THE ELECTROSPINNING FOR WOUND DRESSING FABRICATION OF POLYETHYLENE OXIDE (PEO)

BY

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ABSTRACT

This project presents the fabrication of wound dressing from polyethylene oxide (PEO) and sodium alginate (NaAlg) using the electrospinning technique. The desired properties of wound dressing should be biodegradability, non-adherence, waterproofness, and non-toxicity, all of which are critical for human skin. Both PEO and NaAlg are biocompatible, making them safe to contact with skin. The polymer solution is created using PEO with a molecular weight 200-300 kDa and NaAlg with varying viscosities to observe the electrospun fiber resulting from different concentration. The electrospinning techniques fabricate the electrospun fiber ranging in diameter from nanometer to micrometer diameter, enhancing their properties of fiber including a high porous structure for the exchange of gases and nutrients, and a high surface area to volume ratio. These electrospun fibers of PEO and NaAlg make the wound dressings more effective and biodegradable than pure PEO electrospun fibers. The properties of sodium alginate strengthen the PEO chain. As PEO is soluble in water, a crosslinking method using calcium chloride ($\mathrm{CaCl_2}$) was used to prevent the fibers from dissolving. Calcium ions replace sodium ions, improving the strength and insolubility of the electrospun fibers, resulting in the fabrication of biodegradable and waterproof wound dressings using the electrospinning technique. This project purposes to fabricate insoluble PEO electrospun fiber by studying the effects of electrospinning parameters including voltage, flow rate, distance between needle and collector, and spinning time. The results show that a 4wt% NaAlg/PEO (70/30) solution which use the high viscosity of sodium alginate can fabricate the smooth electrospun fiber. This solution, the electrospinning parameter was carried out 26 kV applied voltage, 0.1 ml/hr flow rate, and 15 cm distance between the needle and collector. The electrospun fiber were successfully fabricated the tested for insolubility using crosslink method which involved treating the electrospun fiber with calcium chloride solution.

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Phuphinee Niyomchon

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS/ABBREVIATIONS

Symbols/Abbreviations	**Terms**
%wt	weight percent
$CaCl_2$	Calcium Chloride
cm	Centimeter
cP	centipose
hr	hour
kDa	Kilodalton
kV	Kilovolt
min	minute
ml/hr	milliliter/ hour
mPas	millipascal-seconds
MW	Molecular Weight
NaAlg	Sodium Alginate
PEO	Polyethylene oxide
w/v	weight per volume

CHAPTER 1
INTRODUCTION

This chapter introduces the background and information of this project. It is about the electrospinning techniques that produce the antibacterial wound dressing by using the polyethylene oxide (PEO) and sodium alginate (NaAlg) as the main material. The research objectives are followed by hypothesis and research scope.

1.1 Background and significance of the study

Electrospinning techniques is a fiber production that uses electrical force to stretch the polymer solution. It produces polymer fibers with a diameter ranging from nanometers to micrometers. This technique consists of three parts, including the high voltage power supply, spinneret, and rotating mandrel. The benefit of this technique is that it performs the fiber with a high surface area to volume ratio, adjustable porosity, and malleability to adapt a range of its shape and size [1]. These properties can support tissue engineering applications such as scaffold fabrication.

Wound dressings are medical devices that conceal wounds from environmental pollutants and prevent the growth of bacteria. The ability of wound dressing should be insoluble and non-adherent to human skin because it will prevent damage to the wound surface during patient changing of the wound dressing. Wound dressing should maintain the moisture of the wound [2].

Polyethylene oxide (PEO) and sodium alginate (NaAlg) are two polymers that various uses in the medical field, including drug delivery, tissue engineering or wound healing. Recently, there has been growing interest in using these polymers in the form of fiber for wound dressings. The fiber form provides several advantages, including improved mechanical strength, flexibility, and surface area coverage. Additionally, both PEO and sodium alginate fibers are biocompatible which means they are not toxic when in contact with human skin [3].

1.2 Objectives

1.2.1. To fabricate the insoluble wound dressing from PEO by electrospinning technique.

1.2.2. To investigate the effect and the suitable the electrospinning parameters including voltage, flow rate, distance between needle and collector and type of needle.

1.2.3. To improve the properties of electrospun fiber by using the crosslink method of sodium alginate (NaAlg) and calcium chloride ($CaCl_2$).

1.3 Scope of the study

1.3.1. The polyethylene oxide (PEO) and sodium alginate (NaAlg) are used for the fabrication of wound dressing, were used in this study.

1.3.2. The electrospinning techniques were used to fabricate the electrospun fiber.

1.3.3. The crosslinking for improving the electrospun fiber were used in the study.

1.4 Report outline

The following contents of this report is organized as follows:

Chapter 2 reviews the various theories and literature related to this research.

Chapter 3 describes the use of the electrospinning device and the preparation of the solution.

Chapter 4 demonstrates the effect of concentration of the solution and investigates the variation of electrospinning parameters.

Chapter 5 discusses the results and conclude the key points of this research, providing good suggestion for the future work.

CHAPTER 2
REVIEW OF THEORY RELATED

2.1 Introduction of Electrospinning technique

Electrospinning technique is a fiber formation technique that uses electrical force to produce nanofibers of polymer with diameters ranging from nanometers to micrometers, by utilizing a polymer solution. Additionally, it can be used to fabricate nanofibers of metals, ceramics, and composites [4]. This technique involves the creation of scaffolds that consist of a mixture of polymers and nanoparticles. This method utilizes an electrically charged stream of viscoelastic polymeric solution, which is directed onto a conductive collector to produce continuous nanofibers. Understanding the underlying physics of electrospinning, such as electrostatics, fluid rheology, and polymer solution properties, is a complex and distinctive aspect of this method within the scientific community [5]. The electrospinning device consists of three main parts including high-voltage power supply, a syringe pump which connects with a needle and the conductive collector, which is shown in figure 1.

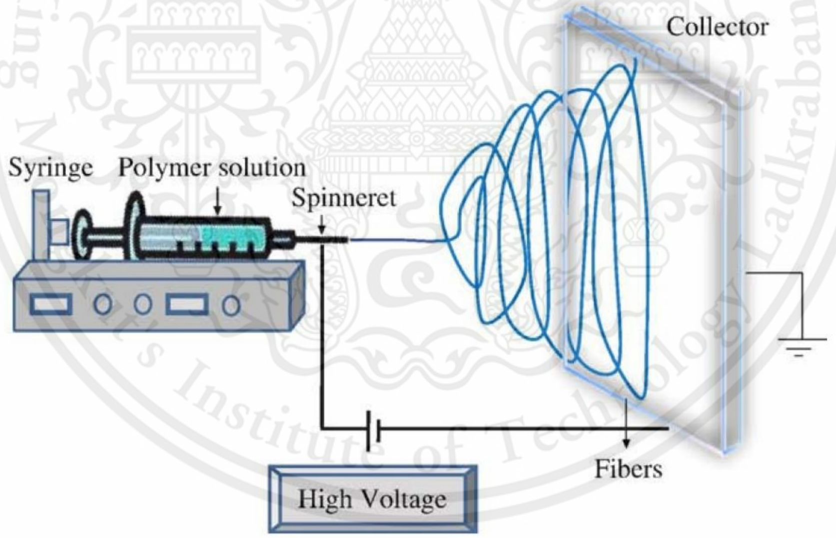

Figure 1. The schematic of electrospinning device

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2.1.1 History of Electrospinning

The electrospinning technique originated from the concept of how electrostatics affects liquids. Strong electric potentials can be applied to fluid droplets to create aerosols, and the release of a drop's surface tension requires a specific number of charges. The process by which an electric charge excites a dielectric liquid is known as electrodynamics. Electrospinning was first used to create fibers in the early 1900s, likely due to the insights gained from studying these phenomena. Despite the existence of numerous electrospinning setups, which have been patented since the early 1900s, it is only recently that academia has begun exploring the potential of electrospinning to fabricate various nanofibrous assemblies [4].

2.1.2 The process of electrospinning

The electrospinning technique comprises of three essential components: a high-voltage power supply, a syringe pump connected to a spinneret, which contains the polymer solution that is ejected to form the electrospun fibers, and a collector, which can either be a stationary plate or a rotating collector. Initially, the technique involved applying high voltage to a metallic needle connected to the syringe pump, resulting in the movement of electric charges. The polymer solution was then ejected from the spinneret, and the flow rate of the solution was controlled to ensure a steady process. As the solution left the spinneret, it produced an electrostatic charge, and the induced charges dispersed across the surface, resulting in the expansion of the polymer solution into a fiber [6]. An electric field is generated between the needle tip and the conductive collector, which is influenced by the distance between these components. The electrostatic force draws the polymer solution and transforms it into an electrospun fiber on the conductive collector.

High-Voltage source

In the electrospinning process, the high-voltage source is one of the most important for ejecting the polymer solution into the electrospun fiber onto the collector. It affected the electric charge that is applied to the solution. The suitability voltage that is used in the electrospinning techniques should be 15 to 20 kV [7]. Either direct current (DC) or alternating current (AC) can be used as the power source for these techniques [8]. It is anticipated that a higher applied voltage will cause the solution to stretch more, which should result in thinner fiber [9].

Syringe pump

Syringe drivers, also known as syringe pumps, are powered tools that precisely control the flow of fluid from a syringe by mechanically advancing or retraction of the plunger. Stepper motors are used in syringe pumps to precisely move a platform that is coupled to the plunger of a syringe. The syringe's body is secured to the unit's body such that the motor's movement is the only source of movement. There are 2 types of syringe pump such as medical syringe pump and laboratory syringe pump [10].

1. **Medical syringe pump**

It is an infusion pump that uses a syringe rather than an intravenous bag is known as a medical syringe pump, which is shown in figure 2. It is applied in the in vivo diagnosis, treatment, and care of patients to give medication or other fluids. To protect the patient's safety, medical infusion pumps frequently include drug-specific pre-sets and pre-programmed hard and soft restrictions.

Figure 2 The medical syringe pump

2. **Laboratory syringe pump**

It is also known as scientific syringe pumps, which is shown in figure 3. It can precisely transfer small amounts of liquid. They may frequently be programmed with intricate routines, and some of them can be operated by computers and integrated with other devices. Syringe pumps for laboratories are made to be flexible and adaptive. A syringe pump can be used in a wide variety of research settings, including thin film production, mass spectrometry, flow chemistry, microfluidics, and other areas.

Figure 3. The Laboratory syringe pump

Syringe

A syringe is a fundamental reciprocating pump made out of a plunger that securely fits inside a cylindrical tube known as a barrel. The syringe may take in and release liquid or gas through a discharge hole at the front (open) end of the tube by linearly pulling and pushing the plunger along the inside of the tube. There are two units of measurement for syringe size or capacity: milliliters (ml) and cubic centimeters (cc). The volume of a liquid is measured in milliliters, but the volume of a solid is measured in cubic centimeters. About 1 milliliter (ml) is equal to 1 cubic centimeter (cc). There are 7 sizes of syringe that are commonly used in general, including 1 ml, 2-3 ml, 5 ml, 10 ml, 20 ml, 30 ml, and 50-60 ml, which is shown in figure 4.

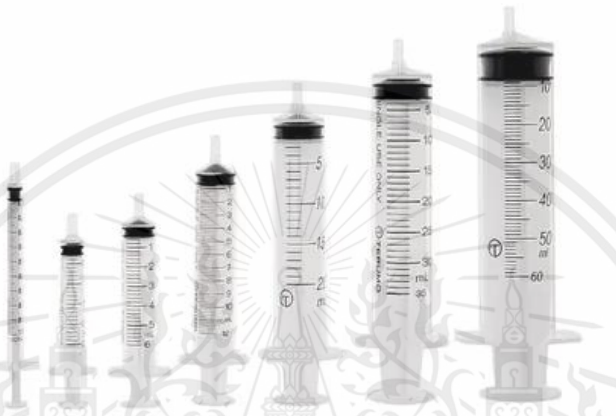


Figure 4. The several size of syring which is available on the market

Hypodermic needle

A hypodermic needle is frequently used to inject substances into the body or draw fluids out of it. They can also be used to extract liquids from the body, such as blood by venipuncture. When treating catastrophic blood loss or shock, large-bore hypodermic intervention is particularly helpful. It also enables quick liquid delivery. Additionally, it is utilized when an injectable medication cannot be consumed orally due to liver damage or the fact that it would not be absorbed, like with insulin [11]. There are many types of needles which using in the medical field, which is shown in the figure 5 [12].

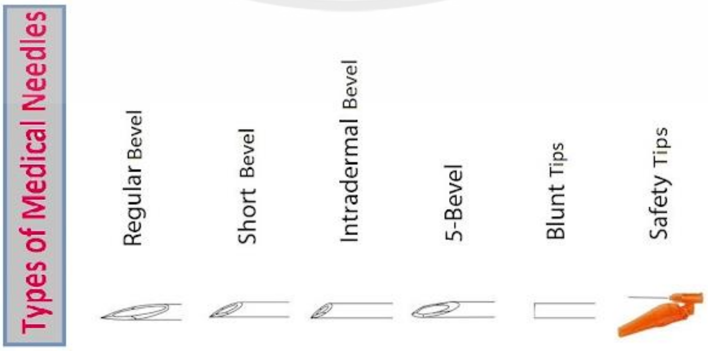


Figure 5. The several types of needles

1. Regular Bevel

The regular bevel is a frequently used tip type for hypodermic needles and is typically employed for both subcutaneous and intramuscular injections. As one of the sharpest points available for hypodermic needles, it allows for a smooth insertion and reduced tissue trauma for patients.

2. Short Bevel tip

Short bevel tips are used for specialty applications such as arterial blood gas sampling or nerve blocks. Short Bevel tip type of needle allows penetration of the skin and delivery of local anesthetic to the desired anatomical location.

3. Intradermel Bevel

Needles with short bevel tips are typically reserved for specialized procedures, such as arterial blood gas sampling or nerve blocks, where precision is key. Short bevel tips enable the needle to penetrate the skin and deliver local anesthetics directly to the desired anatomical location, making them a valuable tool for certain medical applications.

4. 5-Bevel

The use of a 5-bevel needle has been shown to provide a less painful injection experience for patients. Compared to traditional needle types, the 5-bevel needle design is more comfortable, easier to insert, and can significantly reduce the pain associated with injections. This type of needle may be a preferable option for healthcare professionals and patients alike.

5. Blunt tips or Dispensing Needles

Blunt-tip needles are designed to minimize the risk of needle stick injuries during medication preparation, such as when drawing medication from a vial or ampule. The blunt tip can also help prevent damage to stoppers, which can reduce the risk of contamination or leakage. However, blunt-tip needles require more force to penetrate tissue and may cause more discomfort for patients compared to sharp-tip needles.

6. Safety tips

Needle stick injuries can be a serious risk for healthcare workers, and safety tip needles are designed to help reduce this risk. Safety tip needles come in a variety of types, such as safety glide and shielding, and are specifically engineered to prevent accidental needle stick injuries. By using these specialized needles, healthcare workers can protect themselves while administering injections and performing other medical procedures.

Collector

For electrospinning techniques, the collector is a grounded to establish a stable voltage. It needs to be conductive for collecting the electrospun fiber in the sheet form. The productivity, organization, and final structure of the nanofibers are all significantly influenced by the collector. This is because it has an impact on how easily charges on deposited fibers can be transmitted to ground, which in turn has an impact on how many fibers are gathered on the substrate [13]. Additionally, the form and characteristics of the produced nanofiber are impacted by the type of collector used. There are several types of collectors utilized, including rotating drum collectors, moving belt collectors, revolving wheels with bevelled edges, parallel bars, basic mesh collectors, multifilament thread collectors, etc [14].

2.1.3 The parameter of electrospinning

The electrospinning techniques has many parameters that can affect during the testing. The morphology of the fiber is affected by many of parameters which combine to fabricate the electrospun nanofiber [15]. It can be classified into 3 parameters such as process parameter (The applied electric field, flow rate, distance between the syringe and collector), solution parameters (polymer concentration, molecular weight, viscosity, surface tension, conductivity) and environmental parameters (temperature and humidity).

- **Process Parameters**

The process parameters are a parameter which affected during the working of electrospinning device including the applied electric field, flow rate and distance between the syringe and collector.

1. **The applied electric field**

   The applied electric field is the applied electric voltage which provides the surface charge on the spinneret of electrospinning and affects the diameter of the fiber product. The current from a high voltage power supply, which is connected to the polymer solution source through the needle, causes a spherical droplet to deform into a Taylor cone and generate ultrafine fibers. An increase in the applied voltage will tend to produce the smaller diameter of nanofibers. This is caused by the stretching of the polymer solution expanding in proportion to the electric charge. Furthermore, the electric field can also be used to control the deposition of nanofibers.

2. Flow rate

The flow rate is the rate at which polymer solutions are ejected from the needle, which is controlled by the hydrostatic pressure of the used syringe pump. If the electrospinning process is performed in the vertical direction, gravity will affect the drop of polymer solution. The needle diameter of the spinneret tip and the viscosity of the solution are the two factors that influence the force that delivers a solution at a constant rate. If the flow rate was decreased, the solution would solidify in the spinneret and be unable to produce the Taylor cone due to insufficient flux. Moreover, the flow rate and the electric field are inversely proportional because the surface charge density depends on these two factors. An increase in flow rate leads to the merging of electrospun fiber onto the collector because it increases the electric field and decreases the surface charge density.

3. The distance between the collector and the needle

The distance between the collector and the needle affects the morphology of nanofiber. This parameter can be affected by the deposition time, evaporation rate, and whipping of the solution. The ideal separation varies depending on the polymer system, especially how its concentration relates to the voltage being applied. The fiber will have enough time before reaching the collector if the distance between the needle and the collector is kept at a minimum. While the diameter of the fiber reduces, the distance between the needle and the collector expands. The large diameter of the fiber will be performed when the distance is kept small.

- **Solution Parameter**

Solution parameter are a factor of polymer solution which might affect to the product of nanofibers. It includes molecular weight of polymer, the polymer concentration, viscosity, surface tension, and conductivity.

1. Molecular weight of solution

Molecular weight of polymer affects the morphology of nanofiber. It can be impact to the permeability and electrical characteristics of the solution. It linked to the viscosity, surface tension, and conductivity. High molecular weight polymers have a propensity to easily approach the entanglement concentration, a necessary concentration for enabling fiber production. However, using a polymer with a high molecular weight does not ensure that the process will be successful, as the fiber may have a wide range of diameters and large dimensions.

2. **Polymer concentration**

The polymer concentration is another important factor that affect the electrospinning technique. It impacts to the morphology of nanofibers. An increase in the concentration pf polymer solution can tend to increase the diameter of nanofibers.

3. **Surface Tension**

Surface Tension is a parameter that influences the electrospinning techniques. It is the main force opposing the applied voltage during electrospinning. Due to the instability of the jets and the production of the droplets, high surface tension will forbid the electrospinning process during the testing. On the other hand, low surface tension causes the formation of beads-free, smooth, continuous fibers and allows the process to take place at a lower voltage. Surface can be used to reduce surface tension, which makes it possible to prevent bead formation along the fibers.

4. **Conductivity**

Conductivity is a parameter that affects the polymer and solvent type, polymer concentration, and temperature. The electrospinning process cannot produce the nanofiber if there is zero conductivity for the polymer solution. The conductivity of polymer solution has enough free charges to flow onto the surface of the fluid and form a Taylor cone to initiate the electrospinning process. It affects the Taylor cone formation and controls the diameter of nanofiber. A decrease in conductivity, the solution will demonstrate insufficient elongation of the jet by electric force to produce consistent fiber. On the other hand, an increase in conductivity will lead to formation of the Taylor cone and effect the decreasing of fiber's diameter.

- **Environment Parameter**

Environment parameter is a factor from the environment which affects the electrospinning process and nanofiber production. It includes temperature and humidity.

1. **Temperature**

Temperature from the environment will reduce the viscosity of the solution and accelerate solvent evaporation. Both these 2 effects impact the reduction in the diameter of nanofibers.

2. **Humidity**

Humidity can modify the diameter of nanofiber by regulating the charged jet's process of solidification. Low humidity can form the thicker nanofibers with more homogeneous dimensional distribution. On the other hand, high humidity affects the flow of evaporation of water, it will increase the drying time and large fiber which can be obtained.

2.1.4 The electrospinning solvents

The polymer in a suitable solvent is the first and most important stage in the electrospinning process, the solvent utilized to prepare polymer solutions has a substantial impact on its spinnability. Solvents need to preserve the consistency of the polymer solution and possess qualities like good volatility, vapor pressure, and boiling point [1]. It is well known that solution characteristics like viscosity and surface tension have a significant impact on the morphology and size of electrospun nanofibers. Surface tensions may vary depending on the solvent. The concentration of the polymer determines the solution viscosity, although the value of surface tension is affected by both the polymer and solvent [16].

2.1.5 Application of electrospinning

Electrospinning is an easy and cheap process for creating ultrafine fibers with diameters ranging from a few micrometers to a few hundred nanometers. According to many specialists in this sector, the synthesis of very thin fibers with huge surface areas and few nanometers thickness, ease of functionalization for varied uses, better mechanical qualities, and simplicity of procedure are the key benefits of electrospinning. The electrospun nanofiber mat exhibits the properties of high specific surface area, high porosity, modifiable voids, and tiny diameter. The most common applications for it are in the areas of sensors, catalyst carriers, biomedicine, energy conversion and storage, filtration and separation, and other. Numerous nanofibrous materials have been created using various polymers, solutions, or melt systems, as well as various electrospinning theories. The following categories are some possible uses for nanofibers in industry, which is shown in figure 6 [17].

The advancements in the field of electrospinning for biomedical applications, including the electrospinning of synthetic, natural, and blends of synthetic and natural polymers, as well as of chemically designed and modified polymers, are presented here rather than attempting to provide a comprehensive collection of the related literature. The significance of electrospinning in general for biomedical applications including tissue engineering, drug release, wound dressing, enzyme immobilization, etc [18].

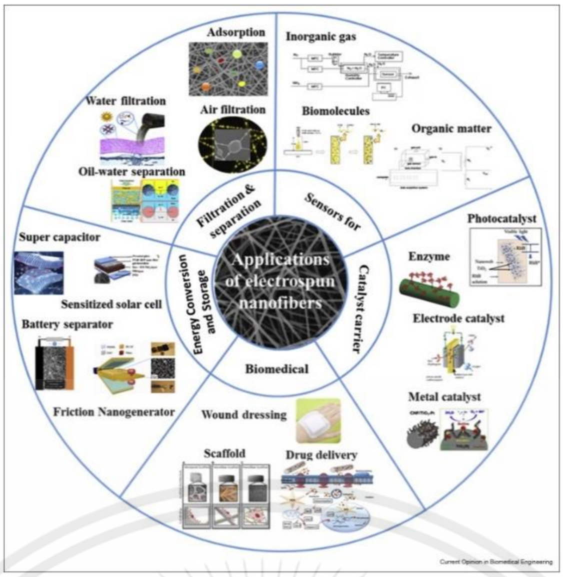


Figure 6. Application of electrospun nanofibers

2.1.6 The wound dressing from the electrospinning techniques

Electrospinning nanofiber have special qualities including high porosity because of fiber entanglements and linked pores, as well as a huge surface area, allowing wound dressings to imitate collagen fibers in the extracellular matrix. Therefore, compared to traditional (gauze, lint, plasters, and wadding) and conventional/moist (film and foam dressings, hydrogels, and hydrocolloids) dressings, wound dressings manufactured utilizing the electrospinning technology may have several advantages. Furthermore, these dressings are distinguished by their excellent absorption capacity, ability to regulate exudates, and ability to allow appropriate gaseous exchange due to their structural characteristics. Additionally, the electrospinning process makes it simple to load medications with active substances like antibiotics or chemicals that boost cell proliferation [18]. The example of wound dressing is shown in figure 7 [19].

Figure 7. Wound dressing which fabricates from the electrospinning technique

2.2 Wound healing

Wound healing is the process by which the body repairs damaged tissue or skin after injury. The process involves several stages, including hemostasis, inflammation, proliferation, and remodeling. The wound healing process can be influenced by a variety of factors, such as the type and severity of the wound, the age and overall health of the person, and the presence of any underlying medical conditions [20].

2.2.1 Stage of wound healing

Wound healing can be classified as into 4 stages: hemostasis, inflammation, proliferation, and remodeling. The image of 4 stages is shown in the figure 8 [21].

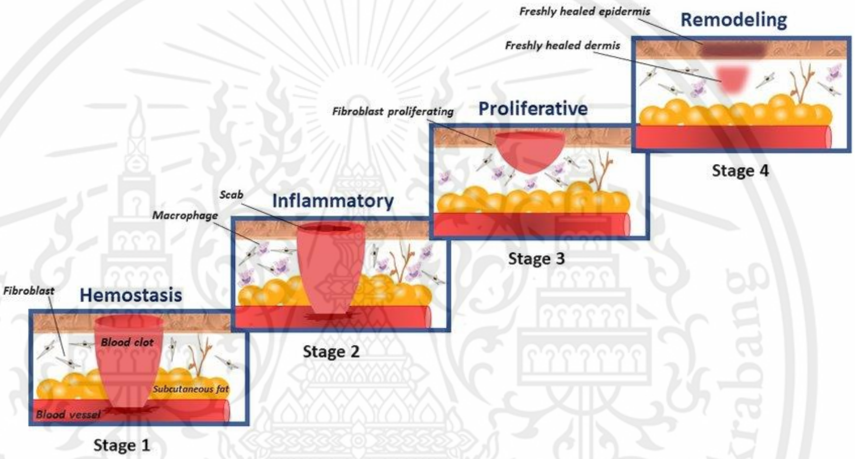


Figure 8. The stages of wound healing

Hemostasis

The first stage of wound healing is hemostasis, which occurs immediately after injury. This stage involves the constriction of blood vessels and the formation of a blood clot to stop bleeding.

Inflammation

The second stage is inflammation, which lasts from a few hours to a few days after injury. During this stage, white blood cells and other immune cells are recruited to the wound site to remove any foreign materials or bacteria and begin the process of tissue repair.

Proliferative

The third stage is proliferation, which occurs from a few days to a few weeks after injury. During this stage, new blood vessels form to bring oxygen and nutrients to the wound site, and new tissue begins to grow to replace the damaged tissue.

Remodeling

The final stage is remodeling, which can last for several months to a year after injury. During this stage, the new tissue that was formed in the previous stage is strengthened and reorganized to restore the structure and function of the damaged tissue as much as possible.

2.2.2 Factor that affecting the wound healing.

The process of wound healing can be affected by various factors. These factors can be broadly categorized as local and systemic. Local factors directly affect the wound itself, while systemic factors relate to the overall health or disease state of the individual, which can influence their ability to heal. There is often an interplay between these factors, as systemic factors can affect the local wound environment, which in turn can impact healing. It is important to consider both local and systemic factors when evaluating impaired wound healing. Impaired wound healing can result from a variety of local and systemic factors. Local factors include inadequate oxygenation of the wound, infection, the presence of foreign bodies, and insufficient venous return. Systemic factors can be related to the individual's overall health, such as age and gender, sex hormone levels, stress, underlying diseases such as diabetes or autoimmune disorders, obesity, medications, alcohol consumption, smoking, and poor nutrition. These factors can interact with each other and affect the various stages of wound healing, leading to delayed or incomplete tissue repair. Therefore, understanding the interplay between these factors is crucial in developing effective wound healing therapies [22].

2.3 Wound dressing

Wound dressing is a medical device used to cove wounds and protect them from further trauma and microbial infections. The dressing should not adhere to human skin to prevent damage around the wound surface. Additionally, the material used to make the dressing should be biodegradable, non-toxic, and non-allergenic to human skin [23].

2.3.1 Type of wound dressing

There are two main types of wound dressings: traditional and modern. Traditional wound dressings include gauze, bandages, and adhesive tapes. These dressings are commonly used for small, superficial wounds. On the other hand, modern wound dressings are designed to provide a more advanced level of wound care. They can be further categorized into several types based on their intended purpose, such as hydrocolloid dressings, foam dressings, alginate dressings, and film dressings. These dressings are particularly useful for larger, more complex wounds, as they provide additional benefits such as moisture management, absorption, and antimicrobial properties [24].

- **Traditional Wound Dressing**

Traditional wound dressings are commonly used for dry wounds and do not aid in maintaining moisture levels. They can serve as either primary or secondary dressings, or as part of a composite dressing system designed for a specific purpose. Various types of traditional wound dressings are available in the market, such as gauze, lint, plasters, bandages, and cotton wool [25].

1. **Gauze Dressing**

Gauze dressings are made from woven or non-woven fibers such as cotton, rayon, or polyester and provide a level of protection against bacterial infection. Sterile gauze pads are often used to absorb exudate and fluid from open wounds using the fibers in the dressing. However, these dressings require frequent changes to prevent maceration of healthy tissues. Additionally, gauze dressings are less cost-effective and can become adherent to the wound, making it painful when removed, especially if the dressing becomes moistened due to excessive wound drainage [24]. The image of gauze dressing is shown in a figure 9 [26].

Figure 9. Gauze Dressing

2. **Lint Dressing**

The lint dressing is a plain-woven cotton cloth that is commonly used as a first aid dressing. It is manufactured to meet the superior quality standard set by the British Pharmaceutical Codex. Lint dressings are suitable for use as a secondary dressing over exuding wounds due to their high absorption capacity. They are soft, flexible, and can be easily cut to fit the size and shape of the wound. The cushioned protection provided by absorbent lint is particularly beneficial for wounds on difficult-to-treat areas like joints [27]**.** The image of lint dressing is shown in the figure 10 [28].

Figure 10. Lint Dressing

3. Plasters

The plasters bandage or meaning as an adhesive bandage, is a small dressing used for minor injuries that do not require a large bandage. Its functions by protecting the wound and scab from friction, bacteria, damage, and dirt [29]. The image of plasters bandage is shown in the figure 11 [30].

Figure 11. Plasters Bandage

4. Bandage dressing

A bandage dressing is a medical device used to cover and protect wounds, absorb exudate, and provide support to the injured area, which is shown in the figure 12 [31]. It is usually made of a soft, flexible material that can conform to the shape of the body and is held in place with adhesive tape, clips, or self-adhesive straps [32]. Bandage dressings come in various sizes and shapes, and they can be used alone or in combination with other wound care products, such as gauze, pads, or compression wraps. They are commonly used in both acute and chronic wound care settings, such as in hospitals, clinics, and home care.

Figure 12. Bandage Dressing

5. **Cotton wool**

Cotton wool is a soft, fluffy, and highly absorbent material made from cotton fibers that have been carded and sterilized. It is commonly used in medical settings as a dressing for wounds or for cleaning and drying skin. Cotton wool can also be used for a variety of household purposes, such as cleaning, arts and crafts, and insulation [33]. The image of cotton wool is shown in a figure 13 [34].

Figure 13. The cotton wool

- **Modern Wound Dressing**

Modern wound dressings are advanced medical devices designed to promote wound healing by creating a moist wound environment, protecting the wound from further trauma, and controlling bacterial contamination. These dressings are made of biocompatible materials that are non-toxic, non-allergenic, and can be biodegradable. Modern wound dressings can be categorized into several types including hydrocolloid dressings, hydrogel dressings, foam dressings, alginate dressings, and composite dressings, each with unique properties that can meet the specific needs of different types of wounds [24]. These dressings can help reduce pain, promote wound healing, and ultimately improve patient outcomes.

1. Hydrocolloid dressing

Hydrocolloids are a modern type of wound dressing that contain gel-forming agents such as sodium carboxymethylcellulose (NaCMC) and gelatin, is shown in a figure 14 [35] . These agents are often combined with elastomers and adhesives and applied to a carrier, usually polyurethane foam, or film, to form an absorbent, self-adhesive, and waterproof wafer. The dressing is initially impermeable to water vapor, but as the gelling process occurs, it gradually becomes more permeable [36].

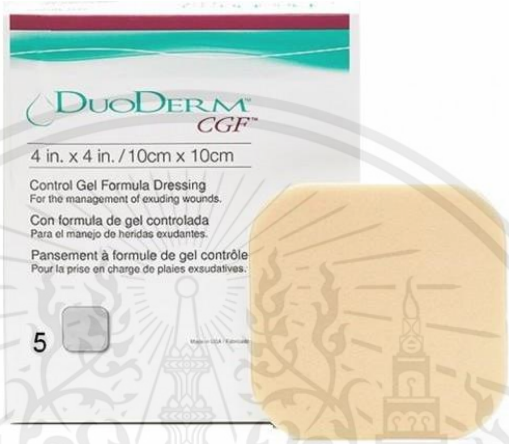


Figure 14. The hydrocolloid dressing

2. Hydrogel dressing

Hydrogel dressings are composed of complex hydrophilic polymers with a high-water content of up to 90%. They are semi-occlusive and designed to hydrate wounds, promote autolytic debridement, and rehydrate eschar. Hydrogels come in sheet, amorphous gel, or sheet hydrogel-impregnated dressings, and they expand in water as insoluble polymers. They provide a moist environment for cell migration and can absorb some exudate [37]. The image of hydrogel dressing is shown in a figure 15 [38].

Figure 15. Hydrogel Dressing

3. Foam dressing

Foam dressings are highly absorbent and promote autolytic debridement, is shown in a figure 16 [39]. It made from a polyurethane base with a heat- and pressure-modified wound contact layer. They allow for the permeation of gases and water vapors and are typically used to maintain a moist wound environment in wounds with moderate-to-heavy exudate. These dressings are also highly adaptable and provide cushioning, making them well-suited for bony prominences or areas with increased friction [40].

Figure 16. Foam dressing

4. Alginate dressing

Alginate dressings are designed to manage moderate to large amounts of exudate and are highly absorbent, is shown in a figure 17 [41]. They are typically made of seaweed derivatives that are spun into ropes or sheets. Alginate dressings can be non-occlusive or semi-occlusive, and as they absorb fluid, they are converted into a gel that provides moisture to the wound bed. However, alginate dressings always require a secondary dressing to keep them in place [42].

Figure 17. Alginate dressing

5. Composite dressing

Composite dressings are wound dressings that combine multiple layers of materials with different functions into a single dressing, which is shown in the figure 18 [43]. These dressings are designed to address multiple wound care needs, such as promoting healing, absorbing exudate, protecting the wound from infection, and maintaining moisture balance. Composite dressings typically consist of an absorbent layer, a non-adherent contact layer, and an outer layer that protects the wound from contamination and trauma. Some composite dressings may also include additional layers, such as foam, hydrogel, or silicone, depending on the specific wound care requirements [44].

Figure 18. Composite Dressing.

2.4 Polyethylene Oxide (PEO)

Polyethylene oxide (PEO), also known as polyethylene glycol (PEG) or polyoxyethylene (POE), is a water-soluble polymer that has numerous applications in various industries, including pharmaceuticals, cosmetics, food, and biomedicine. Its biocompatibility, hydrophilic nature, and unique properties make it a versatile synthetic compound, suitable for applications in medical, chemical, and industrial fields. Its low toxicity and biocompatibility make it a popular choice in drug delivery, tissue engineering, and other biomedical applications.

2.4.1 The properties and characteristics of PEO

PEO is a water-soluble thermoplastic resin that can dissolve in various organic solvents and nonionics, creating a highly viscous solution. Its high-molecular-weight products have dispersing and coagulation properties. PEO is fragrance-free, colorless, non-toxic, and nonvolatile. It is highly soluble in water and organic solvents like benzene, tetrachloride, and chloroform. Its unique characteristics make it an ideal choice for many applications in various industries [45].

Chemical Structure

The chemical structure of PEO is a liner structure which is represented as $\mathrm{H-(O-CH2-CH2)}_n\mathrm{-OH}$ where n indicates the number of repeating ethylene oxide units. The chemical structure of PEO is shown in the figure 19.

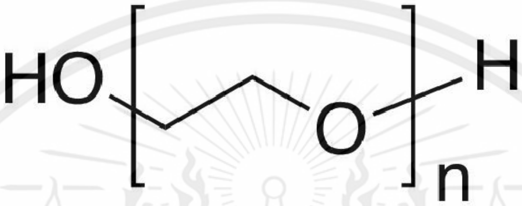


Figure 19. The structure of PEO

Molecular weight

The molecular weight of PEO is determined by the average weight of its repeating units, represented by the value of n in its chemical structure. Increasing n results in an increase in the number of repeating units and the molecular weight of PEO. It can vary widely, from as low as 200 g/mol up to several million g/mol. The molecular weight of PEO can be classified into 3 ranges as follows [46]:

- Low molecular weight PEO: Typically has a molecular weight less than 20,000 g/mol and is often referred to as PEG.
- Intermediate molecular weight PEO: Generally, has a molecular weight between 20,000 to 100,000 g/mol.
- High molecular weight PEO: Usually has a molecular weight greater than 100,000 g/mol and is often referred to as PEO.

The molecular wight for each category may vary slightly depending on the specific application and source of PEO.

Thermal Properties

The thermal properties of PEO can vary depending on its molecular weight and other factors. However, generally, PEO has a melting point range of approximately 60-70°C and a glass transition temperature (Tg) range of approximately -50°C [47].

2.4.2 Application of PEO

Polyethylene oxide (PEO) has a wide range of applications across various industries, including:

- Pharmaceuticals: PEO is used as an excipient in drug formulations, acting as a binder, solubilizer, and thickener.

- Personal care products: PEO is found in many personal care products, such as shampoo, toothpaste, and skin cream, where it functions as a thickener, emulsifier, and moisturizer.

- Food industry: PEO is used as a food additive to improve texture, stability, and shelf life of various food products.

- Water treatment: PEO is used in water treatment to flocculate and coagulate suspended particles, making them easier to remove from the water.

- Industrial applications: PEO is used as a lubricant, binder, and emulsifier in various industrial applications, including the production of paints, coatings, and adhesives.

- Biomedical applications: PEO is used in biomedical applications, such as tissue engineering and drug delivery, due to its biocompatibility and ability to improve cell adhesion and growth.

These are just a few examples of the many applications of PEO. Its unique properties make it a versatile and valuable material in a wide range of industries.

2.5 Sodium alginate (NaAlg)

Sodium alginate (NaAlg) is a combination between the alginic acid and the salt (Na). It is a naturally occurring polysaccharide that is extracted from brown seaweed. It is a water-soluble salt that is commonly used as a thickener, stabilizer, and emulsifier in various food, pharmaceutical, and industrial applications. Sodium alginate forms a gel-like substance when it comes into contact with calcium ions, making it useful in creating gels, films, and coatings. It is also biodegradable, non-toxic, and renewable, making it an eco-friendly alternative to synthetic thickeners and stabilizers [48].

2.5.1 Properties of Sodium alginate

Sodium alginate is a compound with a density of 1.0 g/cm3 at 25 °C. It has a melting point of 99°C and a boiling point of 495.2°C at 760 mmHg. Sodium alginate is soluble in water but insoluble in alcohol, chloroform, and ether. When it is dissolved in water, it forms a viscous colloidal solution with slow solubility. This solution is insoluble in ethanol, ether, and chloroform. Sodium alginate has a pH value of below 3, and it is resistant to acids with a pH value below 3 [49].

2.5.2 Type of Sodium alginate

Sodium alginate can be classified based on its viscosity, molecular weight, and degree of polymerization. There are 3 main types of sodium alginate including low viscosity, medium viscosity, and high viscosity.

- Low viscosity: This type has a low molecular weight and a low degree of polymerization. It is commonly used in applications where a quick and efficient gelling or thickening effect is required, such as in the food and pharmaceutical industries. This type has a viscosity range of 5-50 mPa·s (1% solution at 25°C).

- Medium viscosity: This type has a medium molecular weight and degree of polymerization. It is often used in applications where a slower and more sustained gelling or thickening effect is desired, such as in the production of textiles or paper. This type has a viscosity range of 50-200 mPa·s (1% solution at 25°C).

- High viscosity: This type has a high molecular weight and degree of polymerization. It is commonly used in applications where a very thick or viscous solution is required, such as in the production of pharmaceuticals or cosmetics. This type has a viscosity range of 200-800 mPa·s (1% solution at 25°C).

2.6 The crosslink process which using the calcium chloride.

Crosslink process is the process for forming a two or more molecules of covalent bonds or chemical bonds. This process will perform in the creation of a three-dimensional network of interconnected structures. It can enhance the morphology of the material which can make it more stable, durable, and resistant to deformation.

Sodium Alginate is a polysaccharide made up of monosaccharide units that repeat, and each contain a carboxylate ion as shown in the figure 20. The crosslink process using calcium chloride involves the reaction of calcium ions with carboxyl groups on the sodium alginate molecule. When sodium alginate is exposed to a solution of calcium chloride, the calcium ions replace the sodium ions in the alginate molecule, resulting in the formation of a three-dimensional network structure. This network structure, or gel, is formed through the crosslink of adjacent sodium alginate chains by calcium ions, which creates a strong and stable matrix. The degree of crosslink can be controlled by varying the concentration of calcium ions and the duration of the crosslinking reaction. This process is commonly used in the food and pharmaceutical industries to create gels or beads with controlled release properties [50]. The calcium ions will replace the sodium ions during the crosslinked alginate, which is shown in the figure 21. As for the alginate itself, it remains in the solution. The crosslinking process causes the alginate chains to become interconnected, resulting in the formation of a gel-like substance. This gel, composed of crosslinked alginate chains, will typically remain in the calcium chloride solution during and after the crosslinking process.

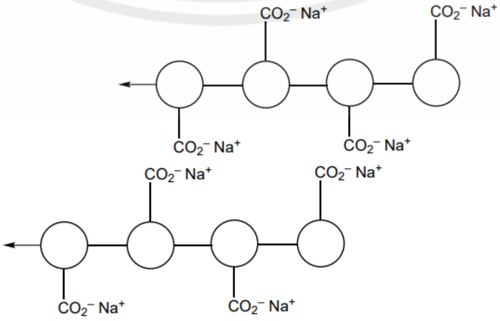


Figure 20. Structure of sodium alginate

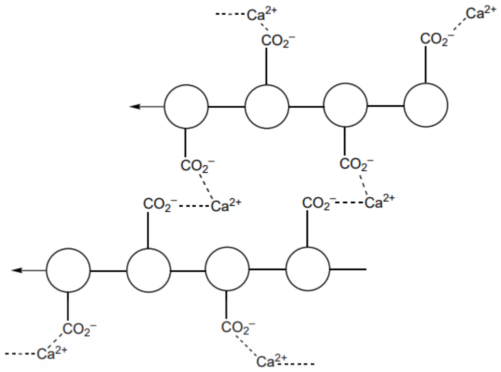


Figure 21. The cross-linked polymer

CHAPTER 3

METHODOLOGY

In Chapter 3, it described the preparation of solution which using the polyethylene oxide (PEO) and sodium alginate (NaAlg) as the main material. The electrospinning device was used to fabricate the electrospun fibers, which was carried out in three main steps: using a syringe pump containing the polymer solution, a collector, and a high-voltage power supply. This chapter provides a detailed description of each experimental procedure.

3.1.Prepare polyethylene oxide (PEO) for testing with electrospinning device

Polymer solutions are mixtures that have dissolved polymers. It is used to create fiber, films, glues, and other polymer-based products. It can fabricate the fiber by using electrospinning techniques. Polyethylene oxide (PEO) solution was made up of PEO powder that had been dissolved in water. The PEO concentration was 7% w/v, which was 5 grams of PEO power and 70 ml of distilled water. It was stirred for 24 hours or until it became homogeneous, which is shown in figure 22. PEO was used for testing with the electrospinning device because it is not solidified at room temperature.

Figure 22. The polyethylene oxide solution

3.2. Prepare polyethylene oxide (PEO) and low viscosity of sodium alginate for fabrication the electrospun fiber

The polyethylene oxide (PEO) with a molecular weight of 200-300 kDa was mixed with the low viscosity sodium alginate (from SIGMA-ALDRICH) which is shown in figure 23. Initially, both were mixed at a concentration of 2 wt% based on the research [51], which involved adding 2 grams of PEO powder, 2 grams of sodium alginate, and 96 ml of distilled water. However, the resulting solution was too liquid for use in electrospinning. To increase the molecular weight of the PEO powder, adding more sodium alginate and PEO powder was suggested to increase the solution's viscosity. For this purpose, three experiments were conducted with varying amounts of PEO powder and sodium alginate. The first experiment involved mixing 2 g of PEO with 3 g of sodium alginate. The second experiment used 3 g of PEO and 3 g of sodium alginate. The third experiment involved 4 g of PEO and 3 g of sodium alginate.

Figure 23. The mixing of polyethylene oxide and low viscosity sodium alginate solution

3.3. Prepare polyethylene oxide (PEO) and high viscosity of sodium alginate (NaAlg) for fabrication the electrospun fiber

To mix the polyethylene oxide (PEO) with high viscosity sodium alginate (from PanReac), two experiments were conducted with different ratios of NaAlg/PEO in 4 wt%. The solution was prepared as described in the research [52]. The first experiment involved a mixing of 2.8 grams of PEO and 1.2 grams of NaAlg in 96 ml of distilled water, resulting in a 4 wt% NaAlg/PEO (PEO:NaAlg, 70:30) solution which is shown in a figure 24. The second experiment involved a mixing of 1.2 grams of PEO and 2.8 grams of NaAlg in 96 ml of distilled water, resulting in a 4 wt% NaAlg/PEO (PEO:NaAlg, 30:70) solution which is shown in figure 25.

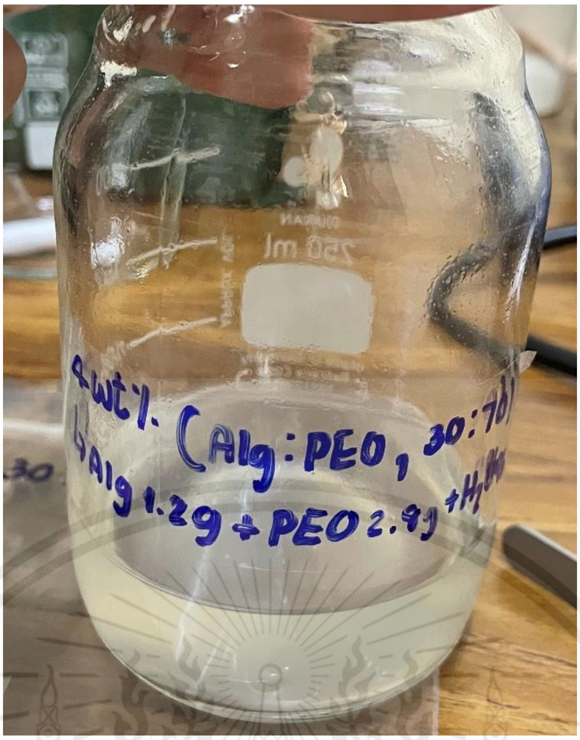


Figure 24. The 4wt% NaAlg/PEO (PEO:NaAlg, 70:30) solution

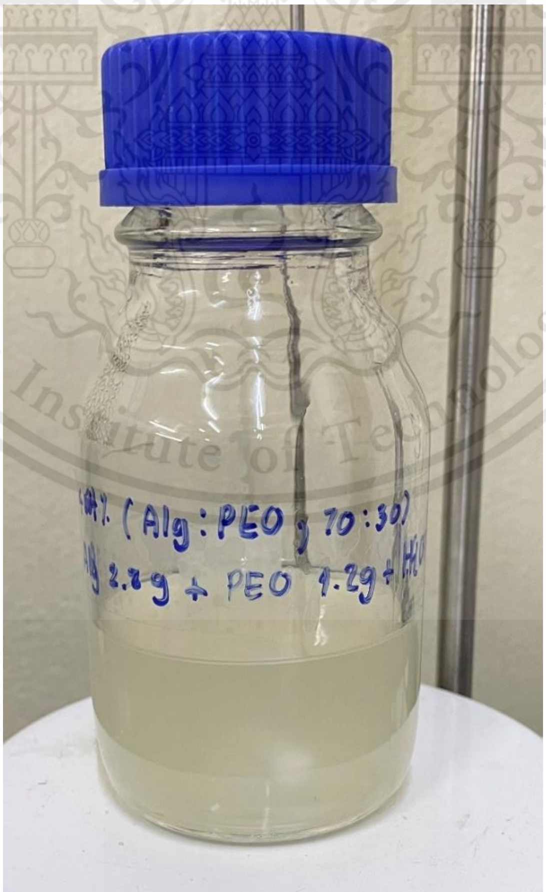


Figure 25. The 4wt% NaAlg/PEO (PEO:NaAlg, 30:70) solution

3.4.The basic set-up of electrospinning device

The electrospinning device consists of three main parts, including a high-voltage power supply, a syringe pump with a spinneret, and a collector plate. In this study, it used the high voltage power supply, which can apply a voltage of 3kV-30kV. In the syringe pump part, it was used the syringe pump TE-311 for pushing the syringe, which had the polymer solution inside. The collector was set at the proper distance to fabricate the electrospun fiber and it was measured the distance by the ruler. The set-up is shown in figure 26.

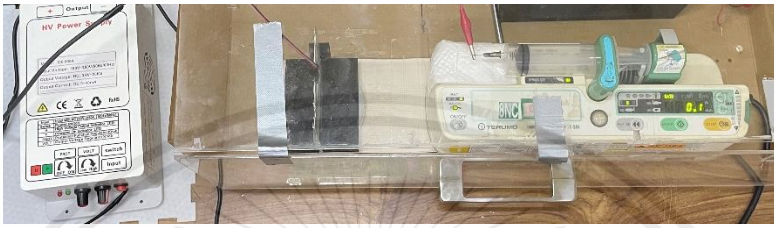


Figure 26. The set-up of electrospinning device

3.5.High voltage power supply

The high voltage power supply supports the electrospinning process by producing an electrically charged of polymer solution. It works as an alternative source for an electrospinning device. The range of voltage that is suitable for electrospinning should be 2K-15KV. In this study, I used the high-voltage power supply which a model is CX-300A, as shown in figure 27.

Figure 27. The high-voltage power supply that uses in this study

3.6. Measuring the voltage of the high voltage power supply

Before using the electrospinning device, it is necessary to check the voltage of the applied voltage from the high-voltage power supply because it will be safety for using proper voltage.

The high voltage source can be measured by using the high voltage probe which is shown in figure 28. The high voltage probe is used for measuring the voltage between 2 positions. In this study, the high-voltage probe connected with the multimeter. The red wire was connected with the needle of the syringe and the black wire was connected with the collector plate which is shown in the figure 29.

Figure 28. The high-voltage probe

Figure 29. Measured the voltage with the high voltage probe

3.7. Syringe pump TERUMO - TE-311

The TERUMO - TE-311 syringe pump is a medical device used to deliver fluid to patients, which is shown in figure 30. In this study, the syringe pump TERUMO - TE-311 was used to support the pushing of the syringe, which contains the polymer solution. It can set the flow rate of the process. It can be connected with 10, 20, 30, and 50 ml of the syringe.

Figure 30. The TERUMO - TE-311 syringe pump

3.8. Size of syringe

There are many sizes of syringes available on the market. Depending on the application, each size is used. However, the size of the syringe used can also depend on other factors such as the viscosity of the polymer solution and the desired flow rate. It's important to note that the size of the syringe used in electrospinning does not directly affect the diameter of the electrospun fibers. In this study, a 50 ml syringe has been used in this study which is shown in the figure 31.

Figure 31. The 50 ml syringe which uses in this study

3.9.Type of needle

In this study, two types of needles were used to fabricate electrospun fibers, which is shown in the figure 32. The first type was a regular bevel needle, which is a standard type of needle commonly used in electrospinning. The second type was a blunt tip needle, which has a flat or rounded end instead of a sharp point. Both types of needles were connected to a 50 ml syringe for the electrospinning process. The choice of needle type can affect the diameter and morphology of the electrospun fibers, so it is important to carefully consider the application and materials being used when selecting a needle type.

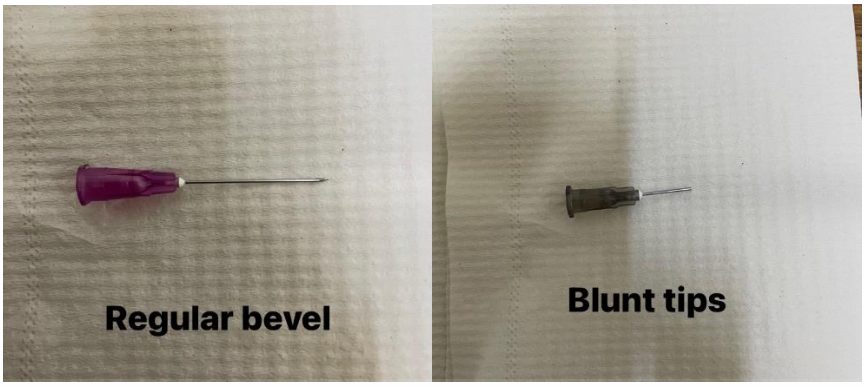


Figure 32. During the experiment, the needle type was changed from regular bevel to blunt tips

3.10. Collector

In this study, a collector plate was used, which comprises a metallic plate, foil paper, and a base. The metallic plate was covered with foil paper and placed on the base. The collector plate was connected to the ground of the high-voltage power supply and used for collecting the electrospun fiber ejected from the syringe pump. Figure 33 is shown the setup of the collector plate.

Figure 33. The set-up of collector plate

3.11. Preparation of the crosslinking solution and the method of crosslinking.

The crosslinking method was used to improve the electrospun fiber after it was removed from the collector plate. The method of crosslinking followed the public research [51]. The fiber was soaked in ethanol for 1 minute. The calcium chloride solution was prepared by dissolving 2 wt% in a 1:5 ratio of ethanol to water. The ethanol and water were mixed in a ratio of 100 ml to 500 ml, respectively. This solution was then mixed with 2 grams of calcium chloride and 98 ml of solution. The fiber was soaked in this solution for 10-15 minutes. After being dried from the previous solution, the fiber was soaked in water for 1 minute to test its water insolubility and the effectiveness of the crosslinking method. Figure 34 is shown the solution which was used in this method.

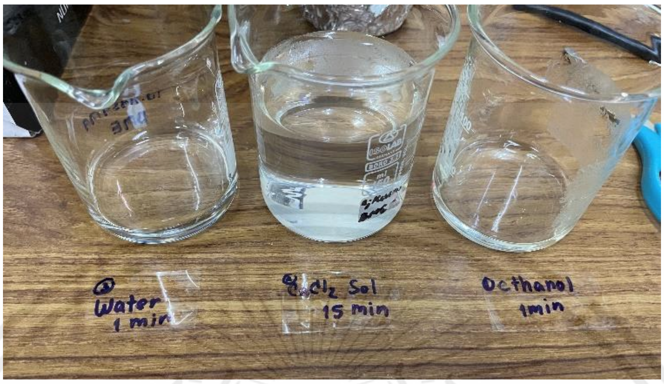


Figure 34. The crosslink solution of $CaCl_2$ *and ethanol*, and water to test the fiber insolubility

CHAPTER 4

EXPERIMENTAL RESULT AND DISCUSSION

In chapter 4, the results of the electrospun fibers from the PEO solution for testing the electrospinning device are presented. The electrospinning parameters, such as time, voltage, flow rate, and distance between the needle and collector plate, were varied. Additionally, the results of the electrospun fibers from the PEO-NaAlg solution were presented, which were prepared with different types of viscosity by varying the electrospinning parameters. The electrospun fibers from the PEO-NaAlg solution were fabricated for wound dressing. Lastly, the results of the crosslinking process were also presented.

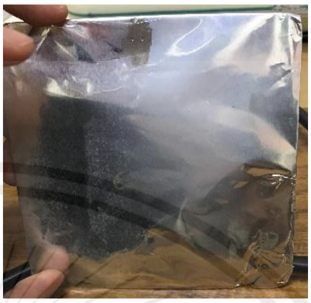
4.1 The result of PEO electrospun fiber for testing the electrospinning device

In this experiment, the PEO solution was used to test the electrospinning device and process. Various electrospinning factors, such as flow rate, voltage, and distance between the collector and needle, were varied. As the objective of this project is to fabricate wound dressings from the electrospun fiber product, the electrospun fiber should be able to peel off the foil paper that is part of the collector plate.

In the Table 1 shows the results of the electrospun fiber from the PEO solution. The solution was contained in a 20 ml syringe and a blunt tip needle was used. Various electrospinning parameters were varied to find the suitable result to fabricate the electrospun fiber.

From the results in Table 1, it was found that the fabrication of the electrospun fiber was bothered by the electric field generated by the syringe pump device (TE-311). To solve this problem, the equipment was changed by increasing the size of the syringe from 20 ml to 50 ml and changing the needle type from blunt tip to regular bevel tip. With the longer distance between the syringe and the pump device and the longer needle, the electric field generated by the syringe pump device could be avoided. Table 2 shows the results of various electrospinning parameters after changing the syringe and needle. The results demonstrate that changing the syringe and needle helped achieve successful fabrication of the electrospun fiber. When the spinning time and the distance between the needle and collector were increased, this result was observed in the electrospun fiber, while maintaining a constant applied voltage and flow rate. Therefore, the 50 ml of syringe and regular bevel tip would be used in the next experiment for fabricating the electrospun fiber.

Table 1. The electrospun fiber results were obtained by testing the electrospinning device with various factors, using a 20 ml syringe and a blunt tip needle with the PEO solution.

PEO solution					
Voltage (kV)	**Flow rate (ml/hr)**	**Distance between needle and collector (cm)**	**Time (min)**	**Result**	**Observable Result**
6	1	18	30		There was some electrospun fiber fabricated on the foil paper.
6	2	18	30		Nothing fabricates on the collector plate.
15	2	10	30		Nothing fabricates on the collector plate.
15	1	6	20		There are some electrospun fiber was fabricated on the left corner of foil paper with the thin layer.

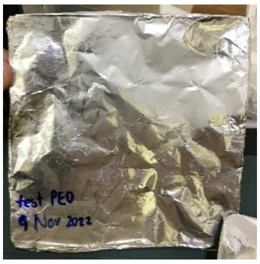
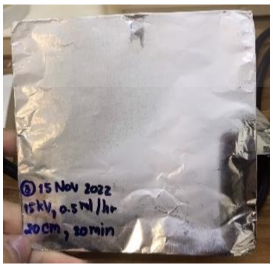
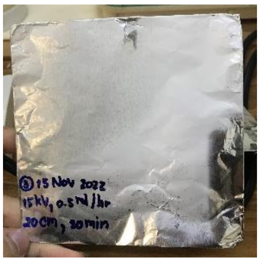
15	1.5	6	20		The electrospun fiber can fabricate. It was thicker layer than the previous one.

Table 2. The electrospun fiber results were obtained by testing the electrospinning device with various factors, using a 50 ml syringe and a regular bevel tip needle with the PEO solution.

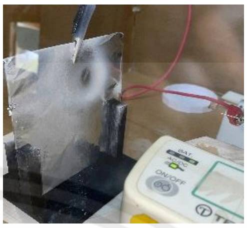
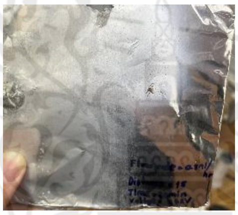
PEO solution					
Voltage (kV)	**Flow rate (ml/hr)**	**Distance between needle and collector (cm)**	**Time (min)**	**Result**	**Observable Result**
15	0.5	10	20		The electrospun fiber was fabricated and it spread throughout.
15	0.5	15	20		More fabricated fiber on collector plate than 10 cm result.
15	0.5	20	20		More fabricated fiber on collector plate than 20 cm result.

15	0.5	15	30		More fabrication time would increase the electrospun fiber.

4.2 Fabrication of electrospun fiber from PEO-NaAlg low viscosity solution

The electrospinning device was set up with a syringe pump device (TE-311) containing a 50 ml syringe and a regular bevel needle. The main objective of this experiment was to fabricate an effective wound dressing using electrospun fiber. To enhance its effectiveness, a low viscosity of sodium alginate was mixed with PEO powder to create the PEO-NaAlg solution, as sodium alginate has properties that support crosslinking of the PEO structure. The electrospinning process was conducted with different solution concentrations and various electrospinning factors. Increasing the amount of PEO or NaAlg in the solution was done to increase its viscosity. Initially, a 2wt% concentration of both PEO and NaAlg was used, which was prepared by dissolving 2 g PEO and 2 g NaAlg in 96 ml distilled water. However, the resulting solution was too liquid for electrospinning. One solution was to increase the amount of NaAlg by adding 1 g (PEO 2g and NaAlg 3g), which resulted in a more viscous solution, as shown by the results of the electrospun fiber in Table 3. After trying different voltage values, it was found that the suitable voltage for fabricating the electrospun fiber was 26 kV. This voltage value would be used in the next experiment. The result show that increasing the distance between needle and collector allowed the electrospun fiber to have enough time for drying on the collector plate. Additionally, increasing the spinning time led to a wider spread of the electrospun fiber on the collector plate. Therefore, the electrospinning parameters used in the next experiment were 26 kV applied voltage, 0.1 ml/hr flow rate, 15 cm distance between needle and collector, and 20 min spinning time.

Table 3. The result of varies factor for fabricate the electrospun fiber which made from the PEO 2g and NaAlg (low viscosity) 3g solution.

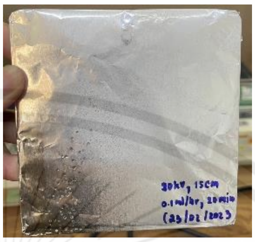
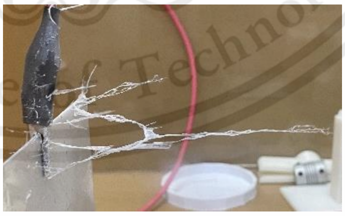
PEO 2g + NaAlg (low viscosity) 3g					
Voltage (kV)	**Flow rate (ml/hr)**	**Distance between needle and collector (cm)**	**Time (min)**	**Result**	**Observable Result**
26	0.1	10	10		The solution is too liquid to use in the fabrication, and the short distance between needle and collector does not allow enough time for the material to dry.
26	0.1	15	20		The electrospun fiber wasn't crosslink properly, resulting in many small gaps or holes in the collector.

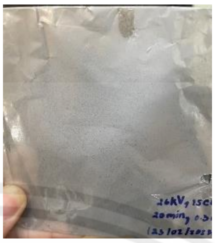
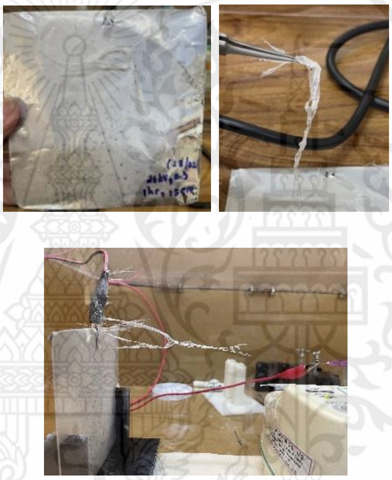
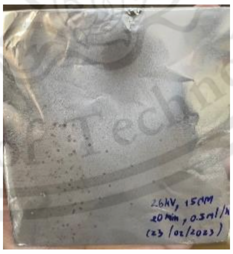
However, the resulting fibers did not adhere well enough to be used as a wound dressing, likely due to inadequate crosslinking during the electrospinning process, which resulted in small gaps in the collector. To address this issue, 1 g of PEO was added to the solution (PEO 3g and NaAlg 3g), resulting in a more viscous solution that was used to fabricate the electrospun fiber in the next experiment. Despite increasing the amount of PEO in the solution, the resulting electrospun fiber still had small gaps and did not adhere well enough to be used as a wound dressing. This suggests that the fiber was not crosslinked properly. The experimental results are shown in Table 4. Based on the results of the experiment, an additional 1g of PEO powder was added (resulting in PEO 4g and NaAlg 3g) to increase the viscosity of the solution and produce electrospun fibers with fewer beads and better crosslinking, as shown in Table 5. The experiment also varied the electrospinning parameters to observe their effects on the resulting electrospun fibers. The increasing of voltage from 20 kV to 26 kV resulted in more stable ejection of the electrospun fiber from the needle to collector plate. It also enhanced the electric field to overcome surface tension forces. The suitable distance between needle and collector was determined to be 15 cm. If the distance was shorter, the electrospun fiber did not have enough time to dry. On the other hand, if the distance was longer, it caused irregular fibers that could break during the process. For the optimal flow rate, it was determined that 0.1 ml/hr is suitable. Increasing the flow rate resulted in the increasing of the solution droplets on the collector plate, indicated that higher flow rate could make the solution for drying slowly. Increasing the spinning time led to increase the amount of electrospun fiber, and it also created the fiber alignment in a linear pattern.

Table 4. The result of varies factor for fabricate the electrospun fiber which made from the PEO 3g and NaAlg (low viscosity) 3g solution.

PEO 3g +NaAlg (Low viscosity) 3g					
Voltage (kV)	**Flow rate (ml/hr)**	**Distance between needle and collector (cm)**	**Time (min)**	**Result**	**Observable Result**
20-21	0.1	15	20		The flow rate was too low, causing the electrospun fiber to take longer to dry. Additionally, the fiber was too thin to be used as a wound dressing.
26	0.1	15	20		The electrospun fiber wasn't crosslink adequately, which resulted in the formation of small gaps or holes.

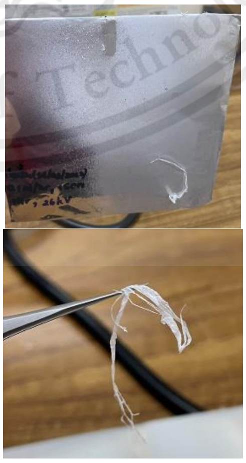
Table 5. The result of varies factor for fabricate the electrospun fiber which made from the PEO 4g and NaAlg (Low viscosity) 3g solution.

PEO 4g + NaAlg (Low viscosity) 3g					
Voltage (kV)	**Flow rate (ml/hr)**	**Distance between needle and collector (cm)**	**Time (min)**	**Result**	**Observable Result**
20-21	0.1	15	20		The voltage was set too low, which caused the electrospun fiber to dry too slowly.
26	0.1	15	20		The electrospun fiber is irregularly and it broke during the process.
26	0.1	15	60	  	The electrospinning process created the fiber to align in the line and it connected to the ground wire. For the next time, it is important to clean the ground wire before beginning the process.
26	0.1	18	20		The solution dried too slowly when the distance between the needle and collector was increased to 18 cm compared to the optimal 15

					cm distance condition. The longer distance caused irregular fibers that could break during the process.
26	0.3	15	20		It looks similar to the condition with a flow rate of 0.1 ml/hr, but the electrospun fiber doesn't crosslink as well due to the faster flow rate.
26	0.3	15	60		The flow rate is faster than 0.1 ml/hr condition, which means that the solution will need more time to dry. However, this can cause the fibers to link together in a line.
26	0.5	15	20		The flow rate is too fast for fabricating the electrospun fiber, and the solution isn't drying fast enough. This can cause the fibers to link together in a line.

Due to the alignment of fibers with the ground wire during the 60-minute spinning process, along with the small gaps on the collector plate, resulted in insufficient crosslinking of the electrospun fibers. To prevent the fibers from sticking to the ground wire, it was cleaned before spinning the solution. Another solution to this problem was to change the needle type from a regular bevel to a blunt tip. The tip of a regular bevel needle is diagonal, which can spread the electric field between the collector and the solution and result in insufficient crosslinking. In contrast, the tip of a blunt tip needle is truncated, allowing for smoother and more regular fabrication of electrospun fibers. Table 6 presents the results of using the same solution as in Table 5 but with the needle type changed and the ground wire cleaned, resulting in more effective fabrication of electrospun fibers with proper crosslinking. The results in Table 6 showed that the used of a blunt tip needle type resulted in smoother and more regularly arranged electrospun fibers compared to the use of a regular bevel needle type. Additionally, increasing the spinning time did not only increase the quantity of electrospun fiber on the collector plate but also enhanced the length of fiber alignment.

Table 6. The result of the electrospun fibers made from a solution of PEO 4g and NaAlg (low viscosity) 3g, using the needle type change and ground wire cleaning method.

PEO 4g + NaAlg 3g (Using the blunt tips needle and cleaning the ground wire)					
Voltage (kV)	**Flow rate (ml/hr)**	**Distance between needle and collector (cm)**	**Time (min)**	**Result**	**Observable Result**
26	0.1	15	30		The electrospun fiber was smooth and the arrangement was more regular than before.
26	0.1	15	60		It created the fiber to align in the line and it connected to the ground wire.

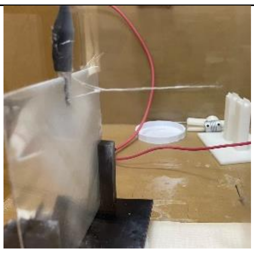
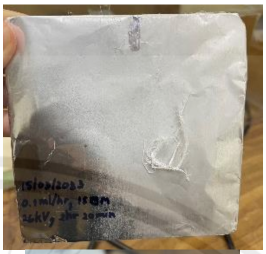
					
26	0.1	15	120	  	The amount of electrospun fiber on the foil paper has increased, and the fibers that are sticking to the ground wire are longer. Droplets can be seen on the foil paper.

Table 3 to 6 show the results of fabricating electrospun fibers from PEO-NaAlg low viscosity solution using different combinations of PEO and NaAlg weights. Based on the results, the best solution for fabricating electrospun fibers with proper crosslinking was found to be 4g of PEO and 3g of NaAlg. Adding PEO increased the viscosity of the solution and using a blunt tip needle type resulted in smoother and more regularly arranged fibers on the collector plate. The experiment aimed to observe the effect of various electrospinning factors on the resulting fibers. The optimal values for each factor were determined as follows: the suitable voltage for electrospinning should be 26kV, as lower voltages resulted in an uneven electric field and irregular fibers on the collector plate. The suitable flow rate should be 0.1 ml/hr, as higher rates caused the solution to be ejected too quickly, without sufficient time for drying. The suitable distance between the needle and the collector should be 15 cm, as shorter or longer distances resulted in irregular or lower yields of fibers. Longer spinning times resulted in more fibers on the collector plate, but also showed droplets due to the slow drying of the solution. Spinning for longer than 60 minutes caused aligned fibers to stick to the ground wire.

4.3 Fabrication of electrospun fiber from PEO-NaAlg high viscosity Solution

The electrospinning setup involved a syringe pump device (TE-311) with a 50 ml syringe and a blunt tip needle, which was previously used in the experiment. In this experiment, high viscosity sodium alginate was used instead of low viscosity. The high viscosity sodium alginate has properties that increase viscosity and strengthen gel strength, enhancing the entanglement and crosslinking between PEO molecules.

- **The solution of 4wt% NaAlg/PEO (30/70)**

Initially, the solution was prepared by dissolving 2.8 g of PEO and 1.2 g of NaAlg in 96 g of distilled water, resulting in a 4 wt% NaAlg/PEO (ratio: 30/70) solution. The experiment varied the electrospinning factor, such as flow rate and time, while keeping the voltage (26kV) and distance between needle and collector (15 cm) constant. Table 7 shows the results of electrospun fiber at a flow rate of 0.1 ml/hr that was spun for various times, including 10-, 20-, 30-, and 60-min. Tables 8 and 9 show the results of increasing the flow rate to 0.3 and 0.5 ml/hr, respectively, and spinning for various times. It was observed that the thicker the electrospun fiber, the higher the flow rate and the longer the spinning time.

Table 9 presents the results for two different longer spinning times, 240 and 300 min, as the electrospun fiber appeared thicker than the others and may have been able to peel off from the foil paper. The electrospinning parameter were conducted using 26 kV applied voltage, 0.5 ml/hr flow rate and 15 cm distance between needle and collector.

Table 7. The result of electrospun fiber at a 0.1 ml/ hr flow rate that was spun for various times which made from 4wt% NaAlg/PEO (30/70).

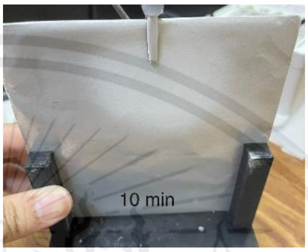
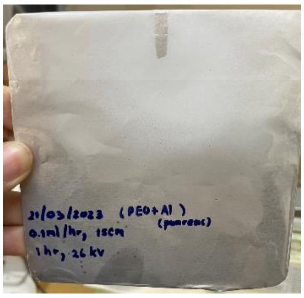
4wt% NaAlg/PEO (30/70) NaAlg (350-550 mPas, High viscosity) 1.2 g + PEO 2.8g + Distilled water 96 g					
Voltage (kV)	**Flow rate (ml/hr)**	**Distance between needle and collector (cm)**	**Time (min)**	**Result**	**Observable Result**
26	0.1	15	10		The electrospun fiber was spread throughout
26	0.1	15	20		Spending more time in fabrication, more electrospun fiber was collected.
26	0.1	15	30		More fabricated fiber on collector plate than 20 min result.
26	0.1	15	60	21/03/2023 (PEO+Al) 0.1ml/hr, 15cm 1hr, 26kV	More fabricated fiber on collector plate than 30 min result.

Table 8. The result of electrospun fiber at a 0.3 ml/ hr flow rate that was spun for various times which made from 4wt% NaAlg/PEO (30/70).

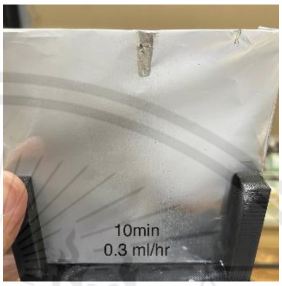
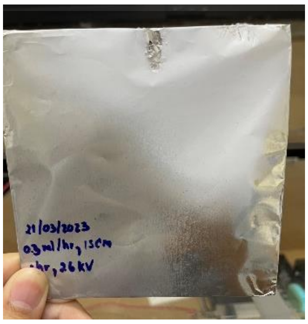
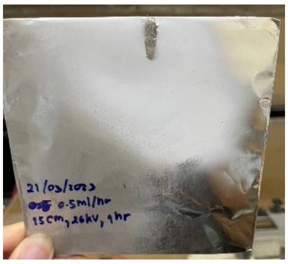
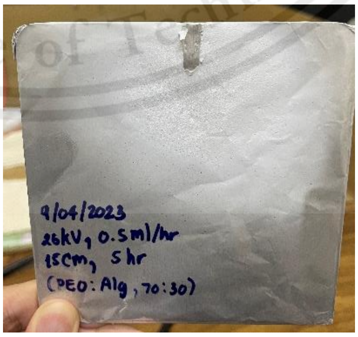
4wt% NaAlg/PEO (30/70) NaAlg (350-550 mPas, High viscosity) 1.2 g + PEO 2.8g + Distilled water 96 g					
Voltage (kV)	**Flow rate (ml/hr)**	**Distance between needle and collector (cm)**	**Time (min)**	**Result**	**Observable Result**
26	0.3	15	10		Increasing the flow rate, the electrospun fiber is thicker than 0.1 ml/hr result with the same time.
26	0.3	15	20		Spending more time in fabrication, more electrospun fiber was collected.
26	0.3	15	30		More fabricated fiber on collector plate than 20 min result.
26	0.3	15	60		More fabricated fiber on collector plate than 30 min result.

Table 9. The result of electrospun fiber at a 0.5 ml/ hr flow rate that was spun for various times which made from 4wt% NaAlg/PEO (30/70).

4wt% NaAlg/PEO (30/70) NaAlg (350-550 mPas, High viscosity) 1.2 g + PEO 2.8g + Distilled water 96 g					
Voltage (kV)	**Flow rate (ml/hr)**	**Distance between needle and collector (cm)**	**Time (min)**	**Result**	**Description**
26	0.5	15	10		Increasing the flow rate, the electrospun fiber is thicker than 0.3 ml/hr result with the same time.
26	0.5	15	20		Spending more time in fabrication, more electrospun fiber was collected.
26	0.5	15	30		More fabricated fiber on collector plate than 20 min result.
26	0.5	15	60		More fabricated fiber on collector plate than 30 min result.

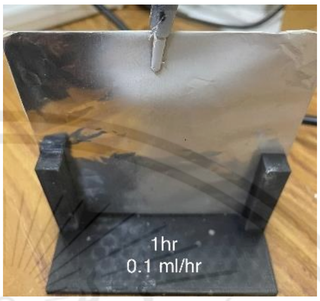
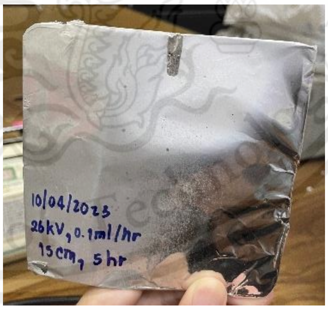
26	0.5	15	240 (4hrs)		The electrospun fiber is thicker as increasing the time and flow rate. It sticks on the ground wire and align to the line. I use the paper punch for making the sample size, it can be peeled from the foil paper.
26	0.5	15	300 (5hrs)		The electrospun fiber was thicker as increasing the time. it was spread throughout. This obtain that electrospun fiber sample was further crosslinked by 2wt% of $CaCl_2$ solution.

- **The solution of 4wt% NaAlg/PEO (70/30)**

For this experiment, a solution was prepared by dissolving 1.2 g of PEO and 2.8 g of Alg in 96 ml of distilled water, resulting in a 4 wt% Alg/PEO (ratio: 70/30) solution. This solution is different from the previous one in terms of the amount of PEO and Alg used. In the research has shown that this percentage of solution is capable of producing fibers, making it suitable for observing the morphology of the electrospun fiber which is shown the result in the Table 10.

Table 10. The result of electrospun fiber at a 0.1 ml/ hr flow rate that was spun for various times which made from 4wt% NaAlg/PEO (70/30).

4wt% NaAlg/PEO (70/30) NaAlg (350-550 mPas, High viscosity) 2.8 g + PEO 1.2g + Distilled water 96 g					
Voltage (kV)	**Flow rate (ml/hr)**	**Distance between needle and collector (cm)**	**Time (min)**	**Result**	**Observable Result**
26	0.1	15	10		The electrospun fiber was thin and the amount of fiber was lower previous case (NaAlg/PEO (30/70)).
26	0.1	15	20		The electrospun fiber is thicker than 10 min result.
26	0.1	15	30		The electrospun fiber wasn't significant different compared to 20 min result.

					
26	0.1	15	60		The electrospun fiber was spread than 30 min result.
26	0.1	15	120 (2hrs)		The electrospun fiber was wider. The droplets were observed.
26	0.1	15	300 (5hrs)		The electrospun fiber was thicker. The droplets were observed.

This solution could fabricate the electrospun fiber less than the previous solution (4wt% NaAlg/PEO (30/70)). The experiment varied the spinning time (10, 20, 30, 60,120, 300 min), while keeping the voltage (26kV), flow rate (0.1 ml/hr) and distance between needle and collector (15 cm) constant. As spending more spinning time, the electrospun were observed to spread wider and become thicker and the droplets were also observed.

4.4 The result of crosslink

Since the purpose of this research is to develop insoluble wound dressing, it is important to prevent the electrospun fiber from dissolving in water. Therefore, a crosslinking method would be implemented to enhance the stability of the electrospun fiber. To enhance the stability of the fiber, a crosslinking method would be employed, specifically on the sample made from high viscosity sodium alginate, which is effective in increasing the fiber's viscosity.

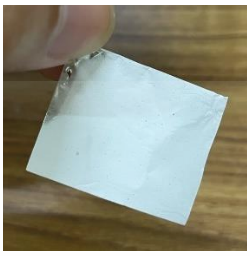
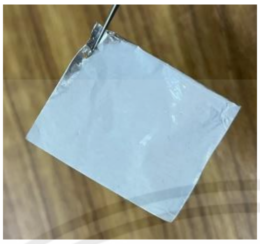
- **Crosslinking the electrospun fiber from the 4wt% NaAlg/PEO (30/70) solution (4hrs spinning)**

  A. Kyzioł, et al., 2017 [51] and C. A. Boninoa, et al., 2011 [53] report the crosslinking electrospun fiber with the calcium chloride solution achieved at different time of soaking 10 seconds and 10 min. Therefore, we tried to perform the crosslink at 10 seconds and 10 min soaking $CaCl_2$. The results of crosslinking are shown in the Table 11 and 12 for the 10 seconds and 10 min soaking time of $CaCl_2$ solution, respectively.

Table 11. The crosslinking result after 10 seconds soaking in $CaCl_2$ solution of the electrospun fiber made from 4 wt% NaAlg/PEO (30/70) with 4 hours spinning.

Before Soaking	**Soaking ethanol 1 min**	**Soaking $CaCl_2$ solution 10 seconds**	**Soaking water 1 min**
			

Table 12. The crosslinking result after 10 minutes soaking in $CaCl_2$ solution of the electrospun fiber made from 4 wt% NaAlg/PEO (30/70) with 4 hours spinning.

Before Soaking	**Soaking ethanol 1 min**	**Soaking $CaCl_2$ solution 10 minutes**	**Soaking water 1 min**
			

After soaking in the $CaCl_2$ solution, the sample was dried for 15 minutes before being soaked in water. The results in Table 12 showed more insoluble electrospun fibers than those in Table 11. Some of the electrospun fibers remained on the foil paper, possibly due to the longer time of soaking in $CaCl_2$ solution make the electrospun fiber is more stable. In contrast, the results in Table 11 showed that after soaking in the $CaCl_2$ solution for 10 seconds, some solution dropped onto the foil paper during the drying process. The final result showed remaining electrospun fibers with the drop of $CaCl_2$ solution during drying. Therefore, the crosslinking of electrospun fibers was successful with the $CaCl_2$ solution soaking for 15 min. This achieved condition was used in the next experiment.

- **The comparation of the crosslinking result between the electrospun fiber from the 4wt% NaAlg/PEO (30/70) solution and NaAlg/PEO (70/30) (5hrs spinning)**

  In this experiment performed the same crosslinking method as in the previous experiment, but with a longer soaking time of 15 min in the $CaCl_2$ solution. The objective of this experiment is to find the optimal conditions for the crosslinking process that can provide the highest resistance to water soaking for at least 1 min, while maintaining a high amount of electrospun fiber. It would compare the results of the crosslinking process between the 4wt% NaAlg/PEO (30/70) solution and theNa Alg/PEO (70/30) solution (5 hours spinning) to determine which solution is more suitable for the intended application. The results are shown in Table 13 and 14 for the electrospun fiber solutions of 4wt% NaAlg/PEO (30/70) and NaAlg/PEO (70/30), respectively.

Table 13. The crosslinking result after 15 minutes soaking in $CaCl_2$ solution of the electrospun fiber made from 4 wt% NaAlg/PEO (30/70) with 5 hours spinning

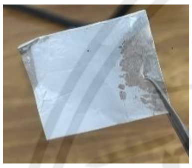
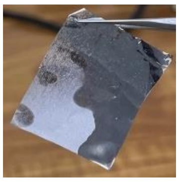
No.	**Before Soaking**	**Soaking ethanol 1 min**	**Soaking $CaCl_2$ solution for 15 min**	**Soaking water 1 min**	**After drying**
1					
2					

Table 14. The crosslinking result after 15 minutes soaking in $CaCl_2$ solution of the electrospun fiber made from 4 wt% NaAlg/PEO (70/30) with 5 hours spinning.

No.	**Before Soaking**	**Soaking ethanol 1 min**	**Soaking $CaCl_2$ solution 15 min**	**Soaking water 1 min**	**After drying**
1					
2					

The results of Table 13 and 14 show the crosslinking efficiency of the electrospun fiber using the 4wt% NaAlg/PEO (30/70) solution and the NaAlg/PEO (70/30) solution, respectively. Based on the findings, it can be concluded that the electrospun fiber obtained from the NaAlg/PEO (70/30) solution is better at resisting water soluble than that of the 4wt% NaAlg/PEO (30/70) solution. The fiber's color after drying remained the same as before soaking, as white color, and the electrospun fiber was more regular alignment. The higher content of sodium alginate in the solution led to better crosslinking with $CaCl_2$, resulting in enhanced water insolubility compared to the electrospun fiber from the 4wt% NaAlg/PEO (30/70) solution.

CHAPTER 5
CONCLUSION

In Chapter 5, the results related to this research was summarized. The suitable equipment used for setting up the electrospinning process was discussed, along with the various electrospinning factors that depend on the solution. The conclusions of the electrospun fiber results from each solution and the crosslinking result were presented. Suggestions that may be useful for those interested in this research and further plans that can improve its effectiveness was also provided. This conclusion summarized the list of objectives that were obtained from the experiment and its result, along with recommendations for further improvements or advancements in this research.

5.1 The electrospun fiber can be fabricated from PEO by electrospinning technique.

Based on the results, the electrospinning parameters can significantly impact the fabrication of electrospun fibers. The electrospinning process involves adjusting a range of factors until the desired outcome is achieved. The equipment used in the experiment is important in ensuring successful fabrication. From this experiment, it is concluded that using a 50 ml syringe and regular bevel tips with the syringe pump device effectively prevents electric field interference. Additionally, increasing the voltage, distance between the needle and collector, and spinning time leads to a greater production of electrospun fibers, as observed from the results on the foil paper placed on the collector plate. Furthermore, the experiments detailed in Tables 1 and 2 provide support for the conclusion that electrospun fibers can be successfully fabricated from PEO solution using the electrospinning technique.

5.2 The suitable solution and electrospinning parameters for fabrication the PEO and high viscosity NaAlg electrospun fiber

In this experiment, sodium alginate was added to enhance the effectiveness of the electrospun fiber wound dressing by coordinating with the PEO structure. Since we only had PEO with a molecular weight of 200-300 kDa, which cannot be easily increased, we investigated the impact of different viscosities of sodium alginate in this research. The use of high viscosity sodium alginate properties is better than the low viscosity sodium alginate in enhancing the morphology, strength, and the entanglement and crosslinking between PEO molecules in the electrospun fibers. The high viscosity sodium alginate used in this study had a viscosity range of 350-550 mPas.

From the comparison between the difference weight ratios of PEO and sodium alginate solutions, we found that the solution with a higher weight of sodium alginate relative to PEO demonstrated better insolubility after crosslinking with a calcium chloride solution. Specifically, the 4wt% NaAlg/PEO (70/30) solution is better than the 4wt% NaAlg/PEO (30/70) solution, as shown in Table 13 and 14.

Based on our study, the suitable electrospinning parameters for the 4wt% NaAlg/PEO (70/30) solution were identified as follows: voltage = 26 kV, flow rate = 0.1 ml/hr, distance between the needle and collector = 15 cm, and the use of blunt tips for the needle.

From the results and experiments of fabricating the electrospun fiber from the PEO and sodium alginate solution, it can be concluded that high viscosity sodium alginate can significantly improve the properties of electrospun fibers, including morphology, strength, and crosslinking with a calcium chloride solution. These findings contribute to the understanding and development of electrospun fiber wound dressings with enhanced performance.

5.3 The electrospun fiber properties is improved by crosslink method of NaAlg and $CaCl_2$

As the PEO can easily dissolve in the water, the crosslink with $CaCl_2$ is enhanced the properties of the electrospun fiber which fabricated from the PEO and high viscosity of sodium alginate. From the result, which is presented in Table 13 and 14, it can be concluded that the crosslink method improves the insolubility of the electrospin fiber. However, the electrospun fiber from the 4wt% NaAlg/PEO (70/30) solution exhibit better insolubility and a more organized structure compared to the 4wt% NaAlg/PEO (30/70) solution.

5.4 Suggestion

For suggestions to enhance the effectiveness of the wound dressing in this research, the use of scanning electron microscopy can be recommended to confirm the presence of electrospun fibers and observe their arrangement in microscopic images. Another way to improve effectiveness is by adding the antibacterial agents into the electrospun fibers and conducting bacterial testing. This method aims to enhance the antimicrobial properties of the electrospun fiber wound dressing.

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