International Journal of Recent Technology and Applied Science
p-ISSN: 2721-2017, e-ISSN: 2721-7280

Original Research Paper

Application of Nanofibers from Electrospinning in Development of Smart Textiles for Military Clothing

Anisa Setianingsih[1*], Khairunnisa Ulfitri[1], Mas Ayu Elita Hafizah[1]

[1] *Department of Weapons Technology, Faculty of Defense Science and Technology, Indonesia Defense University. Sentul, Indonesia.*

Article History
Received:
20.11.2024

Revised:
13.04.2025

Accepted:
28.04.2025

***Corresponding Author:**
Anisa Setianingsih
Email:
anisasetia13.as@gmail.com

Abstract: This paper examines the application of nanofibers produced via electrospinning in the development of smart textiles for military clothing. Smart textiles represent a significant advancement, integrating functionality with comfort to enhance traditional military garments. This study explores the potential of smart textile technology to improve the efficiency and effectiveness of military operations through capabilities such as monitoring soldiers' physiological conditions, facilitating enhanced communication, and providing protection against environmental threats. A literature review methodology was employed to analyze existing research on smart textiles in the context of military applications. This review covers technological components, benefits, challenges, and the potential of nanofibers in military clothing. The results highlight the capacity of electrospun nanofibers to improve the protective, communicative, and adaptive properties of military wear, with a focus on materials like carbon nanotubes and graphene and their applications in enhancing tensile strength, conductivity, and UV protection. This paper contributes to a deeper understanding of smart textile technology and its potential to advance the defense industry and improve the quality of protective equipment for soldiers.

Keywords: Carbon Nanotubes, Electrospun Nanofibers, Military Clothing, Protective Clothing, Smart Textiles.

1. Introduction

Technological advancements significantly impact the defense and military sectors, with smart textiles emerging as a notable innovation that combines functionality with comfort. Traditional military clothing, focused on durability and protection, is being enhanced by smart textile technology to be more interactive and responsive. Smart textiles can improve the efficiency and effectiveness of military operations through physiological monitoring, enhanced communication, and environmental protection. For example, sensors can measure temperature, heart rate, and humidity, enabling faster and more precise medical treatment. Additionally, military clothing can adapt to environmental conditions by changing color or increasing water resistance.

Nanofiber-based smart textiles have garnered increasing attention due to their unique properties and potential applications. Previous research has explored various nanofiber materials and fabrication technique for smart textiles [1]. For example, electrospun nanofibers have been investigated for their enhanced sensing capabilities and mechanical strength when integrated into fabrics, showcasing their promise for creating advanced military garments.

The development of smart textiles for military applications represents a significant opportunity to enhance soldier performance and safety. However, realizing this potential requires addressing several challenges that can be framed within the context of affordance theory. Affordance theory, as it applies to technology, suggests that the perceived and actual properties of an object determine how it can be used. In the context of military clothing, smart textiles must afford the necessary functionalities (e.g., physiological monitoring, environmental adaptation, enhanced communication) without compromising the comfort, durability, and practicality that soldiers require in extreme conditions. Currently, the problem lies in translating the theoretical potential of nanofiber-based smart textiles into practical, real-world solutions. While nanofibers, particularly those produced via electrospinning, offer unique properties such as high surface area, strength, and flexibility, their integration into textiles faces several barriers. One critical aspect is ensuring that the smart textiles afford seamless integration with existing military protocols and equipment. If the technology is too complex, requires extensive training, or hinders mobility, it will not be readily adopted. Moreover, the longevity and reliability of these materials under harsh conditions must be considered. Can these textiles withstand repeated washing, exposure to extreme temperatures, and the physical demands of combat situations? This durability directly impacts the perceived "usability" of the technology, a key component of affordance. Another challenge is the cost-effective production and scalability of nanofiber-based smart textiles. Current methods may be too expensive for widespread adoption, particularly given the large quantities required by military forces. Finally, ethical considerations, such as data privacy related to physiological monitoring and the potential for misuse of advanced textile technologies, must be addressed.

This study reviews the application of electrospun nanofibers in smart textiles for military clothing, focusing on their potential to enhance protection, communication, and adaptability. The integration of nanofibers, particularly carbon nanotubes and graphene, offers significant improvements in tensile strength, conductivity, and UV protection, thereby improving the safety and effectiveness of military personnel. Further research should focus on optimizing nanofiber integration into textile structures, evaluating long-term durability, and addressing scalability challenges for mass production to fully realize the potential of smart textiles in military applications. It aims to provide a deeper understanding of smart textile technology, contributing to the development of the defense industry and improving the quality of soldiers' protective equipment.

2. Nanotechnology, Nanotechnology in Textile

2.1. Nanotechnology

According to the National Nanotechnology Initiative (NNI) factor of view, nanotechnology is classified as the exploitation of systems with at least one-nanometer size for the manufacture of substances, devices, or systems with unique or extensively greater houses because of their nanoscale size [1]. The international of nanomaterials includes an extensive type of thrilling substances, starting from one to one thousand nm, and with first-rate bodily and chemical houses. These substances encompass zero-dimensional nanoparticles or quantum dots, one-dimensional nanowires, nanorods, nanofibers, and nanotubes, in addition to two-dimensional nanosheets [2].

Nanotechnology is a brand-new area that is anticipated to have vast implications in all fields of technological know-how and era along with substances technological know-how, substances processing era, mechanics, electronics, optics, medicine, electricity and space, plastics, and textiles. Although this era remains in its early stages, it's been tested to enhance fabric performance. New packages of nanotechnology in textiles offer a whole lot of houses that can be progressed and utilized in new products.

2.2. Nanotechnology in Textile

Nanofibers have dimensions that are about 50 to hundred instances smaller than everyday fibers recognized today, which include wool, cotton, silk, and polyester fibers. This nano measurement offers new traits to nanofibers. These fibers may be very strong, having a totally big floor place according to mass (e.g., greater than a thousand m2/gram) that is known as a particular floor place [3]. Nanoparticles are very promising whilst utilized in textiles (clothing) or inside the fibers that make up fabric materials.

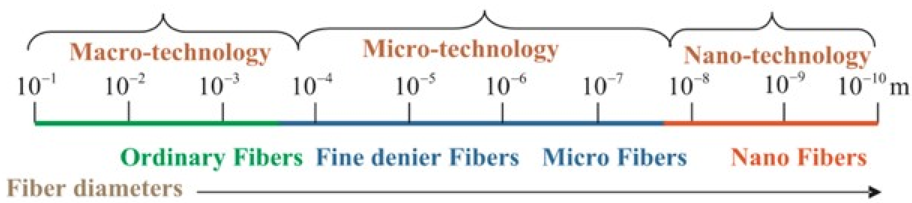


Figure 1. Fiber's Diameter Size

The specific surface area of nanofibers is a key factor that enhances their functionality. For instance, cellulose nanofibers can achieve specific surface areas of around 430 m^2/g under optimal processing conditions, which can be further increased with additional energy input during manufacturing [25]. This large surface area allows for greater interaction with other materials, making nanofibers ideal for applications in filtration, drug delivery, and as reinforcement in composite materials [26].

Nanofibers exhibit superior mechanical properties compared to their larger counterparts. The tensile strength of electrospun polymer nanofibers can reach values significantly higher than traditional fibers due to the alignment of polymer chains during the electrospinning process [26].

2.2.1. Electrospinning

Electrospinning is a mechanical and electrical technique for producing ultrafine fibers in the submicron diameter range using high voltage. Electrospinning is a direct extension of electric spraying which is also called electrohydrodynamic spraying which was first patented in 1902 by Morton and Cooley who both discovered a method capable of dispersing liquids using electrostatic forces [4].

To understand the basic principles of the electrospinning process, consider a charged, low molecular weight conducting fluid droplet placed in a vacuum. The liquid drops experiences two forces: (1) disintegrative repulsion and (2) surface tension which attempts to hold the liquid drop in a spherical shape.

During the electrospinning process, a high electrical voltage is applied to the liquid droplets from the polymer melt/solution at the tip of the spinneret. As the high voltage continues to be increased, the liquid droplet will begin to elongate into a conical shape known as a "Taylor cone". Elongation begins when electrostatic repulsion overcomes surface tension. The charged liquid jet is directed towards the collector metal after the Taylor cone is produced. The fluids mentioned here may be melted polymers, polymer solutions, or emulsions. Solid fibers will develop as the melt cools or the solvent evaporates from the whipping action that occurs throughout the process from the Taylor cone to the collector, depending on the viscosity of the fluid. As a result, the collector is covered with a non-woven fiber mat [5].

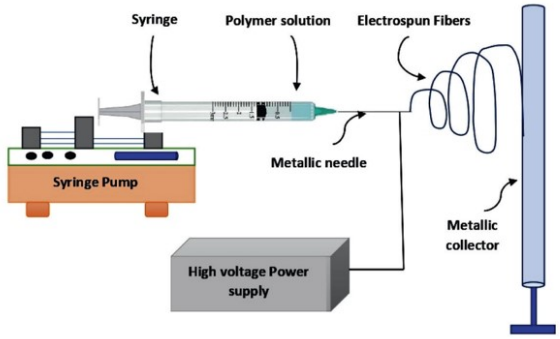


Figure 2. A Series of Basic Tools for The Horizontal Electrospinning Process

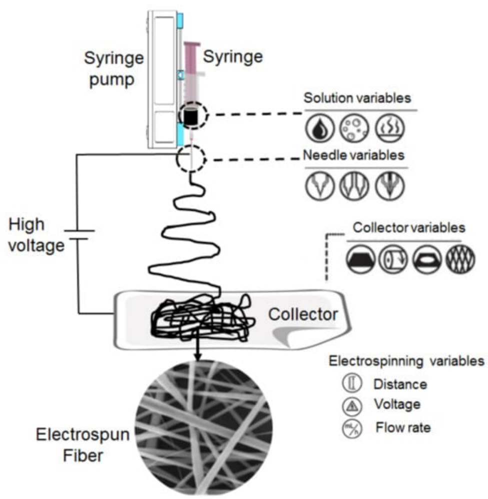


Figure 3. A Series of Basic Tools for The Vertical Electrospinning Process

2.2.2. Voltage in Electrospinning Process

The electrospinning process depends on operating parameters, material parameters, and environmental parameters that influence fiber morphology. The operating parameters consist of the applied voltage or electric field, the flow rate of the polymer melt/solution, and the distance between the metal needle tip and the collector. Small changes in operating parameters can cause significant changes in fiber morphology [5].

The applied voltage has some influence on the electrospinning process because it influences the amount of charge applied to the solution. Increasing the voltage will speed up the rotation of the electrojet and this can result in a larger volume of solution sucked from the tip of the needle. If the solution feed rate remains constant, this will result in a smaller and less stable Taylor Cone and ultimately cause the Taylor Cone to shrink into the needle [6].

2.2.3. Polymer Melt/Solution Flow Rate

The flow rate of the melt/solution flowing through the syringe is also a factor that influences the diameter of the fibers that will be produced from the electrospinning process. Reducing the flow rate will reduce the possibility of polarization. High flow rates produce large-diameter fibers rather than fine filaments [7]. Increasing the flow rate causes the pore size to also increase from 90nm to 150nm [8].

In addition, if the flow rate is too large it can bead on the fiber. This is due to incomplete evaporation and minimum stretching of the solution from the nozzle to the collector. The minimum flow rate is more effective in creating nanofibers and forming a stable Taylor Cone [9]. The spinning solution feed rate typically applied during the electrospinning process is in the range of 0.5–2.0 mL/h. The feed rate and voltage work simultaneously to produce a stable Taylor cone shape, to avoid droplet formation [10].

2.2.4. Nozzle and Collector Distance

The distance between the nozzle and collector affects the jet path and travel time before it rests on the collector. If the voltage is kept constant then the electric field strength will be inversely proportional to the distance. In an electrospinning setup, this distance ranges from 10 to 15 cm, which generally allows sufficient time (flight time) for the solvent to evaporate so that dry fiber strands are collected. Moreover, in the case where the voltage is kept constant while the distance is varied, the behaviour of the electrospinning jet and the collected fiber profile are similar to the case where the voltage is varied while maintaining the tip-to-collector distance. Increasing the distance between the tip and the collector can reduce the fiber diameter because the strain distance becomes larger [6].

2.2.5. Other Parameters

In addition to the electrospinning process parameters, solution properties, and environmental parameters also show an influence on fiber production and morphology [6]. Solution conductivity shows an increase in fiber quality, such as reducing beads and making the fiber diameter thinner. Increasing solution conductivity will increase the stretching of the solution jet because of the high level of charge carried by the solution. In addition, increasing solution conductivity will increase the instability of the folds and lengthen the jet path.

The higher the solution viscosity, the larger the fiber diameter. When the viscosity increases, the charge that initiates spinning may not be enough to stretch the polymer solution to the desired fiber diameter. Solution volatility More volatile solvents can produce ribbon/flat fibers and fibers with surface pores. Solutions made from solvents with very low volatility can produce wet fibers, fused fibers, or even no fibers collected. Conversely, high volatility can result in discontinuous spinning due to polymer compaction at the spinneret tip.

Table 1 shows the relevance between electrospinning parameters and military clothing performance.

Table 1. The Impact of Electrospinning Parameters and Military Clothing Performance

Parameter	Impact on Nanofiber Properties	Military Relevance
Voltage	Higher voltage accelerates jet rotation, reducing fiber diameter but risking unstable Taylor cones. Optimal range: 10–30 kV.	Thinner fibers enhance breathability and flexibility for lightweight, adaptive uniforms.
Flow Rate	Low flow rates (0.5–2.0 mL/h) minimize bead formation and stabilize Taylor cones.	Uniform fibers improve durability and conductivity for integrated sensors/communication systems.
Nozzle-Collector Distance	Shorter distances (<15 cm) reduce solvent evaporation time, increasing fiber diameter. Longer distances (>20 cm) produce thinner fibers.	Controlled fiber diameter optimizes tensile strength (critical for bulletproof vests) and UV protection.
Solution Conductivity	Higher conductivity enhances jet stretching, producing thinner fibers with reduced bead defects.	Critical for integrating conductive nanomaterials (e.g., carbon nanotubes) for real-time health monitoring.
Polymer Viscosity	High viscosity increases fiber diameter; low viscosity risks incomplete fiber formation.	Balances flexibility and strength in composite fabrics (e.g., graphene-reinforced textiles).
Humidity/Temperature	High humidity causes rapid polymer precipitation, thickening fibers. High temperatures reduce viscosity, thinning fibers.	Ensures consistent performance in extreme environments (desert heat, tropical humidity).

Higher or lower humidity results in larger fiber diameters. At higher humidity, this is due to the rapid polymer precipitation when water condenses on the surface of the electrospinning jet, especially at high relative humidity this prevents further polymer elongation and thus produces thicker fibers. While at lower humidity, the faster solvent evaporation and the resulting increase in solidification rate will increase the fiber diameter. Lastly is the temperature parameter, high temperatures will produce thinner fiber diameters. Higher temperatures will increase the evaporation of the solution and reduce the viscosity of the polymer solution.

2.3. Nanotechnology in Military Textiles

2.3.1. Ballistic Protection Enhancement

Nanofibers produced via electrospinning significantly improve ballistic resistance in military textiles due to their high strength-to-weight ratio. The addition of 20% mass fraction of CNTs into PVA increases the Young's modulus up to 137.71 Mpa. This high Young's modulus indicates that the material is stiffer and more resistant to deformation, which is critical for withstanding the impact of projectiles. The 1.8x increase in Young's modulus from pure PVA occurs due to interfacial reinforcement of the CNT-PVA [27]. CNTs form a distributed network within the PVA matrix, effectively transferring loads through strong covalent bonds. Multilayered graphene oxide nanofibers block shrapnel through their hexagonal lattice structure while remaining 40% lighter than Kevlar.

2.3.2. Adaptive Camouflage System

Nanofibers enable dynamic camouflage by responding to environmental stimuli, as shows in Table 2.

Table 2. Adaptive Camouflage System

Technology	Mechanism	Military Application
Photochromic Nanofibers	TiO_2 nanoparticles in PU nanofibers change color under UV exposure.	Desert-to-forest environment adaptation.
Thermochromic Layers	VO_2 nanofibers shift IR signatures at 68°C, masking body heat from thermal scopes.	Night operations stealth.
Electroactive Textiles	Polyaniline nanofibers alter reflectivity when voltage is applied (0–5 V).	Instant urban/woodland pattern switching.

2.3.3. Enemy Detection Capabilities

Polyaniline-CNT composites detect explosives (e.g., TNT) at 0.1 ppm concentration via resistivity changes. Silver nanoparticle nanofibers neutralize anthrax spores within 15 seconds of contact. Cellulose acetate nanofibers with graphene quantum dots provide real-time humidity mapping (accuracy: ±2% RH).

3. Methodology

This study employs a systematic literature review approach to identify, collect, select, and evaluate relevant research on smart textile technology in the context of military clothing. The methodology is designed to analyze trends, challenges, and potential applications of nanofiber-based smart textiles, ensuring a comprehensive understanding of the topic. The identification and selection of sources were conducted using the following databases from Scopus, ScienceDirect and Google Schoolar. The search was performed using specific keywords to ensure relevance to the research topic: electrospinning for military textiles, nanotechnology in military fabrics, smart textiles for defense applications, nanofibers in ballistic protection and adaptive camouflage using nanotechnology.

To ensure the quality and relevance of the selected literature, the following inclusion criteria were applied. Studies published between 2012 and 2024 to focus on recent advancements, and research specifically addressing nanofiber applications in military textiles.

The following types of literature were excluded articles published before 2015 to avoid outdated findings, and studies unrelated to military applications of nanotechnology or smart textiles.

The selection process involved three stages. Initial screening, titles and abstracts were reviewed for relevance to smart textiles and military applications. Full-text review, selected articles underwent a detailed review to assess their methodological rigor and relevance to this study's objectives. Final selection, only studies meeting all inclusion criteria were included in the analysis.

Key data points extracted from the selected studies included applications of nanofibers (e.g., ballistic protection, adaptive camouflage, enemy detection), electrospinning parameters influencing fiber properties (e.g., voltage, flow rate), and challenges in integrating nanotechnology into military textiles (e.g., scalability, durability). The extracted data were synthesized to identify trends, challenges, and future directions for smart textile technology in military clothing.

4. Finding and Discussion

Nanofibers produced via electrospinning have demonstrated significant potential in enhancing military textiles, particularly in ballistic protection, adaptive camouflage, and enemy detection capabilities. While the cited studies provide valuable insights, a comparative analysis reveals key trends, challenges, and areas for improvement.

Both the wearer's condition and the environment can be sensed by smart fabrics. Smart textiles can detect changes in health conditions or temperature increases. Wearable computing and smart clothing differ in how the materials are integrated. Electronic components in smart clothing must be properly woven into the fabric rather than merely added or fastened. Comfort is important, but it's not just about technology. The electrical materials must be well-designed so as not to disrupt the coziness. Sensors for detection, data processing for data processing, actuators for response, storage for data storage, and communication for communication are the five fundamental functions of smart textiles [11]. Smart textiles must continue to be long-lasting, comfortable to wear, and easily maintained like regular textiles. Military uniforms, protective gear, gloves, socks, and other items are made from military materials. All of these are necessary for soldiers to defend themselves. With an anticipated global smart textile market of over 1.5 billion USD, the protective and military apparel industry is growing. The electrospinning process of creating nanofibers works well for applications where conductivity is a top priority. The most widely utilized polymer is polyaniline. Combining nanoparticles, such as carbon nanotubes and silver, can improve electrical conductivity or produce antimicrobial fibers. Stronger and longer-lasting textiles can be created by mixing nanoparticles with either organic or inorganic substances. One type of nanoparticle that is utilized to defend against ultraviolet (UV) rays is titanium oxide (TiO2). The textile industry has started using microencapsulation technology, which involves inserting ingredients that are fire or heat-resistant inside tiny capsules that adhere to the fabric. Clothes can be made more odor- and bacteria-resistant by adding silver nanoparticles [12]. The toughness factor, or the material's capacity to absorb energy when distorted before breaking, is a crucial component in the production of high-quality protective materials. High-toughness materials are crucial, for instance, in bulletproof vests. Here are some examples of nanomaterials used in textile finishing [19].

Table 3. Nanomaterials Used in Textile Finishing

Finishing	Nanomaterial
UV protection	ZnO, TiO_2
Coloring dan anti-fade	Hydrocarbon nanopore, carbon black, SiO_2 matrix
Moisture absorbing	TiO_2
Self-cleaning dan waterproof	TiO_2, fluoroacrylate, CNT, SiO_2 matrix
Health products	Montmorillinite (nano clay), SiO_2 matrix
Antistatic and conductive	CNT, carbon black, copper, polypyrrole, polyaniline
Durability	Al_2O_3, SiO_2, ZnO, CNT, polybutylacrylate
Antibacterial	Chitosan, Ag, SiO_2 matrix, TiO_2
Flame retardant	Boroxosiloxane, CNT, Montmorillinite (nano clay), Sb_3O_2

International Journal of Recent Technology and Applied Science, vol 7, no. 2, pp. 55-70, September 2025. **DOI: 10.36079/lamintang.ijortas-0702.780**

4.1. Ballistic Protection Enhancement

Bulletproof vests and other ballistic protection systems rely on a combination of material properties and engineering principles to balance protection, mobility, and wearability. Have high tensile strength to resist penetration, absorb kinetic energy through controlled deformation, and lightweight for soldier mobility.

The cylindrical structure of CNTs (Figure 4) distributes the impact energy of a projectile throughout the fiber network, reducing stress concentration. Van der Waals forces between CNTs allow temporary elastic deformation before breaking, increasing energy absorption capacity. CNT-PVA has a 10x higher strength-to-weight ratio than conventional fibers (e.g., Kevlar®), meeting the need for lightweight yet protective military textiles.

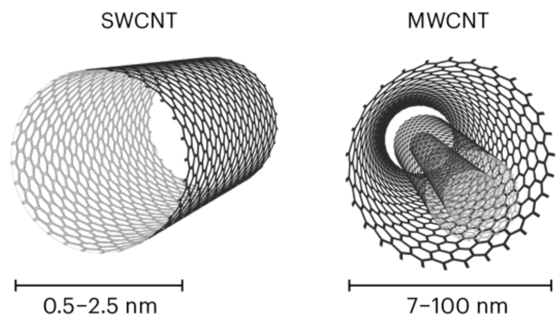


Figure 4. Single Wall Carbon Nanotubes and Multi Wall Carbon Nanotube's Structure

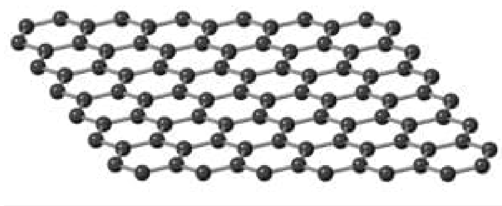
4.1.1. Carbon Nanotubes

One of the promising tough materials is carbon nanotubes (CNT). CNT has a cylindrical structure that resembles a honeycomb and has unique mechanical properties, especially in increasing tensile strength. The special toughness is due to the very strong covalent bonds between the carbon atoms in the tube. Nanotubes tend to form bonds due to weak van der Waals forces, this causes nanotubes to be easily rolled up. When nanotubes are given high pressure, they will unite to produce a strong network with unlimited length [12].

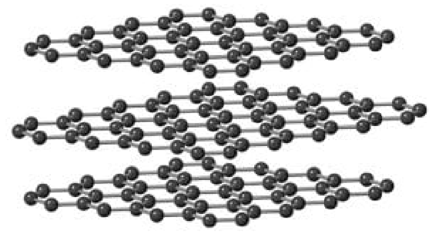
Single-wall carbon nanotubes (SWCNT) are dissolved in a surfactant solution before being injected into a container of polymer solution, such as water-based polyvinyl alcohol (PVA), to create nanotube-based fibers. The fiber is then gradually removed from the container. The clustering and alignment of the nanotubes are made possible by this mechanism. The main goal of adding CNTs to the fiber is to alter its electrical and mechanical characteristics. Nanotube-based fibers may be twisted as far as feasible without breaking, in contrast to regular carbon fibers.

4.1.2. Graphene

Graphene is one of the allotropes of carbon that is in the form of a two-dimensional sheet. It can be said that graphene is a single layer of graphite arranged in a regular hexagonal pattern. Having light and strong properties, graphene is the strongest material ever discovered. Consisting of a carbon layer that is only one atom thick, the distance between atoms is only 0.142 nanometers. Each carbon atom has one free electron. This nanomaterial has delocalized pi-electrons in each hexagon on its surface, causing graphene to have very good electrical conductivity. Graphene is a semiconductor even though it is made of carbon, so it is often called a quasi-metal [12]. To obtain material properties with high conductivity, graphene nanoparticles can be composited with polyacrylonitrile nanofibers using the electrospinning synthesis method [20]. There are several forms of graphene, namely single-layer graphene which has one layer of atoms. Then there is bilayer or multilayer graphene consisting of two or more layers of graphene. Next are graphene nanoplatelets (GNPs), small pieces of graphene that can be used to improve the mechanical properties or conductivity of other materials [12]. Here is a picture of the structure of three types of graphene [21].



(a)



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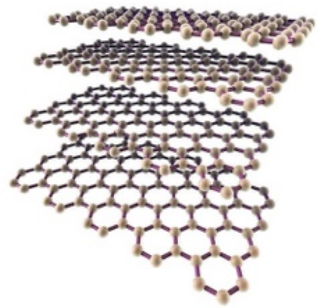

(c)

Figure 5. Structure of Three Types of Graphene
(a) Single-Layer Graphene
(b) Bi-Layer or Multi-Layer Graphene
(c) Graphene Nano Platelets (GNPS)

4.1.3. Bulletproof Vest

A bulletproof vest made of carbon nanotubes (CNT) is a solution for safeguarding, because this armor is 117 times stronger than steel [13]. Traditional bulletproof vests are made of woven or laminated polymer fibers with high stiffness and toughness, formed in layers. When a bullet hits the armor, the fabric material will absorb the energy from the impact by stretching the fibers. The stiff fibers will distribute the load from the bullet to a wider area so that it is not only focused on one point.

Carbon nanotubes (CNT) are an ideal candidate for bulletproof vests because of their unique combination of very high elastic modulus and high yield strain. Thus, bulletproof vests made of CNT are not only strong but can also block bullets better than other fibers.

The ability of CNT-based body armor to be integrated with smart technology is among its most intriguing possibilities. CNTs' electrical conductivity may make it possible to integrate biometric sensors or heating components into the armor, turning it into "smart clothing" with extra features or the ability to track health indicators [21] [22].

Methods for optimizing CNT fibers for ballistic applications are still being investigated. Recent developments have shown that lab-produced carbon nanotube (CNT) fibers are more suitable for high-performance ballistic protection [21] [23] because they can sustain supersonic impact loads more effectively than conventional aramid fibers. CNT fibers could soon take the place of current ballistic materials like Kevlar and UHMWPE as manufacturing processes advance, creating a new class of ultra-lightweight body armor [21] [23].

In conclusion, because of their superior mechanical qualities, capacity for energy absorption, and potential for intelligent integration, carbon nanotubes offer a viable path toward improving bulletproof vest technology. Personal protection equipment for military, law enforcement, and civilian purposes might be greatly enhanced by further research and development in this area.

4.1.4. Performance Comparison

CNTs enhance the mechanical properties of PVA significantly. For instance, a CNT-PVA composite with 20% CNT showed a Young's modulus of 137.71 MPa, indicating substantial tensile strength improvements compared to standard PVA [27]. Graphene composites generally exhibit superior mechanical properties due to graphene's high strength and stiffness. They provide better reinforcement than CNTs in some applications because of their two-dimensional structure, which allows for greater surface area interaction with the polymer matrix [28].

CNT-PVA composites also demonstrate improved electrical conductivity due to the high aspect ratio of CNTs, which facilitates electron transport within the matrix. For example, a PVA composite with 5% CNT achieved a maximum AC conductivity of 2.72×10^{-7} S/m [29]. Graphene-based materials often outperform CNTs in terms of electrical properties as well. They exhibit enhanced charge transport capabilities and lower resistivity, making them more suitable for applications like energy storage devices [30].

CNTs contribute to increased thermal conductivity in PVA composites, with some studies reporting significant enhancements at low loading levels compared to other polymer composites [31]. Graphene's thermal conductivity is even higher than that of CNTs, making graphene-based composites preferable for applications requiring effective heat dissipation [30].

The production of carbon nanotubes can be achieved through several methods, including chemical vapor deposition (CVD) and laser ablation. While these methods can yield high-quality CNTs, they often involve complex processes that can drive up costs. However, advancements in production techniques are gradually improving scalability and reducing costs [32]. Graphene manufacturing is currently hindered by high costs and scalability issues. Common methods such as mechanical exfoliation and CVD are expensive and not easily scalable for mass production. As a result, while graphene offers superior properties, its widespread application is limited due to these economic factors [32] [30].

While CNT-PVA composites exhibit promising mechanical and electrical properties with relatively simpler production processes compared to graphene-based materials, the latter often provides superior performance characteristics. However, the high costs and scalability challenges associated with both materials present significant barriers to their commercial application. Future research should focus on optimizing production techniques for both CNTs and graphene to enhance their feasibility for large-scale use in various industries.

4.2. Military Uniform

Thermal comfort plays a crucial role in maintaining the body temperature of soldiers. Cold climates make it difficult for soldiers to survive. Sweat produced during activity reduces the insulation value of clothing materials because sweat and rain can cause clothes to become damp. So, it is significant how textile materials can control humidity. Thermal insulation depends on two things, to be specific the thermal conductivity of the fiber and the amount of air trapped in the textile structure [14]. One of the materials is expanded polytetrafluoroethylene (ePTFE). This material has a light and thin membrane with tiny pores that can block water but still allow water vapor to escape [15].

By improving breathability and temperature control, recent advancements like GORE-TEX Stretch technology have significantly increased thermal comfort. This method greatly reduces thermal stress [24] while enabling more mobility by combining elastic components with sturdy materials. These developments are essential because they allow soldiers to carry out physically taxing duties without feeling constrained or overheated.

By combining drugs into biodegradable polymers, we can produce dose forms that can be released and controlled according to time or physiological conditions. Some types of polymers that are common and successfully used in medical applications include polyesters such as poly (glycolide) and poly (D, L-lactide) [17]. This technology can be applied to military clothing, where nanofibers composited with antibiotics can become a physical barrier during the wound healing process and act as a barrier to microorganisms, thereby reducing the local inflammatory response.

In addition, the ability of military clothing to camouflage is also important to protect soldiers from enemy detection. The variety of colors and camouflage patterns varies by country. Two important aspects in the design of patterns and color selection of military clothing, the color must be able to blend with the environment without being too contrasting in color intensity and the pattern chosen must be able to change the shape or outline of the object, making it difficult to recognize. Digital camouflage patterns can blend with the environment more quickly from a certain distance [14].

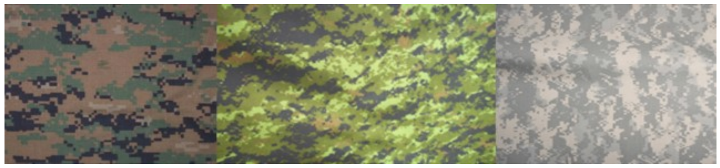

Figure 6. Digital Camouflage Pattern

Nanotechnology offers the opportunity to modify the surface properties of materials at the molecular level. One concept that is applied is biomimicry, where fabrics can be made to have the ability of chameleon camouflage. This means that a soldier's clothing can change color according to the environment, so it is more difficult to detect.

Stealth material is a type of material that is specifically designed to reduce or prevent detection by radar, infrared, or other sensor systems. The goal in this context is to protect soldiers from being seen or detected by the enemy. Important aspects of this stealth material, namely the first is the reduction of emissivity or the amount of infrared radiation emitted by the object. By reducing the heat signature of the target, it will be more difficult to detect by the infrared radar system. The second is the barrier of radar waves, the ability to absorb or refract radar waves. The third is the combination of functions, not only focusing on reducing detection but also having additional functions such as antibacterial and self-cleaning properties. Finally, the design and shape aspects, in addition to materials, design, and shape also play a role in stealth capabilities. One of the stealth materials is the PAN/AL-ZnO/Ag (PAN/ZAO/Ag) nanofiber composite made by the electrospinning method [18].

The PAN/ZAO/Ag stealth material offers a much-needed solution for challenging combat settings by fusing these elements. Using materials that can prevent infrared detection, keep things clean, and have antibacterial qualities is essential in a diverse and frequently dangerous battlefield.

Adaptive camouflage involves changing the appearance of a material or object to blend in with its surroundings. Different actuation mechanisms can achieve this, each with unique advantages and limitations. Electrical actuation utilizes electrical signals to change color or patterns. This often involves electrochromic materials that alter their optical properties when an electric current is applied. Chemical actuation relies on chemical reactions to induce changes in color or texture. This includes thermochromic materials that respond to temperature changes or materials that react to specific chemicals in the environment. Mechanical actuation Involves physical movement or deformation of materials to achieve camouflage effects. This can include shape-memory alloys or hydrogels that change shape or color in response to mechanical stimuli.

Table 4. Summary of Actuation Mechanism

Actuation Mechanism	Response Time	Power Supply	Complexity	Advantages	Disadvantages
Electrical	Rapid	Required	High	Fast, easy sensor integration	Requires power, complex integration
Chemical	Slow	Not Required	Low	Simple, cost-effective, passive operation	Slow response, requires specific conditions
Mechanical	Slow	Not Required	Medium	Robust, versatile	Slow, may require complex mechanical designs

4.3. Chemical Biological Radioactive Nuclear Protective Clothing

Nowadays, most protective clothes come with activated charcoal that has been infused with metal. The process of a substance becoming completely saturated is called impregnation. By filling the pores with an active metal solution through metal adsorption that is, by soaking in an active metal solution—saturation is accomplished. Physically absorbing chemical or biological molecules is its purpose. After the garment is utilized, there is a chance of waste, nevertheless, which must be considered. Because of its high surface area and reactive concentration, this activated charcoal possesses potent adsorbent qualities. To incorporate nanoparticles into nanofibers in a safer manner, researchers concentrate on the method of directly mixing them with polymer solutions before the electrospinning process [17].

Filtration or isolation materials used for protective clothing against chemical warfare agents (CWA) usually only provide a physical barrier to chemical toxins. This means that after use, this material requires a proper decontamination and disposal process. So, there is a need to develop materials that not only provide a physical barrier but can also neutralize or degrade chemicals.

One way to create materials that can decompose hazardous chemicals and organic materials is by applying nanotechnology, especially metal oxide nanoparticles that have photocatalytic activity. TiO2 (titanium dioxide) nanoparticles have proven effective for this purpose because of their abundant availability, low cost, and low toxicity [16]. Often, chemicals are released in the form of vapors, so to detect these vapors, several semiconductor metals such as TiO2, SnO2, and ZnO are added, which are known to be able to detect insignificant gas concentrations. Nanowires from these fibers function as sensitive, fast, stable, and easily reproducible gas sensors [17].

As gas sensors, nanofibers containing semiconductor nanoparticles can swiftly and precisely identify harmful vapors. These fibers' special qualities provide nanowires made from them with their sensitivity and stability, which makes them perfect for monitoring chemical exposure in real-time during conflict. In addition to improving individual safety, this capacity offers vital information for operational decision-making.

The ongoing research into the application of nanotechnology in protective clothing is enabling more responsive, intelligent gear that surpasses traditional protection measures. Future developments might include self-decontaminating materials, which are textiles that can clean themselves after encountering contaminants. Adaptive camouflage refers to textiles that can change color or pattern in response to environmental stimuli. Integrated health monitoring is clothing that tracks physiological responses and environmental conditions to provide the wearer with real-time feedback.

Explosive detection technologies rely on different sensing mechanisms, each with distinct strengths and limitations. Here is a comparison of electrochemical, optical, and mass-based sensing technologies. Electrochemical detects explosives by measuring changes in electrical properties (e.g., resistance, current, or voltage) caused by interactions between the sensor material and explosive molecules. Optical sensors Uses light-based techniques such as fluorescence quenching, infrared absorption, or Raman spectroscopy to identify explosive materials. Mass-based sensors detects changes in mass caused by the adsorption of explosive molecules onto a sensitive surface (e.g., quartz crystal microbalance).

Table 5. Comparison of Sensing Mechanisms

Sensor Type	Sensitivity	Selectivity	Response Time	Portability	Cost
Electrochemical	High	Moderate	Moderate	High	Low
Optical	High	High	Fast	Moderate	High
Mass-Based	Very High	Low to Moderate	Moderate	Moderate	Moderate

Nanofiber-based sensors are particularly promising for wearable platforms due to their lightweight, flexibility, and high surface area. Wearable sensors could integrate multiple sensing technologies (e.g., electrochemical and optical) for enhanced accuracy. The challenges are wearables require compact, long-lasting power sources, real-time analysis of sensor data demands efficient algorithms and hardware, also Reliable wireless transmission of data is essential, especially in remote or hostile environments.

Machine learning (ML) can significantly improve the accuracy and reliability of explosive detection systems. ML algorithms can analyze complex datasets to distinguish between explosives and benign substances, reducing false positives. Adaptive models can adjust to environmental changes (e.g., humidity or temperature) that might affect sensor performance. ML can predict sensor degradation over time, ensuring consistent performance. The use of machine learning could revolutionize both explosive detection and antimicrobial textiles by improving selectivity, reducing false positives, and enabling predictive maintenance. Further research should focus on scalable production methods, minimizing environmental impact, and enhancing integration into wearable systems for real-world applications.

4.4. Smart Textile and Affordance Theory for Military Applications

4.4.1. Ballistics Protection Enhancement

Nanofibers such as CNTs (Carbon Nanotubes) integrated into PVA increase the material's Young's Modulus, enhancing ballistic resistance. Improved safety (ballistics protection), provides a higher level of protection against projectiles and shrapnel, affording the soldier increased survivability in combat situations. Offers comparable or superior protection to traditional materials like Kevlar, but with a lighter weight, affording increased mobility and reduced fatigue. The enhanced protection should not hinder movement or flexibility, allowing the soldier to perform necessary tasks without restriction. The material must withstand multiple impacts and maintain its structural integrity under various environmental conditions, ensuring consistent protection over time. The integration of nanofibers should not compromise breathability or increase stiffness. The textile should remain comfortable for extended wear.

4.4.2. Explosive Detection Sensors

Incorporates electrochemical, optical, or mass-based sensors using nanofibers (e.g., Polyaniline-CNT composites). Improved safety detection by detecting explosives at trace levels, the textile afford the soldier enhanced safety by providing early warnings of potential threats. Real-time data feedback enhances situational awareness, affording proactive threat assessment and response. Integration must be seamless. The sensor system should not require extensive training or cumbersome operation, ensuring it doesn't hinder movement or add complexity in high-stress situations. An AI powered system could aid in this. Nanofibers must withstand harsh conditions, including repeated washing, exposure to extreme temperatures, and physical stress. Coatings and encapsulation can protect the sensors from degradation. Sensors and associated electronics should be lightweight and flexible, avoiding irritation or restriction of movement. Breathable fabrics and ergonomic sensor placement are crucial.

4.4.3. Adaptive Camouflage Systems

Utilizes nanofibers that change color or thermal signature in response to environmental stimuli (e.g., electrospun nanofibers, thermochromic nanofibers). Enhanced concealment By adapting to the surrounding environment, the textile afford the soldier improved concealment, reducing visibility to enemy forces. Thermal regulation, thermochromic nanofibers afford thermal camouflage, reducing detection by thermal imaging devices. Camouflage adaptation should be automatic and instantaneous without manual adjustments, ensuring soldiers can focus on their mission. Nanofibers must maintain their functionality under various weather conditions (UV exposure, rain, extreme temperatures). Robust encapsulation and UV-resistant coatings are essential. The integration of adaptive materials should not compromise breathability or increase weight. Lightweight, flexible nanofibers are preferred.

4.4.4. Antimicrobial Textile

Incorporates nanofibers with antimicrobial properties (e.g., silver nanoparticles, chitosan-based nanofibers) to neutralize pathogens. Improved hygiene by killing bacteria and fungi, the textile affords the soldier reduced risk of infection, promoting better health in the field. Antimicrobial properties help control odor, enhancing comfort during extended operations. Antimicrobial properties should be long-lasting and require minimal maintenance. Washing should not diminish effectiveness.

Nanofibers must withstand repeated washing and abrasion without losing antimicrobial properties. Proper encapsulation and bonding to the textile matrix are necessary. The use of non-toxic and hypoallergenic materials is crucial. Chitosan-based nanofibers offer a more biocompatible option compared to silver nanoparticles.

5. Conclusion

Smart textile technology, which combines functional features with comfort, holds great potential to improve the efficiency and effectiveness of soldier protective equipment. Nanofibers and nanotechnology textiles can respond to the environment and the wearer's body and provide better protection against various threats, such as UV rays, microbes, or even chemical weapons.

One of the key points of this research is the use of electrospinning methods to create extremely strong and lightweight nanofibers. This contributes to the creation of more comfortable and durable protective clothing, bulletproof vests, and military uniforms. In addition, the nano-capability features of the fibers can increase durability, toughness, and conductivity, making them more adaptive to the environment.

However, behind all its potential, some challenges need to be overcome, such as how to integrate electronic materials without compromising wearer comfort and ensuring that these clothes are as easy to care for as regular clothes. In addition, the use of nanomaterials also requires more attention in terms of environmental impact and safety.

Despite the promising benefits of smart textiles, several challenges must be addressed for widespread adoption. Durability, smart textiles must withstand harsh environmental conditions without compromising their functionality. The circuits woven into these materials need to be robust enough to endure rigorous use while remaining comfortable for the wearer. Cost, the production costs associated with advanced smart textiles can be high, which may limit procurement by military organizations, especially in developing countries. Regulatory compliance, military applications require adherence to strict regulations regarding safety and performance standards. Ensuring that smart textiles meet these requirements while integrating advanced technologies presents a significant hurdle.

There are some potential areas for future research that could be explored. Optimizing nanofiber integration and long-term durability, Investigate methods to improve the integration of nanofibers into textile structures to enhance durability and resistance to environmental factors. Scalability and cost-effective production methods, address the challenges associated with scaling up the production of nanofiber-based smart textiles to make them economically viable for widespread military use. Ethical and environmental considerations. Assess the potential health risks associated with exposure to nanofibers during manufacturing, use, and disposal.

References

[1] A. K. M. A. Hosne Asif and Md. Z. Hasan, “Application of Nanotechnology in Modern Textiles: A Review,” *International Journal of Current Engineering and Technology*, vol. 8, no. 02, Jan. 2018.

[2] Kenry and C. T. Lim, “Nanofiber technology: current status and emerging developments,” *Progress in Polymer Science*, vol. 70, pp. 1–17, Jul. 2017.

[3] P. Kiekens, “1b4_0487_ Textiles / Clothing And Nanotechnology: Where Are We Now?,” in *Autex*, *openjournals ugent*. [Online]. Available: http://dx.doi.org/10.21825/autex.63813. [Accessed: Nov. 27, 2024].

[4] I. Alghoraibi and S. Alomari, “Different Methods for Nanofiber Design and Fabrication,” in *Handbook of Nanofibers*, Cham: Springer International Publishing, pp. 79–124, 2019.

[5] G. Kumar Sharma and N. Rachel James, “Electrospinning: The Technique and Applications,” in *Recent Developments in Nanofibers Research*, IntechOpen, 2023. [Online]. Available: http://dx.doi.org/10.5772/intechopen.105804. [Accessed: Nov. 27, 2024].

[6] Y.-Z. Long, X. Yan, X.-X. Wang, J. Zhang, and M. Yu, “Electrospinning,” in *Electrospinning: Nanofabrication and Applications*, pp. 21–52, 2019.

[7] B. A. Chinnappan, M. Krishnaswamy, H. Xu, and M. E. Hoque, “Electrospinning of Biomedical Nanofibers/Nanomembranes: Effects of Process Parameters,” *Polymers*, vol. 14, no. 18, p. 3719, Sep. 2022.

[8] J. V. Patil, S. S. Mali, A. S. Kamble, C. K. Hong, J. H. Kim, and P. S. Patil, "Electrospinning: A versatile technique for making of 1D growth of nanostructured nanofibers and its applications: An experimental approach," *Applied Surface Science*, vol. 423, pp. 641–674, Nov. 2017.

[9] T. Ilma Sari, "Optimasi Nanofiber Hasil Elektrospinning," Institut Teknologi Sepuluh Nopember, 2018. [Online]. Available: https://repository.its.ac.id/50051/7/1114100007-Undergraduate_Theses.pdf. [Accessed: Nov. 27, 2024].

[10] F. Fadil, N. D. N. Affandi, M. I. Misnon, N. N. Bonnia, A. M. Harun, and M. K. Alam, "Review on Electrospun Nanofiber-Applied Products," *Polymers*, vol. 13, no. 13, p. 2087, Jun. 2021.

[11] D. Canan Çelikel, "Smart E-Textile Materials," in *Advanced Functional Materials*, IntechOpen, 2020. [Online]. Available: http://dx.doi.org/10.5772/intechopen.92439. [Accessed: Nov. 27, 2024].

[12] M. Hassan, "Nano technology applications in textile to improve puncture resistant of fabrics," *International Design Journal*, vol. 10, no. 1, pp. 147–154, Jan. 2020.

[13] A. Tiwari, "Military Nanotechnology," *International of Engineering Science and Advance Technology*, vol. 2, no. 4, pp. 825–830, 2012.

[14] F. Steffens, S. E. Gralha, I. L. S. Ferreira, and F. R. Oliveira, "Military Textiles - An Overview of New Developments," *Key Engineering Materials*, vol. 812, pp. 120–126, Jul. 2019.

[15] S. Ebnesajjad, "Manufacturing of Various Shapes of Expanded Polytetrafluoroethylene (ePTFE)," in *Expanded PTFE Applications Handbook*, *Elsevier*, pp. 129–161, 2017.

[16] D. Simić *et al.*, "Nanotechnology for military applications: A survey of recent research in Military technical institute," *Scientific Technical Review*, vol. 68, no. 1, pp. 59–72, 2018.

[17] A. Vaseashta, "Loaded Electrospun Nanofibers: Chemical and Biological Defense," in *NATO Science for Peace and Security Series A: Chemistry and Biology*, pp. 31–45, 2018. [Accessed: Nov. 07, 2024].

[18] H. Wang *et al.*, "Multifunctional PAN/Al–ZnO/Ag Nanofibers for Infrared Stealth, Self-Cleaning, and Antibacterial Applications," *ACS Applied Nano Materials*, vol. 5, no. 1, pp. 782–790, Dec. 2021.

[19] G. M. N. Islam, "Applications of Nanotechnology in Textiles: A Review," *Advance Research in Textile Engineering*, vol. 4, no. 2, 2019.

[20] M. A. Shah, B. M. Pirzada, G. Price, A. L. Shibiru, and A. Qurashi, "Applications of nanotechnology in smart textile industry: A critical review," *Journal of Advanced Research*, vol. 38, pp. 55–75, May 2022.

[21] T. DexMat, "Carbon Nanotube Fibers for Ballistic Armor," Dexmat. [Online]. Available: https://dexmat.com/blog/carbon-nanotube-fibers-for-ballistic-armor/. [Accessed: Nov. 27, 2024].

[22] "Carbon Nanotube Body Armor for Enhanced Protection." [Online]. Available: https://nanografi.com/blog/carbon-nanotube-body-armor-for-enhanced-protection/. [Accessed: Nov. 27, 2024].

[23] N. Atlas, "Lightweight armor material made of nanotube mats outperforms Kevlar," New Atlas. [Online]. Available: https://newatlas.com/materials/ultralight-armor-material-outperforms-kevlar-steel/. [Accessed: Nov. 27, 2024].

[24] Gore-Tex, "GORE-TEX Stretch technology for the military combines thermal comfort with maximum freedom of movement," *Gore-Tex*, Nov. 10, 2023. [Online]. Available: https://news.goretexprofessional.com/en/gore-tex-stretch-technology-for-the-military-combines-thermal-comfort-with-maximum-freedom-of-movement/. [Accessed: Nov. 17, 2024].

[25] C. Moser, G. Henriksson, and M. E. Lindström, "Specific Surface Area Increase during Cellulose Nanofiber Manufacturing Related to Energy Input," *BioResources*, vol. 11, no. 3, Jul. 2016.

[26] A. Al-Abduljabbar and I. Farooq, "Electrospun Polymer Nanofibers: Processing, Properties, and Applications," *Polymers*, vol. 15, no. 1, p. 65, Dec. 2022.

[27] T. Wahyudi, M. Setyaningsih, A. Subagio, H. Widiyandari, P. Pardoyo, and M. Ahyani, "Pembuatan Komposit Carbon Nanotube-Polyvinyl Alcohol (Cnt-Pva) Serta Evaluasi Sifat Mekaniknya," *Arena Tekstil*, vol. 27, no. 1, Jun. 2012.

[28] Bhattacharya M. Polymer Nanocomposites-A Comparison between Carbon Nanotubes,

Graphene, and Clay as Nanofillers. *Materials (Basel)*. vol. 9, no. 4, p. 262, April 2016.

[29] S. A. Shah, H. Ali, M. I. Inayat, E. E. Mahmoud, H. AL Garalleh, and B. Ahmad, “Effect of carbon nanotubes and zinc oxide on electrical and mechanical properties of polyvinyl alcohol matrix composite by electrospinning method,” *Scientific Reports*, vol. 14, no. 1, Nov. 2024.

[30] Y. Du *et al.*, “Advances in the Field of Graphene-Based Composites for Energy–Storage Applications,” *Crystals*, vol. 13, no. 6, p. 912, Jun. 2023.

[31] Y. Wu *et al.*, “Highly Thermally Conductive Triple-Level Ordered CNT/PVA Nanofibrous Films,” *Polymers*, vol. 16, no. 6, p. 734, Mar. 2024.

[32] J. Li, H. Zeng, Z. Zeng, Y. Zeng, and T. Xie, “Promising Graphene-Based Nanomaterials and Their Biomedical Applications and Potential Risks: A Comprehensive Review,” *ACS Biomaterials Science & Engineering*, vol. 7, no. 12, pp. 5363–5396, Nov. 2021.