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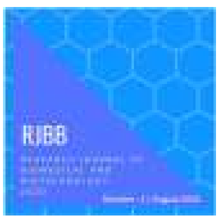

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The Electrospinning of Different Hemostatic Agents and Their Effectiveness

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Keywords: Astringents, Hemorrhage, Bleeding Time, Ankaferd Blood Stopper, Adrenaline, Tranexamic Acid

Abstract

The purpose of this study is to present an effective solution for severe bleeding and tissue damage occurring during situations such as conflicts, disasters, and crises. The aim is to produce nanofibers that can serve as a hemostatic wound dressing, capable of both accelerating wound healing and controlling bleeding. Nanofibers are produced through the electrospinning method by combining hemostatic agents such as adrenaline (ADR), Transamin® (TXA), and Ankaferd Blood Stopper® (ABS) with polyvinyl alcohol (PVA) polymer. The morphology, chemical bonding structure, and hemostatic activity of these nanofibers are extensively analyzed. The feasibility of these nanofibers for medical applications, particularly as wound dressings, was investigated. Results: Field emission scanning electron microscopy (FESEM) images reveal that increased concentrations of adrenaline, TXA, and ABS result in the formation of beaded fibers. While ABS/PVA and TXA/PVA nanofibers have similar average diameters, ABS/PVA exhibits a more beaded morphology. According to hemostatic activity tests, clotting times were similar for adrenaline/PVA and TXA/PVA nanofibers, whereas ABS/PVA nanofibers exhibited a shorter clotting time. Among the findings, adrenaline/PVA nanofibers had the longest clotting time at 4.088 seconds. On the other hand, ABS/PVA nanofibers had the shortest clotting time at 3.819 seconds. An effective hemostatic agent should be able to stop bleeding within 2 minutes after application to the wound site in in vitro settings, without requiring mixing or preparation, and should be easily applicable to wounded areas. The developed hemostatic nanofibers demonstrated the ability to form clots within seconds. The resulting nanofibers from this study will not only contribute to public health but also significantly enhance survival processes.

Farklı Hemostatik Ajanların Elektroeğirme Yöntemiyle Üretimi ve Etkinliği

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Özet

Bu çalışmanın amacı, çatışmalar, felaketler ve krizler gibi durumlar sırasında meydana gelen ciddi kanama ve doku hasarına yönelik etkili çözümler sunmak amacıyla hem yara iyileşmesini hızlandırabilen hem de kanamayı kontrol edebilen bir hemostatik yara örtüsü olarak kullanılabilecek nanolifler üretmektir. Nanolifler, elektroeğirme yöntemiyle adrenalin (ADR), Transamin® (TXA) ve Ankaferd Blood Stopper® (ABS) gibi hemostatik maddeler ile polivinil alkol (PVA) polimerinin birleşimiyle elde edilmektedir. Çalışmada nanoliflerin morfolojisi, kimyasal bağ yapısı ve hemostatik aktivitesi ayrıntılı şekilde analiz edilmektedir. Bu nanoliflerin tıbbi uygulamalarda, özellikle yara örtüsü olarak kullanılabilirliği araştırılmıştır. Alan emisyonlu taramalı elektron mikroskobu (FESEM) görüntülerine göre, adrenalin, TXA ve ABS konsantrasyonunun artmasıyla boncuklu lifler oluşmaya başlamıştır. ABS/PVA ve TXA/PVA nanoliflerinin ortalama çapları aynı olmasına rağmen, ABS/PVA daha fazla boncuklu morfolojiye sahiptir. Hemostatik aktivite testlerine göre, adrenalin/PVA ve TXA/PVA nanoliflerinin pıhtılaşma süreleri benzerdi; ancak ABS/PVA nanoliflerinin pıhtılaşma süresi daha kısaydı. Bulgulara göre, adrenalin/PVA nanolifleri en uzun pıhtılaşma süresine sahipti ve bu süre 4.088

saniyeydi. Öte yandan, ABS/PVA nanolifleri en kısa pıhtılaşma süresine sahipti ve bu süre 3.819 saniyeydi. İyi bir hemostat, in vitro uygulamalarda yara bölgesine uygulandıktan sonra 2 dakika içinde kanamayı durdurabilmeli, karıştırma veya hazırlama gerektirmemeli ve yaralı bölgelere basitçe uygulanabilmelidir. Bu çalışmada elde edilen hemostatik nanoliflerin saniyeler içinde pıhtı oluşturabilme yeteneği gösterilmiştir. Geliştirilen nanolifler, sadece halk sağlığı açısından değil, aynı zamanda hayatta kalma süreçlerine güçlü bir katkı sağlayacaktır.

1. Introduction

Hemostatics are a type of drugs that promote hemostasis, which is the natural process of forming clots to prevent or stop bleeding [1]. The hemostasis process involves vasoconstriction, platelet plug formation, and blood coagulation [2]. Hemostatic agents can be classified into two main categories: topical and systemic. Topical hemostatics are administered directly at the site of bleeding, where they function by either forming a physical barrier, initiating the coagulation process, or improving platelet aggregation. Some illustrations of topical hemostatics comprise collagen, gelatin, cellulose, fibrin sealants, and thrombin [3]. Systemic hemostatics, on the other hand, are given intravenously and function by increasing clotting factor levels, inhibiting fibrinolysis, or boosting platelet function. Examples of systemic hemostatics include tranexamic acid, aminocaproic acid, desmopressin, and recombinant factor VIIa [3]. In situations where there is a high risk of severe bleeding, hemostatics are essential in various health fields. Military medicine is one field where hemostatics can be utilized to treat combat casualties with traumatic hemorrhage. Up to 90% of potentially survivable deaths among soldiers in modern warfare are due to hemorrhage. Hence, the use of hemostatics can considerably improve survival rates and reduce morbidity among injured soldiers. Soldiers can self-administer these hemostatics at the injury site, during evacuation, or at the hospital, or they can be administered by combat medics. Some of the hemostatics evaluated or used by the military include QuikClot®, HemCon®, WoundStat®, Celox®, Combat Gauze, and TXA. However, hemostatics pose several limitations and challenges, such as cost, availability, safety, efficacy, applicability, and compatibility with various wound types. Therefore, further research and development are necessary to optimize the use of hemostatics.

Hemorrhage, especially from noncompressible areas like the splanchnic and junctional areas, continues to be the primary cause of avoidable fatalities on the battlefield [4, 5]. In the United States, during conflicts in Iraq and Afghanistan a staggering 90% of combat casualties succumbed to their injuries before reaching surgical facilities. Among these casualties, Hemorrhage was responsible for about 90% of potentially survivable fatalities, with 67% occurring in truncal areas, 19% in junctional areas, and 14% in extremities [5, 6]. It is worth mentioning that a considerable proportion of in-hospital fatalities occur during the first hour of admission [7]. Hence, the development and deployment of effective hemostatic agents for use both in the prehospital and early in-hospital stages are of paramount importance.

Electrospinning is a cost-effective and straightforward method that involves four essential components: 1. a high-voltage power source, 2. a spinneret, 3. a collector, and 4. a feeding system. Electrospun nanofibers have been widely employed in the biomedical sector, with significant applications in fields such as tissue engineering [8] and wound dressings [9]. In times of conflict and crises, severe bleeding and wound infections resulting from tissue injuries are primary contributors to casualties. Hence, the development of hemostatic agents for early use in both prehospital and early in-hospital settings is of paramount importance. There is a growing interest in harnessing nanofibers to achieve swift hemostasis, and nanofibers tailored for this purpose have attracted considerable attention. These nanofibers possess an extensive surface area and substantial porosity, enabling them to adhere tightly to the bleeding spot. Additionally, they facilitate platelet attachment and activation, expediting the local formation of blood clots [10].

Archana et al. [11] successfully developed a chitosan-PVP-Ag_2O hemostatic membrane. The incorporation of Polyvinylpyrrolidone (PVP) not only enhanced the strength and mechanical characteristics of the hemostatic membrane but also led to cost reduction. Additionally, the effective combination of nano silver's strong antibacterial properties with chitosan's inherent antibacterial qualities resulted in a dual antibacterial effect that outperformed other materials used for healing purposes. In the study conducted by Lu and colleagues [12], they integrated silver/zinc oxide into a chitosan sponge, which was prepared through lyophilization and intended for use in hemostasis. This composite exhibited notable porosity and swelling characteristics. The results of animal experiments indicated that this composite dressing not only improved coagulation and antibacterial efficacy but also displayed minimal toxicity. Furthermore, the dressing was found to facilitate the process of re-epithelialization and the deposition of collagen. Fatahian et al. [13] produced a hemostatic wound dressing by mixing TXA with PVA. It has investigated blood coagulation properties. According to the study results, PVA-TXA dressings showed acceptable blood clotting capacity.

Epinephrine, commonly known as adrenaline, is a catecholamine hormone with a wide range of functions in the human body's physiology. It is released into the bloodstream when the sympathetic nervous system is activated [14]. Initially, it was thought that adrenaline primarily affected hemostasis by constricting blood vessels [15]. However, subsequent research has revealed that human platelets possess α2A-adrenergic receptors (AR) that are associated with Gz proteins, a subtype of Gi protein [16-18]. When adrenaline binds to these platelet α2-AR receptors, it inhibits the activity of adenylate cyclase (AC), resulting in a decrease in cytosolic cyclic AMP concentration. This reduction in cyclic AMP levels, which acts as a negative regulator of platelet activation, suggests that adrenaline may, in fact, facilitate the platelet activation process and thus contribute to the formation of blood clots (thrombus) [19, 20].

Tranexamic acid is a synthetic compound derived from lysine, and its primary mode of action involves antifibrinolytic effects. It achieves this by obstructing the lysine binding sites found on plasminogen molecules, thereby preventing the interaction between plasminogen, formed plasmin, and fibrin. Consequently, this inhibition of plasminogen activation leads to the stabilization of the pre-existing fibrin network created during the secondary hemostasis process [21]. ABS is an herbal extract that has been traditionally used in Turkey and Bosnia and Herzegovina to treat bleeding. ABS has antibacterial, antiseptic, and antimicrobial properties. Laboratory studies conducted in controlled environments have demonstrated that ABS exhibits effectiveness against a broad spectrum of bacteria, including both Gram-positive and Gram-negative types [22]. It has also displayed efficacy against foodborne pathogens [23], drug-resistant nosocomial (hospital-acquired) pathogens [24], and drug-resistant strains of Tuberculosis. These antimicrobial properties of Ankaferd can be attributed to its chemical composition and ingredients.

The objective of this study was to manufacture a nonwoven nanofiber material suitable for use as a hemostatic wound dressing. In this study, nanofibers possessing hemostatic properties were produced through the electrospinning method, employing ADR, TXA, and ABS as hemostatic agents in combination with PVA polymer. The investigation involved the analysis of the morphology and chemical bonding structures of these hemostatic nanofibers, and the assessment of their hemostatic efficacy.

2. Method and Materials

2.1. Materials

PVA (125,000 MW, 99% hydrolyzed) used in the production of nanofibers, and Glutaraldehyde (GA) (50% aqueous solution) was purchased from Sigma-Aldrich Co. (St. Louis, U.S.A.). ABS was purchased from Trend Teknoloji İlaç A.Ş. (Istanbul, Turkey). TXA, ADR, and medical sterile gauzes were purchased from commercial sources. All reagents were analytical grade and used as received.

2.2. Solution Preparation

PVA solution (12 %, w/w) was prepared by dissolving PVA in pure water under stirring gently at 100 °C until completely dissolved then cooled to room temperature. ADR/PVA, solution was prepared by adding ADR to PVA solution at 50% of the total polymer solution weight. The obtained solution was stirred with a magnetic stirrer at 200 rpm for 2 hours. The same process was done for the TXA and ABS solutions. To improve the spinnability of the ABS/PVA solution 0.01 g of NaCl was added to the PVA solution (12 %, w/w).

2.3.Fabrication of Hemostatic Membranes

The spinning solution was prepared and then moved to a 5 mL syringe with a 20 G stainless steel needle. The distance between the needle and the collector, which was covered with aluminum foil and sterile gauze, was adjusted to 15 cm. The electrospinning process was carried out at room temperature, hemostatic nanofibers were produced at a steady flow rate of 0.8 ml/h and 14 kV. The resulting electrospun fibers were stored for future use and labeled according to the hemostatic agents employed: PVA, ADR/PVA, TXA/PVA, and ABS/PVA.

2.4. Binding Nanofiber Samples to Fabric

Since nanofiber materials are sensitive, they are not expected to have mechanical strength, and therefore mechanical strength tests were not performed. The purpose of combining these materials with nonwoven textile surfaces is to obtain mechanically durable nanofibers. The hemostatic nanofibers obtained within the study were attached to fabric samples using an ultrasonic binding process. The ultrasonic binding procedure was carried out at a speed of 5 m/min at a frequency of 20 kHz. Table 1 summarizes the nanofiber samples utilized in the binding procedures, binding techniques, and fabric properties acquired from the Mogul company.

2.5. Characterization

2.5.1. FESEM

The morphology of the nanofiber samples were analyzed by Field Emission Scanning Electron Microscopes (FESEM). Each sample was coated with a conductive surface gold-palladium (Quorum Q150R). All FESEM images (SUPRA 40VP, Carl Zeiss, Germany) were obtained at 20 kV. Image J software was used to calculate the average diameters of the nanofibers.

2.5.2. FT-IR

The chemical bond structures of hemostatic nanofibers were analyzed by Fourier Transform Infrared Spectrophotometer (IS50 FT-IR, Thermo Scientific, USA) containing Diamond ATR crystal. FT-IR spectra were recorded between 450 and 4000 cm^{-1} with a resolution of 1 cm^{-1}.

2.5.3. Nanofiber samples swelling rate

Since the obtained samples are instantly soluble in water, crosslinking of the samples with GA vapor was carried out. In this context, PVA, ADR/PVA, TXA/PVA and ABS/PVA nanofibers were exposed to GA vapor in a closed container for 24 hours at room temperature. Then the swelling and weight loss percentages of the nanofibers were calculated by soaking them in distilled water for 24 hours, then drying and weighing them. In the first step, nanofiber samples of similar sizes were weighed and noted. In the second step, the nanofiber samples were soaked in distilled water for 24 hours. After that, the samples were taken out, placed on filter paper briefly to eliminate any excess surface water, and then weighed.

Table 1. Nanofiber samples, binding methods and fabrics used in the binding processes

NO	Used fabric layers	Used Nanofiber Sample	Binding Method	Strength of Materials MD* (N/5 cm)	Strength of Materials CD* (N/5 cm)
1	A4 40 gsm spunlace flat Bio-based	PVA	Ultrasonic	95	110
2	A4 40 gsm spunlace flat Bio-based	ADR/PVA	Ultrasonic	95	110
3	A4 40 gsm spunlace flat Bio-based	TXA/PVA	Ultrasonic	95	110
4	A4 40 gsm spunlace flat Bio-based	ABS/PVA	Ultrasonic	95	110

* MD = Machine Direction, CD = Cross Direction

In the third step, the samples were dried at room temperature for 24 hours and weighed again. The measurements were taken three times. In addition, the average and standard deviation values were calculated. The percentage swelling was calculated according to equation 1 and weight loss was calculated according to equation 2.

$$\text{Swelling Percentage (\%)} = \frac{M - M_d}{M_d} \times 100 \quad (1)$$

and

$$\text{Weight Loss (\%)} = \frac{M_i - M_d}{M_i} \times 100 \quad (2)$$

M_i: Initial weight, M: Swollen weight, M_d: Dry weight

2.5.4. Determination of hemostatic nanofibers hemostatic efficiency

Clotting time was calculated using fresh human blood drawn from a volunteer. The drop measurement approach was used in this context, where a drop of blood was deposited on the hemostatic nanofiber samples and the clot formation time was evaluated. For each nanofiber sample, the measurement technique was performed ten times, and the average clotting time was determined. The study was approved by Pamukkale University Noninterventional Clinical Research Ethical Committee
(Decision no: 07, Date: 18.04.2023).

3. Results

3.1. FESEM

The morphology of PVA, ADR/PVA, TXA/PVA, and ABS/PVA was investigated using FESEM images (Figure 1). The average diameter of 30 random fibers was calculated after measuring their diameters. This procedure was followed for all samples. Table 2 shows the minimum, maximum, and the average sizes of the observed nanofibers.

Table 2. Minimum, maximum, and average diameters of hemostatic nanofibers

Sample	Minimum Diameter (nm)	Maximum Diameter (nm)	Average Diameter (nm)	Standard Deviation
PVA	390	1079	605.933	0.1870
ADR/PVA	168	403	251.667	0.0514
TXA/PVA	151	512	226.867	0.0938
ABS/PVA	163	293	226.867	0.0382

3.2. FT-IR

The chemical structures of PVA, ADR/PVA, TXA/PVA and ABS/PVA were characterized using FT-IR spectroscopy. FT-IR spectra of hemostatic nanofiber samples are given in Figure 2.

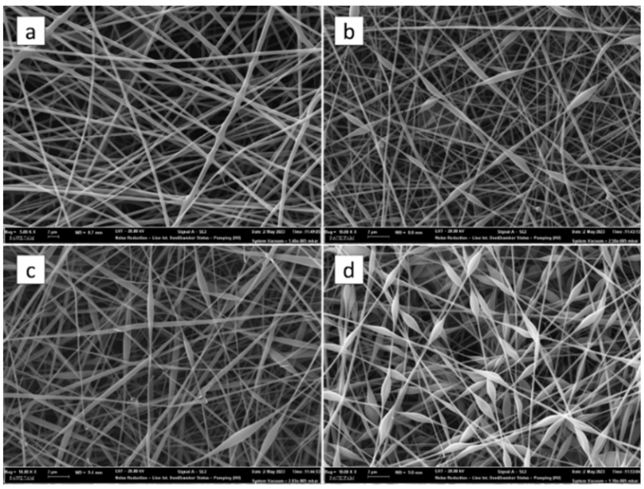

Figure 1. FESEM images of hemostatic nanofibers at 10000X magnification (Scale Bar: 2 µm). a) PVA, b) ADR/PVA, c) TXA/PVA, d) ABS/PVA.

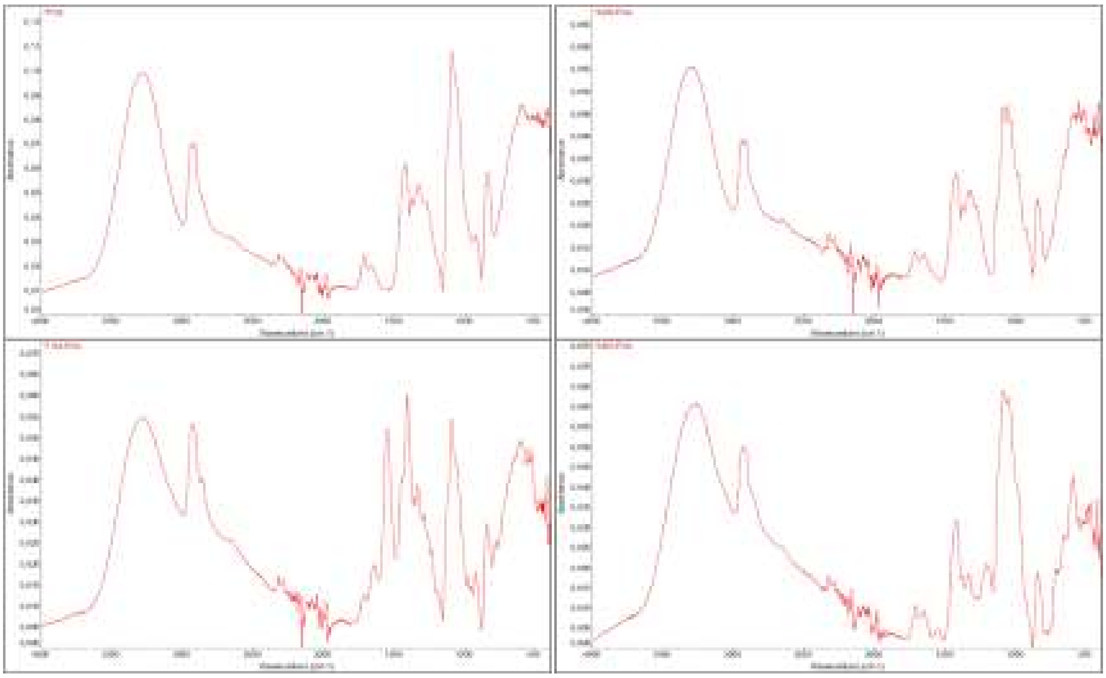

Figure 2.FT-IR spectra of a) PVA, b) ADR/PVA, c) TXA/PVA and d) ABS/PVA nanofiber samples

3.3. Nanofiber Samples Swelling Rate

Figure 3 Shows the swelling ratio and weight loss of the hemostatic nanofiber samples. The average and standard deviation of the starting weight, swollen weight, and dry weight are presented in Table 3.

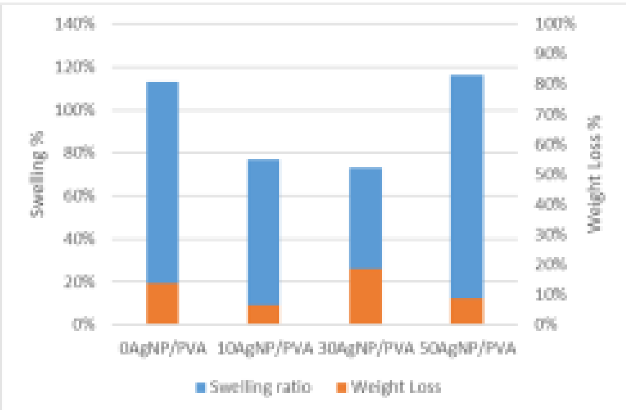

Figure 3. Swelling ratio and weight loss of PVA, ADR/PVA, TXA/PVA and ABS/PVA nanofibers

3.4. Determination of Hemostatic Nanofibers Hemostatic Efficiency

According to the measurements, the clotting times of ADR/PVA and TXA/PVA nanofibers were similar, yet ABS/PVA had a lower clotting time. Table 4 shows the results of the hemostatic activity measuring experiments.

Table 4. Hemostatic activity measurement test results

Sample	Minimum clotting time (sec)	Maximum clotting time (sec)	Average clotting time (sec)
PVA	No clotting was observed	No clotting was observed	No clotting was observed
ADR/PVA	2	6	4.088
TXA/PVA	3	8	4.602
ABS/PVA	2	6	3.819

Table 3. The average and standard deviation of the starting weight, swollen weight, and dry weight of nanofibers samples

	Initial weight (g)		**Swollen weight (g)**		**Dry weight (g)**	
Sample	**Average**	**Standard Deviation**	**Average**	**Standard Deviation**	**Average**	**Standard Deviation**
PVA	0.00493	0.00006	0.00923	0.00045	0.00433	0.00015
ADR/PVA	0.00277	0.00015	0.00460	0.00030	0.00260	0.00010
TXA/PVA	0.00383	0.00015	0.00560	0.00040	0.00323	0.00006
ABS/PVA	0.00537	0.00021	0.01067	0.00115	0.00493	0.00012

4. Discussion

PVA polymer is a hydrophilic, semi-crystalline, semi-crystalline, hydrophilic polymer with high thermal and chemical stability, is generally regarded as safe (GRAS), is non-toxic, and has good thermal and chemical stability, according to the literature. It is extensively utilized in electrospinning systems because of its great biocompatibility and inexpensive cost [25, 26]. As a result, PVA polymer was chosen for the fabrication of hemostatic nanofibers.

According to the FESEM images, beaded fibers started to form with the addition of ADR, TXA and ABS. ABS/PVA and TXA/PVA nanofibers had the same average nanofiber diameter, yet ABS/PVA had more beaded morphology than TXA/PVA.

Figure 2a shows the FTIR spectrum of PVA nanofibers. The absorption bands seen in the spectrum of PVA nanofibers are as follows: The peak at 3272 cm^{-1} refers to the stretching vibration due to the O-H group. The 2913 cm^{-1} and 1332 cm^{-1} bands show symmetric stretching vibration of -CH_2 group, 1710 cm^{-1} and 1649 cm^{-1} bands show C=O stretching vibration, 1420 cm^{-1} band shows CH_2 bending vibration, 1086 cm-1 band shows C-O stretching vibration, and 839 cm^{-1} band shows C-C stretching vibration. These results agree with previous studies in literature [27-33].

Figure 2b shows the FTIR spectrum of ADR/PVA nanofibers. The peak observed at 3400 cm^{-1} in the spectrum can be ascribed to the N-H bonds present in epinephrine. Furthermore, the presence of ADR (presumably adrenaline) appears to enhance the vibration at 3282 cm^{-1}, which corresponds to the O–H bond. It's worth noting that the absorbance in the 3282 cm^{-1} region may also be attributed to the benzene structure present in epinephrine [34, 35].

Figure 2c shows the FTIR spectrum of TXA/PVA nanofibers. In the PVA spectrum, the primary vibrational modes arise from the hydroxyl and acetate groups. To be more specific, the peak observed at 3296 cm^{-1} corresponds to the stretching of O–H bonds, while the peak at 2923 cm^{-1} results from the asymmetric stretching vibration of alkyl groups' C–H bonds. On the other hand, in the TXA spectrum, we observe peaks at 1450 cm^{-1} (methylene group), 1532 cm^{-1} (indicative of the presence of carbonyl groups), and 2858 cm^{-1} (associated with C–H stretching vibrations) [36]. Figure 2d shows the FTIR spectrum of ABS/PVA nanofibers. In the interpretation of the spectrum of ABS/PVA samples, the FTIR peaks formed by ABS content [37] were analyzed. The peak at 2937 cm-1 can be attributed to the aliphatic CH_3 – CH_2 stretching vibration [38]. 2918 cm^{-1} can be attributed to the stretching vibration, 1333 cm^{-1} can be attributed to NO_2, and 1085 cm^{-1} peak can be attributed to C-F stretching vibration [39]. The characteristic indications of Thymus Vulgaris include the bending of O-H groups within the range of 1340-1255 cm^{-1}, the absorption peak associated with C-OH stretching at 1053 cm^{-1}, and peaks attributed to the out-of-plane bending of O-H groups in the region between 736-590 cm^{-1} [40]. These peaks overlap with the peaks formed by *Timus vulgaris*, *Glycyrrhiza glabra*, *Vitis vinifera*, *Alpinia officinarum* and *Urtica dioica* in ABS [40-48].

The swelling characteristics of PVA, ADR/PVA, TXA/PVA, and ABS/PVA samples were examined by immersing the nanofiber membrane in distilled water for a 24-hour period. TXA/PVA displayed the lowest swelling ratio, at 73%, while ABS/PVA exhibited the highest swelling ratio, reaching 118%. The reduction in PVA concentration due to an increase in the concentration of hemostatic agents led to the production of thinner fibers. Notably, thinner fibers demonstrated reduced swelling properties. TXA/PVA nanofibers showed a greater weight loss compared to PVA, ADR/PVA, and ABS/PVA nanofibers. Overall, all the samples underwent successful crosslinking with glutaraldehyde vapor, and no significant weight loss was observed.

Hemostasis is a mechanism that prevents excessive blood loss after vascular injury and keeps the physiological process that regulates blood fluidity in check while also preventing blood from coagulating. Primary and secondary hemostasis are two types of hemostasis. Primary hemostasis takes about 4 to 7 minutes and deals with the body's initial reactions to the injury [49,50]. Mucocutaneous bleeding (petechiae, epistaxis, gingival bleeding, hematuria, and menorrhagia) and severe bleeding after trauma or incisions are frequent in diseases that affect primary hemostasis. Local control of bleeding is essential and beneficial in primary hemostasis disorders. This can be achieved by exerting pressure on the bleeding area and applying local hemostatic agents like tranexamic acid, adrenalin, and ABS [51,52].

Since nanofiber materials are sensitive, they are not expected to have mechanical strength. The hemostatic nanofibers were adhered to nonwoven textiles thus mechanically durable nanofiber surfaces were obtained. The ultrasonic binding process preserved the suppleness of the samples. However, the layers can separate if they are forced. The nonwoven fabrics did not affect the hemostatic activity of the nanofibers since they were adhered only to one side. The hemostatic activity of the obtained nanofibers was evaluated. In this context, tests were performed using the drop measurement technique. According to the results ADR/PVA had the longest clotting time with 4.088 second while ABS/PVA had the shortest clotting time with 3.819 second.

There are currently various hemostatic agents available for achieving rapid hemostasis. Adrenaline, an adrenergic substance, can be applied directly to the bleeding site to assist in controlling bleeding. When administered in low doses, adrenaline activates the coagulation system and may help reduce bleeding during surgery and in the immediate postoperative period. Adrenaline works by stimulating receptors on the mucous membrane, leading to local vasoconstriction (53). Another hemostatic option is ABS, which is a standardized mixture containing five different plant extracts: *Vitis vinifera*, *Thymus vulgaris*, *Glycyrrhiza glabra*, *Alpinia officinarum*, and *Urtica dioica*. ABS achieves its hemostatic effect by creating an encapsulated protein network that promotes the essential physiological aggregation of erythrocytes, all without interfering with the normal coagulation processes of individuals. ABS is used effectively in medical settings on patients with primary and secondary hemorrhagic diathesis [53]. In a study done by Badovinac et al., TXA was found to be just as effective as adrenaline in managing severe endobronchial hemorrhage [54]. In an animal experiment, it was shown that ABS stopped epistaxis more quickly than gelatin foam, adrenaline + lidocaine, and serum physiologic as negative control [55]. In accordance with these results, our study found that ADR/PVA and TXA/PVA nanofibers had nearly similar clotting times, but ABS/PVA had a quicker clotting effect.

Nanofibers have shown great promise in the field of hemostasis due to their structural similarity to fibrin clots. Extensive research has been conducted over the past two decades to develop various manufacturing processes for the creation of nanofibrous materials that can be used for both external and intracavitary hemostatic control. The ideal hemostat for in vivo applications should clot blood quickly, be biocompatible and biodegradable, not carry the risk of bacterial or viral contamination, and promote wound healing. Furthermore, good hemostats should stop bleeding in in vitro applications within 2 minutes after administration to the wound site, should not require mixing or prior preparation, and should be simple to administer to injured regions [56]. The hemostatic nanofibers obtained in this study showed the ability to form clots within seconds. The behavior of the obtained hemostatic nanofibers under different conditions needs to be investigated. These additional tests are planned for future research. The developed nanofibers will have a strong added value effect not only in terms of public health but also in survival processes.

Nanofibers have shown great promise in the field of hemostasis due to their structural similarity to fibrin clots. Extensive research has been conducted over the past two decades to develop various manufacturing processes for the creation of nanofibrous materials that can be used for both external and intracavitary hemostatic control. The ideal hemostat for in vivo applications should clot blood quickly, be biocompatible and biodegradable, not carry the risk of bacterial or viral contamination, and promote wound healing. Furthermore, good hemostats should stop bleeding in in vitro applications within 2 minutes after administration to the wound site, should not require mixing or prior preparation, and should be simple to administer to injured regions [56]. The hemostatic nanofibers obtained in this study showed the ability to form clots within seconds. The behavior of the obtained hemostatic nanofibers under different conditions needs to be investigated. Additional optimization studies are planned for future research. The developed nanofibers will have a strong added value effect not only in terms of public health but also in survival processes.

Conflict of Interest

No conflict of interest was declared by the authors.

Financial Disclosure

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Kültür Mantarından (*Agaricus bisporus*) İzole Edilen Kitosanın Hemostatik ve Antimikrobiyal Yara Örtüsünde Kullanımın Araştırılması

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Özet

Bu çalışmada, Agaricus bisporus'tan kitosanı izole ederek elde edilen kitosanın yara örtüsünde kullanmak üzere antimikrobiyal ve hemostatik aktiviteleri araştırılması hedeflenmiştir. Bu çalışmada Agaricus bisporus kültür mantarına demineralizasyon işlemi ve ardından deproteinizasyon işlemi uygulayarak kitin elde edilmiştir. Elde edilen kitine deasetilasyon işlemi uygulayarak kitosan elde edilmiştir. Elde edilen kitosanın morfolojisi, kimyasal yapı ve deasetilasyon derecesi araştırılmıştır. Çalışma kapsamında antimikrobiyal edilen kitosanın Gram negatif ve Gram pozitif bakterilere karşı antimikrobiyal özelliği araştırılmıştır. Elde edilen kitosanın hemostatik aktivitesi araştırılmış ve kanamayı durdurmak için geçen süreyi belirlenmiştir. FE-SEM ile elde edilen morfoloji analiz sonuçlarına göre kitosanın yüzey morfolojisi amorf yapıya sahiptir. FT-IR spektroskopisi ile elde edilen kimyasal analiz sonuçlarında, kitosan için karakteristik pikler olan amid I bandının ve amid II'nin sırasıyla 1633 cm-1 ve 1558 cm-1 absorpsiyon bantları gözlemlenmiştir. Antimikrobiyal test sonuçlarına göre, Gram negatif ve Gram pozitif bakterilere karşı duyarlılık göstermiştir. Bununla birlikte elde edilen kitosan üzerine kan damlası bırakılarak pıhtı oluşum süresi 5 ve 14 saniye aralığında olduğu belirlenmiştir. Agaricus bisporus'tan elde edilen kitosan, antibakteriyel ve hemostatik özellikleriyle yara örtülerinin üretiminde ve biyomedikal uygulamalarda önemli bir bileşen olma potansiyeline sahiptir.

The Use of Chitosan Extracted from Grown Mushrooms (*Agaricus bisporus*) in Hemostatic and Antibacterial Wound Dressing

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Abstract

The objective of this study was to examine the antimicrobial and hemostatic properties of chitosan derived from Agaricus bisporus, with the intention of utilizing it in wound dressings. This study involved the extraction of chitin from Agaricus bisporus mushrooms through demineralization and deproteinization techniques. The resulting chitin was then subjected to deacetylation to obtain chitosan. The morphology, chemical structure, and degree of deacetylation of the chitosan were examined. Furthermore, the antimicrobial efficacy of the chitosan was evaluated against both Gram-negative and Gram-positive bacteria. The study also investigated the hemostatic properties of the chitosan by determining the time required for bleeding cessation. Based on the morphology analysis using FE-SEM, it was found that the surface structure of the chitosan exhibited an amorphous nature. The chemical analysis using FT-IR spectroscopy revealed characteristic peaks for chitosan, specifically the absorption bands at 1633 cm-1 and 1558 cm-1, corresponding to the amide I and amide II bands, respectively. The antimicrobial testing demonstrated the chitosan's effectiveness against both Gram-negative and Gram-positive bacteria. Moreover, upon applying a drop of blood to the chitosan surface, it was observed that clot formation occurred within a timeframe ranging from 5 to 14 seconds. Chitosan obtained from Agaricus bisporus, with its antibacterial and hemostatic qualities, holds potential as a key component in the manufacture of wound dressings and biomedical applications.

1. Giriş

Kitin, böceklerin, yengeçlerin, karideslerin ve ıstakozların dış iskeletinde, karidesler ve böcekler gibi diğer omurgasızların iç yapısında, ayrıca mantarların ve mayaların hücre duvarında bulunan sert, elastik olmayan ve beyaz bir polisakkarittir. Kitin, selülozdan sonra en bol bulunan ikinci biyopolimerdir [1]. Kitin, β (1-4) glikozidik bağlantı ile birleştirilmiş n-asetil-d-glukozamin doğrusal bir polimerdir: (1 → 4, 2-asetamid-2-deoksi-β-D-glukan) ve α, β ve γ olmak üzere üç farklı polimerik formu vardır [1-4]. Kitosan, rastgele β-(1-4) D-glukozamin (deasetillenmiş birim) dağılmış zincirleri ve kitin deasetilasyonu olarak bilinen bir süreçten gelen n-asetil-d-glukozamin (asetillenmiş birim) tarafından oluşturulan doğrusal bir polisakkarittir [4]. Kitin, kimyasal olarak su, alkoller, aseton, hekzan gibi yaygın çözücülerde çözünmemektedir. Bu nedenle kitin inert bir malzeme olarak kabul edilen bir maddedir. Ancak, kitosan, bazı asitlerin sulu çözeltilerinde çözülebilme yeteneği sayesinde daha reaktif bir biyopolimer olarak kabul edilir. Bu özelliği nedeniyle günümüzde birçok çalışma ve uygulama fırsatlarına sahiptir, bu da farklı alanlarda çeşitli uygulamaların sayısının artmasına yol açmıştır [4-6]. Bu durum kitosanı kitinden daha çok kullanılan bir ürün haline getirmiştir, bunun ana nedeni kitosanın işlevselliği ve çözünürleştirme kolaylığıdır. Bu özellikler kitosanın çeşitli şekillerde dönüşüme açık olmasını mümkün kılmaktadır [1]. Kitosan, antimikrobiyal, antifungal ve antiviral aktiviteler, biyouyumluluk, biyobozunur, emülsifiye etme, yağ emme, kirletici metalleri adsorbe etme ve filmojenik olmak gibi özelliklere sahiptir. Bu nedenle kitosanın çeşitli endüstriyel alanlarda geniş kapsamlı uygulamalara sahip olduğu düşünülmektedir [7]. Literatürde kitosanı izole etmek için kullanılan çeşitli teknikler rapor edilmiştir, çoğunlukla balıkçılık endüstrisinde elde edilen kaynağın özelliklerine bağlıdır. Bununla birlikte, iyi kitin ve kitosan kaynakları olarak kabul edilebilecek çeşitli alg ve mantarlardan kitosan izole etmek mümkündür. Günümüzde mantarlar, daha yüksek saflıkta ve daha iyi kalitede kitosan üretimi için ilginç bir alternatif kaynak olarak kabul edilmektedir [8, 9]. Aslında, mantarlardan elde edilen biyokütlenin kullanımı, kitin ve kitosanın büyük ölçekte eşzamanlı olarak ekstraksiyonu, yıl boyunca bulunabilirlik gibi çeşitli avantajlara sahiptir. Bunun yanı sıra, ekstraksiyon işlemi kabuklu deniz ürünlerinin ekstraksiyon işlemlerine göre daha ekonomik, kullanımı kolay ve zaman açısından daha verimlidir [10, 11]. Mantarladan kitin ve kitosan elde etmek için kullanılan yöntemler oldukça benzerdir [12]. Genel olarak, kitin ve kitosan elde etme işlemleri birbirini takip eden şu aşamalarla gerçekleştirilir: (1) Hammaddenin hazırlanması, (2) Protein ekstraksiyonu (deproteinasyon), (3) İnorganik safsızlıkların giderilmesi (demineralizasyon) (mantarlardan kitin ekstraksiyonunda gerekli olmayan bir aşamadır), (4) Elde edilen kitinin renginin bozulması ve (5) Kitin deasetilasyonu. Kitinin ekstraksiyonunu takiben, kitin kitosana dönüştürme aşamaları gerçekleşmektedir. Bu da kimyasal süreçler veya mikrobiyolojik fermantasyon reaksiyonları ve enzimatik reaksiyonlar dahil olmak üzere biyolojik yöntemlerle yapılabilmektedir. Ancak biyolojik yöntemler iyi verim sağlamazlar ve henüz ekonomik olarak uygun değillerdir [12].

Bu çalışmada *Agaricus bisporus* mantarından elde edilen kitosan, sürdürülebilir ve ekonomik bir üretim sürecini göstererek biyopolimer üretiminde yenilikçi bir adım sunmaktadır. Aynı zamanda, antimikrobiyal aktivite ve hemostatik özellikleri tıbbi alanlarda kitosanın potansiyelini vurgulanmaktadır. Bu çalışma kapsamında *Agaricus bisporus*'a demineralizasyon ve deproteinizasyon işlemleri uygulandıktan sonra kitin elde edilmiştir. Kitinin deasetilasyonu sonucunda kitosan sentezlenmiştir. Elde edilen kitosanın özellikleri FE-SEM ve FT-IR spektroskopisi kullanılarak karakterize edilmiştir. Elde edilen kitosanın antibakteriyel ve hemostatik aktivitesi, yara örtülerinin geliştirilmesinde ve biyotıp uygulamalarında hammadde olarak kullanımını doğrulamak amacıyla değerlendirilmiştir.

2. Malzeme ve Yöntem

2.1. Gereç

Taze *Agaricus bisporus* mantarları marketten (Denizli, Türkiye) satın alınmıştır. Sodyum hidroksit çözeltisi ve hidroklorik asit çözeltisi Sigma Aldrich'ten (St Louis, A.B.D.) tedarik edilmiştir. Kullanılan tüm reaktifler yüksek saflık derecesine sahiptir ve tüm reaktif çözeltileri için deiyonize su kullanılmıştır.

2.2. Kitin İzolasyonu

Daha önce literatürde rapor edildiği gibi kitin izole edilmiştir [13]. Kültür mantarı şebeke su ile yıkanarak blenderde parçalanmış ve yaklaşık 10 gün oda sıcaklığında kurutulmuştur. Demineralizasyon basamağında numune 1:20 (g/mL) oranında 0.5 M HCl çözeltisine eklenmiştir. Daha sonra 500 rpm'de 15 dakika 50 oC'de karıştırılarak distile su ile nötr olana kadar yıkanmıştır. Mantarlarda düşük oranda mineral bulunduğu için kısa süreli ve düşük konsantrasyonlu HCl çözeltisi uygulanarak mineral içeriğinden arındırılmıştır. Elde edilen numune 7 gün oda sıcaklığında kurutulmuştur. Minerallerinden ayrıştırılan numunenin yapısındaki proteini uzaklaştırmak için 2 M NaOH 1:20 (g/mL) oranında 4 saat 80 ^{o}C'de 700 rpm ile karıştırılmıştır. Ardından distile su ile yıkanmıştır ve 7 gün boyunca oda sıcaklığında kurutulmuştur.

2.3. Kitin Deasetilasyon Prosedürü

Kitinin deasetilasyon prosedüründe yapılan işlemler daha önce literatürde rapor edilmiştir [14]. Elde edilen kitin ve % 60 NaOH 1:10 (g/mL) oranında, 700 rpm 90 ^{o}C'de 4 saat karıştırıldıktan sonra distile su ile nötr olana kadar yıkanmıştır ve 7 gün boyunca oda sıcaklığında kurutulmuştur.

2.4. Karakterizasyon

2.4.1.Alan emisyonlu taramalı elektron mikroskobu (FESEM)

Elde edilen toz kitosan numunelerin görüntü analizleri alan emisyonlu taramalı elektron mikroskobu (Field Emission Scanning Electron Microscopes, FESEM) ile yapılmıştır. Her bir numune altın-paladyum ile kaplanmıştır (Quorum Q150R). Tüm FESEM (SUPRA 40VP, Carl Zeiss, Almanya) görüntüleri 20 kV'ta alınmıştır. 10000X büyütme oranları ile çalışılmıştır.

2.4.2. Fourier dönüşümlü kızılötesi spektroskopisi (FT-IR)

Elde edilen kitosan numunelerin kimyasal bağ yapıları, Diamond ATR kristali içeren Fourier Dönüşümlü Infrared Spektrofotometresi (IS50 FT-IR, Thermo Scientific, ABD) ile analiz edilmiştir. FT-IR spektrumları 450 ile 4000 cm^{-1} arasında 1 cm^{-1} çözünürlük ile kaydedilmiştir.

2.4.3. Deasetilasyon derecesi (DD)

Numunenin deasetilasyon oranı FTIR spektrumu ile elde edilmiştir. Bu spektroskopik teknik, bazı amid bantlarını (I-III) ve kullanılan potasyum bromür peletinin kalınlığını düzeltmek için bir iç referans gibi başka bir bandı içeren bazı absorbans bantlarının korelasyonu yoluyla DD belirlenmesini sağlamaktadır. 1633 ve 3282 cm^{-1}'deki amid I ve -OH gerilme titreşimi bantlarının absorbans oranlarına göre kitosanın DD aşağıdaki formül (1) kullanılarak hesaplanmıştır [15, 16].

$$\%DD = 97.67 - (26.486\frac{A_{1633}}{A_{3282}}) \quad (1)$$

Burada A_{1633}, N- asetil grubu amid I bandının absorbans değeridir. A3282 ise hidroksil grubundan kaynaklanan O-H gerilme titreşim bandının absorbans değeridir.

2.4.4. Kitosan numunelerin antimikrobiyal etkisi belirlenmesi

Antimikrobiyal testleri kapsamında Mueller Hinton Agar üzerine hazırlanmış bakterilerden 8 log kob/mL stok hazırlanarak 100 µL agar yüzeyine aktarılarak drigalski spatülü ile yayılmıştır (Tablo 1). Bu kapsamda toz formunda hazırlanan kitosan numuneleri yüzeye konulmuştur ve 37°C'de 24 saat inkübe edilmiştir.

Tablo 1. Antimikrobiyal testinde kullanılan bakteri kültürleri

Bakteri Suşu	Gram Türü	ATCC NO
Escherichia coli	Gram Negatif	25922
Klebsiella pneumoniae	Gram Negatif	700603
Pseudomonas aeruginosa	Gram Negatif	27853
Staphylococcus aureus	Gram Pozitif	25923
Bacillus subtilis	Gram Pozitif	6633
Listeria monocytogenes	Gram Pozitif	19115

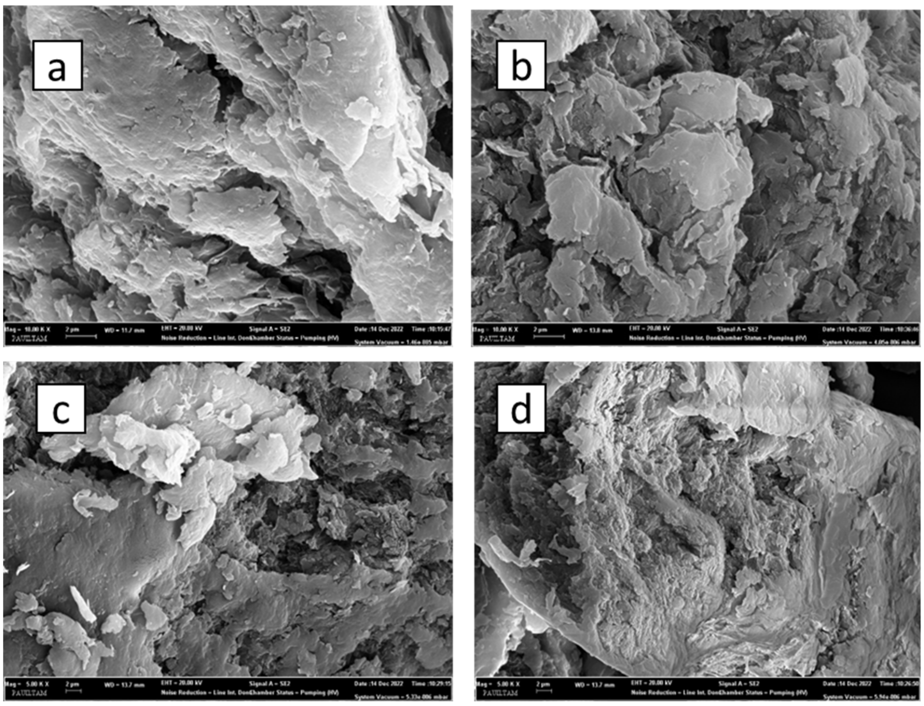
2.4.5. Kitosan numunelerinde hemostatik aktivite belirlenmesi

Çalışma kapsamında gönüllü olarak katılan bir kişiden alınan kan ile pıhtılaşma süresi belirlenmiştir. Damlama ölçüm tekniği kullanılarak birer kan damlası toz kitosan ve kitosan ile hazırlanan yara örtüsü üzerinde pıhtı oluşumu izlenerek pıhtılaşma süreleri kayıt altına alınmıştır.

3. Sonuçlar

3.1. Morfolojik Analiz Sonuçları

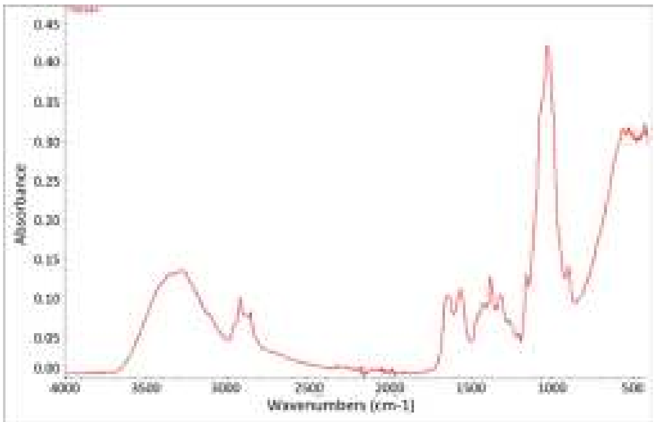
Agaricus bisporus 'tan elde edilen kitosanın FE-SEM görüntüsünde bazı bölgelerde parça parça bulut şeklinde (Şekil 1a, Şekil 1b) bazı bölgelerde yassı yüzeyinin bulunduğu görülmektedir (Şekil 1c, Şekil 1d). Ayrıca yüzey morfolojisi amorf yapıya sahiptir.



Şekil 1. Kitosan numunelerine ait FESEM görüntüleri (scale bar: 2 µm). a) bulut şeklinde bulunan kitosan örneği. b) bulut şeklinde bulunan kitosan örneği. c) yassı bulut şeklinde bulunan kitosan örneği. d) yassı bulut şeklinde bulunan kitosan örneği

3.2. Kimyasal Analiz Sonuçları

Elde edilen numunenin kimyasal yapıları, FT-IR spektroskopisi kullanılarak karakterize edilmiştir (Şekil 2, Tablo 2).



Şekil 2. Kitosan numunesine ait FT-IR spektrumu

Tablo 2. Kitosana ait önemli ATR-FT-IR absorbans bant değerleri

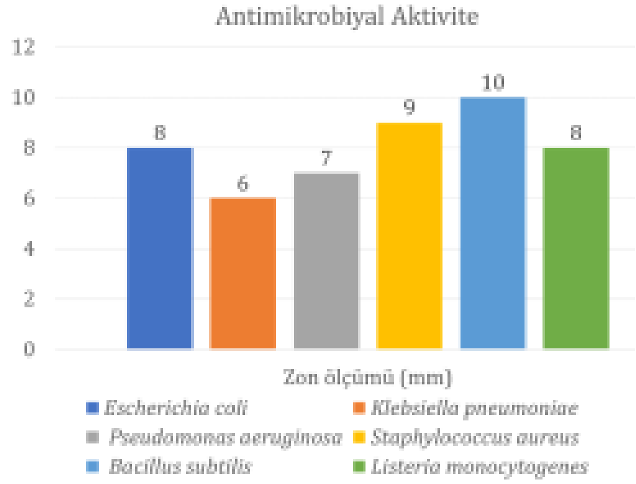
Dalga Sayısı (cm-1)	**Absorbans bantları**
3282	Birincil aminlerde (NH2) gerilme ve piranoz halkasında (OH) gerilme
2918	CH2OH grubunda (CH2) asimetrik gerilme titreşimi
2850	Piranoz halkasında (C-H) gerilmes
1633	NHCOCH3 grubunda (C=O) gerilme (Amid I bandı)
1558	NHCOCH3 grubunda (NH2) gerilme (Amid II bandı)
1152	(C-O-C) asimetrik gerilme (glikozidik bağ)
1024	İkincil OH grubunda (C-O) gerilme
896	Piranoz halka iskeleti titreşimleri

3.3. Deasetilasyon Derecesi (DD)

Kitosanın FTIR spektrumunda amid I bandının (~1633 cm^{-1}) absorbans değeri ve -OH gerilme bandının (~3282cm^{-1}) absorbans değerleri sırasıyla 0,11164 ve 0,13462 olarak tespit edilerek denklem (1) de yerine yazarak deasetilasyon derecesi hesaplanmıştır. Bu kapsamda sentezlenen kitosanın DD'si %75,70 olarak belirlenmiştir.

3.4. Antimikrobiyal Aktivite Test Sonuçları

Yapılan analizde, incelenen tüm bakteri suşlarının kitosana duyarlı olduğu gözlemlenmiştir. Antimikrobiyal test sonuçlarına göre, *Escherichia coli*, *Klebsiella pneumoniae*, *Pseudomonas aeruginosa, Staphylococcus aureus, Bacillus subtilis* ve *Listeria monocytogenes* suşları, kitosana karşı duyarlılık göstermiştir (Şekil 3). Bu bulgular, test edilen kitosan bu belirli bakteri suşlarına karşı etkili olduğunu ve potansiyel tedavi seçenekleri olarak kullanılabileceğini göstermektedir.



Şekil 3. Kitosanın Gram negatif ve Gram pozitif bakterilere karşı antimikrobiyal etkisi

Suşlar içerisinde; *Klebsiella pneumoniae* etrafında belirgin şekilde oluşan zonları, elde edilen kitosanın antimikrobiyal aktiviteye sahip olduğunu göstermiştir (Şekil 4).

Şekil 4. Kitosan numunenin *Klebsiella pneumoniae* üzerindeki antimikrobiyal etkisi ve inhibisyon bölgesi ölçümü

Yapılan çalışmada, antibiyotikler, yani amoksisilin, seftriakson ve sefotaksim, *E. coli* üzerinde agar plakalarında test edilmiştir. Bu antibiyotikleri içeren disklerin çevresindeki inhibisyon bölgeleri sırasıyla yaklaşık 18 mm, 22 mm ve 20 mm ölçülmüştür. Ayrıca, kitosan, etrafında yaklaşık 8 mm ölçülen bir inhibisyon bölgesi sergilemiştir. Bu bulgular, bu varsayımsal senaryoda, seftriakson'un *E. coli*'nin büyümediği en geniş alanı gösterdiğini, onu yakından gentamisin ve amoksisilin izlediğini göstermektedir. Kitosan, etkili olmasına rağmen, deneyde bu antibiyotiklere göre daha küçük bir inhibisyon bölgesine sahip olduğu görünürmüştür.

3.5. Hemostatik Aktivite Ölçüm Sonuçları

Taze insan kanı ile pıhtılaşma damlama ölçüm tekniği kullanılarak pıhtı oluşumu izlenerek süresi belirlenmiştir. Toz kitosan üzerine kan damlası bırakılarak pıhtı oluşum süresi 5 ve 14 saniye aralığında olduğu belirlenmiştir.

4. Tartışma

Kitin deniz kabuklularında (yengeç, karides gibi), kelebek kanatlarında, arı gibi böceklerin kabuklarında, mikroorganizma ve mantarlarda bulunmaktadır. Bu çalışma kapsamında *Agaricus bisporus* kullanma nedenlerinden biri ülkemizde seralarda ve organik atıkların geri dönüşümü ile yetiştirilen, yenilebilir bir mantar olmasıdır. Kitin ve kitosanın ticari olarak piyasada karides, yengeç ve kerevit gibi canlıların kabuk yapısının işlenmesinden sonra elde edilmektedir.

Mantar ve mikroorganizmalardan elde edilen kitin ile kabuklu canlılardan elde edilen kitin arasındaki fark, kabuklulardan kitin elde edilirken mevsimsel ve bölgesel farklılıkların ve kalsiyum karbonat ile diğer minerallerin uzaklaştırılması için ağır asit işlemine ihtiyaç duyulmasıdır. Mantarlarda, minerallerin kabuklulara göre daha düşük olduğu için demineralizasyon aşaması genellikle ihmal edilebilir [17]. Ancak, bu çalışmada, kitosanın yüksek saflık oranına sahip olması için düşük konsantrasyonda HCl kullanarak demineralizasyon aşaması gerçekleştirilmiştir.

Bu çalışmada *Agaricus bisporus* 'a demineralizasyon ve deproteinizasyon işlemleri uygulandıktan sonra kitin elde edilmiştir. Kitinin deasetilasyonu sonucunda kitosan sentezlenmiştir. Elde edilen kitosanın karakterizasyonu için FE-SEM ve FT-IR spektroskopisi ile gerçekleştirilmiştir. Elde edilen kitosanın antibakteriyel ve hemostatik aktivitesi, yara örtülerinin geliştirilmesinde ve biyotıp uygulamalarında hammadde olarak kullanımını doğrulamak amacıyla değerlendirilmiştir.
Son araştırmalar, kitosanın belirli bir alanda etkin bir şekilde kullanılmasında yüzey morfolojisinin önemli bir faktör olduğunu göstermektedir.

Kitosanın yüzey morfolojisi organizmalara göre değişmektedir. Genel olarak kitosan üç yüzey morfolojisine ayrılabilir: (1) gözenekli ve mikrofibriler yapılı, (2) gözeneksiz veya mikrofibriler yapılı ve (3) sadece mikrofibriler yapıya sahiptir. Metapenaeus stebbingi (karides) kitosanı [18] ve ipekböceği krizaliti kitin ve kitosan [19] yapıları hem mikrofibril hem de gözenekli yapılar göstermektedir. Bazı çalışmalar [20, 21] mantar kitininin mikrofibril yapısına sahip olduğunu gösterse de Yen ve Mau tarafından incelenen mantar kitini ve kitosan yapıları mikrofibril veya gözenekli yapılar göstermemiştir [22]. Bu çalışmada, kitosan yüzey morfolojisi mikrofibril veya gözenekli yapı göstermemiştir.

Kitosan numunenin kimyasal yapısı, FT-IR spektroskopisi kullanılarak karakterize edilmiştir. Bu kapsamda kitosanın FTIR spektrumunda, kitosan için karakteristik pikler olan amid I bandının ((C=O)'nun gerilmesi) ve amid II'nin ((NH2)'nin gerilmesi) sırasıyla 1633 cm^{-1} [23] ve 1558 cm^{-1} [24] absorpsiyon bantları gözlemlenmiştir. Kitosan tipik olarak kitinin kısmi deasetilasyonu ile elde edilmektedir. Elde edilen kitosan, N-asetilglukozamin birimleri ve D-glukozamin birimlerinden oluşan bir akopolimerdir. Deasetilasyon derecesi kitosanı karakterize eden ana parametrelerden biridir. Düşük DD sahip olan kitosanın yüksek DD sahip kitosanlara göre polimerlerinin hızlı parçalanması ve akut inflamasyonu uyarmada daha etkili olduğu bildirilmiştir [25].

Hattori ve Ishihara tarafından yapılan bir çalışmada, kitosanın %75 ila %88 arasındaki deasetilasyon derecesine sahip olanlar, platelet-rich plasma (PRP) içinde tam kan, yıkanmış eritrositler ve trombositlerin en yüksek düzeyde agregasyon göstermiştir [26]. Ospina ve ark., *Ganoderma lucidum* mantarından elde ettiği kitinleri iki farklı deasetilasyon protokolü uygulayarak ilk protokol için %80,14 ikinci protokol için %80,29 olarak deasetilasyon dereceleri elde etmiştir [27]. Bu çalışma kapsamında sentezlenen kitosanın DD'si %75,70 olarak bulunmuştur. Bu sonuçlar çalışmamızdaki elde edilen sonuçlarla örtüşmektedir. Doğal bir antimikrobiyal ajan olarak kitosan, tarım, gıda ve biyomedikal alanlarda uygulanmaktadır. Kitosan ile muamele edilmiş mikroorganizmalarda yapılan transkriptomik analizler ayrıca kitosanın bakteri veya mantarlara karşı etki şeklinin çoklu hücre içi ve hücre dışı etkilere sahip olabileceği sonucuna varmıştır. Kitosan umut vaat eden büyük bir antimikrobiyal potansiyel gösterse de bu çalışmaların çoğu hala laboratuvar düzeyindedir [28]. *Agaricus bisporus* 'tan elde edilen kitosanın antimikrobiyal aktivite testi tayininde disk difüzyon yöntemiyle, numune çevresinin bakteriye karşı inhibisyon alanı oluşturmasıyla tespit edilmiştir. Numunenin altında üreme olması, 1 ve 0 mm arasında zon oluşması ve 1mm'den yüksek zon oluşması antimikrobiyal aktivitenin var olduğu değerlendirilmiştir. Antimikrobiyal testleri kapsamında *Escherichia coli, Klebsiella pneumoniae, Pseudomonas aeruginosa, Staphylococcus aureus, Bacillus subtilis* ve *Listeria monocytogenes* suşları, kullanılmıştır. Kullanılan bakteriler etrafında belirgin şekilde oluşan zonları, elde edilen kitosanın antimikrobiyal aktiviteye sahip olduğunu göstermiştir. Mantarlardan ve deniz kabuklularından elde edilen kitosanın antimikrobiyal özelliği karşılaştırılan çalışmalarda mantar kaynağından sentezlenen kitosanın daha yüksek antimikrobiyal aktiviteye sahip olduğu bildirilmiştir [29].

Hemostatik materyal olarak alkillenmiş kitosan integral aktivasyon üzerindeki etkisi ve trombüsün oluşum süresi gibi keşfedilmesi gereken bazı problemlere sahiptir. Kitosanın kendisi pozitif bir yüke sahiptir; Pozitif yükün alkilasyondan sonra zayıflayıp zayıflamayacağına ait veriler sınırlıdır. Alkillenmiş kitosanın sentezinde genellikle çok fazla organik çözücü kullanılır, bu da çevreye çok zarar verebilmektedir ve müteakip sanayileşmeyi engellemektedir. Ancak elde edilen hemostatik etki ve antimikrobiyal etki seçkin ve belirgindir. Bu kapsamda üretim teknolojilerinin daha yeşil yaklaşımda olması bu ürünün hemostatik olarak kullanımının da önünü açmaktadır [30].

Misgav ve ark. kronik hemodiyaliz hastalarında iğne çıkarıldıktan sonra gazlı bez ve kitosan bazlı ped karşılaştırdığı çalışmada arteriyel giriş bölgesinde kanama durdurma süresi, 18,5 dakikadan 3 dakikaya ve damar girişiminde 13,2 dakikadan 2,8 dakikaya düştüğünü gözlemlemişler [31]. Dowling ve ark. kitosanın hidrofobik olarak modifiye ederek gerçekleştirdikleri çalışmada sıçan femoral ven kesisin de kanama süresini %90 azalma gözlemlemiştir [32].

Bu çalışma kapsamında elde edilen kitosanın hemostatik aktivitesini değerlendirilmiştir. Elde edilen sonuçlara göre kitosan üzerine kan damlası bırakılarak pıhtı oluşum süresi sırasıyla 5 saniye ve 14 saniye aralığında olduğu belirlenmiştir. In vitro uygulamalarda hemostatik ajanlar uygulandıktan 2 dk sonra kanamayı durdurmalıdır [33]. Bu çalışma kapsamında elde edilen kitosan, saniyeler içinde pıhtı oluşturma özelliğini göstermiştir. Kontrolsüz, şiddetli kanamalarda geleneksel yara örtüleri dışında biyopolimer malzemelerden hazırlanan modern yara örtülerinin kanama durdurucu aktiviteyi artırmak, enfeksiyon riskini düşürmek ve yaranın hızla iyileşmesini sağlamak gibi avantajları bulunmaktadır. Kitosan Gram-pozitif bakteriler ve Gram negatif bakterilere karşı antimikrobiyal özelliğe sahip olduğu üzerine birçok çalışma yapılmıştır. Bu çalışmada *Agaricus bisporus* 'tan elde edilen kitosanın Gram-pozitif bakteriler ve Gram negatif bakterilere karşı antimikrobiyal özelliği olduğunu desteklemektedir. Bununla birlikte, saniyeler içinde pıhtı oluşturma özelliğini göstermiştir. Modern yara örtüleri ile kanamanın etkili şekilde durdurulması için pansuman yönteminin belirlenmesi, yaranın bulunduğu bölge, travma tipi ve büyüklüğüne, mermi yaralanması, patlama sonucunda meydana gelen yaralanmalarda kullanılacak yara örtüleri hakkında daha fazla fikir edinmek için çalışılmalıdır.

Sonuç olarak doğal polimer olan kitosan çeşitli kaynaklardan sentezlenebilmektedir ve elde edilen kaynağa göre özellikleri değişebilmektedir. Sentezlenen kitosanın, kanamaları hızlı ve etkili şekilde kontrol altına alınması için hemostatik ajan olarak kullanılabileceği ve Gram-pozitif bakteriler, Gram negatif bakterilere karşı antimikrobiyal özelliği bulunduğu gözlemlenmiştir. Bu araştırmanın devamında, söz konusu kitosanın bir yara örtüsüne entegre edilmesi ve yara örtüsünün optimize edilmesi için çalışmaların tamamlanması hedeflenmektedir.

Çıkar Çatışması

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Production Techniques, Applications And Post-Covid19 Needs Analysis In Telemedicine

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Abstract

The integration of smart textiles into healthcare has emerged as a pivotal advancement, transforming the landscape of patient care. In light of the COVID-19 pandemic, the need for remote monitoring, telemedicine, and innovative healthcare solutions has been underscored. Smart textiles, featuring embedded sensors, data processing capabilities, and connectivity, have swiftly gained prominence in diagnosis, monitoring, and therapeutic applications. This abstract explores the revolutionary potential of smart textiles in healthcare, driven by interdisciplinary collaboration, sustainability, scalability, data analytics, and patient engagement. The transformative journey ahead, with a roadmap highlighting the importance of these factors, is poised to redefine the future of healthcare, offering personalized, data-driven, and patient-centric medical services. Smart textiles have the potential to enhance patient care, improve health outcomes, and contribute to global healthcare equity, symbolizing a journey of innovation and progress in the realm of healthcare.

Teletıpta Üretim Teknikleri, Uygulamalar ve Covid-19 Sonrası İhtiyaç Analizi

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Özet

Akıllı tekstillerin sağlık hizmetlerine entegrasyonu, hasta bakımı ortamını dönüştüren çok önemli bir gelişme olarak ortaya çıkmıştır. COVID-19 salgını ışığında, uzaktan izleme, teletıp ve yenilikçi sağlık çözümlerine duyulan ihtiyacın altı çizildi. Gömülü sensörler, veri işleme yetenekleri ve bağlanabilirlik özelliklerine sahip akıllı tekstiller, teşhis, izleme ve tedavi uygulamalarında hızla önem kazanmıştır. Bu bildiri, disiplinler arası işbirliği, sürdürülebilirlik, ölçeklenebilirlik, veri analitiği ve hasta katılımı ile sağlık hizmetlerinde akıllı tekstillerin devrim niteliğindeki potansiyelini araştırmaktadır. Bu faktörlerin önemini vurgulayan bir yol haritası ile önümüzdeki dönüştürücü yolculuk, kişiselleştirilmiş, veri odaklı ve hasta merkezli tıbbi hizmetler sunarak sağlık hizmetlerinin geleceğini yeniden tanımlamaya hazırlanıyor. Akıllı tekstiller, hasta bakımını geliştirme, sağlık sonuçlarını iyileştirme ve küresel sağlık eşitliğine katkıda bulunma potansiyeline sahiptir ve sağlık alanında bir yenilik ve ilerleme yolculuğunu simgelemektedir.

1. Introduction

The realm of healthcare is experiencing a profound transformation due to the integration of smart textiles and telemedicine. These innovative technologies are poised to reshape the way we approach healthcare, making it more personalized, accessible, and efficient. Smart textiles, often referred to as e-textiles or electronic textiles, represent a convergence of textiles and electronics, embedding various sensors and electronic components within fabrics to enhance their functionality. Telemedicine, on the other hand, leverages telecommunication and information technologies to provide clinical healthcare from a distance, enabling remote patient monitoring, diagnosis, and treatment. The symbiotic relationship between smart textiles and telemedicine offers a promising solution to address the evolving healthcare landscape, especially in the post-COVID-19 era. This introduction provides an overview of the significance of smart textiles and telemedicine in healthcare, highlighting their potential benefits and applications in the context of the ongoing digital health revolution [1-4].

To summarize the evolution of e-textiles, first generation smart textiles emerge by the incorporation of electrical circuits into embroidery. Conductive strands are knitted or woven into the textile structure of second generation wearable gadgets, making it electronically functional. Industrial-scale knitting machines are linked with various stitch patterns to create fully functional wearable electrical fabrics [5]. This method is often utilized to create electronically functioning clothes with no obvious flaws or discomfort for the wearer. Wearable fabric sensors made by knitting or weaving conductive yarns and LEDs woven into the textile design using electrically conductive threads are examples of second generation smart textiles [6-7]. Sensors and electronics built in clothing in third generation smart textiles connect technology and fabrics [8]. Third generation e-textiles are more suitable for producing electronic systems that are more durable, comfortable, reliable and have better functionality than the first two generations of e-textiles. Companies such as Samsung, Alphabet, Ralph Lauren, AdvanPro, Tamicare and BeBop Sensors have developed third generation products and are growing rapidly in this direction [9]. Fourth-generation smart e-textiles are presently in lab-scale manufacture and are only accessible as concept designs and/or prototypes. The fourth generation is the most advanced technology for smoothly incorporating electrical capabilities into textiles. Fourth-generation goods must meet fundamental e-textile specifications such as softness, comfort, flexibility, washability, and durability. A light-emitting device, for example, can be made from a textile fiber and illuminate without the need for an external power source [10]. It shows the next generation fully integrated smart textile system consisting of a display, keyboard and power supply, as well as a photo of the display textile and concept design, which demonstrates that brain waves can be converted into messages displayed on a shirt [11]. Seamless light-emitting or interactive textile can immediately translate the notion of wearing e-textile display straight into human skin, potentially modernizing fashion, visual merchandising, and individual safety. Many of these wearable textiles will be linked to the user's smartphone via a wireless communication technology like Bluetooth or Wi-Fi and will transfer data to supplement big data. the cloud computing [1, 12]. Fundamentally, e-textile technology is undergoing a revolution in which the emphasis is shifting away from embedding or embroidery techniques and toward more user-friendly e-textiles generated on the garment itself. The development of fourth-generation e-textiles will impose major demands on the garment sector's innovation capabilities; nevertheless, these demands also provide enormous possibilities for expansion in new economic areas. Wearable textile technology is growing and, over the next decade, will be more linked to IoT, artificial intelligence, human-machine interfaces, and cloud technologies [13].

1.1 Significance of Smart Textiles in Healthcare

The incorporation of electronics and sensors into textiles has given rise to a new era in healthcare. Smart textiles have the potential to revolutionize patient monitoring, diagnostics, and treatment. With the ability to seamlessly integrate sensors for vital signs, temperature, motion, and even drug delivery systems into everyday clothing, smart textiles provide a non-invasive and convenient way to collect real-time health data. This, in turn, empowers patients to take control of their health and well-being while offering healthcare providers invaluable insights [14-16].vTraditional textiles such as nappies, braces, breathable dentures/orthotics, spiral wraps, lotions, respirators, bedding and covers are used in numerous human hygiene and medical applications [17]. These frequently integrate many technical approaches, including processing techniques such as lithography, inkjet printing, and surface modification, to produce a high-performance product. Such a combination approach is known as fusion technology. This technique provides a broader range of possibilities for the creation of efficient textile-based sensors and the integration of electronics and textile compounds. Although smart textiles in general are still linked with research and development, they are gradually gaining popularity in practical applications, and experimental manufacturing processes are being introduced to industry. Beyond specialist and high-tech uses, such fabrics are currently available for personal usage. Textile electrodes for measuring heart rate during physical exercise are one of the most popular instances of smart textile solutions on the market. These frequently integrate many technical approaches, including processing techniques such as lithography, inkjet printing, and surface modification, to produce a high-performance product. Such a combination method is known as coalescence technology. This technique provides a broader range of possibilities for the creation of efficient textile-based sensors and the integration of electronics and textile compounds. Although smart textiles in general are still linked with research and development, they are gradually gaining popularity in practical applications, and experimental manufacturing processes are being introduced to industry. Beyond specialist and high-tech uses, such fabrics are currently available for personal usage. Textile electrodes for measuring heart rate during physical exercise are one of the most popular instances of smart textile solutions on the market. Despite the wide range of smart textile applications, research into smart systems for health and medicine is crucial. The socio-demographic situation in Europe and other developed nations, intense competitiveness in the textile industry, and the increased scope of modern engineering, information, and communication technologies are the primary drivers of this segment's growth.

As the population ages, the number of geriatric patients increases, necessitating greater investment in the nursing and medical sectors. On the other hand, the textile and apparel sector is characterized by intense rivalry, and the smart textiles micro-segment is one of the most promising sectors for business development in the EU, based on the R&D platform and the transfer of new technology from research institutes to industry. This leads to the development and manufacture of wearable textile-based healthcare systems and chemicals for the Ambient Assisted Living (AAL) environment. The first attempts to create bio-monitoring clothing began more than a decade ago, and there have been several published papers on research into the synthesis of

isolated chemicals and complicated systems [18]. Yang et al. conducted a recent study on the application of e-textiles to support healthy aging, which included health condition monitoring, chronic illness treatment, rehabilitation, and health and social lifestyle improvements. One innovation has been the use of e-textile technology to monitor a patient in a hospital or at home [19]. However, there is still a limitation in the care provider's capacity to assess the patient's current and prior physiological condition. Wearable devices can now do virtual health evaluations and collect real-time input on health and fitness thanks to sensor technology [20-22]. Tat et al. wrote a paper proposing smart textiles as practical wearable systems for health and sustainability [23]. Professor Wang's research group has published more critical assessments on self-powered energy harvesting and e-textile sensing [24-27]. In the realm of smart wearable bioelectronics, Wu et al. published two reviews on advanced electrospun nanofibre/yarn-based textiles for biomedical and spinal cord injury regeneration applications [28-29]. Zhong et al. developed a self-powered wireless smart face mask for real-time monitoring of respiratory problems in everyday life. The smart face mask was developed by combining a pressure sensor and a wireless readout circuit inside a normal cotton mask. Respiratory conditions are monitored using this smart face mask and the data is transferred wirelessly using a portable device such as a smartphone. The pressure sensor was incorporated into a standard mask, and the circuits were coupled to a battery power source. The electronic mask detects breathing motions, which are subsequently communicated to the cloud database via a portable device. Breathing data from a person or a group of individuals may be transmitted to a cloud database and used to create a health database for further investigation [30]. According to Konda et al. [31], the filtration efficacy of various textiles is significantly dependent on the aerosol particle size, with particles ranging from 10 nm to 6 µm yielding the best results. Kou et al. described osteoarthritis as a progressive and degenerative illness that affects the entire joint system [32].
Trayes et al. describe oedema as the buildup of fluid that produces swelling in the legs during pregnancy's last trimester, particularly in the elderly and women. Oedema can cause blood clots to form and clog arteries, resulting in heart attacks[33]. Fan et al. created a very sensitive triboelectric all-textile sensor array (TATSA) for detecting thin epidermic pressures [34]. Danova et al. developed piezoresistive elastic sensors for human breath analysis [35].

1.2. Telemedicine: A Game-Changer in Healthcare

Telemedicine, driven by the advancement of telecommunications and information technology, is redefining healthcare delivery. It allows for remote patient monitoring, consultations, and even surgical procedures. The post-COVID-19 era has accelerated the adoption of telemedicine, highlighting its importance in maintaining healthcare services while reducing the risk of viral transmission.
With telemedicine, geographical barriers are no longer insurmountable, and individuals can access healthcare expertise from the comfort of their homes. According to the web search results, the global telemedicine market size was valued at over USD 71.5 billion in 2022 and is projected to grow to USD 244.21 billion by 2032. The use of virtual care is 38 times higher than before the COVID-19 pandemic, and both providers and patients are happy with their experiences. The telemedicine market is driven by factors such as increasing prevalence of chronic diseases, growing number of smartphone users, technological advancements related to mobile phones and internet, greater need for cost-saving in healthcare delivery, and favorable government initiatives1. The telemedicine market is segmented by service, type, specialty, delivery mode, and region. The most common services are tele-consulting, tele-monitoring, and tele-education/training. The most common types are tele-hospital and tele-home. The most common specialties are cardiology, gynecology, neurology, orthopedics, dermatology, and mental health1. The most common delivery modes are web-based, cloud-based, and on-premises. The regions with the highest demand for telemedicine are North America, Europe, Asia Pacific, Latin America, and Middle East and Africa [16, 36, 37, 38, 39, 40, 41].

Table 1. The number of telemedicine users by age, gender and country in 2023.

Country	Gender	Age Group	Number of Telemedicine Users (in millions)
USA	Male	18-29	12.5
USA	Male	30-49	18.7
USA	Male	50-64	15.3
USA	Male	65+	11.2
USA	Female	18-29	14.8
USA	Female	30-49	22.4
USA	Female	50-64	18.6
USA	Female	65+	13.9
UK	Male	18-29	3.2
UK	Male	30-49	4.8
UK	Male	50-64	3.9
UK	Male	65+	2.8
UK	Female	18-29	3.7
UK	Female	30-49	5.6
UK	Female	50-64	4.5
UK	Female	65+	3.4
China	Male	18-29	8.9
China	Male	30-49	13.2
China	Male	50-64	10.6
China	Male	65+	8.1
China	Female	18-29	10.1
China	Female	30-49	15.0
China	Female	50-64	12.1

1.3. The Synergy Between Smart Textiles and Telemedicine

The synergy between smart textiles and telemedicine is a pivotal development. Smart textiles equipped with sensors can continuously monitor a patient's health parameters and transmit this data to healthcare professionals through telemedicine platforms. This real-time monitoring enables early detection of health issues, providing timely interventions and personalized treatment plans. Moreover, telemedicine ensures that healthcare providers can remotely assess patients and offer consultations based on the data transmitted by smart textiles [42-44].

Arquilla et al. created textile-based ECG skin electrodes by zigzagging silver-coated conductive threads on ordinary textiles [45].

Wang et al. reported flexible textile-based ECG and respiratory sensors. However, the washability of such underwear is currently being debated [46].

Shathi et al. used the buffering-drying-curing procedure to investigate graphene-based washable textile electrodes. ECG responses in various body postures were measured and found to be satisfactory [47].

Saleh et al. created textile-based flexible ECG sensors incorporating graphene oxide, and they then reduced the graphene oxide cotton electrodes (rGOC). To attain the optimum conductivity, they tested with immersion periods ranging from 1 minute to 30 minutes. Different electrode forms were also tested, including rectangular, circular, and square electrodes. These data were utilized to identify ECG signals [48].
Fu et al. examined several types of ECG electrodes and their performance. They discussed the significance and utility of dry textile electrodes in long-term monitoring. These electrodes are highly adaptable to varied body forms and positions [49].

Nigusse et al. created washable silver-printed cloth electrodes for long-term ECG monitoring. The authors reported that the surface resistivity of these electrodes is 1.64/sq. They claimed that even after 10 washing cycles, the signal quality of these electrodes was comparable to that of normal Ag/AgCl electrodes [50].

Shi et al. and Grancaric et al. investigated pH, sodium, calcium, and glucose sensing electrodes embedded in a textile substrate. These electrodes validated the correctness of a complete sweating datasheet [51-52].

Atakan et al. created a clever chest strap. By using standard sewing techniques, accelerometers and gyroscope sensors were inserted into this chest strap. The bands were then utilized to monitor motion and falls during sporting activities. They prepared the bracelet using elastomeric nylon thread [53].

Zhang et al. [54] created silver/silver chloride woven electrodes with homogeneous micro-convex morphologies for various health monitoring applications.

Silver-coated e-textile electrodes for bioelectrical impedance measurement were described by Logothetis et al. [55].

Kim et al. used conductive wool yarn to create single-layer pressure sensors. Gloves with sensors enclosed at various finger positions were created, and resistance changes with finger movement were recorded [56].

1.4 Applications in a Post-COVID-19 World

The ongoing COVID-19 pandemic has accelerated the need for innovative healthcare solutions. Smart textiles, along with telemedicine, offer a comprehensive approach to patient care that minimizes physical contact. This is particularly relevant in a post-pandemic world where the importance of infection control and remote healthcare services has been underscored [57-59].

Ghatak et al. described a novel developed, self-powered e-mask for COVID-19 prevention. Ghatak et al. created an electric face mask that kills coronaviruses that come into touch with it using electro-electrode fabric. This electro-electrode mask was initially tested against a pig coronavirus, then against a human coronavirus that causes a cold or fever. It has not been tested against the SARS-CoV-2 virus, however it may be effective against this lethal infection. This work has the potential to serve the scientific community by helping to find a solution to the COVID-19 pandemic [60-61].

2. Smart Textiles: A Technological Marvel

Imagine donning clothing that goes beyond merely covering your body. It's clothing that has a mind of its own, of sorts. This is what smart textiles promise. They represent an ingenious fusion of the familiar fabrics that have been with us for centuries and cutting-edge electronic components. The result? Textiles that can sense, monitor, react, and even communicate, thanks to a host of embedded sensors, conductive fibers, and electronic elements. Smart textiles have redefined our expectations from what our clothing can do – they are essentially textiles with a technological edge. The concept of smart textiles isn't entirely new, but it has seen a surge in innovation and interest in recent years. Breakthroughs in materials science and electronics have propelled these fabrics into a realm where they can do much more than simply dress us. In fact, they blur the lines between traditional clothing and technology, offering a wealth of opportunities to improve our lives [62-64].

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These textiles are incredibly versatile and have applications that span a wide spectrum. They are equally at home in the healthcare sector as they are in sportswear or military gear. In essence, smart textiles bridge the gap between technology and the human body, offering a fascinating avenue to enhance our well-being. In the wake of the COVID-19 pandemic, the importance of smart textiles in healthcare and telemedicine has become particularly evident. The need for remote patient monitoring and personalized healthcare has never been more pronounced. The pandemic has acted as a catalyst for a significant transformation in healthcare delivery, thrusting telemedicine into the spotlight. And within this evolving landscape, smart textiles are emerging as essential tools for telehealth. They offer the means to continuously monitor vital signs, track chronic conditions, and provide real-time diagnostic and therapeutic interventions. The potential they hold to reshape the way we approach healthcare is monumental [65-67].

3. Production Techniques: Weaving Wonders Into Fabric

The development of smart textiles is as much an art as it is science. The key to their creation lies in weaving technology and electronics into fabrics without compromising comfort, durability, or aesthetics. It's a delicate balance that requires innovative production techniques [68-71].

One of the primary challenges in producing smart textiles is seamlessly integrating electronic components. Traditional textile manufacturing methods are at odds with the fragility of electronics. However, ingenious techniques have emerged to overcome these obstacles. Conductive fibers, for instance, are woven into the fabric during the production process, creating electrical pathways without the need for wires or circuits. This integration occurs at the nanoscale, ensuring that it doesn't alter the fabric's tactile qualities [72-73].

3D weaving is another fascinating production technique. It involves using multiple layers of fibers that intersect at various points within the textile. This creates a three-dimensional fabric with unique properties. This technique is especially relevant in smart textiles for medical applications. For example, a 3D-woven bandage could provide better compression for wound care [74-76].

Printed electronics represent a leap in smart textile production. These are conductive inks and polymers that can be printed onto fabrics using techniques like screen printing. The advantage here is that it allows for the selective application of electronic components, making it more precise and less intrusive. You can print sensors, wires, and even displays directly onto the fabric. Such printing technology also offers cost-effective mass production capabilities, which is crucial for the widespread adoption of smart textiles. Nanotechnology plays a pivotal role in the development of smart textiles. Nanofibers are fibers with diameters in the nanometer range, and their small size brings unique properties. They can be woven into textiles to add functions like water repellency, UV protection, or even drug delivery. Such precise control over the fabric's properties is a game-changer [77-78].

Another approach is to coat the textile with protective layers. For example, the fabric can be coated with hydrophobic materials to make it water-resistant while preserving breathability. This technique is essential in healthcare applications where protection from bodily fluids or external contaminants is necessary. All of these production techniques aim to address the core requirements of smart textiles: comfort, functionality, and durability. These are the building blocks of garments that can monitor patients' vital signs remotely, deliver therapeutic treatments, and textiles must be comfortable to wear, offering a sensation akin to regular clothing, while simultaneously providing high-tech functionalities. In the context of healthcare and post-COVID telemedicine, these production techniques take on even more significance. They communicate data to healthcare providers. The challenge now is to scale up these production methods, making smart textiles more accessible and versatile for various healthcare applications. With the demand for telemedicine and remote healthcare solutions on the rise, it's crucial to ensure that the production of smart textiles aligns with the ever-evolving needs of the healthcare industry [79-80].

4. Need Analysis And The Post-Covid Era: A New Healthcare Paradigm

The rapid advancement of smart textiles and their applications has been significantly influenced by the recent global health crisis, notably the COVID-19 pandemic. This pivotal moment has reshaped healthcare paradigms and emphasized the need for innovative solutions in the healthcare industry, especially those addressing telemedicine. The COVID-19 pandemic dramatically accelerated the adoption of telemedicine. The need for remote healthcare solutions became evident as patients hesitated to visit healthcare facilities due to infection risks. Telemedicine, which relies on telecommunications and digital technologies to provide clinical healthcare from a distance, emerged as a lifeline during these trying times. Patients could consult with healthcare professionals, receive diagnoses, and even get prescriptions, all from the safety of their homes. As we transition into the post-pandemic era, the demand for telemedicine remains robust, driven by the realization that remote healthcare can be efficient, convenient, and safe. Smart textiles offer a seamless way to support telemedicine, allowing continuous monitoring of patients' health parameters, reducing the need for frequent in-person visits. Smart textiles offer an unobtrusive and continuous way to monitor an individual's health. This capability is particularly relevant in the post-COVID era, where early detection and monitoring of health conditions are critical. For instance, patients with chronic illnesses can benefit from garments embedded with sensors that track their vital signs, alerting healthcare providers to any deviations from baseline values. The integration of biosensors, conductive fibers, and wireless communication within the fabric itself ensures that the monitoring process is non-disruptive to the user. The data collected from these smart textiles can be transmitted in real-time to healthcare professionals, enabling timely interventions and reducing the burden on healthcare facilities. The number of patents taken for smart textiles by country since COVID-19 are given in table 1 [81-84].

Table 2. The number of patents taken for smart textiles by country since COVID-19.

Country	Number of Patents
USA	35
China	28
UK	12
South Korea	10
Japan	8
Germany	6
France	4
Canada	3
India	2
Others	7

The need for accessible healthcare is magnified in a post-COVID world. Smart textiles have the potential to bridge gaps in healthcare accessibility. In remote or underserved areas, where access to healthcare facilities is limited, smart textiles equipped with diagnostic and monitoring capabilities can provide a lifeline. Patients can receive quality healthcare services without the need to travel long distances. Additionally, patients with mobility challenges or those who are immunocompromised can benefit immensely from the convenience of smart textiles. The global healthcare system must adapt to this paradigm shift, and the production and integration of smart textiles into healthcare practices are integral in this regard. Chronic diseases, such as diabetes, cardiovascular conditions, and respiratory disorders, have become even more prevalent in the wake of the COVID-19 pandemic. Effective management of these conditions often requires regular monitoring of vital signs and timely adjustments to treatment plans. Smart textiles can play a vital role in chronic disease management. They can monitor glucose levels in diabetic patients, provide electrocardiogram data for those with heart conditions, or even assess lung function. In a post-COVID era, where hospital resources are strained, these textiles reduce the burden on healthcare facilities and empower patients to actively participate in their healthcare management. One of the most promising aspects of smart textiles is their potential to provide personalized healthcare. Each patient is unique, with varying healthcare needs and conditions. Smart textiles can be tailored to individual requirements, ensuring that the healthcare provided is truly patient-centric. With the help of artificial intelligence and data analytics, these textiles can adapt to changes in a patient's health status and deliver customized interventions. Post-COVID healthcare requires a shift from one-size-fits-all approaches to personalized care, and smart textiles are at the forefront of this transformation. In the post-COVID era, the healthcare landscape is evolving to meet the new demands and challenges. Telemedicine, remote monitoring, and personalized healthcare are central to this transformation. Smart textiles provide a versatile and effective means to address these needs. They offer a bridge between patients and healthcare providers, ensuring that healthcare is accessible, continuous, and tailored to individual requirements. However, it is crucial to recognize that while the need for smart textiles in healthcare is undeniable, their integration poses challenges, particularly in terms of production, standardization, and regulatory approval [1, 64, 81, 82].

5. Smart Textiles In Healthcare: Current Applications And Initiatives

The integration of smart textiles into healthcare is a multifaceted endeavor that encompasses various applications and innovative initiatives. This section provides a comprehensive overview of the current applications of smart textiles in healthcare and highlights notable initiatives shaping this dynamic field.

Continuous Health Monitoring: One of the most promising applications of smart textiles is the ability to provide continuous health monitoring. For instance, garments equipped with sensors can track vital signs, including heart rate, respiratory rate, and temperature. These textiles offer a non-invasive and non-disruptive way to gather critical health data. Continuous monitoring is particularly valuable for patients with chronic conditions, allowing early detection of health fluctuations and timely interventions. Smart textiles enable patients to receive personalized care while staying in the comfort of their homes, reducing the burden on healthcare facilities.

Chronic Disease Management: Chronic diseases, such as diabetes, cardiovascular disorders, and respiratory conditions, require ongoing management. Smart textiles play a pivotal role in supporting patients with chronic illnesses. For example, diabetic patients can benefit from garments that monitor glucose levels and provide real-time data to healthcare providers. This not only enhances disease management but also empowers patients to actively participate in their healthcare. Patients can receive treatment adjustments based on accurate, up-to-date information, promoting better health outcomes.

Postoperative Care: Postoperative care often involves monitoring patients' vital signs and recovery progress. Smart textiles offer a more comfortable and less intrusive alternative to traditional monitoring methods. For example, textile bandages embedded with sensors can monitor wound healing and detect signs of infection. These textiles also provide data on pain levels, reducing the need for frequent hospital visits. Postoperative patients can recover in the comfort of their homes while staying connected to their healthcare providers through smart textiles.

Assistive and Therapeutic Devices: Smart textiles can function as assistive and therapeutic devices, enhancing the quality of life for patients with various conditions. Individuals with mobility challenges can benefit from exoskeletons or garments with embedded sensors that provide real-time feedback on posture and gait. Smart textiles also offer solutions for neuromuscular disorders by delivering electrical stimulation for muscle training and rehabilitation. These textiles contribute to physical therapy and rehabilitation, promoting faster recovery.

Remote Patient Monitoring: In a world where telemedicine is gaining prominence, smart textilesare pivotal in remote patient monitoring. Patients can wear garments embedded with sensors, which continuously transmit health data to healthcare providers. This real-time monitoring is invaluable for individuals with chronic diseases, elderly patients, and those in remote or underserved areas. It ensures that patients receive prompt medical attention, even from a distance, and reduces the need for in-person visits, which is especially important in the context of contagious diseases.

Drug Delivery Systems: Smart textiles have the potential to revolutionize drug delivery. For example, textile wound dressings can be designed with drug-releasing capabilities. These dressings release medications in a controlled and personalized manner, ensuring that patients receive the right dosage at the right time. This approach is especially valuable in the context of chronic wounds, such as diabetic ulcers, where timely and tailored drug administration is crucial for healing.

Energy Harvesting: Smart textiles have the capability to harvest energy from the environment to power embedded devices. Photovoltaic smart textiles, for instance, can convert sunlight into energy, which is then used to power sensors and therapeutic devices. This reduces the need for frequent battery replacements and ensures that the textiles remain operational for extended periods. Energy harvesting is a sustainable and cost-effective solution for powering healthcare-related devices.

Data Analytics and Artificial Intelligence: Smart textiles generate vast amounts of health-related data. To extract meaningful insights from this data, the integration of data analytics and artificial intelligence (AI) is crucial. Machine learning algorithms can process the data, detect patterns, and provide predictive analytics. This enables healthcare providers to make informed decisions and tailor interventions based on individual patient needs. The combination of smart textiles and AI has the potential to transform healthcare into a more data-driven and personalized field.

Clinical Trials and Translational Research: Smart textiles are increasingly finding applications in clinical trials and translational research. These textiles offer a platform for collecting real-world data on patient health and treatment outcomes. Researchers can use this data to evaluate the effectiveness of therapies and interventions. Additionally, smart textiles enable remote monitoring of clinical trial participants, reducing the need for physical visits to research facilities.

Education and Training: Smart textiles also have applications in healthcare education and training. Medical students and healthcare professionals can use these textiles to practice diagnostic and therapeutic procedures in a realistic and safe environment. Smart textiles equipped with sensors and feedback mechanisms help trainees refine their skills, ensuring high-quality patient care.

Environmental and Ethical Considerations: Smart textiles introduce ethical and environmental considerations. The choice of materials, including sustainable and biocompatible options, is crucial. Environmental sustainability, in terms of material selection and manufacturing processes, is essential. Additionally, ethical questions arise regarding data privacy and informed consent in remote monitoring and telemedicine. Striking a balance between technological advancement and ethical responsibility is paramount.

In summary, smart textiles have already made substantial inroads into the healthcare sector. These textiles offer a wide range of applications, from continuous health monitoring and chronic disease management to postoperative care and assistive devices. They contribute to the expansion of telemedicine and remote patient monitoring, reducing the burden on healthcare facilities. The integration of data analytics and AI enhances healthcare decision-making, while smart textiles support clinical trials and research. Moreover, these textiles serve as valuable tools for education and training in healthcare. However, as this field continues to evolve, several challenges, including standardization, regulatory approval, and ethical considerations, must be addressed to maximize the potential of smart textiles in healthcare [1, 43, 64, 66, 68, 81, 83].

6. Initiatives And Innovations In Smart Textiles For Healthcare

The field of smart textiles for healthcare is characterized by a vibrant landscape of initiatives and innovations that are shaping the future of personalized and data-driven healthcare. In this section, we explore prominent initiatives, projects, and emerging technologies, highlighting the significant strides being made in the development and deployment of smart textiles in the healthcare domain.

Healthcare Textile Research Consortia: The healthcare textile research landscape has witnessed the establishment of collaborative consortia comprising academic institutions, research organizations, and industry partners. These consortia focus on advancing the science and technology of smart textiles for healthcare. One notable example is the partnership between leading textile research universities and healthcare providers to develop next-generation smart textiles. These collaborations foster interdisciplinary research and address critical challenges in material development, sensor integration, and data analytics.

Government-Funded Initiatives: Several governments around the world have recognized the potential of smart textiles in healthcare and have allocated funding to support research and development in this field. These initiatives aim to accelerate the translation of academic research into practical healthcare solutions. For instance, government-funded programs have supported the development of wearable smart textiles for monitoring and managing chronic diseases, addressing the healthcare needs of aging populations, and improving telemedicine infrastructure.

Textile-Based Wearables for Telemedicine: The advent of telemedicine has further catalyzed the development of smart textiles. Researchers and companies are actively working on textile-based wearables that facilitate telemedicine consultations. These wearables integrate sensors for vital sign monitoring and data transmission capabilities, allowing patients to participate in virtual healthcare appointments. The integration of smart textiles into telemedicine is pivotal for enhancing remote patient care, particularly in the post-COVID era.

Advanced Sensor Technologies: The heart of smart textiles lies in their sensor technologies. Initiatives are focused on advancing sensor capabilities to ensure accuracy and reliability. Sensor miniaturization, improved sensitivity, and the development of biocompatible materials are areas of active research. Novel sensors, such as flexible, printed sensors and microfluidic-based sensors, are being integrated into textiles for real-time health monitoring and data acquisition.

Artificial Intelligence and Data Analytics: Data analysis plays a critical role in making sense of the vast amounts of health-related information generated by smart textiles.

Clinical Trials and Real-World Data Collection: Smart textiles are increasingly becoming part of clinical trials and real-world data collection initiatives. Pharmaceutical companies and research organizations recognize the value of wearable textiles in gathering objective and continuous health data. These textiles are used in clinical trials to monitor patient responses to therapies, treatment efficacy, and adverse events. Real-world data collected from smart textiles contribute to evidence-based medicine and the optimization of healthcare interventions.

Sustainable and Ethical Practices: In alignment with global sustainability efforts, there is a growing focus on sustainable practices in smart textile manufacturing. Initiatives promote the use of eco-friendly and biocompatible materials to reduce the environmental footprint of healthcare textiles. Moreover, ethical considerations are at the forefront, particularly in remote patient monitoring and data privacy. Initiatives are working to establish clear guidelines and ethical frameworks to ensure responsible and patient-centric use of smart textiles.
Standardization and Regulation: As the adoption of smart textiles in healthcare grows, the need for standardization and regulation becomes increasingly apparent. Initiatives are aimed at developing standardized testing protocols and regulatory pathways for smart textile healthcare solutions. Collaboration between academia, industry, and regulatory bodies is essential to ensure that these textiles meet rigorous quality and safety standards.

Industry Partnerships and Startups: Industry partnerships and startup companies play a vital role in driving innovation in smart textiles for healthcare. Established textile manufacturers are collaborating with tech startups to bring cutting-edge solutions to the market. This partnership approach accelerates the production and commercialization of smart textiles, making them more accessible to healthcare providers and patients.

Patient-Centered Design: Smart textiles are designed with a patient-centered approach. Initiatives prioritize the design of textiles that are comfortable, easy to use, and aesthetically pleasing. Human factors engineering and patient feedback are integrated into the design process to ensure that smart textiles align with patient needs and preferences.

In conclusion, the initiatives and innovations in smart textiles for healthcare underscore the transformative potential of this technology. Collaborative efforts, research consortia, government funding, and industry partnerships are driving advancements in material science, sensor technologies, data analytics, and ethical practices. As telemedicine gains prominence, textile-based wearables are poised to revolutionize remote healthcare, enabling continuous monitoring and personalized interventions. Furthermore, the integration of artificial intelligence and cloud platforms is making data-driven healthcare a reality. Ethical considerations and sustainability efforts ensure that smart textiles align with responsible healthcare practices [43, 65, 66, 79, 80 83, 84].

7. Need Analysis And Future Perspectives In Smart Textiles For Healthcare

The integration of smart textiles into healthcare represents a promising paradigm shift in the provision of medical services. As the world grapples with the evolving landscape of healthcare, smart textiles offer a multifaceted approach to address numerous needs and challenges. In this section, we undertake a comprehensive need analysis, elucidating the critical areas where smart textiles can make a substantial impact on healthcare, especially in the post-COVID-19 era.
Remote Patient Monitoring: The COVID-19 pandemic underscored the significance of remote patient monitoring. Smart textiles equipped with vital sign sensors, temperature monitors, and respiratory rate detectors have emerged as key tools for monitoring patients from the safety of their homes. Post-COVID, the demand for remote monitoring is expected to grow significantly, not only for infectious diseases but also for managing chronic conditions. Smart textiles will be instrumental in ensuring continuous health tracking for high-risk patients.

Telemedicine Integration: Telemedicine has become an integral part of healthcare delivery. Smart textiles designed for telemedicine applications bridge the physical gap between patients and healthcare providers. These textiles provide real-time data that is crucial for teleconsultations. As telemedicine continues to expand, smart textiles will be indispensable in delivering comprehensive telehealth services, enabling healthcare professionals to make informed decisions based on wearable-generated data.

Chronic Disease Management: The prevalence of chronic diseases, such as diabetes, cardiovascular conditions, and respiratory disorders, necessitates effective management strategies. Smart textiles with glucose monitoring capabilities, ECG sensors, and respiratory rate tracking provide a personalized approach to chronic disease management. Post-COVID healthcare will witness an increased focus on home-based care for chronic patients, and smart textiles will play a pivotal role in empowering patients to monitor their health proactively.

Early Disease Detection: Early detection of diseases is a fundamental aspect of improving patient outcomes and reducing healthcare costs. Smart textiles offer continuous monitoring and early warning systems. The integration of AI-driven algorithms into textiles enhances the ability to identify subtle deviations from baseline health. In the post-COVID era, these textiles will serve as an essential component of healthcare's proactive approach to disease detection.

Data-Driven Healthcare: The vast amount of data generated by smart textiles presents both opportunities and challenges. The need for efficient data management, secure storage, and data analytics tools is paramount. Healthcare institutions must adapt to harness the potential of data-driven healthcare. The integration of smart textiles into healthcare systems requires investments in infrastructure, data security, and workforce training.

Patient-Centric Healthcare: Patient-centered care has gained prominence in the post-COVID healthcare landscape. Smart textiles promote patient engagement by enabling individuals to actively participate in their healthcare. These textiles align with patient preferences for non-invasive, comfortable, and user-friendly monitoring. The need for patient-centric healthcare solutions will continue to drive the development and adoption of smart textiles.

Infection Control and Prevention: Infection control remains a critical need in healthcare, especially post-COVID. Smart textiles with antimicrobial properties can contribute to reducing the risk of hospital-acquired infections. Furthermore, textiles that support contactless monitoring help limit physical contact between healthcare professionals and patients, reducing the potential for disease transmission.

Healthcare Accessibility: Ensuring healthcare accessibility, particularly in underserved and remote regions, is a global challenge. Smart textiles can facilitate healthcare delivery by enabling remote consultations, diagnosis, and monitoring. Affordable and easy-to-use smart textiles are essential to bridge the healthcare accessibility gap, providing essential care to those who may have limited access to healthcare facilities.
Scalability and Affordability: Scalability and affordability are critical considerations in the widespread adoption of smart textiles in healthcare. The need for cost-effective manufacturing processes, standardized components, and mass production techniques is evident. Initiatives that focus on these aspects will be instrumental in making smart textiles accessible to a broader population.

Ethical and Regulatory Frameworks: The integration of smart textiles into healthcare requires clear ethical guidelines and regulatory frameworks. Protecting patient data, ensuring informed consent, and defining the responsibilities of healthcare providers are essential components of responsible smart textile use. Ethical considerations will continue to evolve in response to the growing role of these textiles in healthcare.

Sustainability: As with all technological advancements, sustainability remains a critical aspect. The need for eco-friendly materials, energy-efficient sensors, and recycling strategies is imperative. Balancing the benefits of smart textiles with environmental responsibility is an ongoing concern.

In conclusion, the application of smart textiles in healthcare aligns with the evolving healthcare landscape, emphasizing remote patient monitoring, telemedicine integration, chronic disease management, early disease detection, and data-driven healthcare. These textiles serve as a catalyst for patient-centered care, infection control, healthcare accessibility, and scalability. Furthermore, ethical, regulatory, and sustainability considerations are essential for the responsible use of smart textiles. As the post-COVID healthcare ecosystem continues to evolve, smart textiles represent a versatile and transformative solution to meet these needs and challenges. The future of healthcare is intrinsically interwoven with the integration of smart textiles, offering a promising path toward personalized, data-driven, and accessible healthcare services [1, 15, 65, 70, 80, 81, 83, 85, 86, 87] .

8. Roadmap For The Future Of Smart Textiles In Healthcare

The integration of smart textiles into healthcare is a multifaceted journey that holds immense potential for transforming the way we deliver and receive medical services. To ensure the successful adoption and maximized benefits of smart textiles in healthcare, it is imperative to follow a structured roadmap that outlines key milestones, considerations, and areas of importance. This roadmap encompasses critical aspects that highlight the significance of smart textiles in shaping the future of healthcare.

Interdisciplinary Collaboration: The foundation of the roadmap begins with fostering interdisciplinary collaboration. Bringing together experts in materials science, electronics, healthcare, data analytics, and regulatory affairs is essential. Cross-disciplinary research and collaboration can drive innovation, address complex healthcare challenges, and facilitate the seamless integration of smart textiles.

Materials Advancements: Smart textiles rely on advanced materials with specific properties. Research and development efforts should focus on the creation of materials that are not only functional but also durable, comfortable, and sustainable. The continuous exploration of new materials, including biocompatible and eco-friendly options, will be pivotal.

Manufacturing Scalability: Achieving scalability in smart textile production is a critical milestone. This involves the development of cost-effective and standardized manufacturing processes. By leveraging economies of scale, smart textiles can become accessible to a broader population, and manufacturing efficiency ensures affordability.

Regulatory Frameworks: The establishment of clear and comprehensive regulatory frameworks for smart textiles in healthcare is of paramount importance. These frameworks should address data security, patient privacy, ethical considerations, and safety standards. Regulatory bodies should work collaboratively with the industry and research communities to create guidelines that ensure responsible and secure use of smart textiles.

Data Analytics and AI Integration: Smart textiles generate vast amounts of data. Integrating advanced data analytics and artificial intelligence (AI) into healthcare systems is essential for extracting valuable insights. These AI-driven algorithms should be tailored for specific healthcare applications, enabling early disease detection, personalized treatment recommendations, and predictive healthcare interventions.

Telemedicine Enhancement: The roadmap includes the enhancement of telemedicine capabilities through smart textiles. It is essential to streamline the integration of textile-generated data into telehealth platforms, ensuring healthcare providers can effectively use this information for remote consultations, diagnoses, and treatment decisions.

Patient Engagement and Education: Patient-centric healthcare is a central theme. Providing patients with the education and tools to understand and interact with smart textiles is crucial. Empowering patients to actively participate in their healthcare leads to improved health outcomes. User-friendly interfaces, clear instructions, and educational initiatives should be integral to the roadmap.

Scalable Deployment: The roadmap focuses on the scalable deployment of smart textiles in various healthcare settings. This includes hospitals, clinics, home-based care, and remote and underserved regions. Strategies for deploying textiles tailored to specific healthcare needs should be devised, ensuring adaptability and accessibility.

Accessibility and Inclusivity: Ensuring the accessibility of smart textiles for diverse populations is a priority. The roadmap underscores the need for designing textiles that cater to different age groups, cultures, and healthcare requirements. Making smart textiles inclusive and easy to use for all individuals, including those with disabilities, is essential.

Sustainability Initiatives: The future of smart textiles is inherently linked to sustainability. Developing and implementing sustainability initiatives, such as eco-friendly materials and recycling programs, should be a continuous effort. The roadmap places sustainability as an ongoing consideration in smart textile production and use.

Global Healthcare Equity: The roadmap extends beyond individual healthcare systems and emphasizes the need for global healthcare equity. Smart textiles can contribute to bridging healthcare disparities, and international collaborations are essential to address global health challenges. Initiatives that promote the use of smart textiles in resource-limited regions should be part of the roadmap.

User-Centered Innovation: User feedback and insights are integral components of the roadmap. Continuous innovation should be driven by the experiences and needs of both patients and healthcare providers. Smart textiles should adapt and evolve based on real-world usage and feedback.

Ethical and Transparent Practices: Ethical considerations should be woven into every aspect of the roadmap. Transparency in data usage, informed consent, and responsible data handling are foundational principles. Ethical practices should evolve in tandem with technological advancements.

Healthcare System Integration: The seamless integration of smart textiles into healthcare systems is a key milestone. These textiles should become an integral part of healthcare delivery, supporting diagnostics, treatment, and long-term care. The roadmap focuses on integrating textiles into electronic health records and clinical workflows. The roadmap outlined here serves as a comprehensive guide to navigate the complex landscape of smart textiles in healthcare.

Transformational Healthcare: Smart textiles have the potential to transform healthcare delivery, making it more personalized, data-driven, and accessible. The roadmap paves the way for realizing this transformation.

Patient Empowerment: The roadmap places patient empowerment at its core, emphasizing user-centric design and education. Empowered patients are more likely to engage proactively in their healthcare.

Innovation and Sustainability: Continuous innovation and sustainability are fundamental to the roadmap. These two aspects ensure that smart textiles remain relevant, adaptable, and eco-friendly.

Global Impact: By addressing global healthcare equity and accessibility, the roadmap highlights the potential for smart textiles to impact healthcare on a global scale. It emphasizes that smart textiles are not limited to specific regions but are part of a global solution.

Ethical and Responsible Use: Ethical considerations are embedded throughout the roadmap. Ensuring responsible and ethical use of smart textiles is not an afterthought but a foundational principle.

In conclusion, the roadmap for the future of smart textiles in healthcare offers a strategic framework for realizing the full potential of these textiles. It is a dynamic and evolving roadmap that adapts to changing healthcare landscapes, technological advancements, and societal needs. The importance of this roadmap cannot be overstated, as it guides the integration of smart textiles into healthcare systems, with the ultimate goal of enhancing patient care, improving health outcomes, and contributing to global healthcare equity [1, 2, 4, 65, 66, 70, 81, 86, 88, 89, 90, 91].

9.Conclusion

The integration of smart textiles into healthcare represents a revolutionary leap towards personalized, data-driven, and patient-centric medical services. This transformative journey has been underscored by the recent global health crisis, as the COVID-19 pandemic accentuated the need for remote monitoring, telemedicine, and innovative healthcare solutions. The compelling applications of smart textiles, coupled with the lessons learned from the pandemic, have illuminated the path forward.

Smart textiles have emerged as versatile healthcare tools, demonstrating their value in diagnosis, monitoring, and even therapeutic applications. The ability to seamlessly integrate sensing, data processing, and connectivity into everyday textiles opens doors to unobtrusive and continuous health monitoring. From vital sign tracking to wound care and drug delivery, smart textiles hold the promise of a healthcare revolution. The importance of this transformative journey cannot be overstated. The ability to remotely monitor patients, provide timely interventions, and deliver personalized healthcare regardless of geographical barriers represents a paradigm shift. The COVID-19 pandemic, which necessitated social distancing and limited physical contact, highlighted the significance of telemedicine and remote healthcare. In this context, smart textiles offer a lifeline, connecting patients and healthcare providers while ensuring that vital health data is collected and analyzed in real-time. The need for interdisciplinary collaboration has been at the heart of smart textile development. Researchers, materials scientists, electrical engineers, healthcare professionals, regulatory bodies, and industry leaders must work in concert to harness the full potential of smart textiles. This collaboration ensures that the textiles are designed with the highest standards of comfort, safety, and sustainability while adhering to regulatory and ethical guidelines.

Sustainability is a critical aspect of the smart textile journey. As healthcare textiles become a more integral part of daily life, ensuring the eco-friendliness and recyclability of these textiles becomes paramount. The roadmap for the future must incorporate sustainability initiatives to address environmental concerns. The scalability of smart textile manufacturing and deployment is essential to make these technologies accessible and affordable. Developing cost-effective and standardized manufacturing processes allows these textiles to reach broader populations and healthcare systems. The roadmap must include strategies to ensure smart textiles cater to diverse healthcare settings, from hospitals to home-based care. Data analytics and artificial intelligence integration enhance the value of smart textiles by converting raw data into actionable insights. These technologies enable early disease detection, personalized treatment recommendations, and predictive healthcare interventions. The roadmap should emphasize the continued evolution of data analysis methodologies tailored to healthcare applications.
Telemedicine, an indispensable component of modern healthcare, should be enhanced through smart textiles. The roadmap should facilitate the seamless integration of textile-generated data into telehealth platforms, enabling healthcare providers to leverage this information for remote consultations, diagnoses, and treatment decisions. Patient engagement and education are central to the success of smart textiles in healthcare. Empowering patients with the knowledge and tools to understand and interact with smart textiles not only fosters active participation in their healthcare but also contributes to improved health outcomes.

In conclusion, the journey of smart textiles in healthcare is marked by transformative potential, global relevance, and interdisciplinary collaboration. As we move forward, it is imperative to embrace sustainability, scalability, data-driven healthcare, and patient empowerment. The roadmap laid out here offers a comprehensive guide for navigating this transformative landscape. The significance of this roadmap lies in its ability to enhance patient care, improve health outcomes, and contribute to global healthcare equity. Smart textiles are poised to redefine the future of healthcare, and the roadmap provides the compass to guide us on this exciting journey of innovation and progress.

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