

Various techniques can be employed to integrate drugs into the fibre, such as emulsification, surface absorption subsequent to the fabrication process, and direct blending of the drug with the polymeric

mixture [15]. Extensive investigation has been conducted in the field of electrospinning, with particular emphasis on diverse carrier materials encompassing both natural and synthetic polymers, as well as their hybrid counterparts [9]. The drug release process is influenced by both the diffusion and degradation of the carrier polymer. In order to enhance drug release kinetics [16], [17], electrospinning techniques are utilised to regulate the spatial arrangement of the drug within the fibrous structure. By acquiring knowledge on the kinetics of release, one can make informed decisions regarding the most suitable technique for fibre synthesis in order to achieve the intended outcome. The release profiles are significantly influenced by various production techniques, fibre morphology, and drug loading [18]. Li *et al.* [19] developed a multilayer synthesis approach for the treatment of breast tumours, wherein various medications were incorporated into distinct polymers. Researchers have successfully coordinated the timing of multiple synergistic chemotherapeutic agents for a predetermined date and time. Electrospinning has the capability to produce a diverse range of nanofibers, with mixed fibres being the most basic form. Figure 2 shows the prepping of dual-drug loaded trilayered structured fibers and time-programmed antitumor drug release in tumor-bearing mice; fabrication of a trilayered fiber membrane using a triaxle electrospinning device (Figure 2(a)), a sectional view of the cavity and fiber (Figure 2(b)), and the release of dual drugs from fibers, as well as their synergistic tumor therapies (Figure 2(c)). The rate at which a drug is released from a polymer structure and their affinities for polymeric materials are both influential factors in drug release.

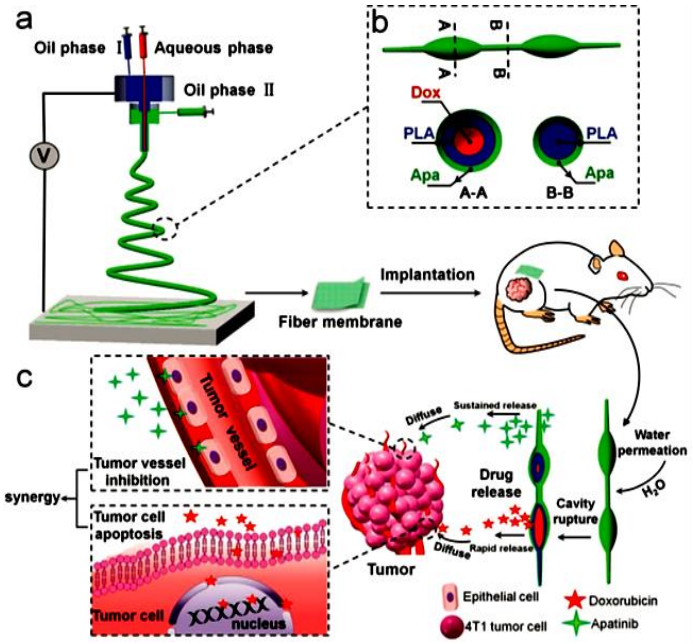


Figure 2. Prepping of dual-drug loaded trilayered structured fibers and time-programmed antitumor drug release in tumor-bearing mice; (a) fabrication of a trilayered fiber membrane using a triaxle electrospinning device, (b) a sectional view of the cavity and fiber, and (c) the release of dual drugs from fibers, as well as their synergistic tumor therapies

Wu *et al.* [20] presented a potential avenue by investigating the characteristics of blends composed of poly (D, L-lactide-co-glycolide) and ciprofloxacin. The process of discharging took place in three distinct stages, which were identified based on the kinetics of release. The initial stage, known as phase one, spanned a few hours and exhibited a first-order pattern. This pattern indicated the dispersion of the integrated drug, as observed through the monitoring of the fibre clump [20]. The Higuchi model's zero-order equation was able to accurately predict a consistent and prolonged release pattern in the second phase, which persisted for multiple days. The final step is determined by the hydrolysis of small oligosaccharides derived from the scaffold, while the distribution of these oligosaccharides within encapsulated substances regulates the ratio at which drugs are released. This phenomenon undergoes a transition into the subsequent stage. The aforementioned condition remains in operation until the fibre is entirely exhausted. The utilisation of twisted pair electrospinning has the potential to mitigate certain challenges related to burst release, as it leads to the formation of a shelled nanofibrous mesh [20]. The polymeric core serves as a barrier between the active ingredient and the remaining components of the formulation. The presence of the shield within the central

nan-mesh provides enhanced protection against environmental degradation, thereby facilitating sustained release of the medicine over an extended duration [21]. A previous study [22] conducted the preparation of Ca-alginate microspheres loaded with bovine serum albumin, followed by the fabrication of poly (L-lactic acid) nanofibrous structures without the use of dispersions. The data presented not only demonstrate the successful integration of Bovine serum albumin, but also indicate that the duration of it is release is extended by a factor of 12 compared to that of free microspheres.

4. ELECTROSPUN NANOFIBERS FOR DRUG DELIVERY APPLICATION

In the field of pharmaceutical development, a wide range of drug delivery strategies has been explored to address the limitations associated with conventional formulations, particularly their toxicity and limited therapeutic efficacy. Traditional drug delivery systems often face challenges such as low bioavailability, rapid degradation, and adverse side effects. To overcome these obstacles, researchers have focused on advanced delivery systems, particularly nanoscale preparations, which include polymeric micelles, nanofibres, and lipid nanoparticles. These nanoscale platforms offer improved control over drug release profiles, reduced systemic toxicity, and enhanced bio-distribution of therapeutic agents. In this context, electrospinning has emerged as a highly versatile technique, providing an adaptable platform for drug carrier applications due to its ability to use various materials and drugs while maintaining high encapsulation efficiency.

Electrospun nanofibers, in particular, have garnered significant attention for their unique properties, which allow for the simultaneous delivery of multiple therapeutic agents and provide enhanced loading capacity. Their nanoscale structure and surface area facilitate efficient drug loading and release, making them ideal candidates for sustained and targeted drug delivery. Additionally, the cost-effectiveness of electrospinning, combined with its ease of application, has positioned nanofibers as a practical and scalable solution for drug delivery applications. This paper aims to examine the utilization of nanofibers in drug delivery systems, highlighting their advantages, challenges, and the strategies required for their further advancement and classification in pharmaceutical applications. The growing interest in nanofiber-based delivery systems reflects the ongoing innovation in the field, with the potential to transform the therapeutic landscape by offering more efficient, targeted, and safer treatments for a wide range of medical conditions.

5. WOUND HEALING AND DRESSING ELECTROSPUN NANOFIBERS

The skin is considered the largest organ of the human body and serves crucial functions in terms of protection, homeostasis, and sensory perception. The skin, despite its crucial function as a protective barrier between the internal and external environments of the body [23], [24], is highly vulnerable to harm. The prompt avoidance of persistent infections and their associated complications can be facilitated by the prompt healing of wounds. The process of wound healing is subject to the influence of various internal and external factors that can impede the recovery and regeneration of tissue [25]. Despite the significant advancements achieved in wound treatment patches and skin substitutes over the past decade, there remains a considerable journey ahead for the magician to address this issue [26]. In order to be suitable for wound healing applications, nanostructures must adhere to certain predetermined requirements. These include the capability to effectively absorb wound exudates, the capacity to mimic the characteristics of the extracellular matrix, and the inherent resistance to bacterial infiltration [27]. The utilisation of electrospinning has the potential to be a valuable technique for obtaining these aforementioned characteristics. The delivery of bioactive chemicals and medicines to the location of chronic wounds has the potential to enhance the protective measures against infection [28].

Bayat *et al.* [29] conducted a study investigating the application of bromelain in combination with a chitosan nanofibrous mesh for the management of burn injuries. The present study investigates the efficacy of debridement in promoting the healing process of burn injuries. Bromelain refers to a composite of proteolytic enzymes that are naturally present in the bodily tissue of pineapples. In the present study, a conventional electrospinning method was employed to fabricate fibres possessing favourable mechanical properties. Moreover, the presence of cytotoxicity was observed in only 4% of the bromelain fibres. The scaffolds underwent in vivo assessment, during which they were compared to unladen chitosan implants. In a study involving mice subjected to a 14-year treatment period, it was observed that conventional collagen fibres exhibited noteworthy wound healing properties, characterised by reduced inflammation, absence of necrosis, and expedited healing.

Varshosaz *et al.* [30] devised the double electrospinning technique to enhance a wound dressing substrate that consists of customised polybutylene and gelatin nanostructure fibres incorporated with doxycycline. Polybutylene is a polyester characterised by its non-toxic nature and remarkable physical

properties. However, it exhibits insolubility and limited biodegradability. Guo *et al.* [31] propose the utilisation of a nanofibrous mesh that is pH-dependent in order to facilitate sequential drug delivery. In this study, the utilisation of polycaprolactone nanofibers incorporating curcumin, an anti-inflammatory agent, and polyethylene glycol, a painkiller, was examined as shown in Figure 3. Lidocaine was promptly administered for pain relief during the initial phases of wound healing. Subsequently, as inflammation ensued and the pH level reached a significantly more acidic state than the biological norm, curcumin was expediently released.

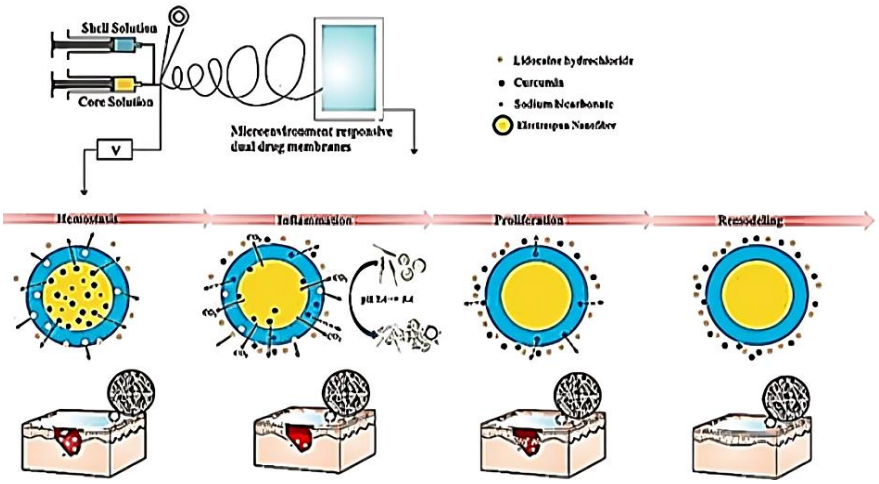


Figure 3. Schematic representation of wound healing using microenvironment-responsive dual-drug-loaded wound dressings

Yang *et al.* [32] conducted a study to determine the antibacterial efficacy of nanofibers composed of Polyvinylpyrrolidone and ethylcellulose, incorporated with ciprofloxacin and silver. The researchers employed a side-by-side technique to assess the antimicrobial properties of these nanofibers. The implementation of this dual approach led to the liberation of ciprofloxacin from the fibres within a time frame of less than 30 minutes. Following a period of 72 hours, the proliferation of bacteria was observed to have increased significantly as a result of the regulated release of silver nanoparticles, which had initially impeded their growth. This particular activity enhances the efficacy of the scaffold as a supplementary tool in wound care by effectively mitigating the transmission of infections.

Faccendini *et al*. [33] conducted a study investigating the application of scaffolds composed of a mixture of polysaccharides as skin grafts. The utilisation of polysaccharide scaffolds for the delivery of Norfloxacin, a fluoroquinolone antibiotic, has been investigated as a potential therapeutic approach for the treatment of wound infections. The fibres were subjected to electrospinning and subsequently coated with either unbound Norfloxacin or a montmorillonite nanocomposite. The process of drug release took place in the context of systemic inflammation, as the lysosomes underwent degradation of the scaffold and facilitated the transportation of the drugs.

Asadi *et al.* [34] sought to address the limited application of zein by integrating it with graphene oxide to fabricate composite nanofibers intended for utilisation in wound dressings. Historically, graphene oxide nanosheets have been utilised for the encapsulation of tetracycline hydrochloride. Subsequently, the achievement of emulsification electrospinning and the fabrication of a composite core integrated with a mesh were facilitated through the process of distributing and blending the polymer solution. The addition of graphene oxide to zein nanofibers resulted in an improvement in their mechanical properties and an extension of the release profile, as compared to zein nanofibers without graphene oxide. Bakhsheshi-Rad *et al.* [35] produced the gentamicin-chitosan-alginate blended fibres. The results of cellular metabolic analysis revealed a positive correlation between higher concentrations of gentamicin and an escalation in the cytotoxic impact of the drug. This finding was observed despite the scaffolds' previously demonstrated efficacy in terms of antibacterial properties, cell adhesion, and proliferation in laboratory settings, as well as their ability to promote skin regeneration in mice. Gentamicin plays a significant role in altering the mechanical properties and cell adhesion characteristics of the substrate in isolation. Hadisi *et al.* [36] developed core-shell nanofibers consisting of hyaluronic acid and silk fibroin. The selection of hyaluronic acid was based on its remarkable ability to regulate the inflammatory response, cell migration, and antigenic response in the context of wound healing. However, it was necessary to combine it with another polymer due to its low physical effects, increased edoema,

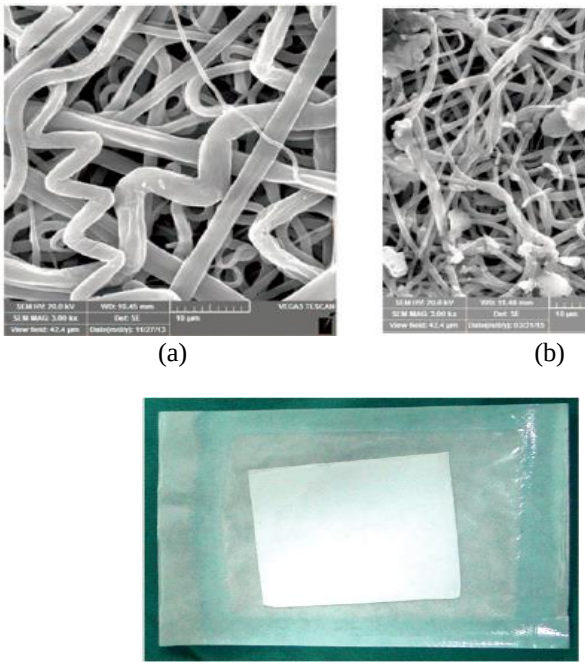
uncontrolled drug delivery, and rapid degradation rate. In order to address the constraints associated with hyaluronic acid, while simultaneously preserving its favourable cytocompatibility, the researchers employed silk fibroin in the aforementioned investigation. The nanofibers were treated with zinc oxide, a substance known for its antimicrobial properties. The nanofibrous mesh incorporating zinc oxide demonstrated favourable performance in an in vitro scratch test, displaying robust cellular adhesion, remarkable wound healing properties, and effective antibacterial activity against both E. coli and S. aureus.

6. ANTIBIOTICS ELECTROSPUN NANOFIBERS THERAPEUTICS DELIVERY

One of the most significant challenges in the field of medicine pertains to the prevalence of infections attributed to microorganisms. Severe illness has the potential to result in sepsis, which is widely recognised as a prominent contributor to mortality [37]. Microbial resistance to antibiotics can emerge. According to projections, by the year 2050, the global mortality rate due to resistance is estimated to reach 50 million individuals per year [38]. Additionally, the efficacy of antimicrobial agents is expected to diminish significantly. The term "antibiotic resistance" pertains to the capacity of a microorganism to endure in the presence of an antimicrobial setting, and the utilisation of antibiotic sequences is frequently employed to enhance effectiveness and hinder the development of resistance. Cystic fibrosis is a pathophysiological condition characterised by the need for recurrent administration of antibiotics to manage persistent infections [39]. Hence, the potential risks associated with the inappropriate use of antibiotics and the subsequent development of bacterial resistance could be effectively addressed by implementing a focused approach that involves the utilisation of innovative antibiotic delivery systems that offer enhanced adaptability and efficacy. Electrospun nanofibers have been identified as a potentially valuable foundation for the development of innovative antibacterial therapeutic drug delivery systems [5], [9]. Behbood *et al.* [40] developed a bio-adhesive oral delivery system by utilising chitosan and gelatin fibres that were loaded with vancomycin, a glycopeptide antibiotic. These implants not only inhibit the metabolic activity that occurs in the liver during the first pass, but also provide a consistent release pattern and improved absorption and availability in the body. The oral bioavailability of vancomycin is limited due to its poor absorption in the gastrointestinal tract, and it is associated with significant adverse effects. Modulating the drug's release rate to achieve higher doses may potentially enhance its therapeutic effectiveness. The results of the in vitro drug release analysis demonstrated that the nanofibrous mesh exhibited a sustained release of vancomycin following a Fickian diffusion mechanism for a duration exceeding three days. In the study conducted by Wei *et al.* [41], the authors presented a drug carrier designed specifically for orthopaedic surgical applications, and their research demonstrated the process of creating Polycaprolactone nanofibers, which were utilised to transport vancomycin into infected critical bone defects. Figure 4 shows resorbable electrospun vancomycin-polycaprolactone membrane electron micrographs; electron microscopy revealed that the test membrane's pore diameter was 10 mm (Figure 4(a)), 3,000x magnification of a resorbable electrospun vancomycin-polycaprolactone membrane (Figure 4(b)), and photograph of the absorbable nanometre polycaprolactone electrospun membrane impregnated with vancomycin (Figure 4(c)).

The scaffolds were designed to promote bone regeneration and reduce bacterial proliferation to slow the spread of disease. The scaffolds' excellent biocompatibility was on display in their capacity to maintain vancomycin release for more than 14 days at a constant rate. To effectively target infections and release antimicrobials, Shi *et al.* [42] devised a unique nanofibrous mesh that relies on contamination. The use of siloxanes in the production process has allowed for the electrospinning integration of additional amino groups into polydopamine-coated fibres. The nitroimidazole antibiotic metronidazole has been esterified onto the nanostructured substrate of the fibres. Intelligent drug delivery systems, which use controlled in vivo injection, may help reduce the prevalence of microbial drug resistance. In order to combat the spread of diseases on skeletal prosthetic limbs, Boncu *et al.* [43] developed a method for making electrospun fibres out of poly (lactic-co-glycolic acid) and polycaprolactone. Antibiotics linezolid and oxazolidinone were infused into these fibres for sustained, timed release. In order to successfully cure an infection with the minimum effective dose of antibiotics, the surrounding soft tissue and bone must be quickly restored. Electrospun meshes have been shown to be highly successful, reducing the need for antimicrobial treatment by a factor of 37 when compared to more traditional treatment methods. To do this, twice-daily medicine administration is no longer required. Antibiotic resistance is a growing problem, but this method has the potential to slow its spread, which in turn could lead to the creation of more cost-effective treatment choices. If this design can be validated in a larger in vivo model, it may lead to a new way of treating an infectious condition that often becomes apparent after surgery. Li *et al.* [44] study from the year 2020 looked into potential uses for a drug carrier that produces stomachic side effects. The system used the polysaccharide galactomannan from B. striata. However, galactomannan hasn't been used as a component in the electrospinning technique's pre-production stage. Lyophilization wafers containing levofloxacin hydrochloride have been used instead. The pills did not have any cytotoxic effects, but they were quite effective at killing H. pylori, the bacteria responsible for acute infectious gastroenteritis. High

drug charging and efficient stomach retention were shown in in vitro and in vivo experiments, showing that the wafer is superior to the free drug carrier in treating H. pylori infection.



(a) (b)

(c)

Figure 4. Resorbable electrospun vancomycin-polycaprolactone membrane electron micrographs; (a) electron microscopy revealed that the test membrane's pore diameter was 10 mm, (b) 3,000x magnification of a resorbable electrospun vancomycin- polycaprolactone membrane, and (c) photograph of the absorbable nanometre polycaprolactone electrospun membrane impregnated with vancomycin

7. ANTICANCER ELECTROSPUN NANOFIBERS THERAPEUTICS DELIVERY

Despite notable advancements in the fields of cancer therapy, diagnosis, and prevention, this disease continues to pose a substantial threat as one of the most lethal conditions globally. Furthermore, it should be noted that this phenomenon is a prominent contributor to mortality rates on a global scale [45]. Cancer is a multifaceted ailment distinguished by the formation of cell clusters that display uncontrolled proliferation and possess the ability to spread to various parts of the body [46]. An earlier diagnosis is often associated with a more favourable prognosis. In order to mitigate the proliferation of cancer, timely detection plays a crucial role, and the emergence of metastases can serve as an indicator for initiating therapeutic interventions or conducting a surgical intervention to eliminate the extraneous mass of the solid tumour [47]. The administration of chemotherapeutic drugs directly to the site of the disease would help maintain their cytotoxic properties while minimising the adverse effects on the entire body. Electrospun scaffolds exhibit favourable characteristics for targeted chemotherapy administration due to their notable biocompatibility and drug release selectivity [48].

In their study, Kuang *et al.* [49] investigated the development of scaffolds capable of controlled release of doxorubicin. The process utilised by the researchers involved the application of combination electrospinning, wherein the hydrophilic polyethylene glycol was combined with the hydrophobic poly-L-lactic acid during the spinning phase. The intended release profile was successfully attained through the utilisation of fibres consisting of a composition of 10% polyethylene glycol and 90% poly-L-lactic acid. Within a span of one hour, it became apparent that polyethylene glycol fibres, with a composition of 100%, underwent complete decomposition, thereby liberating the entirety of the medication they had previously retained. The in vivo bio-distribution of the drug was investigated, revealing it is specific localization to the tumour site while exhibiting an absence of adverse side effects. Nevertheless, it is worth noting that the antitumor effect exhibited by doxorubicin may have been relatively limited, as the initial burst of this drug failed to effectively diminish the growth of the tumour. In their study, He *et al.* [50] employed microfluidic electrospinning as a technique to fabricate a hierarchical nanostructured fibre with the purpose of enabling localised administration of doxorubicin and lapatinib. The process of fibre synthesis commenced by initiating the formation of polymer micelles through the self-assembly of copolymers consisting of 3-aminophenyl boronic acid-polycaprolactone (ethylene glycol) and

doxorubicin. A water-in-oil mixture was prepared using a glass capillary microfluidic device by dispersing specific micelles, glycerine, free doxorubicin, and an oil solution of poly (D, L lactic acid) lapatinib in a monodispersed manner. The experimental findings obtained in vivo provided empirical support for the atypical characteristics of the scaffolds, showcasing precise regulation of drug distribution specifically at the tumour location and remarkable effectiveness in combating cancer through a singular encapsulation process. Following a period of 21 days, the melanoma mass exhibited a reduction of fourfold in the treated mice compared to the control mice. Additionally, the survival rate of the treated rats surpassed that of the control rats. In 2020, a group of researchers led by Zhang *et al.* [51] developed nanostructures with pH sensitivity for the purpose of delivering 5-fluorouracil. The first stage of the process entailed the occurrence of nucleophilic substitution surrounding the cysteine residue present in keratin, leading to the formation of a covalent bond with the administered medication. In order to fabricate a nanostructured mesh for localised cancer chemotherapy, a composite of the polymer and poly-L-lactic acid was blended and subsequently subjected to electrospinning. During the initial 120-hour period following activation, the fibres exhibit a release rate of approximately 83% of the medication, indicating a notable and effective anticancer impact.

Yan *et al.* [52] employed the central electrospinning technique to fabricate nanofibers exhibiting pH-sensitive properties, characterised by a distinct core-shell structure. Both the inner and outer structures were constructed using polyvinyl chloride (PVC) material. The retention and release of doxorubicin from the vital film is contingent upon the pH level. Nanostructured fibres with the thickest shells exhibited the lowest doxorubicin release. The discharge exhibited a sluggish rate in a pH-neutral environment, indicating a potential correlation with pH levels. The assessment of fibres on a cell line associated with cervical cancer demonstrated a period of three days before any discernible impact became evident. Following a period of 7 days, the cellular morphology continued to remain concealed, thereby indicating the efficacy of the medication in inducing cell death. The advantages of an accelerated initial discharge in breast cancer treatment extend beyond captivating behaviour and diminished cytotoxicity.

In their study, Sedghi *et al.* [53] utilised nanostructures fabricated from a chitosan derivative with the aim of reducing the incidence of breast cancer in the local vicinity. The hydrophilicity of chitosan was augmented through the chemical modification involving the addition of a tetraethyl urea thiosemicarbazone moiety. In vitro studies have demonstrated the potential anticancer activity of thiocarbonyl groups, with no observed harm to normal cells. In order to enhance the intrinsic anti-proliferative and antibacterial properties of the fibres, the incorporation of curcumin into the material was implemented, resulting in a gradual release of the compound over a period of time [54]. In the following table, a summary of numerous typical medicines that have been incorporated into electrospun mat for use in drug delivery applications is provided. Table 1 represnts several drugs were loaded into electrospun mat for drug delivery applications.

Table 1. Several representative drugs were loaded into electrospun mat for drug delivery applications

Nanofibrous mat	Drug	Application	Reference
Chitosan	Bromelain	Burn wound recovery	[29]
Gelatin	Doxycycline	Skin wound dressing	[30]
Polyethylene glycol and chitosan	Lidocaine hydrochloride	Wound healing	[31]
Polyvinylpyrrolidone	Ciprofloxacin	Antibacterial patch	[32]
Polysaccharide	Norfloxacin	Skin grafts	[33]
Graphene oxide	Tetracycline hydrochloride	Wound dressings	[34]
Chitosan-alginate	Gentamicin	Skin wound dressing	[35]
Hyaluronic acid and silk fibroin	Zinc oxide	Wound dressings and antibacterial patch	[36]
Gelatin	Vancomycin	Antibacterial carrier	[40]
Polycaprolactone	Vancomycin	Bone healing	[41]
Polydopamine	Metronidazole	Anti-infection agent	[42]
Polycaprolactone	Linezolid, and oxazolidinone	Skeletal prosthetic limb pathogens	[43]
Galactomannan polymer	Levofloxacin hydrochloride	Antibacterial tablets	[44]
Polyethylene glycol	Doxorubicin	Anticancer	[49]
Polycaprolactone (ethylene glycol)	Doxorubicin and apatinib	Anticancer	[50]
Poly-L-lactic acid	5-FU-K-P	Anticancer	[51]
Polyvinyl chloride	Doxorubicin	Anticancer	[52]
Chitosan	Thiocarbonyl groups	Anticancer	[53]

The field of electrospinning has experienced significant advancements and growth in recent decades. The extensive range of possibilities offered by electrospinning presents a strong foundation for the advancement of inventive drug delivery applications that can optimise therapeutic efficacy while minimising negative consequences. The process of drug and polymer selection can be effectively optimised to cater to specific application areas or requirements. The utilisation of nanofibrous mesh has the potential to create new

opportunities for precision medicine through the manipulation of mechanical properties or controlled release kinetics. In addition to the notable benefits offered by this methodology, it is worth noting that only a limited number of clinical investigations have been reported in scholarly publications throughout the years. Furthermore, regulatory bodies such as the food and drug administration (FDA) and the European Medicines Agency (EMA) have not yet endorsed any of these systems. The toxic residue of the mixture used in the spinning process can often persist in the fibre and subsequently be released into the drug. This occurs due to the convenience of electrospinning as a straightforward method for creating controlled and intelligent drug delivery systems [55]–[58].

8. CONCLUSION

The adoption of biocompatible mixtures in lieu of harsh and toxic alternatives stands as a remarkable testament to innovation within the field. An alternative avenue of exploration lies in melt electrospinning, a technique that fabricates nanofibers without the need for solvents, offering a potentially highly effective approach. However, stringent measures must be implemented to safeguard medications from elevated temperatures and prevent degradation. Furthermore, the rapid advancement of knowledge and the evolution of increasingly sophisticated mutual systems hold the potential to foster the development of integrated intelligent devices. Such devices could exhibit precise control over the level of subsequent bodily stimulation triggered by the release of drugs from a nanofibrous substrate. Areas of research concerning nanofibrous meshes in the context of diabetes, hormonal treatment, and immune disorders remain ripe for exploration. Despite strides made in various fields, comprehensive investigations into the utilization of nanofibrous materials in these domains are yet to be thoroughly pursued. This underscores the potential for significant breakthroughs and novel therapeutic approaches in the treatment of complex medical conditions. The adoption of a comprehensive and systematic methodology holds immense promise in effectively addressing the significant challenges posed by electrospun nanofibers. By employing rigorous and well-defined protocols, researchers and practitioners can navigate the complexities inherent in the fabrication, characterization, and application of these nanofibrous materials, thereby unlocking their full potential in various biomedical applications. Looking forward, optimized scaffolds stand poised to emerge as indispensable instruments for fostering seamless integration between medical facilities and patients. These scaffolds represent a sophisticated nexus where tissue engineering converges with precise drug delivery mechanisms, offering a holistic approach to treatment while mitigating the risks of adverse effects. By leveraging advanced materials and engineering principles, these scaffolds hold the capacity to revolutionize therapeutic interventions, offering tailored solutions that address individual patient needs with unparalleled precision and efficacy. The distinctive attributes and inherent user-friendliness of tailored nanofibers are poised to catalyze transformative advancements in the realm of personalized medicine. As the field continues to evolve, nanofibrous materials equipped with tailored properties and functionalities are anticipated to assume increasingly pivotal roles in diagnostic, therapeutic, and regenerative medicine applications. From targeted drug delivery systems to tissue regeneration scaffolds, these nanofibers offer versatile platforms that can be customized to meet the unique demands of patients, ultimately enhancing treatment outcomes and quality of life. In essence, the judicious integration of optimized scaffolds and tailored nanofibers represents a paradigm shift in modern healthcare, offering novel avenues for precision medicine and patient-centered care. Through continued innovation and interdisciplinary collaboration, these advanced materials hold the potential to redefine the landscape of medical practice, ushering in an era of personalized therapeutics and enhanced patient well-being.

Looking ahead, optimized scaffolds hold the promise of becoming indispensable assets for bridging medical facilities and patients. These scaffolds are poised to facilitate the seamless integration of tissue engineering and targeted drug delivery, all while mitigating potential adverse effects. The distinct characteristics and intuitive design of customized nanofibers are poised to play an increasingly pivotal role in the realm of personalized medicine. In the future, optimized scaffolds are poised to revolutionize the way medical facilities and patients interact. By facilitating the seamless integration of tissue engineering and precise drug delivery, these scaffolds offer a multifaceted approach to treatment that minimizes the risk of adverse effects. The tailored nature and user-friendly design of nanofibers make them particularly well-suited for personalized medicine, where individualized treatment approaches are paramount. As such, the utilization of optimized scaffolds represents a significant step forward in enhancing patient care and treatment outcomes.

REFERENCES

[1] I. Khanna, "Drug discovery in pharmaceutical industry: productivity challenges and trends," *Drug Discovery Today*, vol. 17, no. 19/20, pp. 1088–1102, 2012, 10.1016/j.drudis.2012.05.007.

[2] Z. Sanad and A. M.A. M. Al-Sartawi, "Research and development spending in the pharmaceutical industry: does board gender diversity matter?," *Journal of Open Innovation: Technology, Market, and Complexity*, vol. 9, no. 3, 2023, doi: 10.1016/j.joitmc.2023.100145.

[3] G. A. Van Norman, "Phase II trials in drug development and adaptive trial design," *JACC: Basic to Translational Science*, vol. 4, no. 3, pp. 428–437, 2019, doi: 10.1016/j.jacbts.2019.02.005.
[4] O. S. Fenton, K. N. Olafson, P. S. Pillai, M. J. Mitchell, and R. Langer, "Advances in biomaterials for drug delivery," *Advanced Materials*, vol. 30, no. 29, 2018, doi: 10.1002/adma.201705328.
[5] B. Pant, M. Park, and S. J. Park, "Drug delivery applications of core-sheath nanofibers prepared by coaxial electrospinning: a review," *Pharmaceutics*, vol. 11, no. 7, 2019, doi: 10.3390/pharmaceutics11070305.
[6] Z. M. Huang, Y. Z. Zhang, M. Kotaki, and S. Ramakrishna, "A review on polymer nanofibers by electrospinning and their applications in nanocomposites," *Composites Science and Technology*, vol. 63, no. 15, pp. 2223–2253, 2003, doi: 10.1016/S0266-3538(03)00178-7.
[7] H. A. Owida, N. L. Kuiper, and Y. Yang, "Maintenance and acceleration of pericellular matrix formation within 3D cartilage cell culture models," *Cartilage*, vol. 13, no. 2, pp. 847–861, 2021, doi: 10.1177/1947603519870839.
[8] X. Feng, J. Li, X. Zhang, T. Liu, J. Ding, and X. Chen, "Electrospun polymer micro/nanofibers as pharmaceutical repositories for healthcare," *Journal of Controlled Release*, vol. 302, pp. 19–41, 2019, doi: 10.1016/j.jconrel.2019.03.020.
[9] X. Zhang, X. Shi, J. E. Gautrot, and T. Peijs, "Nanoengineered electrospun fibers and their biomedical applications: a review," *Nanocomposites*, vol. 7, no. 1, pp. 1–34, 2021, doi: 10.1080/20550324.2020.1857121.
[10] X. Hu, S. Liu, G. Zhou, Y. Huang, Z. Xie, and X. Jing, "Electrospinning of polymeric nanofibers for drug delivery applications," *Journal of Controlled Release*, vol. 185, no. 1, pp. 12–21, 2014, doi: 10.1016/j.jconrel.2014.04.018.
[11] Q. P. Pham, U. Sharma, and A. G. Mikos, "Electrospinning of polymeric nanofibers for tissue engineering applications: a review," *Tissue Engineering*, vol. 12, no. 5, pp. 1197–1211, 2006, doi: 10.1089/ten.2006.12.1197.
[12] T. Lu, X. Chen, Q. Shi, Y. Wang, P. Zhang, and X. Jing, "The immobilization of proteins on biodegradable fibers via biotin-streptavidin bridges," *Acta Biomaterialia*, vol. 4, no. 6, pp. 1770–1777, 2008, doi: 10.1016/j.actbio.2008.05.006.
[13] S. Quan, C. Xuesi, L. Tiancheng, and J. Xiabin, "The immobilization of proteins on biodegradable polymer fibers via click chemistry," *Biomaterials*, vol. 29, no. 8, pp. 1118–1126, 2008, doi: 10.1016/j.biomaterials.2007.11.008.
[14] G. K. Sharma and N. R. James, "Electrospinning: the technique and applications," *Recent Developments in Nanofibers Research*, 2023, doi: 10.5772/intechopen.105804.
[15] S. Nagarajan, M. Bechelany, N. S. Kalkura, P. Miele, C. P. Bohatier, and S. Balme, "Electrospun nanofibers for drug delivery in regenerative medicine," *Applications of Targeted Nano Drugs and Delivery Systems: Nanoscience and Nanotechnology in Drug Delivery*, pp. 595–625, 2018, doi: 10.1016/B978-0-12-814029-1.00020-X.
[16] B. Wang, Y. Wang, T. Yin, and Q. Yu, "Applications of electrospinning technique in drug delivery," *Chemical Engineering Communications*, vol. 197, no. 10, pp. 1315–1338, 2010, doi: 10.1080/00986441003625997.
[17] J. Zeng *et al.*, "Biodegradable electrospun fibers for drug delivery," *Journal of Controlled Release*, vol. 92, no. 3, pp. 227–231, 2003, doi: 10.1016/S0168-3659(03)00372-9.
[18] N. C. Mishra and S. M. Majumder, "Polymeric nanofibers in regenerative medicine," *Nanomedicine for Drug Delivery and Therapeutics*, pp. 197–225, 2013, doi: 10.1002/9781118636299.ch8.
[19] X. Li, Y. He, J. Hou, G. Yang, and S. Zhou, "A time-programmed release of dual drugs from an implantable trilayer structured fiber device for synergistic treatment of breast cancer," *Small*, vol. 16, no. 9, 2020, doi: 10.1002/smll.201902262.
[20] J. Wu *et al.*, "Mechanism of a long-term controlled drug release system based on simple blended electrospun fibers," *Journal of Controlled Release*, vol. 320, pp. 337–346, 2020, doi: 10.1016/j.jconrel.2020.01.020.
[21] N. Nikmaram *et al.*, "Emulsion-based systems for fabrication of electrospun nanofibers: food, pharmaceutical and biomedical applications," *RSC Advances*, vol. 7, no. 46, pp. 28951–28964, 2017, doi: 10.1039/c7ra00179g.
[22] H. Qi, P. Hu, J. Xu, and A. Wang, "Encapsulation of drug reservoirs in fibers by emulsion electrospinning: Morphology characterization and preliminary release assessment," *Biomacromolecules*, vol. 7, no. 8, pp. 2327–2330, 2006, doi: 10.1021/bm060264z.
[23] M. Venus, J. Waterman, and I. McNab, "Basic physiology of the skin," *Surgery*, vol. 29, no. 10, pp. 471–474, 2011, doi: 10.1016/j.mpsur.2011.06.010.
[24] P. A. J. Kolarsick, M. A. Kolarsick, and C. Goodwin, "Anatomy and physiology of the skin," *Journal of the Dermatology Nurses' Association*, vol. 3, no. 4, pp. 203–213, 2011.
[25] M. Takeo, W. Lee, and M. Ito, "Wound healing and skin regeneration," *Cold Spring Harbor Perspectives in Medicine*, vol. 5, no. 1, 2015, doi: 10.1101/cshperspect.a023267.
[26] A. T. El-Serafi, I. T. El-Serafi, M. Elmasry, I. Steinvall, and F. Sjöberg, "Skin regeneration in three dimensions, current status, challenges and opportunities," *Differentiation*, vol. 96, pp. 26–29, 2017, doi: 10.1016/j.diff.2017.06.002.
[27] K. Vig *et al.*, "Advances in skin regeneration using tissue engineering," *International Journal of Molecular Sciences*, vol. 18, no. 4, 2017, doi: 10.3390/ijms18040789.
[28] M. Norouzi, S. M. Boroujeni, N. Omidvarkordshouli, and M. Soleimani, "Advances in skin regeneration: application of electrospun scaffolds," *Advanced Healthcare Materials*, vol. 4, no. 8, pp. 1114–1133, 2015, doi: 10.1002/adhm.201500001.
[29] S. Bayat, N. Amiri, E. Pishavar, F. Kalalinia, J. Movaffagh, and M. Hahsemi, "Bromelain-loaded chitosan nanofibers prepared by electrospinning method for burn wound healing in animal models," *Life Sciences*, vol. 229, pp. 57–66, 2019, doi: 10.1016/j.lfs.2019.05.028.
[30] J. Varshosaz *et al.*, "RGD peptide grafted polybutylene adipate-co-terephthalate/gelatin electrospun nanofibers loaded with a matrix metalloproteinase inhibitor drug for alleviating of wounds: an in vitro/in vivo study," *Drug Development and Industrial Pharmacy*, vol. 46, no. 3, pp. 484–497, 2020, doi: 10.1080/03639045.2020.1730397.
[31] H. Guo, S. Tan, J. Gao, and L. Wang, "Sequential release of drugs form a dual-delivery system based on pH-responsive nanofibrous mats towards wound care," *Journal of Materials Chemistry B*, vol. 8, no. 8, pp. 1759–1770, 2020, doi: 10.1039/c9tb02522g.
[32] J. Yang, K. Wang, D. G. Yu, Y. Yang, S. W. A. Bligh, and G. R. Williams, "Electrospun Janus nanofibers loaded with a drug and inorganic nanoparticles as an effective antibacterial wound dressing," *Materials Science and Engineering C*, vol. 111, 2020, doi: 10.1016/j.msec.2020.110805.
[33] A. Faccendini *et al.*, "Norfloxacin-loaded electrospun scaffolds: Montmorillonite nanocomposite vs. free drug," *Pharmaceutics*, vol. 12, no. 4, 2020, doi: 10.3390/pharmaceutics12040325.
[34] H. Asadi, A. Ghaee, J. Nourmohammadi, and A. Mashak, "Electrospun zein/graphene oxide nanosheet composite nanofibers with controlled drug release as antibacterial wound dressing," *International Journal of Polymeric Materials and Polymeric Biomaterials*, vol. 69, no. 3, pp. 173–185, 2020, doi: 10.1080/00914037.2018.1552861.
[35] H. R. Bakhsheshi-Rad *et al.*, "In vitro and in vivo evaluation of chitosan-alginate/gentamicin wound dressing nanofibrous with high antibacterial performance," *Polymer Testing*, vol. 82, 2020, doi: 10.1016/j.polymertesting.2019.106298.

[36] Z. Hadisi *et al.*, "Hyaluronic acid (HA)-based silk fibroin/zinc oxide core-shell electrospun dressing for burn wound management," *Macromolecular Bioscience*, vol. 20, no. 4, 2020, doi: 10.1002/mabi.201900328.
[37] R. J. Ulevitch, "Therapeutics targeting the innate immune system," *Nature Reviews Immunology*, vol. 4, no. 7, pp. 512–520, 2004, doi: 10.1038/nri1396.
[38] Food and Agriculture Organization of the United Nations, *Tackling Antimicrobial Use and Resistance in Pig Production*, p. 50, 2019, doi: 10.18356/9d63b715-en.
[39] "The journal of global antimicrobial resistance meets the world health organization (WHO)," *Journal of Global Antimicrobial Resistance*, vol. 18, pp. 305–308, 2019, doi: 10.1016/j.jgar.2019.07.022.
[40] L. Behbood, S. Karimi, E. Mirzaei, G. Mohammadi, M. Azami, and E. Arkan, "Mucoadhesive chitosan electrospun nanofibers containing tetracycline and triamcinolone as a drug delivery system," *Fibers and Polymers*, vol. 19, no. 7, pp. 1454–1462, 2018, doi: 10.1007/s12221-018-8087-1.
[41] S. Wei *et al.*, "Vancomycin-impregnated electrospun polycaprolactone (PCL) membrane for the treatment of infected bone defects: An animal study," *Journal of Biomaterials Applications*, vol. 32, no. 9, pp. 1187–1196, 2018, doi: 10.1177/0885328218754462.
[42] R. Shi *et al.*, "Infection-responsive electrospun nanofiber mat for antibacterial guided tissue regeneration membrane," *Materials Science and Engineering C*, vol. 100, pp. 523–534, 2019, doi: 10.1016/j.msec.2019.03.039.
[43] T. E. Boncu, A. U. Guclu, M. F. Catma, A. Savaser, A. Gokce, and N. Ozdemir, "In vitro and in vivo evaluation of linezolid loaded electrospun PLGA and PLGA/PCL fiber mats for prophylaxis and treatment of MRSA induced prosthetic infections," *International Journal of Pharmaceutics*, vol. 573, 2020, doi: 10.1016/j.ijpharm.2019.118758.
[44] Z. Li, R. Zeng, L. Yang, X. Ren, K. G. Maffucci, and Y. Qu, "Development and characterization of PCL electrospun membrane-coated bletilla striata polysaccharide-based gastroretentive drug delivery system," *AAPS PharmSciTech*, vol. 21, no. 2, 2020, doi: 10.1208/s12249-019-1607-5.
[45] K. D. Miller *et al.*, "Cancer treatment and survivorship statistics, 2019," *CA: A Cancer Journal for Clinicians*, vol. 69, no. 5, pp. 363–385, 2019, doi: 10.3322/caac.21565.
[46] B. A. Helmink, M. A. W. Khan, A. Hermann, V. Gopalakrishnan, and J. A. Wargo, "The microbiome, cancer, and cancer therapy," *Nature Medicine*, vol. 25, no. 3, pp. 377–388, 2019, doi: 10.1038/s41591-019-0377-7.
[47] N. Hawkes, "Cancer survival data emphasise importance of early diagnosis," *BMJ (Clinical research ed.)*, vol. 364, 2019, doi: 10.1136/bmj.l408.
[48] J. Zhao and W. Cui, "Functional electrospun fibers for local therapy of cancer," *Advanced Fiber Materials*, vol. 2, no. 5, pp. 229–245, 2020, doi: 10.1007/s42765-020-00053-9.
[49] G. Kuang *et al.*, "Biphasic drug release from electrospun polyblend nanofibers for optimized local cancer treatment," *Biomaterials Science*, vol. 6, no. 2, pp. 324–331, 2018, doi: 10.1039/c7bm01018d.
[50] Y. He, X. Li, J. Ma, G. Ni, G. Yang, and S. Zhou, "Programmable codelivery of doxorubicin and apatinib using an implantable hierarchical-structured fiber device for overcoming cancer multidrug resistance," *Small*, vol. 15, no. 8, 2019, doi: 10.1002/smll.201804397.
[51] J. Zhang *et al.*, "Novel pH-sensitive drug-loaded electrospun nanofibers based on regenerated keratin for local tumor chemotherapy," *Textile Research Journal*, vol. 90, no. 19–20, pp. 2336–2349, 2020, doi: 10.1177/0040517520919920.
[52] E. Yan *et al.*, "pH-sensitive core-shell electrospun nanofibers based on polyvinyl alcohol/polycaprolactone as a potential drug delivery system for the chemotherapy against cervical cancer," *Journal of Drug Delivery Science and Technology*, vol. 55, 2020, doi: 10.1016/j.jddst.2019.101455.
[53] R. Sedghi, M. Gholami, A. Shaabani, M. Saber, and H. Niknejad, "Preparation of novel chitosan derivative nanofibers for prevention of breast cancer recurrence," *European Polymer Journal*, vol. 123, 2020, doi: 10.1016/j.eurpolymj.2019.109421.
[54] A. Bueno-Orovio, C. Sánchez, E. Pueyo, and B. Rodriguez, "Na/K pump regulation of cardiac repolarization: Insights from a systems biology approach," *Pflugers Archiv European Journal of Physiology*, vol. 466, no. 2, pp. 183–193, 2014, doi: 10.1007/s00424-013-1293-1.
[55] H. A. Owida, G. AlMahadin, J. I. Al-Nabulsi, N. Turab, S. Abuowaida, and N. Alshdaifat, "Automated classification of brain tumor-based magnetic resonance imaging using deep learning approach," *International Journal of Electrical and Computer Engineering*, vol. 14, no. 3, pp. 3150–3158, 2024, doi: 10.11591/ijece.v14i3.pp3150-3158.
[56] A. Y. Alhusenat, H. A. Owida, H. A. Rababah, J. I. Al-Nabulsi, and S. Abuowaida, "A secured multi-stages authentication protocol for IoT devices," *Mathematical Modelling of Engineering Problems*, vol. 10, no. 4, pp. 1352–1358, 2023, doi: 10.18280/mmep.100429.
[57] A. Al Sharah, H. A. Owida, F. Alnaimat, and S. Abuowaida, "Application of machine learning in chemical engineering: outlook and perspectives," *IAES International Journal of Artificial Intelligence*, vol. 13, no. 1, pp. 619–630, 2024, doi: 10.11591/ijai.v13.i1.pp619-630.
[58] H. A. Owida, O. S. M. Hemied, R. S. Alkhawaldeh, N. F. F. Alshdaifat, and S. F. A. Abuowaida, "Improved deep learning approaches for Covid-19 recognition in Ct images," *Journal of Theoretical and Applied Information Technology*, vol. 100, no. 13, pp. 4925–4931, 2022.

BIOGRAPHIES OF AUTHORS

Hamza Abu Owida Ph.D. in biomedical engineering, Assistant Professor at the Department of Medical Engineering, Al-Ahliyya Amman University, Jordan. Research interests focused on biomedical sensors, nanotechnology, and tissue engineering. He can be contacted at email: h.abuowida@ammanu.edu.jo.

Jamal I. Al-Nabulsi Ph.D. in biomedical engineering, Professor at the Department of Medical Engineering, Al-Ahliyya Amman University, Jordan. His research interests are biomedical sensors, digital signal processing, and image processing. He can be contacted at email: j.nabulsi@ammanu.edu.jo.

Nidal M. Turab Ph.D. in computer science Professor at the Department of Networks and Cyber Security, Al-Ahliyya Amman University, Jordan. His research interests include WLAN security, computer networks security and cloud computing security, eLearning, and internet of things. He can be contacted at email: N.turab@ammanu.edu.jo.

Muhammad Al-Ayyad Ph.D. in electrical engineering, biomedical instrumentation, Associate Professor at the Department of Medical Engineering, Al-Ahliyya Amman University, Jordan. His research interests are big home healthcare settings, medical rehabilitation instrumentation, and biomedical measurements. He can be contacted at email: mayyad@ammanu.edu.jo.

Raed Alazaidah received the B.Sc. degrees in computer information system, M.Sc. degrees in computer science from AL al-Bayt University, Jordan, in 2012 and 2015, respectively, and the Ph.D. degree in computer science from Universiti Sains Malaysia, Malaysia, in 2023. He is currently working as an Assistant Professor with the Department of Computer Science, Zarqa University, Jordan. His research interests include deep learning, depth estimation, point cloud, and computer vision. He can be contacted at email: razaidah@zu.edu.jo.

Nawaf Alshdaifat received the B.Sc. degrees in computer science from AL Al-Bayt University and M.Sc. degrees in computer science from the University of Jordan, Jordan, in 2002 and 2011, respectively, and the Ph.D. degree in computer science from Universiti Sains Malaysia, Malaysia, in 2023. His research interests include deep learning and machine learning. He can be contacted at email: nawaf@aabu.edu.jo.