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RESEARCH ARTICLE

A CONDUCTIVE NANOFIBER PVA/ZNO USING ELECTROSPINNING PROCESS AND ITS POTENTIALLY FOR EDIBLE ELECTRONIC

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ABSTRACT

Electrospun nanofibers have been widely used for various applications. PVA/ZnO nanofiber composites have been successfully fabricated and their electrical properties have been tested. The purpose of this research is to investigate the potential of these nanofiber composites as edible electronic materials based on their conductivity. In this experiment, we used commercially available Polyvinyl Alcohol (PVA) and ZnO technical quality. The composites were prepared by mixing PVA and ZnO at weight per volume (w/v) concentrations. Nanofiber fabrication was carried out using the electrospinning technique with high voltage at 14 kV, a flow rate of 2 mL/hour, and humidity around 50%. The PVA/ZnO nanofibers were characterized using a digital microscope, Scanning Electron Microscope to observe surface morphology and diameter of nanofiber, and conductivity measurements were conducted to assess electrical conductivity. The results showed that optimum nanofibers were formed with a 10% concentration and varying ZnO have an average diameter size of 225 ± 0.5 nm. The addition of ZnO to PVA nanofibers enhances their electrical characteristics. The electrical conductivity of PVA/ZnO nanofibers increases with the addition of ZnO. The highest AC conductivity of PVA/ZnO nanofibers is 315 µS.m-2 at a concentration of 5 mg (w/v). This indicates that PVA/ZnO has good enough conductivity to be used in electronic devices. The PVA/ZnO nanofiber has a small diameter due to its viscosity, surface tension, and good molecular weight, making it capable of being drawn by electrospinning. ZnO is chosen for its ready availability and good conductivity properties. Therefore, the combination of these two materials enhances the conductivity characteristics of the nanofibers.

KEYWORDS

Conductivity, Electrospinning, Nanofiber, PVA, ZnO.

1. INTRODUCTION

In recent years, research on green technology has been rapidly developing. Research in this field aims to develop production processes and products that have minimal impact on the environment (Aladag et al., 2018; Jun et al., 2018; Bahmad et al., 2021; Abdulhussain et al., 2023). One of the developed researches is environmentally friendly electronics. These electronic devices are safe to use, can degrade in the human body, and are safe for the environment. Current wearable electronic devices are very popular because they have good mechanical strength, conductivity, and sensitivity. Edible electronics provide several device functions such as sensors, tracking, monitoring, diagnosis, and treatment for humans (Waresindo et al., 2023).

The materials for edible electronics can be based on hydrogels, membranes, and nanofibers (Priyanto et al., 2022). Nanofibers can be made using the electrospinning technique. This technique is widely favored because the production cost is relatively cheap and the production process is easy in producing nanofibers (Hou et al., 2023). These nanofibers have many properties such as good mechanical strength, high porosity, large surface area, and small diameter size (Kang et al., 2021). Additionally, these nanofibers can be easily composited with various other materials. The applications of nanofiber production as edible electronics are diverse, such as membrane separation, drug delivery, protective clothing, wound covering, and internal body disease sensors (Partheniadis et al., 2020).

Several studies have been conducted by making nanofibers composited with several active metal compounds. Nourozi, et.al. made PVA/Ag nanofibers using the electrospinning technique. The result was the formation of small-sized nanofibers with antibacterial properties against gram-positive cultures. The non-doped PVA/PVP mixture with ZnO showed a specific property (Norouzi et al., 2021). Rashmi et, al. conducted a study on PVA nanofiber composites with silver nanoparticles. The result showed good conductivity activity in PVA nanofibers alone and increased conductivity activity after adding ZnO (Rashmi et al., 2015). Halaji et, al. made PVA/ZnO nanofibers as adsorbent materials for absorbing U, CU, and Ni. This study showed a fairly good conductivity property for PVA/ZnO but with a high enough concentration and a quite complicated process (Hallaji et al., 2015). Therefore, in this study, we will make PVA/ZnO nanofibers with a relatively simple process and produce good conductivity properties with a low concentration of ZnO.

2. LITERATURE REVIEW

The electrospinning technique has become a developed technique recently (Munir et al., 2009). This technique has advantages due to its simple, economical, and environmentally friendly methods. This method uses the electrostatic principle on a polymer that elongates and produces fibers on the collector (Abideen Zain Ul Kim Jae-Hun, 2017). The material used is usually a polymer because it has good viscosity and is easy to composite. The principle is when the electrostatic force exceeds the surface tension on the polymer droplet at the tip of the needle, the jet is released and produces nanofibers on the target (Ou et al., 2017). Many factors must be considered in this process such as the magnitude of the voltage, flow rate, surface tension, rotation speed, humidity, and temperature in the electrospinning room (Butylina et al., 2016). These factors will produce nanofibers according to the desired specifications. PVA is a degraded

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polymer that is easily soluble in various types of solvents. Because in this study it becomes one potential that can enter the body. So this polymer can dissolve in water. When PVA polymer is composited with ZnO it will produce a good semiconductor which has good nano structural, electrical, and mechanical properties. The improvement of each of these properties is caused by the structure and concentration of ZnO (Asadpour et al., 2022).

3. Research Method

3.1 Materials

Polyvinyl alcohol (PVA) was purchased from Kimia Mart Bandung with technical specification without using molecular weight in composition. Zinc Oxide (98% in aqueous solution) was purchased from Kimia Mart Bandung with technical specification in powder form soluble and aquadest.

3.2 Synthesis of PVA/ZnO

Polyvinyl Alcohol (PVA) 10% w/v were prepared about 0.5 gram of PVA was dissolved in 10mL of aquadest water at 80°C in 25 mL beaker and stirred over magnetic stirrer for 1h under 500 rpm speed to prepare PVA solution. Likewise, 1 – 5 mg by w/v of ZnO were separately dispersed to PVA solution and stirred over magnetic stirrer for 1h until homogeneous.

3.3 Preparation of Nanofibers Process with Electrospinning

The solution of PVA/ZnO was loaded in syringe 10G from Terumo Syringe. Syringe was stored on an electrospinning device with distance to collector was 15cm. The collector of nanofiber was used the alumunium foil to collect the NF. The positive of high voltage power supply was connected to syringe and ground to collector plate with crocodile clips. A high voltage was set at 15 kV at room temperature and humidity at 45%. The fibers were collected on the alumunium foil with flowrate at 5 mL/h. The fine fibers were dried and save in the dried box for characterization and measurements. All of process was find at figure 1.

3.4 Characterization

The initial results of nanofiber was viewed with digital microscope (SPEK) on 40x zoom. The morphology of nanofibers was investigated by Scanning Electron Microscope (SEM/EDS) (JSM-5300, JEOL Ltd., Japan). Diameter of nanofibers were find using Image J Software. The electrical of composited nanofibers was investigated with digital conductivity test. Hydrophilicity was evaluated by drop test method. Briefly the 5µL of water were dropped on the surface of the films. Capturing the images of droplets were taken immediately and then at 60s. The ImageJ software was applied for measurement of contact angle of water drops. Absorption test was evaluated the nanofiber to water.

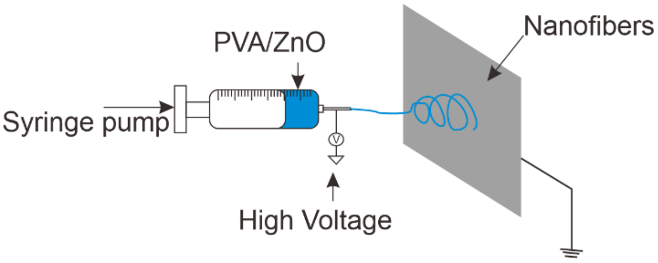

Figure 1: Schematic of process nanofiber using electrospinning method

4. Findings and Discussion

4.1 Morphology of Fibers

Nanofibers have an elongated matrix shape with very small diameter sizes, have a uniform diameter distribution, and a large surface area (Fauzi *et al.*, 2020). In determining the size of nanofibers, a digital microscope can be used as an initial step to observe the formation of nanofibers. The diameter of nanofibers is observed at a magnification of 40x, then a review is conducted using SEM testing to determine the morphology and diameter size of the nanofibers. The morphology of PVA/ZnO nanofibers shown in figure 2.

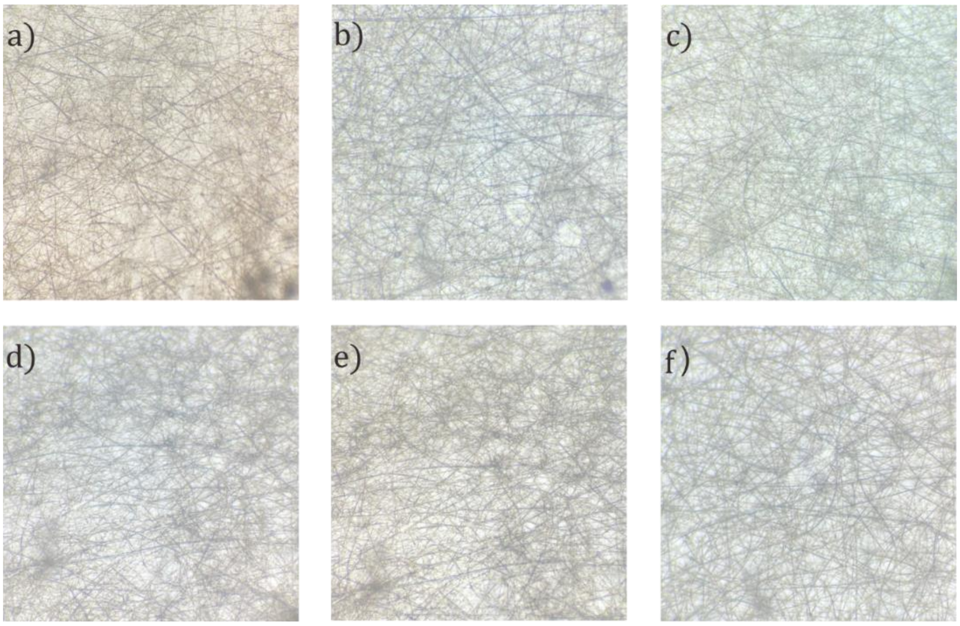

Figure 2: Digital Microscope of sample PVA Nanofiber a) Blank PVA, PVA with various ZnO b) 1mg, c) 2mg, d) 3mg, e) 4mg and f) 5mg.

The digital microscope results show that PVA can be produced into nanofibers using electrospinning. At a concentration of 10%, PVA nanofibers are formed at a voltage of 14 kV. This is indicated by the abundance of fibers scattered on the surface of the PVA sample as shown in Figure 1a. After the PVA is formed at the optimum voltage and concentration, it is then composited with ZnO. The variations of ZnO used are 1mg, 2mg, 3mg, 4mg, and 5mg. The results of the variations show that all samples form nanofibers at the same voltage. Then, under the microscope, it can be seen that the nanofibers are evenly distributed on the surface with very small sizes. This can be influenced by the voltage and concentration of PVA. The higher the concentration, the larger the size of the nanofibers. Similarly, with the voltage, the higher the voltage, the smaller the diameter size of the nanofibers. The diameter of the nanofibers is investigated using ImageJ software on the SEM sample results. The results show that nanofibers are formed with elongated and uniform sizes indicating a diameter size of 225 +- 0.5 nm. This proves that the sample is a nanofiber with a very small size.

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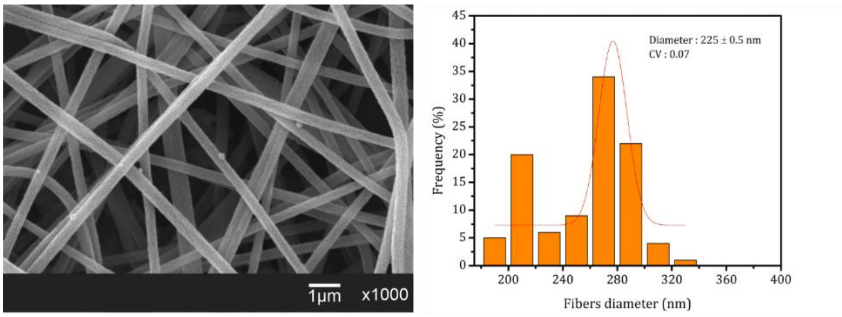

Figure 3: SEM picture of nanofiber PVA/ZnO with average diameter

4.2 Water Contact Angle Measurement of Nanofibers

To investigated the hydrophilic of nanofibers were examined using a contact angle meter with the drop method to measure the static angle (Cha et al., 2018). The contact angle was find with ImageJ software. It was observed that the pure nanofiber are hydrophylic with the contact angle of 87° as shown in figure 4. The water contact angle of the blended nanofibers decreased as the concentration of ZnO nanoparticles increased. The PVA/ZnO nanofibers exhibited the highest hydrophobicity with a contact angle around 100-118°.

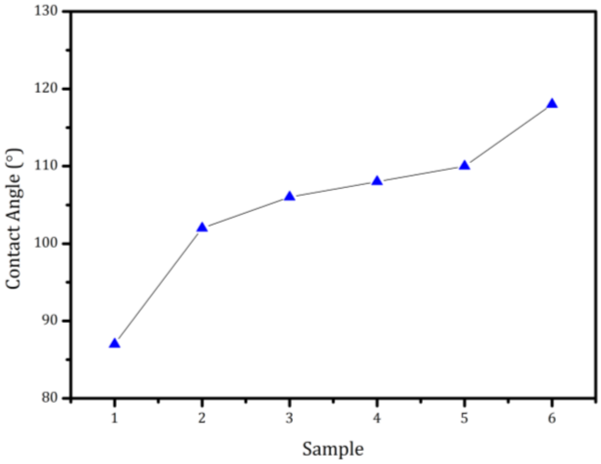

Figure 4: The water contact angle measurement of PVA nanofibers (Sample 1) and various of PVA/ZnO nanofibers (Sample 2-6)

4.3 Conductivity Activity of Fibers

Table 1: The conductivity result of fibers.

Sample	Conductivity (μS.m^{-2})
Blank	120 μS.m^{-2}.
1	125 μS.m^{-2}.
2	229 μS.m^{-2}.
3	268 μS.m^{-2}.
4	297 μS.m^{-2}.
5	315 μS.m^{-2}.

The conductivity of PVA nanofibers and PVA/ZnO nanofibers was studied using a conductivity multitester, which measures the level of conductivity of the nanofibers. This aims to observe the electronic activity that occurs within a nanofiber. An edible electronic device must have good conductivity.

The conductivity values were measured for all samples, from PVA Nanofibers to PVA/ZnO nanofibers, as shown in Table 1. The results indicate that PVA nanofibers have a conductivity value of 120 μS.m^{-2}. This value then increases with the addition of ZnO for several samples, reaching the highest conductivity value in sample 5 at 315 μS.m^{-2}. With the increase in ZnO concentration, the conductivity value also increases. This indicates that ZnO can provide good conductivity values for all samples. This conductivity will be very helpful when an edible electronic device is applied to various needs.

4.4 The Potential of Nanofiber PVA/Zno for Edible Electronic

The burgeoning field of edible electronics holds transformative potential for applications in healthcare, food safety, and smart packaging. Among the myriad of materials explored for these purposes, nanofiber-based composites have emerged as particularly promising due to their unique combination of biocompatibility, mechanical strength, and electrical properties. One composite material that stands out is the combination of Polyvinyl Alcohol (PVA) and Zinc Oxide (ZnO) nanoparticles. This article explores the potential of nanofiber PVA/ZnO for edible electronics, delving into its properties, fabrication methods, applications, and future prospects. Edible electronics refer to devices that can be safely ingested by humans, performing electronic functions within the body before being digested or expelled. These devices are designed to interact with the body or food products, providing real-time monitoring, diagnostics, or even therapeutic interventions. The development of edible electronics hinges on the use of materials that are not only functional but also safe for human consumption. This is where nanofiber composites like PVA/ZnO come into play.

4.5 Properties of PVA and ZnO

Polyvinyl Alcohol (PVA) is a synthetic polymer known for its water solubility, biodegradability, and biocompatibility. It has been widely used in medical applications, such as drug delivery systems and wound dressings, due to its non-toxic nature and ability to form flexible films. PVA provides an ideal matrix for incorporating functional nanoparticles, such as ZnO, into a composite material. Zinc Oxide (ZnO) is a semiconductor with excellent piezoelectric and photocatalytic properties. It is also known for its antibacterial activity and UV-blocking capabilities. ZnO nanoparticles enhance the electrical and functional properties of the PVA matrix, making the composite material suitable for various electronic applications. The combination of PVA and ZnO in nanofiber form leverages the advantages of both materials, resulting in a composite that is flexible, biocompatible, and electrically active.

The fabrication of PVA/ZnO nanofibers typically involves electrospinning, a versatile and cost-effective technique for producing nanofibers with controlled diameter and morphology. In the electrospinning process, a solution of PVA and ZnO nanoparticles is subjected to a high voltage, which causes the solution to form fine jets that solidify into nanofibers as they travel towards a grounded collector. The resulting nanofibers are uniform in size and have a high surface area-to-volume ratio, which is beneficial for enhancing their functional properties. The electrospinning process can be optimized to achieve the desired properties in the PVA/ZnO nanofibers. Factors such as the concentration of PVA and ZnO, the voltage applied, and the distance between the needle and the collector can be adjusted to control the diameter and distribution of the nanofibers.

This flexibility in the fabrication process allows for the production of nanofibers with specific characteristics tailored to different applications.

The exploration of nanofiber composites, specifically those made from Polyvinyl Alcohol (PVA) and Zinc Oxide (ZnO) nanoparticles, has opened new avenues for advanced materials with superior mechanical properties. These nanofibers leverage the individual strengths of both PVA and ZnO, creating a composite that exhibits remarkable mechanical performance, crucial for various high-demand applications. PVA is a synthetic polymer recognized for its flexibility, toughness, and excellent film-forming abilities. When spun into nanofibers, PVA provides a strong yet flexible matrix that can withstand significant mechanical stress and deformation. ZnO nanoparticles, known for their rigidity and high mechanical strength, further enhance the composite by reinforcing the PVA matrix and contributing to its overall durability. This combination results in nanofibers that are not only flexible and lightweight but also possess high tensile strength and elasticity.

The mechanical properties of PVA/ZnO nanofibers make them highly suitable for applications where both flexibility and strength are essential. For instance, in the field of wearable electronics, these nanofibers can be used to create durable yet comfortable sensors and devices that can endure the stresses of daily movement and environmental exposure. In biomedical applications, the mechanical robustness of PVA/ZnO nanofibers ensures that they can be safely used in implants, tissue engineering, and wound dressings without the risk of mechanical failure. Additionally, the rigidity provided by ZnO nanoparticles allows these nanofibers to maintain structural integrity under various conditions, making them ideal for use in flexible electronic circuits and smart textiles.

Furthermore, the fabrication process of PVA/ZnO nanofibers, typically achieved through electrospinning, allows for precise control over their mechanical properties. By adjusting parameters such as the concentration of PVA and ZnO, the applied voltage, and the collection distance, researchers can fine-tune the diameter, orientation, and distribution of nanofibers to achieve desired mechanical characteristics. This level of control ensures that the resulting nanofibers can be tailored to meet the specific demands of different applications, enhancing their versatility and performance. As research and development in this area continue to advance, the exceptional mechanical properties of PVA/ZnO nanofibers are expected to lead to innovative solutions in various industries. From improving the durability of electronic devices to enhancing the performance of biomedical implants, the potential of these nanofibers is vast and far-reaching. Their unique combination of flexibility, strength, and durability not only broadens the scope of applications but also sets a new standard for the development of advanced composite materials.

4.6 Applications of PVA/ZnO Nanofibers in Edible Electronics

4.6.1 Food Quality Monitoring

In the rapidly evolving field of edible electronics, the integration of nanofiber composites such as Polyvinyl Alcohol (PVA) and Zinc Oxide (ZnO) nanoparticles stands out as a groundbreaking innovation with significant potential for food quality monitoring. Edible electronics, designed to be safely ingested and digested, offer novel solutions for real-time, non-invasive monitoring of food products. The unique properties of PVA/ZnO nanofibers, including their biocompatibility, flexibility, and electrical responsiveness, make them exceptionally suited for this purpose. PVA is known for its water solubility and biodegradability, making it an ideal matrix for creating safe, ingestible materials. When combined with ZnO nanoparticles, which possess excellent piezoelectric and antimicrobial properties, the resulting nanofibers can function as sophisticated sensors embedded in food packaging. These sensors can detect and respond to changes in environmental conditions, such as pH levels, temperature, and the presence of harmful microorganisms, by generating measurable electrical signals.

This capability allows for continuous, real-time monitoring of food freshness and safety from production to consumption. For instance, a package equipped with PVA/ZnO nanofibers can alert consumers to spoilage or contamination before the food is consumed, thereby reducing the risk of foodborne illnesses and minimizing food waste. The implementation of such technology in food quality monitoring not only enhances consumer safety but also supports sustainable practices by extending the shelf life of products and optimizing supply chain management. Furthermore, the scalability and cost-effectiveness of producing PVA/ZnO nanofibers through methods like electrospinning ensure that this technology can be widely adopted across the food industry. As research and development continue to advance, the application of nanofiber PVA/ZnO in edible electronics for food quality monitoring promises to revolutionize how we ensure the safety and integrity of our food supply, ultimately contributing to better health outcomes and more sustainable consumption practices.

4.6.2 Drug Delivery Systems

The integration of nanofiber composites like Polyvinyl Alcohol (PVA) and Zinc Oxide (ZnO) nanoparticles into edible electronics presents a transformative opportunity for advancements in drug delivery systems. These nanofiber composites combine the unique properties of PVA and ZnO to create biocompatible, flexible, and responsive materials ideally suited for ingestible drug delivery applications. PVA, a synthetic polymer known for its biodegradability and water solubility, forms a safe and effective matrix that can be ingested without adverse effects. When coupled with ZnO nanoparticles, which possess remarkable piezoelectric and antimicrobial properties, the resultant nanofibers offer enhanced functionality for controlled drug release. In drug delivery systems, these PVA/ZnO nanofibers can be engineered to release therapeutic agents in response to specific physiological triggers, such as pH changes or enzymatic activity within the gastrointestinal tract.

This targeted delivery ensures that the medication is released precisely where and when it is needed, increasing its efficacy while minimizing side effects. For example, drugs encapsulated within PVA/ZnO nanofibers can be designed to remain stable in the acidic environment of the stomach and only release their payload when they reach the more neutral pH of the intestines. Additionally, the piezoelectric properties of ZnO can be utilized to create self-powered drug delivery systems that generate electrical signals in response to mechanical movements within the body, further controlling the release of the drug. This innovative approach to drug delivery not only improves patient outcomes by enhancing the precision and effectiveness of treatments but also opens new possibilities for the development of smart, responsive therapeutic systems.

The ease of fabrication and cost-effectiveness of producing PVA/ZnO nanofibers through techniques like electrospinning make this technology accessible and scalable for widespread medical applications. As research in this area progresses, the deployment of PVA/ZnO nanofiber-based edible electronics in drug delivery systems promises to revolutionize personalized medicine, offering more efficient, safe, and patient-friendly solutions for managing various health conditions.

4.6.3 Medical Diagnostics

The application of nanofiber composites such as Polyvinyl Alcohol (PVA) and Zinc Oxide (ZnO) nanoparticles in edible electronics heralds a new era of innovation in medical diagnosis. These nanofibers combine the favorable properties of both PVA and ZnO, resulting in biocompatible, flexible, and electrically responsive materials ideal for ingestible diagnostic devices. PVA is known for its water solubility, biodegradability, and non-toxic nature, making it a safe matrix for creating materials that can be ingested and digested without adverse effects. ZnO nanoparticles contribute excellent piezoelectric and antimicrobial properties, enhancing the functionality of the composite for electronic applications. In the realm of medical diagnostics, PVA/ZnO nanofibers can be developed into ingestible sensors that monitor various physiological parameters within the human body. These sensors can detect changes in pH, temperature, and pressure, and respond by generating electrical signals that provide real-time data on the body's internal environment. For example, a PVA/ZnO-based sensor could be used to monitor the gastrointestinal tract for abnormalities such as ulcers, infections, or motility disorders.

The piezoelectric properties of ZnO enable these sensors to convert mechanical movements within the digestive system into electrical signals, which can be transmitted wirelessly to an external device for analysis. This real-time monitoring capability offers significant advantages for early detection and continuous tracking of medical conditions, potentially improving patient outcomes through timely interventions. Moreover, the non-invasive nature of these edible sensors enhances patient comfort and compliance compared to traditional diagnostic methods. The fabrication of PVA/ZnO nanofibers using techniques like electrospinning is not only efficient and cost-effective but also allows for precise control over the fiber properties, ensuring consistent performance of the diagnostic devices. As research and development in this field advance, the integration of PVA/ZnO nanofiber-based edible electronics in medical diagnostics promises to revolutionize how we monitor and manage health, offering more accurate, real-time insights into physiological processes and enabling proactive healthcare solutions.

4.6.4 Smart Packaging

The incorporation of nanofiber composites, such as Polyvinyl Alcohol (PVA) and Zinc Oxide (ZnO) nanoparticles, into edible electronics is set to revolutionize the field of smart packaging. These nanofiber composites leverage the unique properties of both PVA and ZnO to create materials that are biocompatible, flexible, and electrically responsive, making them ideal for integration into food packaging. PVA is well-known for its biodegradability, water solubility, and safety, which ensures that the packaging material can be safely ingested and digested without adverse effects. ZnO nanoparticles, with their exceptional piezoelectric, antimicrobial, and UV-blocking properties, enhance the functionality of the composite, providing additional protective and interactive features.

In the realm of smart packaging, PVA/ZnO nanofibers can be utilized to create advanced packaging systems that monitor and communicate the condition of the packaged food in real-time. These smart packages can detect environmental changes such as variations in temperature, humidity, and the presence of gases indicative of spoilage. For instance, the piezoelectric properties of ZnO allow these nanofibers to generate electrical signals in response to mechanical stress or environmental changes, providing immediate feedback on the food's freshness. This capability can be harnessed to develop packaging that changes color or emits a signal when the food starts to spoil, thus alerting consumers and reducing the risk of consuming contaminated products.

Furthermore, the antimicrobial properties of ZnO can help extend the shelf life of food by preventing the growth of bacteria and other pathogens. The integration of PVA/ZnO nanofibers into packaging materials is also beneficial from a sustainability perspective, as these materials are biodegradable and can help reduce plastic waste. The scalability and cost-effectiveness of producing these nanofibers through electrospinning techniques ensure that this technology can be widely adopted across the food industry. As research and development continue to advance, the use of nanofiber PVA/ZnO in edible electronics for smart packaging promises to enhance food safety, improve consumer confidence, and contribute to more sustainable packaging solutions, ultimately transforming how we package, store, and consume food products.

4.6.5 Sensors

The fusion of Polyvinyl Alcohol (PVA) and Zinc Oxide (ZnO) nanoparticles into nanofiber composites is poised to drive significant advancements in the realm of edible electronics, particularly in the development of ingestible sensors. These innovative materials merge the biocompatibility, flexibility, and biodegradability of PVA with the exceptional piezoelectric, antimicrobial, and electrical properties of ZnO, resulting in nanofibers that are safe for human consumption and highly functional for sensing applications. PVA is a synthetic polymer renowned for its non-toxic nature and solubility in water, providing a safe matrix for creating edible sensors. ZnO, a semiconductor with strong piezoelectric properties, enhances the composite by enabling the conversion of mechanical movements into electrical signals. This unique combination makes PVA/ZnO nanofibers ideally suited for use in ingestible sensors that monitor a range of physiological parameters within the human body.

Edible sensors made from PVA/ZnO nanofibers can be designed to detect various changes in the body's internal environment, such as variations in pH, temperature, pressure, and the presence of specific biomolecules. For instance, these sensors can monitor gastrointestinal health by detecting abnormalities like ulcers, infections, or motility disorders, transmitting real-time data wirelessly to an external device for analysis. The piezoelectric properties of ZnO nanoparticles allow these sensors to generate electrical signals in response to mechanical movements or pressure changes, providing continuous, real-time monitoring. This capability is particularly valuable for early diagnosis and ongoing management of medical conditions, offering a non-invasive and patient-friendly alternative to traditional diagnostic methods.

Moreover, the antimicrobial properties of ZnO nanoparticles further enhance the functionality of these sensors, ensuring that they do not introduce any harmful pathogens into the body. The fabrication process of PVA/ZnO nanofibers through techniques like electrospinning is both cost-effective and scalable, enabling the production of uniform, high-quality fibers suitable for widespread application. As research in this field progresses, the deployment of nanofiber PVA/ZnO-based edible sensors promises to revolutionize medical diagnostics, providing more accurate, real-time insights into physiological processes and enabling proactive healthcare solutions. This technological advancement has the potential to improve patient outcomes, reduce healthcare costs, and pave the way for personalized medicine tailored to individual health needs.

4.6.6 Bioactivity Compounds

The integration of Polyvinyl Alcohol (PVA) and Zinc Oxide (ZnO) nanoparticles into nanofiber composites represents a significant advancement in the field of bioactive materials, offering tremendous potential for various biomedical applications. PVA, a biocompatible and biodegradable polymer, serves as an ideal matrix for incorporating bioactive compounds due to its non-toxic nature and excellent film-forming capabilities. When combined with ZnO nanoparticles, the resulting nanofibers exhibit enhanced bioactivity, attributed to the unique properties of ZnO. ZnO is renowned for its antimicrobial, anti-inflammatory, and antioxidant properties, making it an excellent candidate for applications that require bioactivity, such as wound healing, tissue engineering, and drug delivery.

In the context of wound healing, PVA/ZnO nanofibers can be used to create advanced wound dressings that not only provide a physical barrier to protect the wound but also promote faster healing through their antimicrobial and anti-inflammatory effects. ZnO nanoparticles within the nanofibers can inhibit the growth of pathogenic microorganisms, reducing the risk of infection and complications. Additionally, the anti-inflammatory properties of ZnO help to minimize inflammation at the wound site, further accelerating the healing process. The antioxidant activity of ZnO also plays a crucial role in neutralizing harmful free radicals, protecting cells and tissues from oxidative damage. For tissue engineering applications, the bioactive properties of PVA/ZnO nanofibers can support cell growth and differentiation. These nanofibers can be used as scaffolds that mimic the extracellular matrix, providing structural support for cells to adhere, proliferate, and form new tissue. The presence of ZnO can enhance cellular activities, promoting the regeneration of tissues such as skin, bone, and cartilage. This makes PVA/ZnO nanofibers highly suitable for developing biomaterials that facilitate tissue repair and regeneration.

In drug delivery systems, the bioactivity of PVA/ZnO nanofibers can be harnessed to create smart delivery platforms that release therapeutic agents in a controlled and targeted manner. The antimicrobial properties of ZnO can be particularly beneficial in preventing infections when delivering drugs to specific sites in the body. Furthermore, the ability of ZnO to respond to physiological conditions, such as changes in pH, can be utilized to design drug delivery systems that release their payload in response to specific triggers, ensuring that the therapeutic agents are delivered precisely where and when they are needed. The potential of PVA/ZnO nanofibers as carriers of bioactive compounds is further enhanced by their fabrication process.

Techniques like electrospinning allow for the production of nanofibers with controlled diameter, porosity, and surface characteristics, enabling the optimization of their bioactive properties. This level of control ensures that PVA/ZnO nanofibers can be tailored to meet the specific requirements of different biomedical applications, enhancing their effectiveness and safety. As research continues to explore the bioactive potential of PVA/ZnO nanofibers, their applications are expected to expand, leading to innovative solutions in healthcare and medicine. The combination of biocompatibility, biodegradability, and enhanced bioactivity makes these nanofibers a promising material for developing advanced biomedical devices and therapies that improve patient outcomes and quality of life.

4.7 Future Prospects and Challenges

While the potential of PVA/ZnO nanofibers for edible electronics is immense, there are still several challenges that need to be addressed before these materials can be widely adopted. One of the primary challenges is ensuring the uniform dispersion of ZnO nanoparticles within the PVA matrix. Any aggregation of ZnO nanoparticles can affect the mechanical and electrical properties of the nanofibers, compromising their performance. Another challenge is scaling up the production of PVA/ZnO nanofibers for commercial applications. While electrospinning is a versatile and cost-effective technique, it may not be suitable for large-scale production. Researchers are exploring alternative fabrication methods, such as melt spinning or solution blowing, to overcome this limitation and enable the mass production of PVA/ZnO nanofibers.

Additionally, the long-term safety and biocompatibility of PVA/ZnO nanofibers need to be thoroughly evaluated. While both PVA and ZnO are generally considered safe for human consumption, it is essential to ensure that the nanofibers do not pose any health risks when ingested over extended periods. Despite these challenges, the future of PVA/ZnO nanofibers for edible electronics looks promising. Ongoing research and development efforts are focused on optimizing the properties of these nanofibers, exploring new applications, and addressing the challenges associated with their production and use. As our understanding of these materials continues to grow, we can expect to see innovative and practical solutions that enhance food safety, healthcare, and smart packaging, ultimately contributing to improved quality of life and sustainability.

Edible electronics represent a significant advancement from the traditional concept of ingestible electronics, where devices are not only designed for safe swallowing but also fully digestible within the body and environmentally safe for release without the need for retrieval (Waresindo et al., 2023). The concept of a telemetric ingestible device, safely administered in pill form, aligns with the current trend in healthcare toward decentralized home care. This approach aims to reduce the burden on hospital structures by shortening hospital stays and decreasing the need for recovery and readmissions, while increasing patient interactions. Telemedicine has played a significant role in this trend, enabling long-distance and continuous monitoring of patient parameters, leveraging the expansive network provided by the emerging Internet of Things (IoT) (Winkless, 2023).

For a long time, implantable and wearable electronics have been the primary technologies in this field, each with its own strengths and weaknesses. Implantable devices offer high performance in close proximity to the target area but are costly, require invasive implantation procedures, and need device maintenance. Conversely, wearable systems are more affordable and less invasive but offer limited actuation and monitoring capabilities, especially for organs deep within the body (Lamanna *et al.*, 2023). Ingestible electronics bridge this gap by utilizing semi-invasive medical devices that have a limited contact time with the body while providing efficient operation at the gastrointestinal (GI) level. The concept of ingestible electronics dates back to the 1950s, with early examples focusing on circuit design for sensing and telecommunication. Initially, materials selection for ingestible devices was limited to technologies like germanium transistors, later transitioning to silicon. Packaging materials, often rigid impervious polymers like polycarbonate, played a crucial role in enabling ingestion (El-Sayed et al., 2024).

Electrospinning is a method used to produce nanofibers using electrostatic forces. Nanofibers themselves have various advantages such as good conductivity, high surface area, and a range of properties that can be utilized. Essentially, the production of edible electronics applies green electronics, using environmentally friendly materials. In various industries, edible electronics can be utilized as control materials, such as in medicine as ingestible electronic devices that can accurately detect bleeding around the stomach. They can also be used for diagnosing and monitoring fatty acids in the lower digestive tract, among other things. In the field of ingestible electronics, these devices can be made in the form of smart pills that function as digital monitors. Nanofibers composited with ZnO have good conductivity, making them suitable as the smallest component of a smart pill, such as a chip circuit, due to their good conductivity. In terms of hydrophobicity, these nanofibers can be used as coating materials as they repel water. Therefore, PVA/ZnO nanofibers have the potential to be used as materials for the production of edible electronics. Its ease of composability with various materials makes nanofibers capable of being used as binding agents in enhancing the properties of edible electronics.

5. CONCLUSION

The study successfully fabricated PVA/ZnO nanofiber composites using the electrospinning process and investigated their electrical properties. The research aimed to explore the potential of these nanofiber composites as materials for edible electronics based on their conductivity. Commercially available Polyvinyl Alcohol (PVA) and technical-grade ZnO were used in the experiment. The nanofiber fabrication process was conducted using electrospinning with specific parameters. The results showed that optimal nanofibers were formed with a 10% concentration of PVA and varying amounts of ZnO, with an average diameter size of 225 ± 0.5 nm. The addition of ZnO to PVA nanofibers enhanced their electrical characteristics, with conductivity increasing as the amount of ZnO increased. The highest AC conductivity recorded was 315 μS.m-2 at a concentration of 5 mg (w/v), indicating good conductivity for potential use in electronic devices. The study demonstrates the feasibility of using PVA/ZnO nanofibers for edible electronics, highlighting their small diameter, good conductivity, and potential for various applications such as sensors, drug delivery systems, protective clothing, wound coverings, and internal body disease sensors. The ease of composability of nanofibers with other materials further enhances their potential as binding agents for improving the properties of edible electronics.

LIMITATION AND FURTHER RESEARCH

The study successfully fabricated PVA/ZnO nanofiber composites using the electrospinning process and investigated their electrical properties. The research aimed to explore the potential of these nanofiber composites as materials for edible electronics based on their conductivity. Commercially available Polyvinyl Alcohol (PVA) and technical-grade ZnO were used in the experiment. The nanofiber fabrication process was conducted using electrospinning with specific parameters. The results showed that optimal nanofibers were formed with a 10% concentration of PVA and varying amounts of ZnO, with an average diameter size of 225 ± 0.5 nm. The addition of ZnO to PVA nanofibers enhanced their electrical characteristics, with conductivity increasing as the amount of ZnO increased. The highest AC conductivity recorded was 315 μS.m-2 at a concentration of 5 mg (w/v), indicating good conductivity for potential use in electronic devices. The study demonstrates the feasibility of using PVA/ZnO nanofibers for edible electronics, highlighting their small diameter, good conductivity, and potential for various applications such as sensors, drug delivery systems, protective clothing, wound coverings, and internal body disease sensors. The ease of composability of nanofibers with other materials further enhances their potential as binding agents for improving the properties of edible electronics.

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