Portable In-situ Electrospinning Devices for Personalized Healing in Emergency Wound Care

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Abstract:

Portable in-situ electrospinning devices have emerged as a transformative solution for personalized wound care, particularly in emergency situations. These devices enable the direct deposition of nanofiber layers onto wound sites, providing a protective barrier, promoting hemostasis, and facilitating the incorporation of antimicrobial agents and healing accelerators. This review examines the technological advancements in portable electrospinning devices, various application methods, and their clinical relevance in emergency wound care. The fundamentals of electrospinning technologies, including needle-based, needle-free, melt, emulsion, and solution electrospinning, are discussed, elucidating their unique strengths and limitations. The development of battery-operated and generator-powered portable devices has expanded the scope of electrospinning applications, enabling their utilization in diverse environments such as remote locations, surgical settings, and home care. Comparative analysis of portable electrospinning devices and traditional methods for wound healing applications reveals the potential of these devices to produce nanofiber dressings with enhanced mechanical properties, barrier functions, and biocompatibility. However, challenges persist in achieving consistent fiber quality, scalability, and further refinement of device portability. The future of portable in-situ electrospinning devices presents significant potential for revolutionizing wound care, tissue engineering, and personalized medicine, with advancements in automation, material innovation, and the integration of bioactive components expected to drive further progress in this field.

Keywords: Portable electrospinning, emergency wound healing, nanofiber dressings, in-situ application, personalised medicine, tissue regeneration

1. Introduction

Millions of individuals sustain injuries annually, necessitating immediate medical attention due to accidents, burns, and surgical procedures [1], [2]. In emergency situations, expeditious and efficacious wound management is crucial to mitigate the risk of infection, expedite healing, and enhance patient comfort [3]. Conventional wound dressings are frequently manufactured with standardised dimensions and configurations, which may inadequately address wounds with irregular surfaces or profound tissue damage [4]. In this context, portable in-situ electrospinning devices present a transformative solution by facilitating the direct application of nanofiber layers to the wound site [5]. Electrospinning enables the production of nanofibers from biocompatible polymers that conform precisely to the morphology and structure of the wound [6]. This approach not only provides a protective barrier but also allows the incorporation of antimicrobial agents and healing accelerators directly into the wound area [7].

In emergencies, the advantages of portable electrospinning devices are substantial. Their capacity for on-site application renders them invaluable for utilisation outside hospital settings, including in accident scenes and remote locations [5]. By generating customised nanofiber dressings, electrospinning devices ensure that each wound is treated with a layer that is specifically tailored to its dimensions and depth [8], [9]. This capability is particularly crucial for irregular or complex wounds, which are challenging to manage with conventional dressings [10].

Electrospinning technology also facilitates rapid hemostasis by applying fibre layers that promote clotting and reduce haemorrhage [11]. This process enables immediate wound coverage, which can significantly minimise blood loss and initiate tissue repair [12]. Furthermore, the nanofiber layers function as a barrier against microorganisms, reducing the risk of infection. The fibres can be infused with antibacterial agents to further enhance the protective properties of the dressing [13], [14].

The portable and lightweight design of battery-powered or generator-supported electrospinning devices enhances their utility in field environments, rendering them suitable for military operations, disaster relief, and rural healthcare [15]. The development of these devices represents a significant advancement in wound care, extending beyond hospital settings to provide essential support during emergencies, natural disasters, and remote medical situations [16]. This article examines the technological advancements in electrospinning devices, various application methods, and their clinical relevance in emergency wound care.

Melt electrospinning, in contrast to its solution-based counterpart, is considered more advantageous and environmentally sustainable because it does not involve solvents, thus eliminating harmful residues. This method allows the utilisation of biocompatible polymers that lack suitable solvents at room temperature. The unique properties of melt electrospinning render it particularly well-suited for in situ applications [17]. Conventional melt electrospinning devices typically rely on heating methods, such as resistance wires, lasers, microwaves, or heated air and oil, all of which require a main power supply. This dependence on electricity limits their practicality, particularly in remote or outdoor settings [17]. Alternative methods involving alcohol lamps or candles have been attempted, but these are often cumbersome, inefficient, and difficult to transport. Efforts to integrate resistance wire heating with high-voltage electrospinning have faced challenges owing to electromagnetic interference, complicating the development of portable devices [18]. To address this issue, a compact and lightweight portable in situ melt electrospinning device was designed. This device operates on AAA batteries and incorporates heat preservation and an antistatic unit to minimise interference. Weighing approximately 450 g and measuring 24 × 6 × 13 cm enables direct electrospinning of polymers, such as PCL, onto wounds. The melt electrospinning gun has potential applications in personal healthcare, medical procedures, cosmetic treatments, and educational demonstrations [19].

Despite advancements in nanofiber technology, there remains a lack of a widely adopted, clinically validated in situ electrospinning device capable of consistently producing nanofibrous dressings directly on wounds in diverse medical settings. This investigation examined the feasibility of developing a portable electrospinning device to address this unmet need [20].

Conventional electrospinning systems, while efficacious in laboratory and controlled clinical settings, lack the requisite portability and scalability for deployment in dynamic, real-world environments such as disaster zones, remote locations, and battlefields. Extant portable devices frequently encounter challenges pertaining to the consistency of fiber production, the incorporation of biocompatible polymers, and the precision necessitated for complex wound morphologies [21]. Moreover, despite advancements in prototype designs, clinical validation of portable in situ electrospinning devices remains limited, impeding widespread adoption [22].

This review addresses these critical gaps by examining advancements in portable electrospinning technologies and proposing future directions to enhance their practicality and reliability in diverse medical settings. Through an analysis of the evolution of these devices and their applications, this work aims to bridge the gap between laboratory innovation and real-world clinical needs.

2. Electrospinning Technologies

Electrospinning is a process driven by high voltage that utilises electrohydrodynamic principles to generate fibres from polymeric solution [23]. The application of a high voltage to a liquid droplet results in its electrification, producing a jet that undergoes elongation and stretching to form fibres [24]. The resultant fibres exhibit diameters ranging from nanometers to several micrometres [25]. A primary advantage of electrospinning is its versatility, which enables the fabrication of fibres with diverse configurations and structures [26].

A typical electrospinning apparatus comprises three primary components [27].

i. High-voltage power supply: This generates the electric field required for fibre formation.
ii. Spinneret (metallic needle) – Directs the polymer droplet for jet formation.
iii. Grounded collector: Collects spun fibres in the form of a non-woven mat.
iv. The collector can assume various forms, including flat plates, spinning drums, or rotating discs.

The fundamental mechanism of electrospinning can be elucidated by considering a charged droplet of conductive liquid. When placed in a vacuum, the droplet experiences two opposing forces:[28]

i. Electrostatic repulsion – Tends to disrupt droplet integrity.
ii. Surface tension: The spherical shape of the droplet was maintained.

As voltage is applied to the droplet at the spinneret tip, the droplet elongates into a conical shape known as a "Taylor cone." The droplet generates a stream directed toward the collector when the electrostatic force exceeds the surface tension. This liquid can be a polymer melt, a solution, or an emulsion. Solid fibres form as the polymer cools, or the solvent evaporates during the trajectory of the jet from the Taylor cone to the collector, resulting in the deposition of fibres on the collector [29]. Electrospinning can be categorised on the basis of the setup shown in Figure 1.

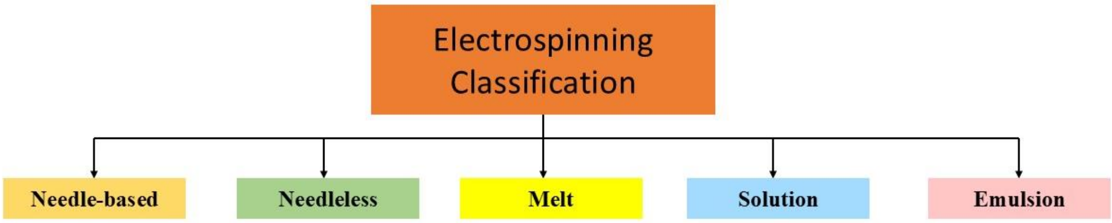

Figure 1. Electrospinning categorisation based on the setup used

This versatile technique can produce fibres with tailored properties for diverse applications, rendering it a critical method in the fields of nanotechnology and materials science.

2.1. Needle-based electrospinning

During needle electrospinning, a spinneret analogous to a needle is used, and a characteristic cone shape is formed at the needle tip when subjected to an electric field [28].

2.1.1. Single nozzle

The most fundamental configuration of electrospinning employs a single needle as the spinneret, as shown in Figure 2. This arrangement facilitated the production of individual nanofibers with controlled diameters and orientations. However, single-needle electrospinning has limitations in terms of the production rate and scalability for industrial applications [30]. To address these constraints, researchers have developed various modifications to the basic configuration, including multi-needle systems and needle-free electrospinning techniques. During this procedure, an equivalent voltage is applied to both solutions, and the resultant fibre typically separates due to repulsive forces between the two liquids [31].

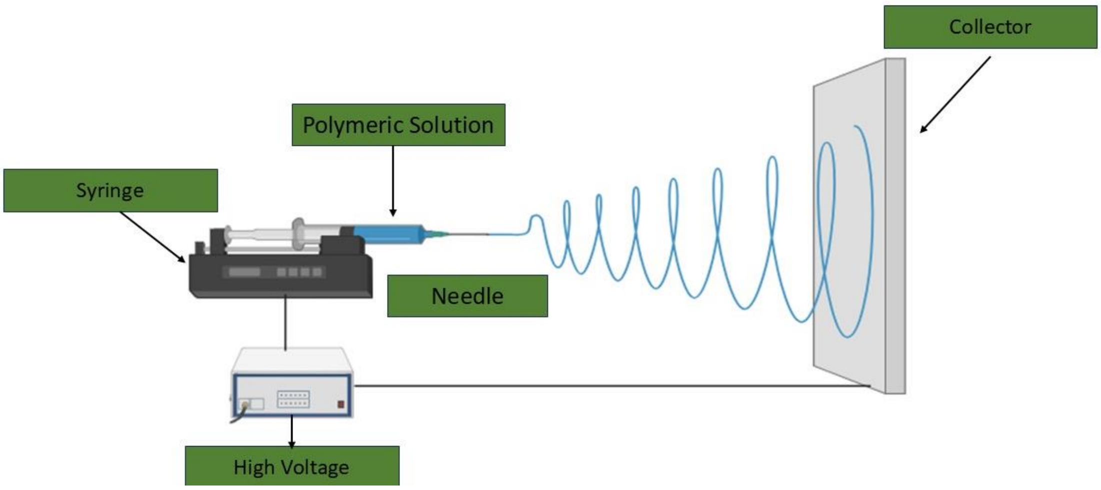

Figure 2. Schematic Design of Needle Electrospinning Setup

2.1.2. Coaxial electrospinning

Coaxial electrospinning uses a coaxial needle comprising two concentric hollow needles to generate a coaxially electrified jet. The conventional method for constructing a coaxial needle involves inserting a smaller inner needle into a larger outer needle in a coaxial configuration. Two syringe pumps were employed to fill the outer and inner needles with separate solutions, enabling independent control of the flow rates [32]. When subjected to an external electric field at the coaxial needle exit, the shell solution envelops the core solution, forming a compound Taylor cone and subsequently ejecting a coaxial jet (Figure 3). The successful fabrication of core-shell nanofibers is contingent upon several factors, including the characteristics of the inner and outer solutions and electrospinning parameters. Specifically, the inner and outer solutions must possess appropriate viscosities to maintain consistent jet flow. Additionally, precise control of the flow rates of the two solutions is crucial to ensure the complete encapsulation of the inner solution by the outer solution. Modulation of these flow rates also allows for modification of the nanofiber diameter and shell thickness [33].

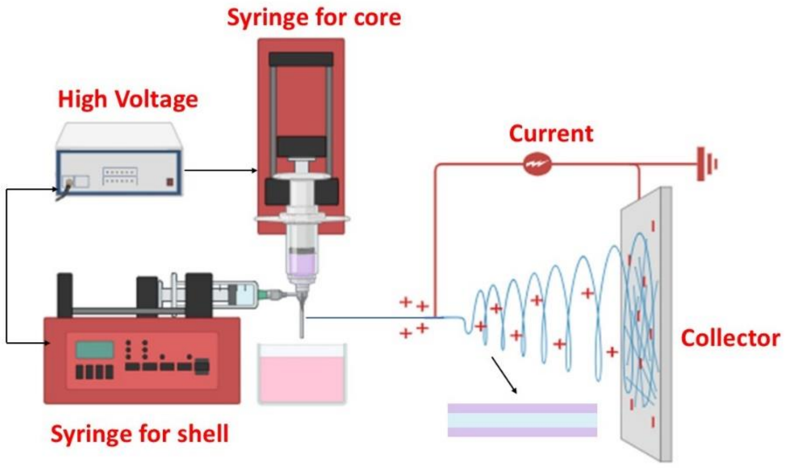

Figure 3. Schematic Design of Coaxial Setup

Coaxial electrospinning provides enhanced control over nanofiber compositions for diverse applications and facilitates the production of nanofibers from unspinnable liquids by utilising them as the inner fluid regulated by the outer fluid. Hollow nanofibers with a customisable wall thickness can be fabricated through selective elimination of the core from the spun core-shell nanofibers [34]. The core-shell structure of coaxially electrospun fibres presents opportunities for the development of multifunctional materials through the incorporation of various functional components into the two compartments of the concentric structure [35].

2.1.3. Tri-axial electrospinning

Figure 4 illustrates the trilayer spinneret and triaxial electrospinning apparatus, which incorporates three nested metal capillaries. This technique is frequently employed to generate a three-layered structure, typically comprising a drug-infused core, hydrophobic middle section, and hydrophilic exterior layer. A significant challenge in producing high-quality multicompartment fibres is preventing the mixing of spinning solutions. To accomplish this, the solutions must be either immiscible or evaporate at identical rates. If one solution evaporates more rapidly than the others, the compartments may separate, thereby compromising the structure of the fibre. Spinneret design is crucial for maintaining fibre integrity, as it must be tailored to specific application requirements [36].

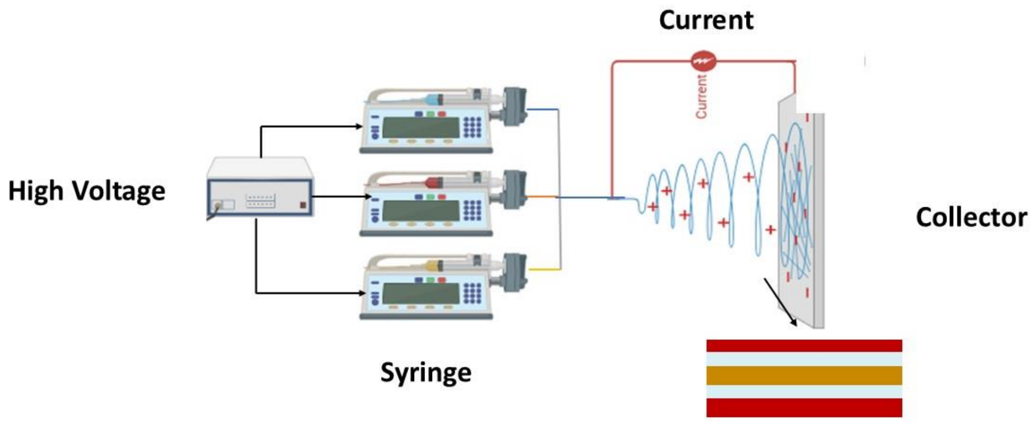

Figure 4. Schematic design of tri-axial electrospinning

A well-engineered spinneret can regulate fluid behaviour under an electric field and serve as a template for creating the desired nanofiber structures. The initial demonstration of triaxial electrospinning utilised a combination of ethanol, lignin, and glycerin arranged from the outermost layer to the innermost layer. Ethanol was employed to prevent Taylor cone solidification, and glycerin served as the template fluid. This pioneering approach established the foundation for the development of intricate fibre architectures for various applications [37].

2.1.4. Multichannel electrospinning

The fundamental configuration for multichannel electrospinning comprises the placement of three metal capillaries at the vertices of an equilateral triangle within a syringe, as illustrated in the schematic representation (Figure 5). This arrangement facilitated the fabrication of complex fibre structures. One of the initial demonstrations of this technique was the introduction of a multifluid compound jet electrospinning method, which enabled the expeditious and efficient production of biomimetic hierarchical multichannel microtubes [38].

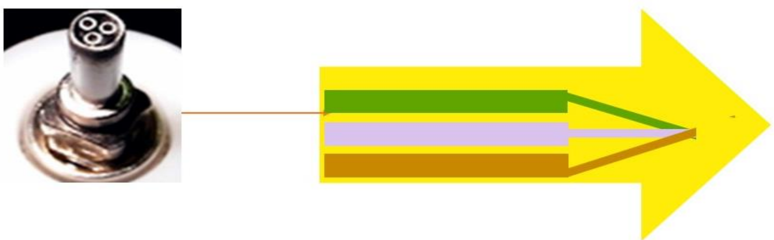

Figure 5. Multichnannel spinneret

In this approach, multiaxial electrospinning was utilised to develop a biomimetic system by employing multiple inner paraffin oil channels within a titanium isopropoxide solution. The organic components were subsequently removed to form multilayer channels that emulated the natural structures. This methodology demonstrates the potential of multichannel electrospinning for fabricating intricate fibre architectures for advanced applications [39].

2.2.Needle-free electrospinning

In response to the limitations of conventional needle-based electrospinning, particularly regarding productivity and scalability, needle-free electrospinning methodologies have been developed and refined [40]. This technique was pioneered by Jirsak et al. at the Technical University of Liberec in the early 2000s [41]. Their primary objective was to overcome the low production rates of needle-based systems, which constrain large-scale manufacturing of nanofibers. Needle-free electrospinning involves the generation of multiple cones without the requirement of a needle or small open structure. The process of jet formation in this methodology is self-organising, occurring on an unconfined liquid surface, and is not driven by capillary action. Instead, it relies on an external agitation force to concentrate the electric field on the free liquid surface, intensifying it to the required level for initiating a Taylor cone [42]. Figure 6 shows a schematic of the needle-free electrospinning setup. In this configuration, the polymer solution was dispensed onto a rotating or vibrating pedestal. The control pump regulated the solution flow. A high voltage is applied to the pedestal, generating multiple jets of fibres from the polymer solution, which are subsequently collected on the collector surface. This design eliminates the need for a traditional spinneret, thus enabling higher productivity and large-scale nanofiber production [43].

This innovative approach facilitates higher throughput and scalability than traditional needle-based electrospinning techniques. The absence of a needle eliminates issues such as clogging and enables the use of more viscous polymer solutions. Furthermore, needle-free electrospinning offers greater flexibility in terms of fibre production because multiple jets can be generated simultaneously from a single liquid surface [44], [45].

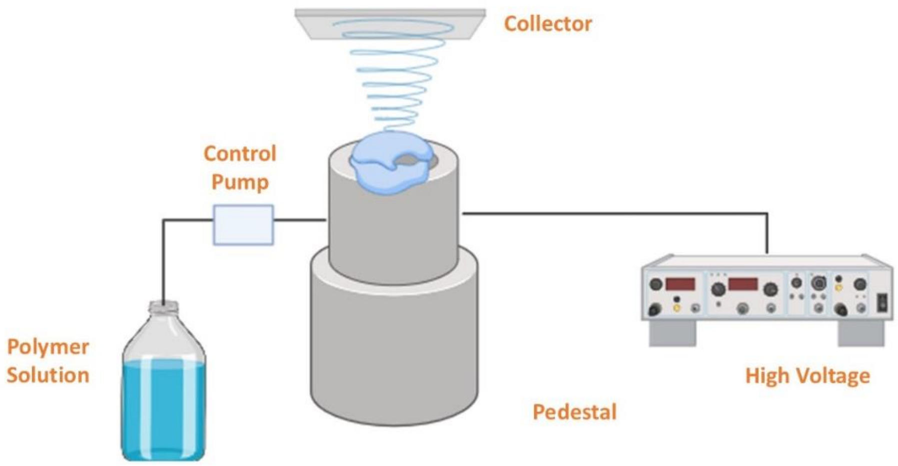

Figure 6. Needle-free electrospinning setup

The primary objective of needle-free electrospinning is to facilitate large-scale production of nanofibers by eliminating the requirement for individual nozzles or needles. In contrast to the utilisation of a spinneret for fibre ejection from a single point, needle-free electrospinning employs a rotating or vibrating surface (such as a wire, disc, or roller) that concurrently generates multiple jets of a polymer solution. This approach substantially enhances the throughput and enables the continuous production of nanofiber mats [46].

2.3.Melt electrospinning

Melt electrospinning eliminates the requirement for solvent removal and recycling, thereby addressing the environmental and toxicity concerns associated with solvent utilisation. In this process, the polymer is melted and introduced into a capillary tube. The entire operation must be conducted under vacuum conditions, necessitating the enclosure of the capillary tube, trajectory of the charged melt fluid jet, and metal collector [47].

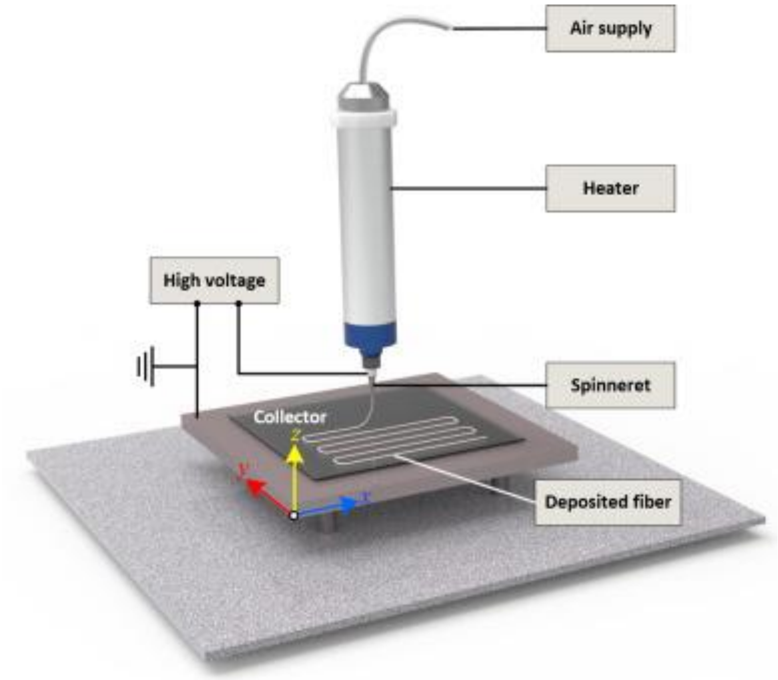

Figure 7. Schematic diagram of melt electrospinning setup [48].

One advantage of melt electrospinning is the production of highly uniform fibres with minimal variations in diameter. However, this methodology exhibits certain limitations, including the requirement for specialised equipment and the challenges presented by the high viscosity and low electrical conductivity of the polymer melt [49]. Despite its advantages, melt electrospinning has not achieved widespread adoption or frequent utilisation compared with electrospinning from polymer solutions. This limited implementation is primarily attributed to the high viscosity, elevated process temperatures, and challenge of producing fibres in the nanometer range [50].

2.4. Emulsion electrospinning

Emulsion electrospinning involves two distinct methods. The first approach involves propelling an emulsion through a single nozzle during the electrospinning process, facilitating the rearrangement of the emulsion structure and resulting in a core-shell fibre analogous to that produced by coaxial electrospinning [51]. The second methodology utilises multiple nozzles to electrospun an emulsion, generating multiple jets, thereby increasing production rates while still yielding core-shell fibres through structural reorganisation [52].

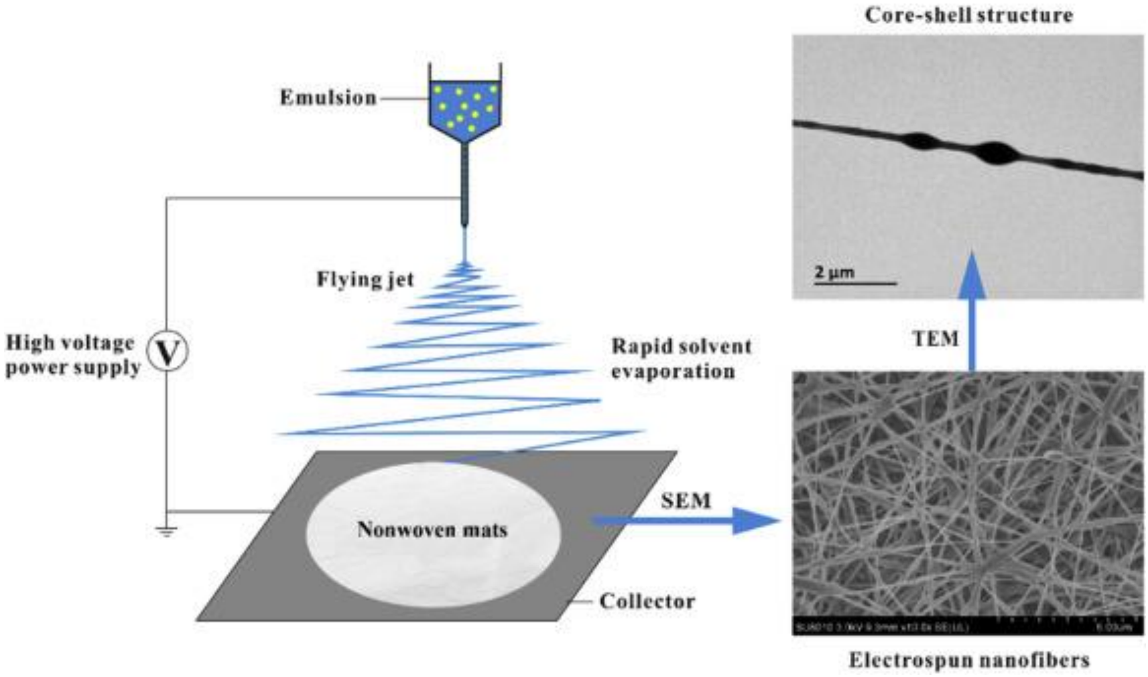

Figure 8. Schematic diagram of emulsion electrospinning [51].

This technique enhances the loading capacity of drug-polymer systems with limited compatibilities, such as water-soluble drugs or proteins incorporated into hydrophobic polymers for extended-release. In contrast to conventional blending techniques, emulsion electrospinning eliminates the necessity for a solvent capable of simultaneously dissolving both the drug and the polymer. Surfactants and other emulsifying agents are frequently used to encapsulate and stabilise the drug phase [53].

2.5.Solution electrospinning

Solution electrospinning is the most frequently employed method, in which the polymer to be electrospun is dissolved in an appropriate solvent at a suitable concentration. The production of nanofibers is predominantly accomplished through solution electrospinning, a technique preferred for its straightforward methodology and adaptability to diverse materials and conditions. In this process, a polymer solution was prepared by dissolving the desired polymer in a suitable solvent at an optimal concentration. The selection of solvent and concentration is critical, as it directly affects the viscosity, surface tension, and conductivity of the solution, which in turn influences fibre formation and morphology [54].

The prepared polymer solution was loaded into a syringe or capillary tube connected to a high-voltage power supply. An electric field is applied between the needle tip and the grounded collector as the solution is extruded through a fine needle or nozzle. This electric field induced charges in the polymer solution, causing it to form a Taylor cone at the needle tip. A fine jet is ejected from the cone toward the collector when the electrostatic forces exceed the surface tension of the solution. During this trajectory, the solvent evaporates, and the jet undergoes stretching and whipping motions, resulting in the formation of ultrafine fibres that are deposited on the collector as a non-woven mat [55].

3. Fundamentals of portable electrospinning devices

The adaptability of mobile electrospinning units is attributed to several modified components, particularly the spinneret and high-voltage supply systems. The degree of mobility for each device varied based on the specific modifications implemented. These modifications include on-site spinnerets connected to standard power supply configurations, the utilisation of compact high-voltage power supplies with converters, and the incorporation of alternative power sources such as batteries or generators [56]. The advantages and disadvantages of the various devices are listed in Table 1. The portability of these electrospinning systems, combined with their compatibility with polymer systems found in existing dressings, is advantageous for the development of personalised wound care. Portable electrospinning devices can potentially be utilised for various wound types, including incised skin of variable depth, irregular grazed skin wounds, burned skin wounds, excised liver wounds, and dural repairs [57]. Moreover, in situ, spinning and precise deposition provide opportunities to manage wound sites expeditiously and promote wound healing. The safety in use partially depends on the lower electrical current during processing (several milliamperes) and readily adjustable operating distances between the spinneret and wound site (2–12 cm) [58]. Furthermore, the compact size, lightweight, and ability to operate independently of the main power supply enable these devices to function both indoors and outdoors, which may be beneficial in emergency situations or remote locations. Recent advances in portable electrospinning device technology and in situ applications in wound care are shown in Table 1.

Table 1. Advantages and Disadvantages of Different Electrospinning Methods

Electrospinning Method	Advantages	Disadvantages	Reference
Needle-based Electrospinning	- Provides high control over fibre diameter and morphology. - Requires low-cost and simple setup.	- Not suitable for large-scale production due to low production rates. - Needle clogging and maintenance may be required.	[59]
Needle-free Electrospinning	- It offers high production capacity, which is advantageous for industrial applications. - Eliminates needle clogging issues.	- Limited control over fibre diameter and distribution.	[42], [45]
Solution Electrospinning	- Allows for the use of various polymers. - Facilitates surface modification and functionalisation of fibres.	- Solvent evaporation can pose environmental and health risks. - Solvent recovery may be necessary during production.	[54]
Melt Electrospinning	- Environmentally friendly, as no solvents	- High temperatures are required, but they	[50]

	are required. - Suitable for producing biocompatible and biodegradable fibres.	are not suitable for heat-sensitive polymers. - Fiber diameter control may be less precise.	
Emulsion Electrospinning	- Enables the production of multilayer or core-shell fibres. - Suitable for drug delivery and biomedical applications.	- Emulsion stability and control can be challenging. - The process is more complex and requires optimisation.	[51]
Portable (In-situ) Electrospinning	- Enables on-site application, which is beneficial for wound dressings. - Compact and user-friendly design.	- Limited production capacity, not suitable for large-scale manufacturing. - Fiber quality and uniformity may depend on operator skill.	[56]

3.1. Advancements in Portable Electrospinning Devices for In-Situ Nanofiber Fabrication

Portable electrospinning devices have revolutionised nanofiber production by enabling on-site and in-situ fabrication for a variety of applications. These devices are designed to provide flexibility, precision, and ease of use, making them suitable for fields such as biomedical engineering, environmental protection, and advanced material development [60]. Depending on the power source and operational design, portable electrospinning devices can be categorised as hand-held spinnerets, battery-powered systems, and generator-powered setups [61]. Each type of device offers distinct benefits and limitations based on its power source, application, and operational constraints (Table 2).

The versatility of these devices allows for customised nanofiber production tailored to specific research or industrial requirements. Hand-held spinnerets offer the highest level of portability and manoeuvrability, making them appropriate for precise small-scale applications in confined spaces. Battery-powered systems strike a balance between portability and operational duration, thereby providing a compromise for medium-scale production in field settings [62].

Table 2. Comparison of Portable Electrospinning Devices

Type of Portable Device	Advantages	Disadvantages	References
Hand-held	Versatile in the application; enables in	It requires mains electricity; it is bulky	[63], [64]

Spinnerets	situ spinning; provides higher voltage; offers precise control over voltage and flow rate; ensures safe and accurate fibre deposition.	and heavy to transport, and it is relatively expensive.	
Battery Powered	Highly portable (compact, lightweight, and easy to handle); adaptable for in situ spinning; ensures safe and accurate fibre deposition; cost-effective.	Voltage capacity is limited; operational time is constrained by battery life.	[62]
Generator Powered	Provides reliable and sufficient power supply; portable and lightweight; adaptable for in situ spinning; cost-effective and safe for use.	High voltage may be inconsistent and unstable, and there may be a limited flow rate; fibre deposition may be difficult to control.	[65]

Hand-held spinnerets are compact instruments that facilitate direct fibre deposition onto surfaces or biological tissues. Their ergonomic design and manoeuvrability render them particularly efficacious for the application of nanofibers to irregular surfaces, such as wounds or complex geometries. These devices typically comprise a polymer reservoir, metallic needle, and integrated heating or airflow system that facilitates real-time fibre production [66], [67]. Their primary advantage lies in their capacity to achieve localised and targeted applications, making them highly valuable in personalised healthcare, wound dressing, and drug delivery [68].

Battery-powered electrospinning devices further enhance portability by eliminating the need for a direct power supply. These systems are equipped with rechargeable or replaceable batteries that power the high-voltage generator required for electrospinning. This design allows for nanofiber fabrication in remote areas or environments where electricity is not readily accessible [69], [70]. The mobility of battery-powered devices renders them suitable for field applications, although their operational time is limited by their battery life, necessitating efficient power management and lightweight construction [71].

Generator-powered electrospinning devices provide stable and continuous power sources for large-scale or long-duration applications. These systems are designed for industrial or outdoor use, and the high voltage required for electrospinning must be sustained over extended periods. Generator-powered setups are advantageous for producing nanofiber mats or coatings on a larger scale, supporting filtration projects, protective textiles, and environmental remediation. However, the added weight and bulk of the generator can reduce the mobility and limit their utilisation in precision-focused tasks [18], [61].

By integrating portability with the advanced capabilities of electrospinning, these devices present new possibilities for real-time fibre deposition across various disciplines. For medical, industrial, and environmental applications, portable electrospinning technology represents a significant advancement towards more accessible and versatile nanofiber production.

3.1.1. Portable electrospinning devices and their in situ applications

The development of portable electrospinning devices has facilitated novel opportunities for in situ fabrication of nanofibers. These hand-held systems offer enhanced flexibility and mobility compared with conventional benchtop apparatuses, enabling the direct application of nanofibers in diverse field environments. The compact nature of these devices, in conjunction with their capacity to produce high-quality nanofibers, renders them particularly promising for applications in wound healing, tissue engineering, and environmental remediation (Figure 9) [72].

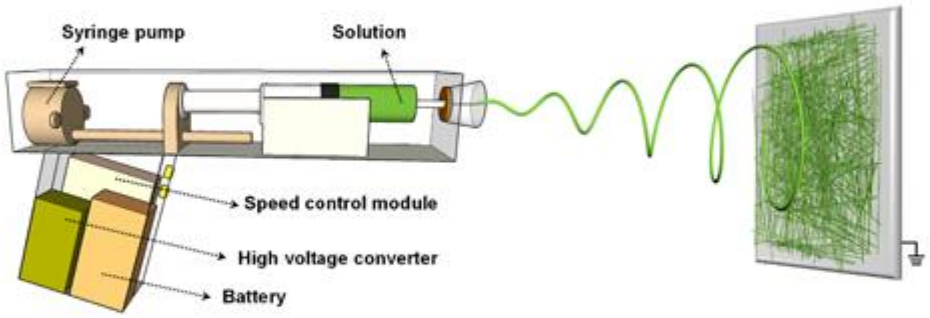

Figure 9. Schematic demonstration of the portable electrospinning device [72].

Yue et al. developed a portable electrospinning device capable of in-situ fabrication of waterproof and breathable (W&B) nanofibrous membranes for wound dressing applications (Figure 10). To address the challenge of developing flexible, skin-like membranes suitable for irregular wound surfaces, the apparatus was designed with adjustable perfusion rates ranging from 0.05 mL/h to 10 mL/h and was capable of generating elevated voltages up to 11 kV [72]. Using this system, thymol-loaded ethanol-soluble polyurethane (EPU) membranes incorporating fluorinated polyurethane (FPU) were fabricated. The resultant membranes exhibited a uniform structure, robust waterproofness with a hydrostatic pressure of 17.6 cm H_2O, excellent breathability at 3.56 kg/m^2/day, high tensile stress of 1.83 MPa, tensile strain of 453%, and strong antibacterial activity. These findings demonstrate the potential of this device as a versatile tool for producing antibacterial membranes directly on wound surfaces, representing a significant advancement in the development of portable electrospinning technology.

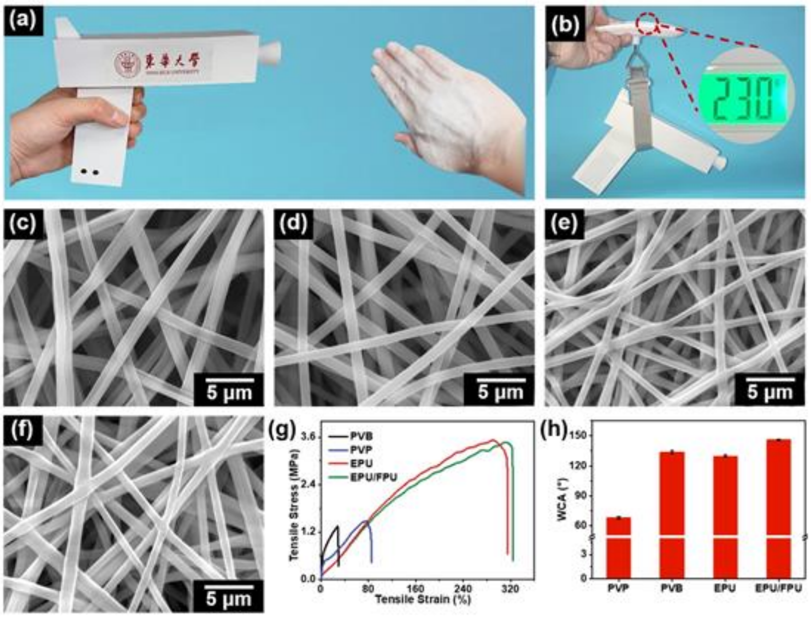

Figure 10. (a) Photographic representation of in situ electrospinning of EPU/FPU/thymol nanofibrous membranes on a human hand. (b) Photographic documentation illustrating the mass of the portable electrospinning device, measured using a portable scale. (c) Scanning electron microscopy (SEM) micrographs of the PVB fibrous membranes. (d) SEM micrograph of PVP fibrous membranes. (e) SEM micrograph of EPU fibrous membranes. (f) SEM micrograph of EPU/FPU fibrous membrane. (g) Stress-strain curves of PVB, PVP, EPU, and EPU/FPU fibrous membranes. (h) Water contact angle (WCA) measurements of PVB, PVP, EPU, and EPU/FPU fibrous membranes [72].

Xu et al. investigated the use of a portable hand-held electrospinning device for the in-situ deposition of polyvinyl alcohol (PVA) and bone marrow-derived stem cells (BMSCs) to promote wound healing in rats (Figure 11). Their findings revealed that electrospun PVA/BMSC scaffolds significantly accelerated the wound healing process compared to the control and PVA-only groups. By day 7, the wound area in the PVA/BMSC group was reduced by approximately 52%, whereas the PVA-only group exhibited a reduction of 33%, and the control group showed only 21% closure. By day 14, the PVA/BMSC group achieved complete wound closure, whereas the PVA-only group achieved approximately 85% closure, and the control group achieved approximately 70% closure. Microscopic examination revealed that the PVA/BMSC-treated group demonstrated the enhanced formation of granulation tissue, increased collagen deposition, and improved vascularisation. The results indicated the efficacy of the hand-held electrospinning device in accelerating wound healing and enhancing skin regeneration, demonstrating its potential for clinical and emergency applications [63].

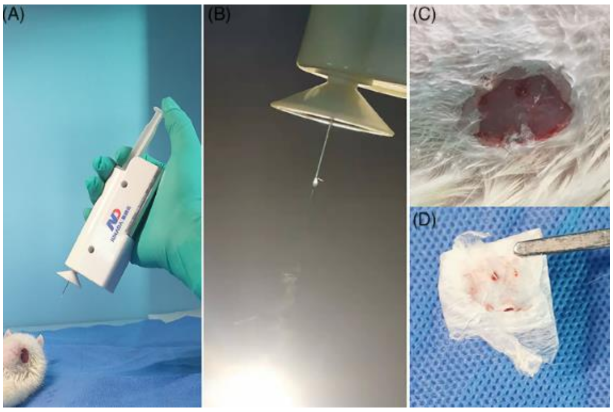

Figure 11. In situ applications of the hand-held apparatus. (A) In situ electrospinning on the wound of rat. (B) Electrospinning jets can be observed from the spinneret. (C) Electrospun mats. (D) Electrospun films obtained from rat wounds [63].

Long et al. developed a device for rapid hemostasis utilising airflow-directed in situ electrospinning. The apparatus comprises four primary components: a high-voltage power supply, a syringe pump, an air pump, and a specially designed coaxial spinneret. As illustrated in Figure 12, an air pump was connected to the coaxial spinneret to enhance electrospinning and regulate the area of fibre deposition. A conical aluminium auxiliary electrode has been recently implemented to facilitate precise and expeditious fibre placement. Furthermore, airflow can be employed to cleanse wound areas prior to initiating in situ electrospinning. Utilising this configuration, fibres of a medical adhesive, 2-octyl cyanoacrylate (OCA), were electrospun and applied to the wound, as demonstrated in Figure 12c [68].

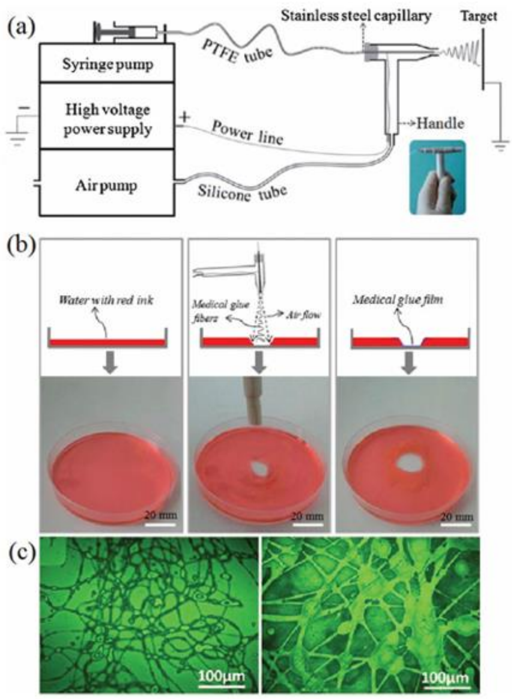

Figure 12. (a) Schematic representation of the airflow-directed in-situ electrospinning apparatus incorporating a custom-designed portable spinneret (inset). (b) Using this apparatus, precise deposition of fibres composed of medical adhesive (OCA) was achieved. (c) Optical micrographs of OCA fibres were fabricated using this apparatus [68].

In recent years, commercially available devices have supplanted homemade electrospinning setups with mobile spinnerets. These mass-produced hand-held electrospinning apparatuses comprise a gun-shaped spinneret (Figure 13a) and an air channel. Consequently, the electrospinning streams are confined by the airflow, as illustrated in Figure 13b, enabling precise deposition of electrospun fibres on the intended surface. The mobility and controllable fibre deposition of this apparatus have further enhanced the potential for on-site electrospinning in wound treatment applications (Figure 13c and d). Although the aforementioned electrospinning devices are portable, only the spinneret component can be manually operated, as the remainder of the unit is excessively bulky and heavy for facile transportation [5].

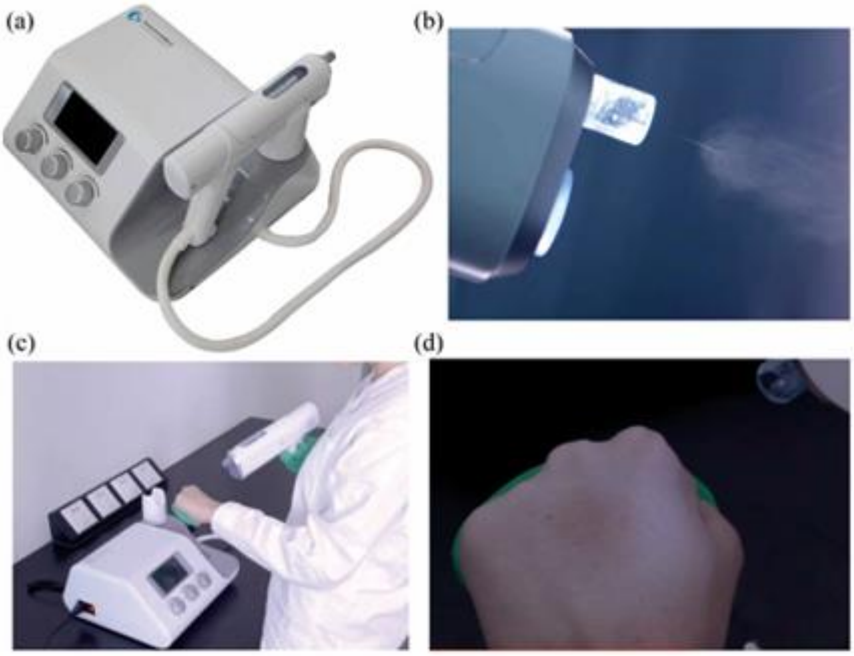

Figure 13. (a) Image of the electrospinning apparatus from Qingdao Junada Technology Co., Ltd. (b) Fibers being directed towards the target site. (c) Utilisation of the hand-held apparatus. (d) Direct deposition of fibres onto a human hand [5].

3.1.2. Battery-operated portable electrospinning devices and their applications

The initial in situ electrospinning systems, as previously described, demonstrated some level of mobility due to their hand-held spinneret design. However, this mobility was limited by the need for a bulky power source and connection to the main electrical supply. To address the constraints imposed by the main electrical connections, researchers have made various efforts, resulting in the creation of battery-operated devices [69]. Researchers have developed a portable, battery-operated electrospinning apparatus capable of depositing biodegradable polymers directly onto soft tissue wounds. This novel device enables the in situ fabrication of fibrous dressings. The hand-held electrospinning instrument, designed for the on-site application of biodegradable polymer dressings to soft tissue injuries, is illustrated in Figure 14.

Figure 14. battery-operated hand-held electrospinning apparatus [69].

Greiner et al. developed a hand-held electrospinning device capable of directly depositing nanofibers onto wound surfaces. The device operates by utilising standard batteries to supply high voltages, enabling modular construction and utilisation of different polymer solutions. This versatility facilitates the application of various polymer-carriers and drugs tailored to different types of wounds. Similarly, researchers at the University of Singapore have proposed a device based on the same principle, although limited technical details and practical applications have been disclosed for these battery-operated systems [62].

Josef Haik et al. investigated the feasibility of this portable electrospinning device for the production of directly applied wound dressings. The device was employed to electrospin various polymers onto wounds for in vivo studies, with macroscopic evaluations conducted on days 2, 7, and 14 to assess the adherence, exudate levels, eschar presence, skin reactions, wound closure, ease of dressing removal, and healing time. The device facilitated rapid application, creating nanofibrous dressings in less than one minute, which significantly reduced the risk of infection and cross-contamination. This hand-held system has subsequently been commercialised as the SpinCare™ System, which comprises a hand-held electrospinning device and sterile pre-filled SpinKit™ solution syringes, providing an efficient and user-friendly approach to wound care (Figure) [57].

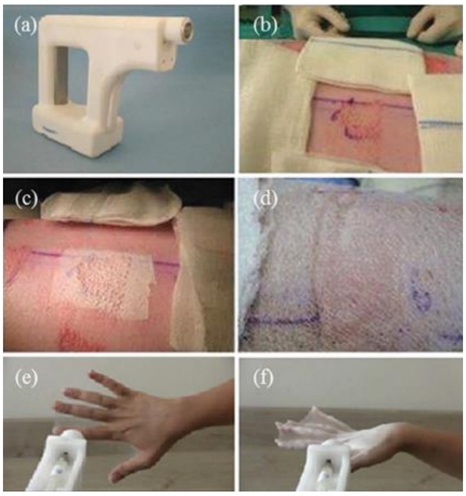

Figure 15. Application of the Portable Electrospinning Device for Wound Dressing (a) portable hand-held electrospinning device developed by Nicast Ltd., Lod, Israel. (b-d) In vivo electrospinning of biocompatible medical-grade polyester, polycarbonate, and polyurethane

polymers directly onto the wound sites. (e-f) Generation of nanofibrous dressings within one minute, demonstrating the appropriate thickness and adherence to the wound [57].

The advent of portable electrospinning devices has expanded the potential for in situ nanofiber fabrication. These hand-held apparatuses provide enhanced versatility and portability compared to conventional benchtop configurations, enabling direct nanofiber applications across diverse field environments. The compact design of these instruments, coupled with their capacity to generate high-quality nanofibers, renders them particularly promising for applications in wound healing, tissue engineering, and environmental remediation [62], [63].

A portable, battery-operated electrospinning apparatus (BOEA) was developed by Long et al. for in situ application in wound healing treatments. This compact instrument is capable of performing electrospinning directly at the point of care [64]. The device operates using two AAA batteries (3 V), providing a high voltage of up to 10 kV and enabling continuous operation for over 15 h with minimal current output. The positive electrode of the high-voltage converter was connected to the syringe needle, whereas the negative electrode was linked to a conductive metal foil. This design allows the user to transfer charge through the body by touching the foil, thereby preventing charge accumulation during the operation [62].

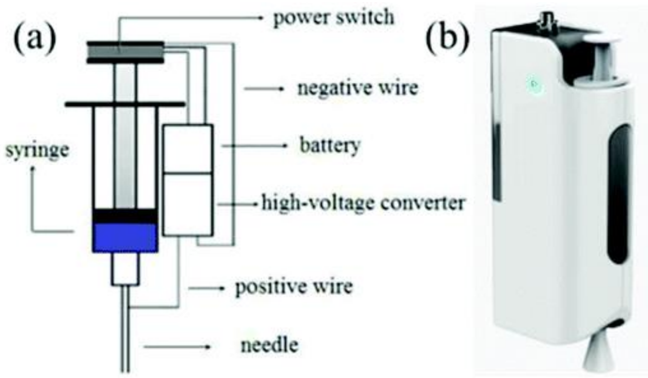

Figure 16. (a) Schematic of the hand-held battery-operated electrospinning apparatus (BOEA) developed by Long et al. The diagram delineates the essential components, including the syringe, high-voltage converter, battery, and wiring for the positive and negative electrodes, facilitating direct nanofiber deposition for in situ applications. (b) Photographic representation of assembled portable electrospinning device [5].

More recently, Long et al. investigated the application of BOEA for direct electrospinning of the medical adhesive, N-octyl-2 cyanoacrylate (NOCA), to produce fibrous media suitable for soft tissue hemostasis, as illustrated in Figure 17, which pertains to liver hemostasis. In this specific application, controlling tissue adhesion post-surgery is crucial, necessitating precise deposition of hemostatic medical adhesive. To achieve precise deposition, a metal cone was affixed to the spinning nozzle, as depicted in Figure 17a. The researchers observed that the deposition range of the electrospun fibres could be modulated by altering the size of the metal cone (Figure 17b). This modified BOEA was subsequently employed for the deposition of NOCA fibres onto the resection site of the rat liver to achieve rapid hemostasis within 10 seconds, as shown in Figure 17c. Postoperative pathological results indicated a reduced inflammatory response and tissue adhesion in this method compared with that in the airflowassisted group [73]. These findings suggest the potential for the modified BOEA to be developed for emergency medical procedures or for community patient care or home care settings, where portability and ease of operation would be particularly advantageous. However, the voltage in this device was fixed, thereby limiting the extent to which the physical properties and dimensions of the dressings produced in situ can be modified. The spinning solution delivery was dependent on the pressure applied by the operator to the trigger, which could fluctuate during use, potentially resulting in inconsistent fibre deposition.

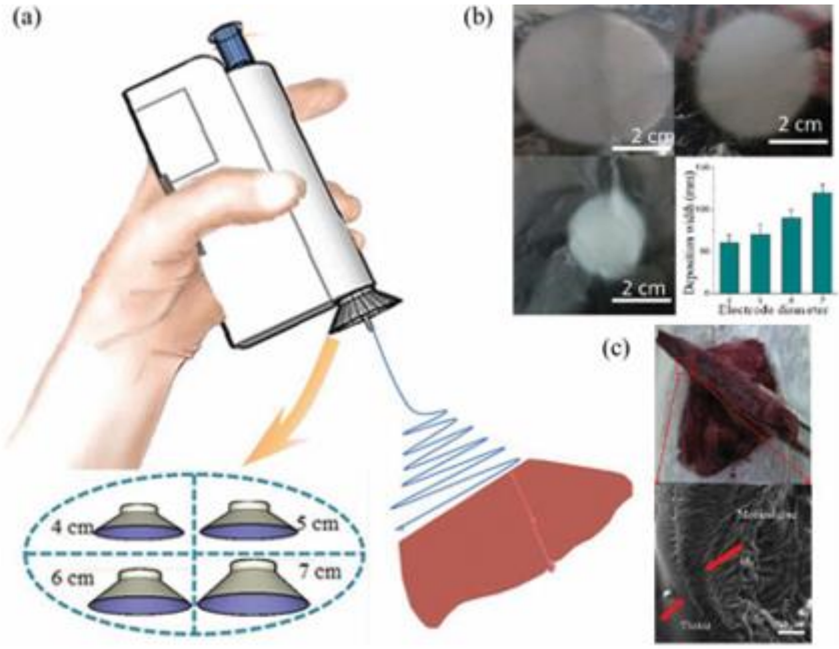

Figure 17. (a) Schematic representation illustrating the process of generating NOCA fibres through electric-field-enhanced electrospinning for liver resection hemostasis, (b) correlation between the metallic cone's diameter and the area of deposition, (c) application of NOCA medical adhesive fibres onto the liver tissue surface utilising an electric field-assisted electrospinning apparatus for achieving hemostasis[73].

Ye et al. investigated the development of a novel portable electrospinning apparatus with an adjustable voltage and flow rate, controlled via a microcontroller, to accommodate a wide range of electrospinning and electrospraying applications. The device, with a mass of 1.11 kg, incorporated three primary components: a high-voltage converter, linear actuator, and rechargeable battery system. A high-voltage converter (model F101, EMCO High Voltage Corporation, US) generated voltages from 0 to 14 kV and was powered by ten NiMH AA batteries. The T-NA linear actuator coupled with a MAX-232 module functioned as a syringe pump, enabling flow rates between 0 and 10 mL/h. Using this device, polycaprolactone (PCL) was electrospun into submicron fibres both directly from a cartridge and through a pen-shaped extension. The electrospun fibres exhibited a uniform morphology and enhanced deposition precision. Furthermore, polylactic-co-glycolic acid (PLGA) microparticles were successfully electrospray to expand the potential applications of the apparatus. The device demonstrated the capacity to electrospun various polymers, including poly(dioxanone) (PDO), poly(3-hydroxybutyrate) (PHB), poly(vinyl alcohol) (PVA), poly(ethylene oxide) (PEO), and poly(vinyl butyral) (PVB). In vivo applications include direct electrospinning of PDO fibres onto pig skin defects and achieving complete coverage of the wound site with fibrous dressings. Similarly, PEO fibres were electrospun directly onto human skin, covering areas such as the arms and hands. The results demonstrate the efficacy of this portable device in producing personalised wound dressings, highlighting its potential for cost-effective, flexible, and transportable medical applications [74].

Battery-operated portable electrospinning devices represent a significant advancement in wound healing and medical applications because they enable in situ nanofiber deposition directly onto wound sites. These hand-held devices mitigate the limitations of traditional electrospinning systems, such as the dependence on the main electricity and large, stationary equipment. By incorporating lightweight designs, battery power, and modular components, researchers, including Greiner, Haik, Long, and Ye, have demonstrated that these devices are capable of producing fibrous wound dressings with enhanced adherence, antimicrobial properties, and accelerated wound closure [52], [57], [60], [74].

In vivo and in vitro studies revealed significant advantages, including a reduction in infection risk, enhanced tissue regeneration, and accelerated healing times. Devices such as the BOEA, SpinCare™ system, and modified electrodes for hemostatic applications have demonstrated efficacy in diverse medical scenarios, from emergency wound care to surgical procedures. However, challenges persist in achieving consistent fibre deposition, adjustable voltage, and controlled delivery, underscoring the need for further refinement and research.

3.1.3. Generator-operated portable electrospinning devices and their applications

Generator-operated portable electrospinning devices provide a reliable solution for in-situ nanofiber fabrication by utilising self-powered high-voltage systems, enabling continuous fibre deposition without dependence on external electrical sources. These devices are particularly valuable for remote or emergency medical applications, allowing the creation of customised wound dressings and tissue scaffolds directly at the site of injury [61].

While hand-held devices exhibit adequate portability, their battery life remains limited. To address this constraint and ensure continuous operation, Han et al. proposed a self-powered electrospinning apparatus utilising a hand-operated Wimshurst generator (Figure 17a and 17b). In contrast to battery-powered devices, this configuration substitutes the high-voltage supply with a Wimshurst generator, capable of producing approximately 15 kV through electrostatic induction. As illustrated in Figure 17a, clockwise rotation of the handle generates positive and negative charges in distinct disc regions, which are subsequently stored separately in two Leyden jars. This process establishes a high voltage differential between the needle and collector, facilitating stable electrospinning jets observable via a high-speed camera (Figure 17c). Various polymer solutions, including polystyrene (PS), PVDF, PCL, and polylactic acid (PLA), have been successfully electrospun into fibre webs (Figure 17d) and three-dimensional fibre structures (Figure 17e) employing this methodology. Additionally, this self-powered apparatus is proposed for in situ electrospinning of wound dressings in scenarios involving power outages (Figure 17f) [61].

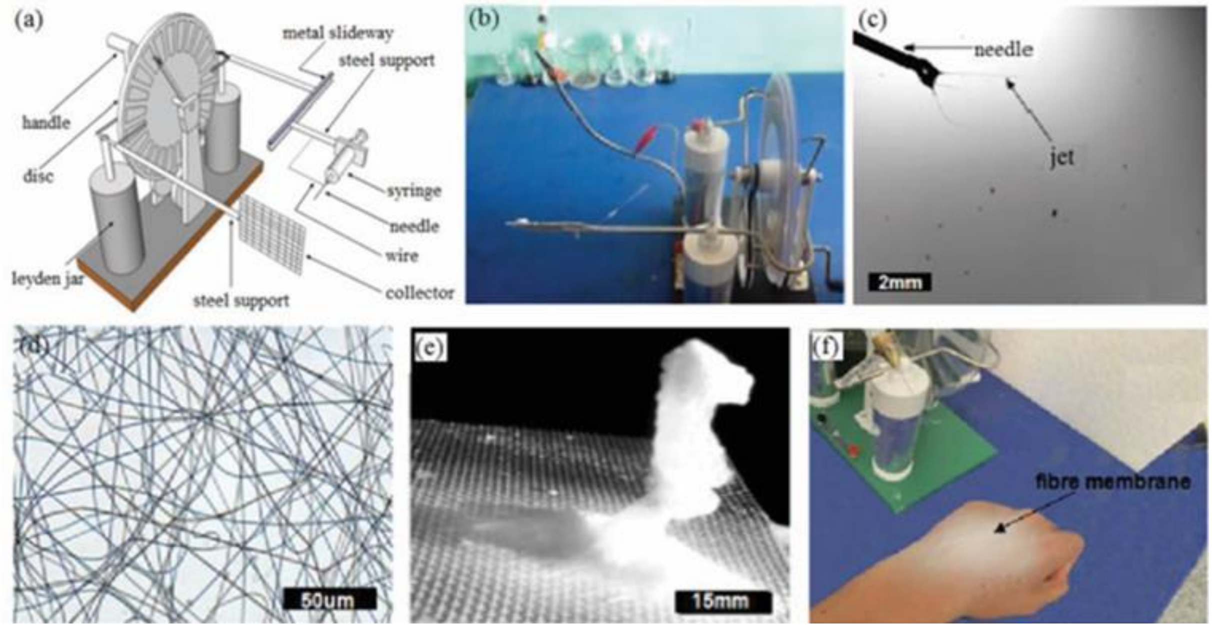

Figure 17. (a) Schematic representation of a self-sustaining electrospinning apparatus utilising a Wimshurst machine, (b) visual depiction of the experimental setup, (c) high-speed camera imagery of the electrospinning process employing this device, (d) optical microscopy image illustrating a network of electrospun PS fibres, and (e) PS fibres arranged in a three-dimensional stratified configuration. (f) Direct deposition of fibres onto the epidermal surface through in situ electrospinning[61].

By substituting the needle and incorporating a heating apparatus, this self-powered device can function as a portable melt-electrospinning system (Figure 18a, 18b). This novel apparatus mitigates electrical interference prevalent in conventional setups and enhances portability. Utilising this device, polymers such as PLA (Figure 18c) and PCL (Figure 18d) melts can be electrospun into fibres with diameters of approximately 20 μm. The absence of residual solvent in melt-electrospun fibres renders them more suitable for direct in situ wound dressings due to reduced toxicity (Figure 18e, 18f). The temperature of melt-electrospun fibres upon contact with porcine liver tissue ranged from 33.6 to 24.2 °C (PCL fibres) as the spinning distance increased from 8 to 10 cm, approximating human body temperature. Furthermore, the adhesion of PCL fibres to liver tissue was approximately 1.0–1.2 N [18], [71].

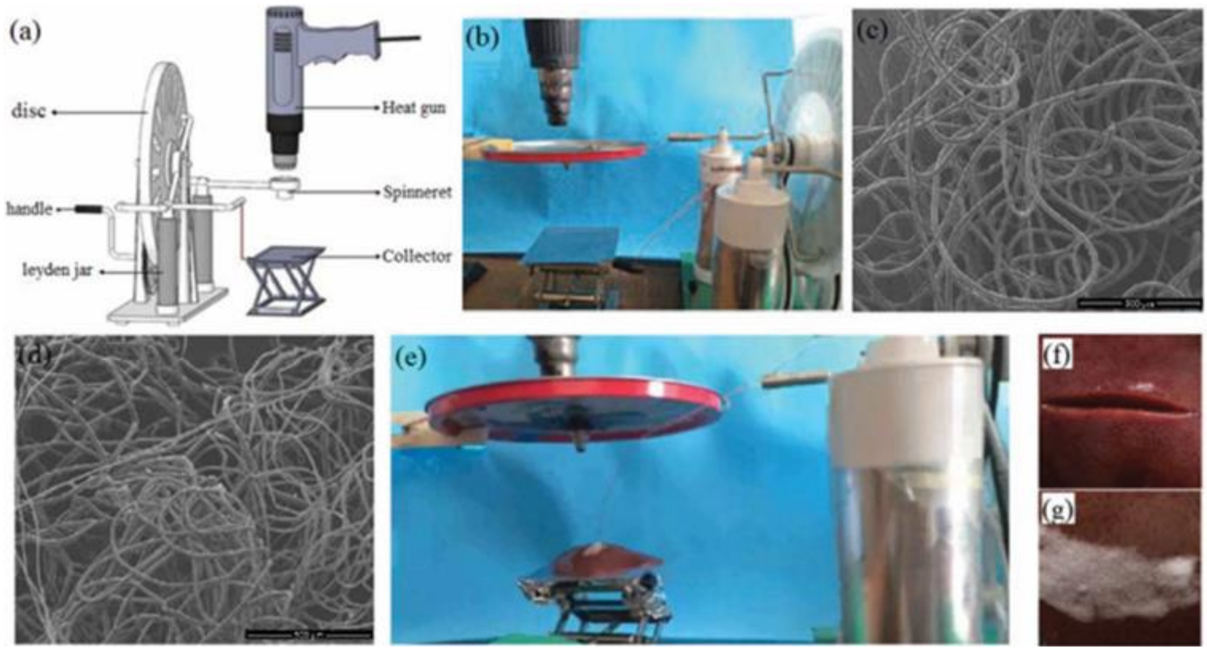

Figure 18. (a) Schematic representation elucidating the conceptual framework and (b) advanced self-powered melt electrospinning apparatus, accompanied by its application for the electrospinning of (c) PCL and (d) PLA fibres. (e) In situ electrospinning of fibres directly onto porcine hepatic tissue, demonstrating (f) an extended surgical incision and (g) melt electrospun PCL fibres applied as a wound dressing[18], [71].

Self-powered electrospinning devices, which operate independently of direct electrical connections or batteries, frequently encounter challenges related to instability in the high voltage generated by Wimshurst generators or R-TENGs. In response to this issue, Yan et al. developed a hand-operated, solar-cell-powered portable electrospinning (SHPE) device, which demonstrates the potential for applications in wound dressings, similar to other reported portable devices [20], [61].

The SHPE device can also be utilised for melt electrospinning by modifying the spinneret into a conical metal nozzle, in which polymer particles can be heated into a melt using a heat gun or alcohol lamp, as depicted in Figure 19a–c. Melt electrospinning jets were subsequently formed during electrospinning (Figure 19c). Materials such as PLA, PCL, and polyurethane (PU) were melt-electrospuned into microfibers using the SHPE device (Figure 19d–f) [20], [61].

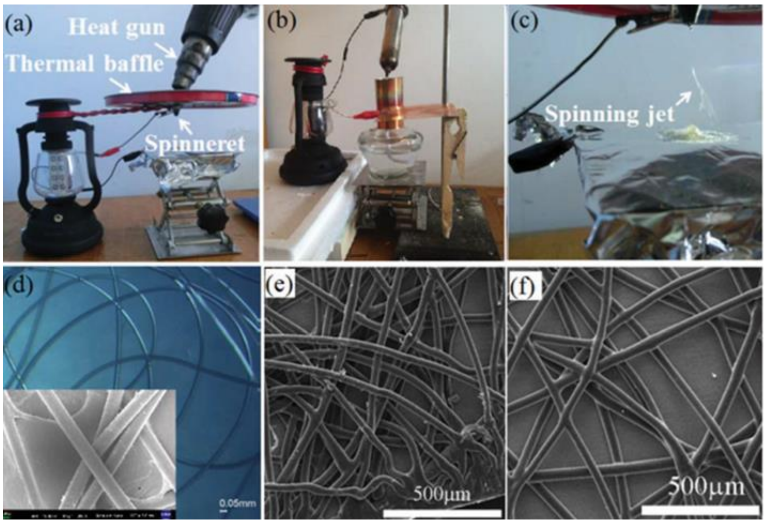

Figure 19. Optical micrographs of the SHPE device for melt electrospinning using (a) a heating gun and (b) an alcohol lamp as the heating system, (c) the melt electrospinning process employing the device, and scanning electron microscopy (SEM) images of the as-spun (d) PLA, (e) PCL, and (f) PU fibres [75].

The generator-operated portable electrospinning apparatus is self-powered and stable during use, but it is larger than battery-operated devices. To reduce volume and weight, Duan et al. proposed a simplified electrospinning setup using a piezoelectric (PZT) ceramic generator (Figure 20a) instead of a high-voltage supply system, resulting in a significantly smaller device ($5 \times 1 \times 1$ cm^3, see Figure 20b and 20c). Using the PZT generator, a high pulsed voltage of approximately 56 kV was generated, which was sufficient to enable electrospinning. Using this apparatus, several types of polymer solutions, such as PVP (Figure 20d), PVDF (Figure 20e), and PS, were successfully electrospun into ultrathin fibres, confirming the feasibility of this apparatus. However, because a pulsed voltage is generated by PZT, the electrospinning process cannot operate continuously, and this device can only be utilised for demonstration purposes. Nevertheless, this approach established a fundamentally novel method for the design of an ultra-portable electrospinning apparatus [76].

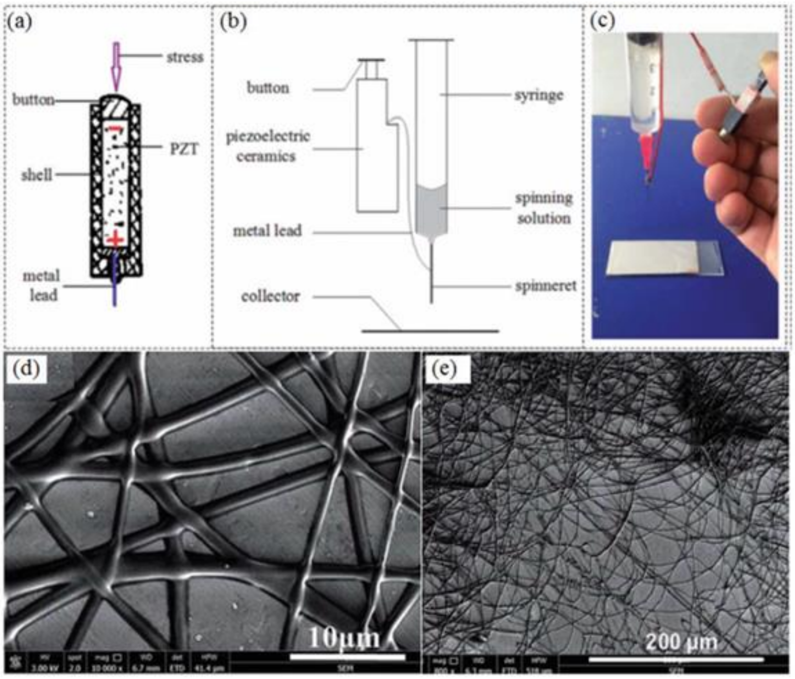

Figure 20. (a) Schematic representation of a PZT, (b) a conceptual illustration of the PZT-driven electrospinning apparatus, and (c) a photographic image of the portable electrospinning device prototype. Scanning electron microscope (SEM) micrographs of electrospun (d) PVP and (e) PVDF fibres fabricated using this apparatus [76].

Portable electrospinning devices exhibit variations in power sources, fibre outputs, and application scopes, offering tailored solutions for diverse environments and requirements. Battery-operated devices, such as BOEA, provide extended continuous operation and precision, rendering them suitable for biomedical applications, including wound dressing. Conversely, manually operated devices, such as the Wimshurst generator, deliver high-voltage output without dependence on external power sources, making them appropriate for field use but with limited control over fibre uniformity. Melt electrospinning devices powered by alcohol lamps facilitate solvent-free fibre production, which is essential for heat-resistant polymers but constrained by larger fibre diameters. Solar-powered devices, such as SHPE, offer sustainable outdoor operation but produce fibres with submicron diameters, thereby limiting scalability [62].

4. Comparative Analysis of Portable Electrospinning Devices and Traditional Methods for Wound Healing Applications

Portable electrospinning devices have emerged as innovative tools for producing nanofiber-based wound dressings directly at injury sites, enabling personalised, efficient, and accelerated healing. Yue et al. investigated the development of a portable electrospinning device for the in situ fabrication of thymol-loaded polyurethane (PU) fibrous membranes intended for wound dressing applications. Their findings indicate that the device operates with adjustable perfusion speeds (ranging from 0.05 mL/h to 10 mL/h) and high voltages up to 11 kV. The electrospun fibrous membranes exhibited significant antibacterial activity, excellent waterproofing properties with a hydrostatic pressure of 17.6 cm H_2O, and superior breathability (3.56 kg/m²/day). The resultant membranes demonstrated a high tensile strength (1.83 MPa) and strain (453%), rendering them suitable for irregular wound surfaces. This research suggests that portable electrospinning technology can be used to fabricate antibacterial membranes directly onto wounds, enhancing the practicality of electrospinning in medical applications. Traditional electrospun polyurethane membranes can achieve tensile strengths of up to 4.95 MPa and hydrostatic pressures of 55.4 cm H_2O. In some instances, polyurethane fibrous membranes fabricated through conventional electrospinning have demonstrated tensile strengths as high as 9.8 MPa and hydrostatic pressures reaching 104.9 cm H_2O. This indicates that while portable electrospinning devices offer enhanced flexibility and capability for in situ application, their mechanical performance and barrier properties may be lower than those of larger, stationary setups.

Liu et al. investigated the development of a portable electrospinning device for the in situ fabrication of "dry-wet" conversion nanofiber dressings aimed at enhancing wound healing. Their study utilised an aqueous solvent-based system to fabricate PVA/SF/SA/GelMA nanofiber dressings that were directly deposited onto wounds of varying sizes. Electrospinning was conducted at 10 kV with a receiving distance of 15 cm and a flow rate of 0.4 mL/h. The dressings exhibited excellent air permeability, tensile strength (9–12 KPa), and strain (60–80%), ensuring mechanical support during healing. Additionally, the dressings absorbed up to eight times their weight in the fluid, forming hydrogel structures that maintain a moist environment conducive to healing. The results demonstrated superior cell compatibility and enhanced cell proliferation owing to the addition of silk fibroin (SF), rendering these dressings highly promising for emergency wound care. In comparison, conventional electrospinning methods generally produce membranes with tensile strengths in the range of 6–10 MPa and tensile strains between 60% and 70%. The nanofiber membranes prepared with the PVA/SF/SA/GelMA system exhibited 35% higher tensile stress and 32% longer tensile strain than those prepared without GelMA, demonstrating the advantages of photo-crosslinking networks in enhancing mechanical properties. Conventional electrospinning methods have achieved tensile strengths of 2–5 MPa for PVA/SA membranes. This comparison shows that while portable electrospinning devices offer significant flexibility and the ability to perform in situ electrospinning, their mechanical properties and tensile strengths tend to be lower than those achieved using conventional setups. However, the ability of portable systems to create hydrogel-forming dressings and adapt to different wound environments renders them a valuable tool for rapid and effective wound care, particularly in emergency scenarios. The portable electrospinning device developed by Liu et al. demonstrated potential for the on-site fabrication of advanced wound dressings with tailored properties. The capability to create "dry-wet" conversion nanofiber dressings directly on wounds of varying sizes illustrates the versatility and adaptability of this technology in emergency wound care scenarios. Furthermore, the superior cell compatibility and enhanced cell proliferation observed with these dressings, attributed to the incorporation of silk fibroin, highlights the potential for improved wound healing outcomes compared to traditional dressing methods.

Recent studies have elucidated the advantages and practical applications of portable electrospinning devices compared to conventional methods for wound healing. Edirisinghe et al. proposed a hand-held electrospinning device capable of depositing PLGA fibres directly onto confined target areas, rendering it suitable for irregular wounds and burn sites. Their investigation demonstrated that fibres could be applied within 300 s to form a thin protective film over wounds. Similarly, Long et al. developed a battery-operated hand-held device that utilised AAA batteries to generate voltages up to 10 kV. This apparatus successfully electrospun fibres, such as PVP, PVDF, and PCL, with diameters in the nanometer range.

Table 4 demonstrates the influence of voltage and device configuration on fibre diameter and morphology across various polymers and electrospinning methodologies. For polyvinylpyrrolidone (PVP), needle-based electrospinning at 15 kV produces fibres with an average diameter of 1320 ± 860 nm, while battery-operated devices at 10 kV generate fibres with a larger diameter of approximately 1.8 μm. Solar hand-powered configurations operating at 3.8 kV yield significantly finer fibres with diameters of 379 ± 120 nm. PZT generator devices exhibit versatility, producing fibres ranging from 650 nm to 1050 nm at voltages between 15 and 25 kV. Polyvinylidene fluoride (PVDF) fibres exhibit varying diameters contingent upon the electrospinning method employed. Needle-free systems at 50 kV generate fibres with diameters between 200 and 500 nm, while needle-based systems at 15–25 kV produce fibres with comparable diameters of 150 to 400 nm. Battery-operated systems at 10 kV yield even finer fibres with diameters of 170 nm. Triboelectric rotating disk or PZT generators at 56 kV result in fibres with larger diameters of approximately 973 nm. For polycaprolactone (PCL), needle-free devices at 70 kV produce extremely fine fibres with diameters of 262.7 nm, whereas needle-based devices at 15 kV generate fibres with larger diameters of approximately 1029.3 nm. Battery-operated systems at 10 kV achieve relatively fine fibres with diameters of 266 nm. Self-powered melt electrospinning at 15 kV produces fibres with diameters ranging from 800 to 900 nm. Polylactic acid (PLA) fibres exhibit varying thicknesses dependent on the electrospinning method utilised. Needle-free electrospinning at 20 kV results in fibres with average diameters of 373 ± 30 nm, while needle electrospinning at 8.5 kV produces fibres with larger diameters of 585 ± 125 nm. Self-powered melt electrospinning at 15 kV, analogous to PCL, yields fibres with larger diameters of 1 μm.

Table 4. Comparison of Portable and Traditional Electrospinning Devices for Wound Healing Applications

Polymer	**Device Type**	**Voltage (kV)**	**Fibre Diameter (nm/μm)**	**Results/Findings**
PVP	**Needle-Free**			
	Needle	15 kV	1320 ± 860 nm	[77]
	Battery-Operated	10 kV	1.8 μm	[60]
	Solar Hand Power	3.8 kV	379 ± 120	[75]
	PZT Generator Device	15-25 kV	650-1050 nm	[78]
PVDF	Needle-Free	50 kV	200–500 nm	[79]
	Needle	15–25 kV	150–400 nm	[79]
	Battery-operated electrospinning	10 kV	170 nm	[60]

	(BOEA)			
	Triboelectric Rotating Disk Generator	56 kV	973 nm	[76]
	PZT Generator Device	56 kV	**973 nm**	[78]
PCL	**Needle-Free**	70 kV	262.7 nm	[80]
	Needle	15 kV	1029.3 nm	[80]
	Battery-operated electrospinning (BOEA)	10 kV	266 nm	[60]
	Self-powered Melt Electrospinning	**15 kV**	**800–900 nm**	[61]
PLA	**Needle-Free**	20 kV	373 ± 30 nm	[81]
	Needle	8.5 kV	585 ± 125 nm	[82]
	Self-powered Melt Electrospinning	15 kV	1 μm	[61]

The findings demonstrate that higher voltages generally produce thinner fibres, particularly in needle-free systems, while lower voltages and melt electrospinning tend to yield thicker fibres. The versatility of self-powered and battery-operated systems, as well as the utilisation of triboelectric and solar-powered devices, underscores the increasing potential for portable and efficient electrospinning solutions, particularly in resource-limited or on-site applications such as wound healing and hemostasis. The capacity to fine-tune fibre diameter through voltage and device type offers significant advantages for tailoring nanofiber properties to specific biomedical, filtration, and textile applications.

5. Conclusion

The development and application of portable in situ electrospinning devices represent a significant advancement in the fields of wound care and biomedical engineering. These devices offer a practical solution to the challenges associated with traditional wound dressings, particularly in emergency and remote environments, where immediate and customised treatment is essential. By facilitating the direct deposition of nanofiber layers onto wounds, portable electrospinning technology enhances wound healing, minimises infection risks, and provides tailored wound coverage, even in complex or irregular cases. As elucidated in this study, various electrospinning techniques, including needle-based, coaxial, and melt electrospinning, demonstrate unique strengths that cater to different medical and industrial needs. The emergence of battery-powered and generator-operated portable devices has expanded the scope of electrospinning applications, enabling their use in field environments, surgical settings, and home care. These devices not only simplify the fabrication of wound dressings but also allow for the integration of antimicrobial agents and other therapeutic compounds, thereby accelerating the healing process and improving patient outcomes.

Despite the promising potential of portable electrospinning devices, challenges persist in terms of achieving consistent fibre quality, scale-up production, and refining device portability. Additionally, addressing the issue of solvent residues and developing more environmentally friendly materials are crucial for ensuring the widespread adoption of this technology. Further research and innovation in electrospinning technology are essential for optimising the device design, improving the operational efficiency, and expanding the range of biocompatible polymers available for use. With continued advancements, portable in situ electrospinning devices have the potential to revolutionise personalised healthcare, providing rapid and efficient solutions for wound care in both clinical and non-clinical settings.

The future of portable in situ electrospinning devices presents a significant potential for revolutionising wound care, tissue engineering, and personalised medicine. As technology advances, improvements in portability, automation, and material innovation will drive the expansion of these devices across medical and industrial fields. Enhancing portability using lighter materials, compact designs, and efficient battery technologies will increase adaptability in emergency and remote environments. Automated systems capable of real-time fibre deposition adjustments are required to minimise operator variability and ensure consistent and precise wound coverage. Material innovations, particularly the development of biocompatible and biodegradable polymers with antimicrobial properties, will enable the production of advanced nanofiber dressings tailored to specific wound types. Furthermore, the integration of growth factors, stem cells, and drug-loaded fibres accelerates tissue regeneration and provides localised treatment, enhancing the overall healing outcomes.

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