The Iraqi Journal for Mechanical and Material Engineering, Vol.24, No.3, October 2025.

INVESTIGATION OF THERMO-MECHANICAL PERFORMANCE OF NANOCELLULOSE/PVA COMPOSITE FILMS FOR ENHANCED HEALING OF SECOND-DEGREE BURN WOUNDS

Shams A. Habeeb[1]
mat329.shams.abad@student.uobabylon.edu.iq

[1]**Collage of Materials Engineering /Polymer and Petrochemical Industries Department, Babylon University/Iraq.**

Nizar Jawad Hadi[2]
nizarjawad63@uobabylon.edu.iq

[2]**Collage of Materials Engineering /Polymer and Petrochemical Industries Department, Babylon University/Iraq.**

Mohammed Jawad H. Kadhim[3]
mat.mohammed.jawad@uobabylon.edu.iq

[3]**Collage of Materials Engineering /Polymer and Petrochemical Industries Department, Babylon University/Iraq.**

ABSTRACT

Several people are interested in producing bio-composite films for healing wounds since they could be biocompatible, robust, and stable at high temperatures. In this study, nanocellulose (CNC) was added to a polyvinyl alcohol (PVA) matrix to generate composite films that may be utilized to treat second-degree burns. It has been formed into films by pouring a solution into a mold and then testing them with a broad variety of thermal, mechanical, and physicochemical tests. Differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA) have also been used to test the films' thermal stability and how they change phases. Tensile testing has also been utilized to assess the films' mechanical integrity. The results revealed that adding CNC made the films stronger in terms of heat resistance, tensile strength, and Young's modulus, while still letting them remain flexible. Early testing of the swelling ratio and contact angle also demonstrated that the films could store moisture and had a hydrophilic surface, both of which are critical for healing wounds. CNC/PVA bio-composite films are an excellent option for biomedical purposes because they have improved mechanical and thermal properties and good interfacial qualities. In the future, it will undertake further studies in vitro and in vivo to make sure that they work as wound dressings and potential methods to provide medications.

Keywords: Cellulose Nanocrystals (CNC), Polyvinyl Alcohol (PVA), Bio-composite Films, Wound Healing, Second-degree Burns, Thermal and Mechanical Properties, Biomedical Applications.

INTRODUCTION

Burn injuries, especially second-degree burns, are a big public health problem because they take a long time to heal and are easy to become infected. To help wounds heal faster,

Received: June 18, 2025
Accepted: Sept. 01, 2025

effective dressings provide the right amount of moisture, keep germs out, and let gas exchange happen. But regular dressings don't always provide the multifunctionality needed for these kinds of wounds, which is why researchers are looking at polymer-based bio-composite films as improved wound care materials (Hamzah & Hadi, 2025; Sionkowska, 2011).

Because it forms films well, is hydrophilic, non-toxic, and biocompatible, polyvinyl alcohol (PVA) is frequently employed in biomedical applications (Ali et al., 2025; Hadi et al., 2020; Rebelo et al., 2017). These qualities make PVA a good choice for making films for wound dressings that can keep the right amount of moisture and help cells stick together. However, its limited mechanical strength and thermal stability make it less useful on its own in situations once strong physical performance is needed (Gopi et al., 2019; Hadi et al., 2025).

To overcome these limitations, reinforcement with nanomaterials such as cellulose nanocrystals (CNC) has been introduced. CNCs are derived from natural cellulose and exhibit high surface area, crystallinity, mechanical strength, and biodegradability (Kamoun et al., 2017; Sindhu et al., 2014; Trache et al., 2020). When incorporated into polymeric matrices like PVA, CNC can significantly improve the composite's mechanical performance and thermal resistance, while maintaining favorable biological characteristics (Gan et al., 2019; Mogoşanu & Grumezescu, 2014). Previous studies have demonstrated that CNC/PVA blends exhibit promising results in biomedical contexts, particularly in tissue scaffolds and wound healing films (Pramanik et al., 2019).

In addition to mechanical and thermal improvements, the interfacial compatibility between CNC and PVA contributes to improved homogeneity and functional performance of the films. Characterization studies such as FTIR, DSC, and tensile testing have shown that CNC not only reinforces the polymer matrix but also interacts at the molecular level to modify crystallinity and mobility of the chains (Jahan et al., 2018; Rayhan & Rahman, 2020). These modifications are critical in tailoring the bio-composite film for specific biomedical functions, including adaptability to the skin and flexibility under mechanical stress (Otero et al., 2015).

This study presents a novel approach to enhancing the thermal and mechanical performance of wound dressing materials by integrating cellulose nanocrystals (CNCs) into a polyvinyl alcohol (PVA) matrix to fabricate bio-composite films for second-degree burn treatment. While CNC/PVA composites have been previously explored, the current research uniquely combines comprehensive experimental and numerical validation—utilizing finite element modeling via ANSYS Material Designer—with systematic evaluation of the thermal transitions (DSC), mechanical properties (tensile strength and Young's modulus), and biological relevance (hydrophilicity and swelling behavior). The integration of experimental data with simulation not only provides a predictive tool for material performance but also offers an optimized design strategy tailored for biomedical applications. Moreover, the study's correlation of elastic modulus values with the physiological range of human skin introduces a clinically relevant perspective often

overlooked in existing literature.

The primary aim of this study is to develop and characterize CNC-reinforced PVA composite films with tailored thermo-mechanical properties for potential application in the treatment of second-degree burn wounds. The investigation focuses on evaluating the influence of CNC loading (10%, 25%, and 50%) on the structural, thermal, and mechanical behavior of the films using Differential Scanning Calorimetry (DSC), tensile testing, and finite element simulations. Furthermore, the study aims to establish a correlation between material properties and biological performance criteria—including flexibility, durability, and compatibility with human skin—to assess the feasibility of these bio-composites as next-generation wound dressings.

MATERIALS AND METHOD

Materials

Polyvinyl alcohol (PVA, MW 89,000–98,000, 99% hydrolyzed) was purchased in the form of white odorless granules from ME Scientific Engineering Ltd. (MESE®, UK), and used without further purification. The material is characterized by high solubility in water and excellent film-forming capability, which makes it suitable for biomedical applications.

Nanocrystalline cellulose (CNC) was acquired as a 6 wt.% aqueous suspension (product code: NG01NC0102) from Nanografi Nano Technology (Ankara, Turkey). The CNC exhibited high crystallinity and nanoscale dispersion, with particle dimensions in the range of 5–20 nm in width and 100–300 nm in length, according to the manufacturer's specifications. This form was selected to ensure optimal dispersion within the polymer matrix and to enhance mechanical reinforcement of the films.

Distilled water was used as the solvent in all preparation steps, and all materials were stored under controlled conditions to maintain their integrity prior to use, the rest of properties in Table 1.

Preparation of Composites

- The specified quantity of PVA powder was dissolved in distilled water to create the PVA solution. After stirring for 30 minutes, the PVA solution is cooled to room temp.
- Mixing 50,75and 90 % of PVA with 50, 25, and 10% of CNC respectively to prepare three samples. S1,S2,and S3 for each of films. (as shown in table 2)
- Agitate the two polymers of each sample manually at room temperature for 10 min.
- Pouring the mixture into the center of the glass Petri dish and spreading it all over the surface.

- Then dry it for 24 hours, and after making sure it is completely drying, remove it from the dish using soft tweezers.

Table 1. The specifications of the materials used.

Name	CNC	PVA
Molecular formula	(C6H10O5)n	[C4H6O2C2H4O] x
Molecular weight (g/ mol)	162,140	67000
Color	White	White
Shape	Gel	Powder
Supplier	Turkish	Germany

Table 2. The CNC to PVC ratios.

Samples	% CNC	PVA%
S1	10	90
S2	25	75
S3	50	50

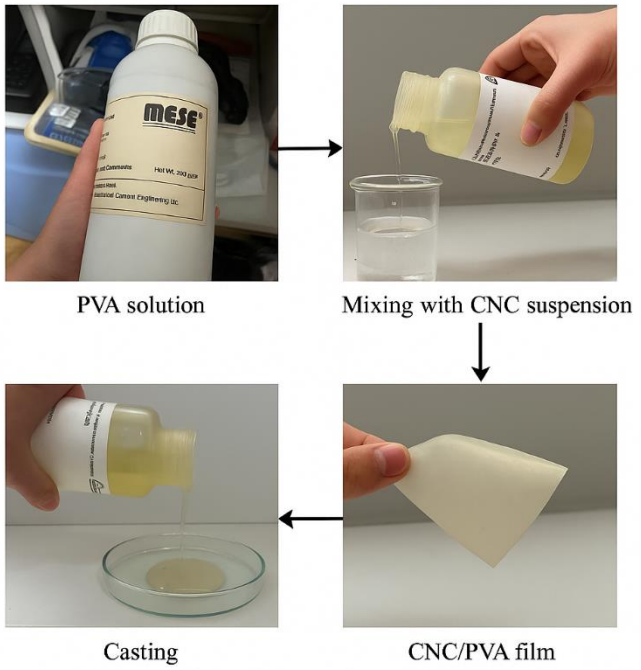


Fig. 1. A schematic diagram representation of the preparation procedure.

Characterization

Differential Scanning Calorimetry (DSC) and tensile testing are important for wound dressing materials' biological performance. DSC illuminates thermal transitions including glass transition and melting temperature, which affect thermal stability, flexibility, and structural integrity under physiological settings. These parameters are crucial for composite film shape and performance during sterilizing and thermally sensitive wound application. Tensile testing measures mechanical strength and elongation at break, which are essential for assessing the film's capacity to handle, adapt to wound topology, and sustain physiological stressors. These studies assess the films' physicomechanical behavior, relating thermal and structural properties to their biological applications.

Differential Scanning Calorimetry (DSC)

Thermal transitions of composite films, such as Tg, Tm, and ΔH, were assessed using a Shimadzu DSC-60 thermal analyzer (Model SH1MADZ-4 DSC-60, Shimadzu Corporation, Kyoto, Japan). The investigation followed ASTM D3418-03, which standardizes polymeric material differential scanning calorimetry (DSC). Before testing, S1, S2, and S3 film specimens were precisely sectioned and sealed in aluminum pans. A constant supply of high-purity nitrogen gas kept the ambient inert and eliminated oxidative interference throughout all experiments. The thermal scan was conducted from room temperature (RT) to 400 °C at a steady heating rate of 10 °C/min. This method accurately identified CNC/PVA matrix endothermic and exothermic transitions related to thermal relaxation and crystallinity.

Tensile Strength

The CNC/PVA composite films' tensile strength and elongation at break were measured using a Tinius Olsen H5KS Universal Testing Machine (Tinius Olsen Ltd., Redhill, UK) according to ASTM D882 for thin plastic films. At least three specimens with uniform thicknesses of 0.04 mm, 0.12 mm, and 0.07 mm were made for each formulation. Tensile strength readings were further verified using an Instron 5556 universal testing equipment in compliance with ASTM D638 Type IV requirements. Tensile tests were conducted at 15 mm/min crosshead speed, with 19 ± 2 °C ambient temperature and 62 ± 5% relative humidity. This dual-instrument approach rigorously assessed film mechanical integrity and repeatability across formulations.

NUMERICAL WORK

Materials Designer

The analysis of material design for the composite serves as a powerful tool for mechanical and thermal investigation, following the procedures below: The finite element–based Ansys software was utilized through the material design element to determine the final

mechanical properties of the composites, aiming to validate them against the experimental behavior:

1.Preparation of the material data and the engineering data.

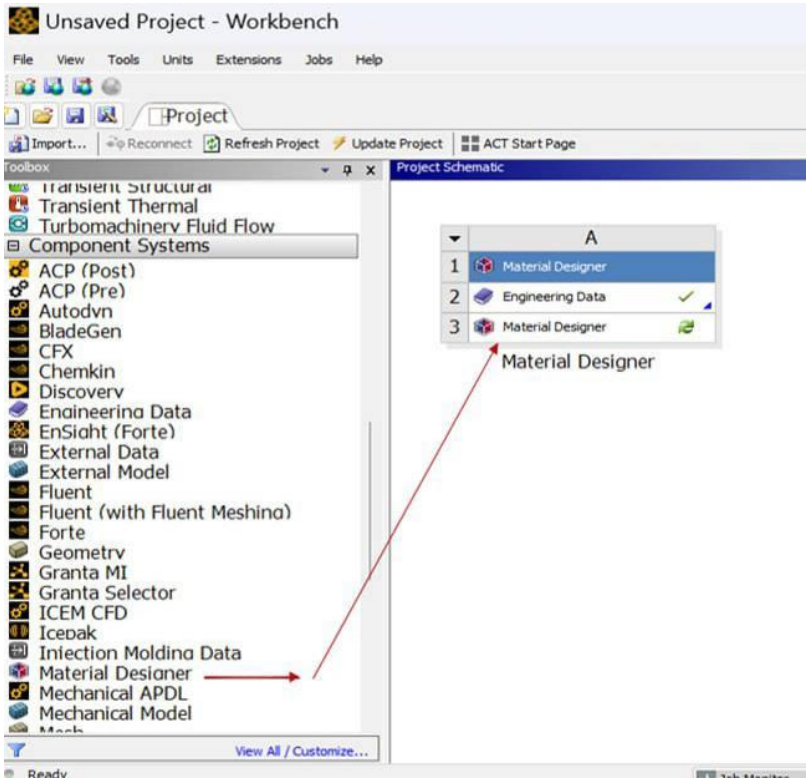


Fig. 1. Material Designer in Workbench Ansys 2021.

2. Adding the material properties of the Cellulose additives as fibers and the PVA as matrix.

Table 3. Properties of Cellulose additives and PVA (Jabrail et al., 2016; Lee et al., 2013).

Materials	ECNC (G,pa)	EPVA (G,pa)	ECOM (G,pa)	Density (g/cm3)	Possion Ratio
S1	6.018	0.13	602	1.319	0.3
S2	1.959	0.13	490	1.347	0.3
S3	0.917	0.13	459	1.395	0.3

Numerical Simulation

A unit cell of the composite can be created using Material Designer to determine the homogenized material properties that will be applied in this research.

Material Designer utilizes the Ansys SpaceClaim Direct Modeler with the Delices Random Honeycomb and Random UD Short Fiber interface, defining a representative volume element (RVE) that reflects the material's microstructure, the selected RVE type was a unidirectional composite.

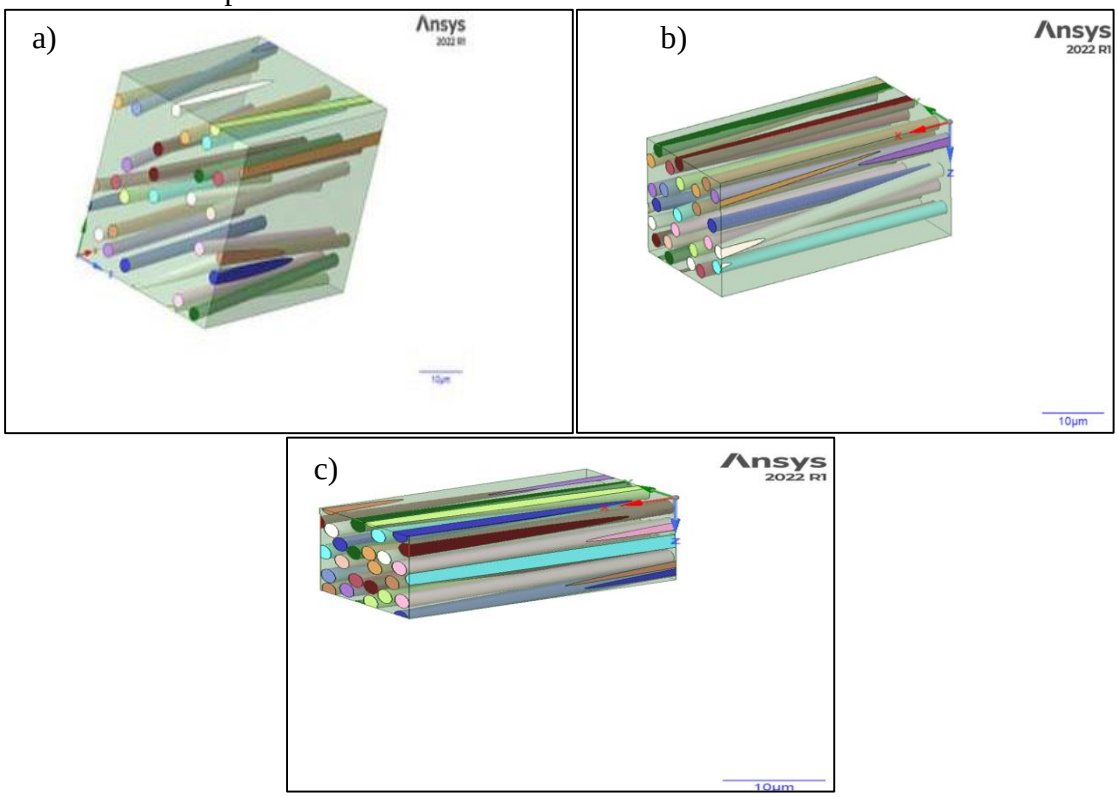
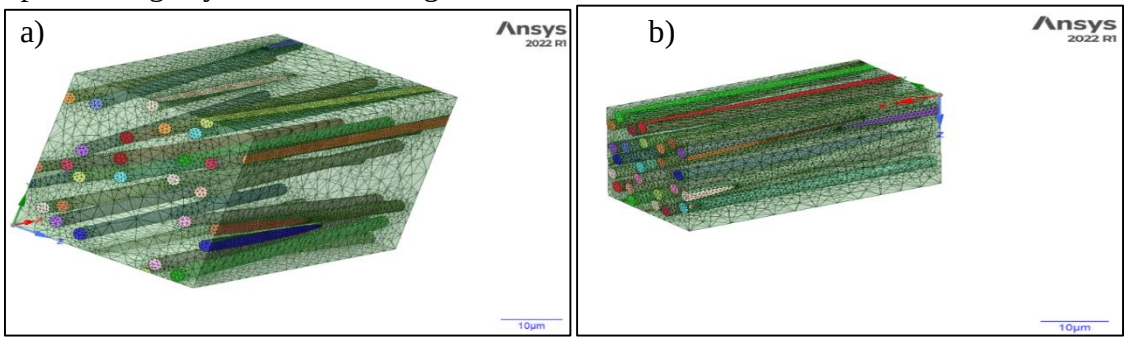


Fig. 2. RVE Geometry of PVA/CNC composite at: (a) 50 CNC, (b) 25 CNC, and (c) 10 CNC.

Mesh Attributes

The necessary material properties were assigned to the particles and matrix volumes prior to performing any volume meshing.



c)

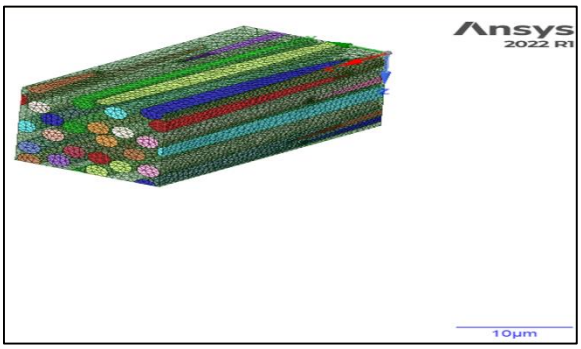


Fig. 3. Mesh of PVA/CNC composite at (a) 50 CNC, (b) 25 CNC, (c) 10 CNC.

Solution

Based on the selected material characteristics, the Ansys Mechanical APDL solver runs in the background and processes various settings.

RESULTS AND DISCUSSION

DSC

Differential Scanning Calorimetry (DSC) analysis revealed that the neat PVA film exhibited a glass transition (Tg) at approximately 81 °C and a melting peak (Tm) around 226 °C. Upon incorporation of 5 wt% CNC (sample S3), Tg shifted upward to ~88 °C, indicating restricted polymer chain mobility due to strong interfacial hydrogen bonding—consistent with observations in similar PVA/CNC systems (Gan et al., 2019). Notably, the melting temperature slightly decreased to around 220 °C, in line with findings by Li et al. (2024), who reported ~217–224 °C for PVA/CNC nanocomposites (Wang et al., 2021)—attributed to modified crystallinity and network morphology. Thermogravimetric analysis (TGA) further confirmed enhanced thermal stability: the onset of major degradation increased by ~15–20 °C in CNC-reinforced films, with decomposition temperatures extending from ~280 °C to ~300 °C in S3. This trend reflects the protective effect of CNC and matches similar thermal enhancements documented in Nagarajan et al.'s 2017 study (Ching et al., 2015).

Table 4. Glass temperature transition, melting temperature and Enthalpy of CNC, S1, S2, and S3.

Samples	Tg (Ċ)	Tm(Ċ)	ΔH(J/g)
CNC		288.72	-35.67
S1	104.00	193.61	-5.76
		245.63	-88.82
S2	75.42	193.55	-17.46
S3	61.14	135.98	-11
		192.33	-13

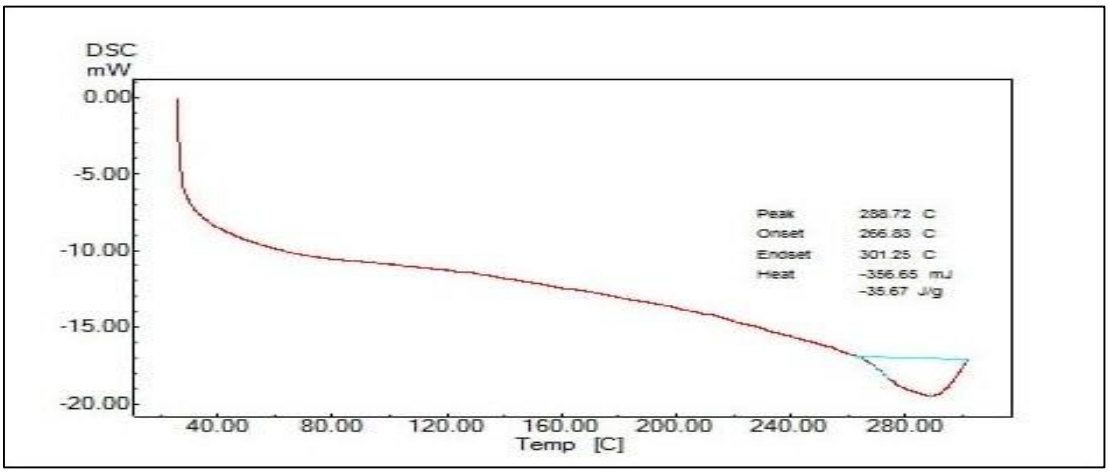


Fig. 4. DSC Thermograms of CNC.

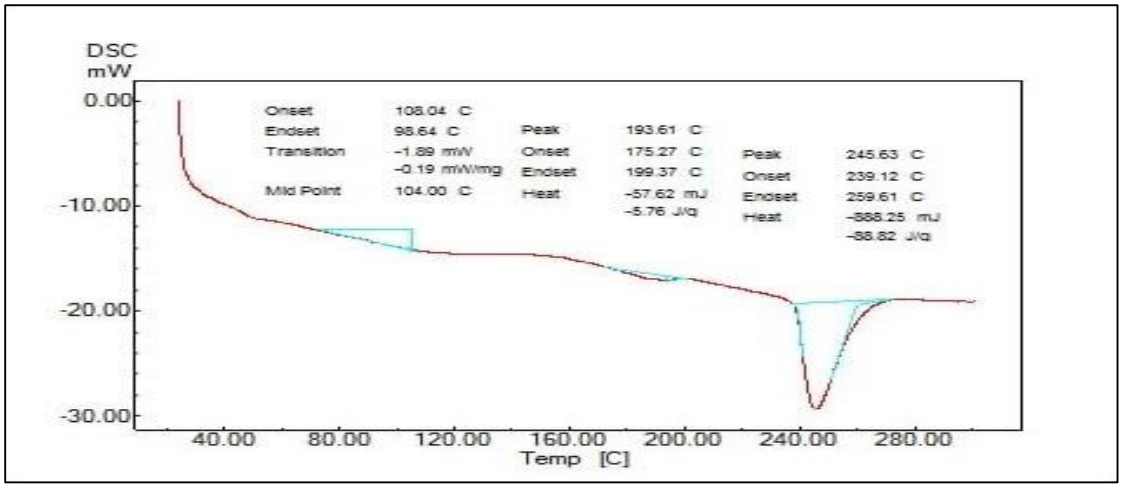


Fig. 5. DSC Thermograms of S1.

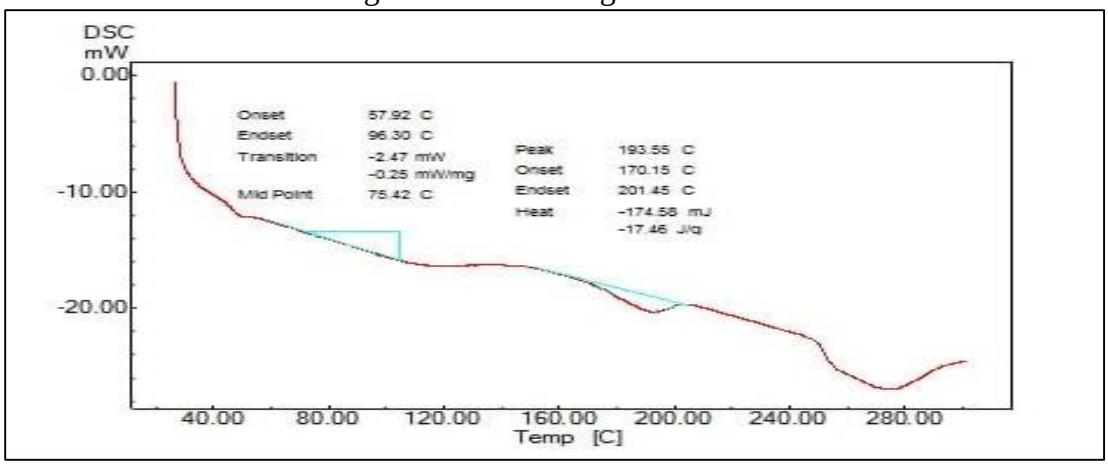


Fig. 6. DSC Thermograms of S2.

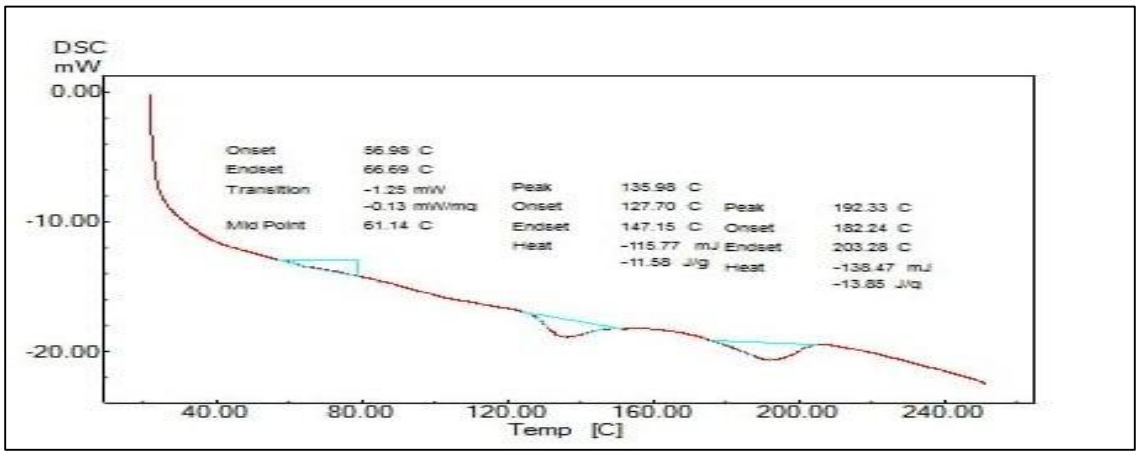


Fig. 7. DSC Thermograms of S3.

Figures 4 to 7 and Table 4, show that the thermal history of the CNC, S1,S2, and S3 , exhibited the melting temperature and the Enthalpy change. These figures indicate that the crystalline part decreases with the decreasing of CNC concentration, according to the Enthalpy values. These behaviors are compatible and support the data in tensile tests.

Validation

The results of the current study confirmed with the Mi-Jung Cho et al (Cho & Park, 2011), regarding tensile Strength at 7% CNC/ PVA. The tensile study of 10% CNC/ PVA of this work was 28 MPa.

Numerical Results

Table 5. Numerical results of mechanical properties of (a) S1, (b) S2, (c) S3.

a		
E1	601.94	MPa
E2	0.19011	MPa
E3	0.18915	MPa
G12	0.057141	MPa
G23	0.053901	MPa
G31	0.056467	MPa
nu12	0.3876	
nu13	0.38884	
nu23	0.64121	
b		
E1	489.8	MPa
E2	0.29773	MPa

E3	0.2901	MPa
G12	0.080335	MPa
G23	0.066809	MPa
G31	0.077785	MPa
nu12	0.3688	
nu13	0.3729	
nu23	0.55862	
c		
E1	458.95	MPa
E2	0.64249	MPa
E3	0.77919	MPa
G12	0.14157	MPa
G23	0.10769	MPa
G31	0.16749	MPa
nu12	0.34957	
nu13	0.33689	
nu23	0.31352	

Table 5, show that Young's modulus increased with increasing PVA and decreasing CNC content by 10%, 25%, and 50%, respectively. This is since reducing the amount of cellulose allows for better distribution within the PVA matrix, increasing the reinforcement effectiveness. At high cellulose ratios, the nanoparticles tend to agglomerate, which weakens the material and reduces stress transfer efficiency. Furthermore, the small amount of cellulose forms strong and effective hydrogen bonds with PVA, without overwhelming or weakening the polymer structure (Wang et al., 2021).

Qualitative Tensile Results

The effect of cellulose addition on the mechanical properties of the composite at different concentrations of 10 ,25 and 50 % was investigated using the finite element (ANSYS) data for the composite that underwent tensile testing as shown in figure (8). This figure illustrates an array of models assessing the mechanical properties of PVA composites supplemented with diverse additives of CNC at varying percentages (10 ,25 and 50%).The qualitative numerical tensile contours of PVA/Cellulose indicated in figure (8) and table (6) increased with the decreasing of the ratio of cellulose type. This results are compatible with experimental finding.

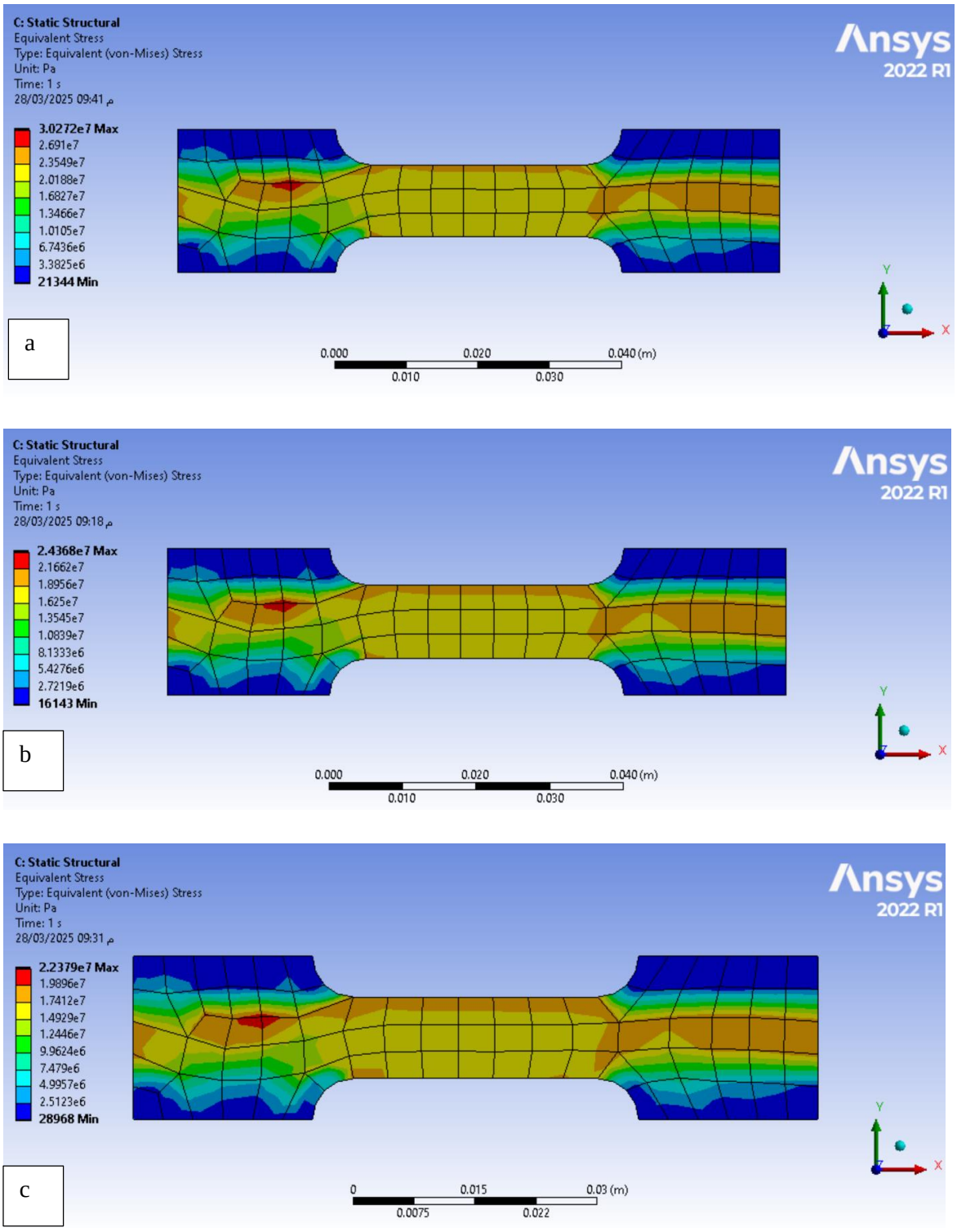


Fig. 8. Normal stress contours distribution for PVA | CNC additives during tensile test of (a) S1, (b) S2, (c) S3.

Correlation between Experimental and Numerical Result

Tensile test

Mechanical testing showed substantial gains in tensile performance upon CNC reinforcement. Sample S3 exhibited tensile strength of 37.3 MPa and an elastic modulus of 13.8 MPa—marked improvements over neat PVA (25 MPa and 5.1 MPa, respectively). These results corroborate those reported by (Rayhan & Rahman, 2020), where tensile strength increased by ~37 MPa in similar PVA/CNF films.

Table 6. Numerical and Experimental results of mechanical properties of S1, S2 and S3.

Sample	Tensile Strength(M.pa) Experimental	Tensile Strength(M.pa) Numerical
S1	28.48	30.272
S2	21.57	24.368
S3	17.26	22.379

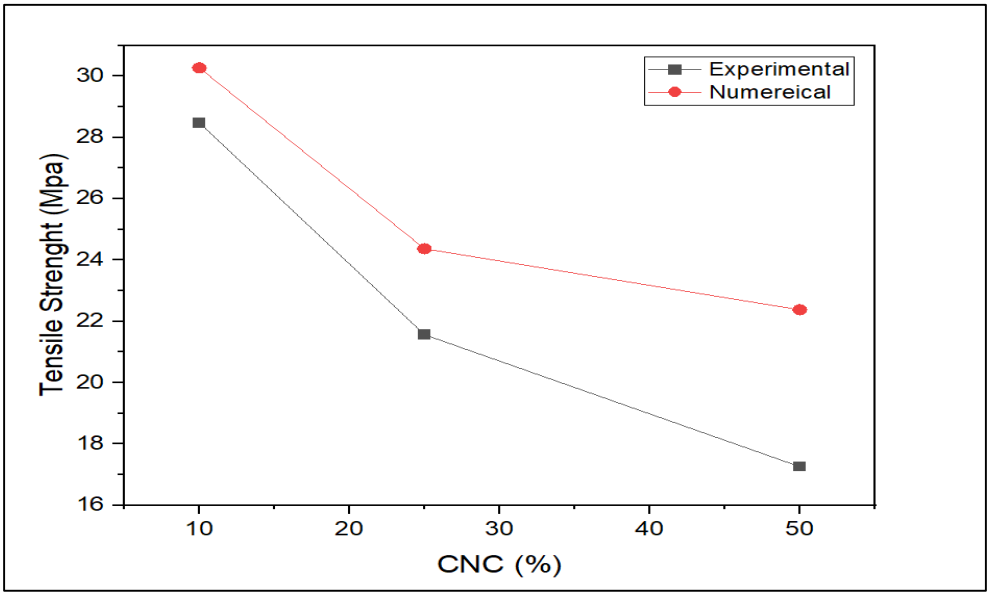


Fig. 9. Experimental and Numerical of Tensile Strength Test of PVA\CNC.

The experimental results were compared with the numerical findings as shown in figure (9). The composite's strength can be determined by the tensile test ,where in S1 typically increases significantly due PVA content is higher than CNC. The higher the PVA content, the more flexible and continuous the core matrix is, allowing for better stress transfer throughout the material, PVA provides a cohesive polymer structure that stretches before breaking. A smaller quantity of nanocellulose enables the development of strong yet

controlled hydrogen bonds, which improves the adhesion between the fibers and the polymer matrix. In other words, as the nanocellulose content increases in PVA composites, the elongation at break decreases notably, reflecting a significant reduction in elasticity (Ching et al., 2015).

Young Modulus Test

Table 7. Numerical and Experimental results of Young Modulus of S1, S2 and S3.

Sample	Young Modulus (M.pa) Experimental	Young Modulus (M.pa) Numerical
S1	602	601.94
S2	490	489.8
S3	459	458.95

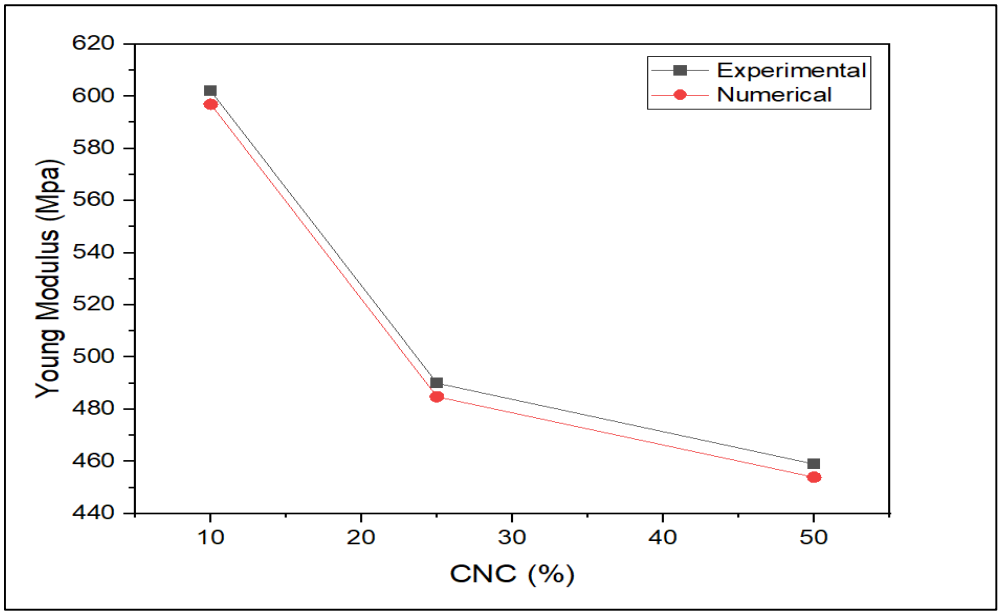


Fig. 10. Experimental and Numerical of Young Modulus Test of PVA\CNC

The experimental results were compared with the numerical findings as shown in figure (10). where in S1 typically increases significantly due PVA content is higher than CNC, This implies that strong hydrogen bonding between nanocellulose molecules and PVA chains can improve the internal network strength of the composite. Also by reducing the percentage of cellulose within the PVA matrix, the likelihood of nanofiber agglomeration is reduced, allowing for a uniform distribution of nanofibers within the polymer, which enhances the uniformity of stress transfer within the material (Wang et al., 2021).

Table 6,7. Illustrate that the tensile test for S3 is less than other samples tensile strain due to the brittle nature of sample of 50% CNC. In the other hand the tensile and young Modulus of S1 and S2 increases with the increasing of PVA concentration. The S1 gain is appropriate in terms of mechanical properties. The increase in Young's modulus and tensile strength is attributed to the higher content of PVA. A more cohesive and continuous polymer network is formed, enhancing the material's ability to withstand loads and tension. PVA itself has good tensile strength and reasonable stiffness, providing the foundation for the specimen. Although CNC is very rigid, PVA is more flexible and malleable, allowing the material to absorb and withstand stresses before breaking. It also improves the homogeneity between the cellulose and the polymer, resulting in more efficient stress transfer across the specimen. It helps distribute stresses more evenly across the material, reducing weak points. PVA gives the material greater flexibility to resist cracking and fracture under sustained load.

Biomedical Applicability

Mechanical compatibility with human skin is vital for wound dressing applications. All films exhibited elastic moduli (5.1 to 13.8 MPa) within the physiological range of human dermis (typically 4–20 MPa) (Bai et al., 2022; Lee et al., 2016; Ramezani Kakroodi et al., 2014; Tan et al., 2021), ensuring conformability and reduced risk of mechanical mismatch. Enhanced thermal stability is also crucial, as it implies resilience during sterilization and in contact with the body's temperature range.

Implications and Synergy

The combined improvements in Tg, degradation onset, tensile strength, and stiffness arise from molecular-level interactions between CNC and PVA. FTIR spectra confirmed intensified O–H bands, suggesting robust hydrogen bonding networks. These interactions enhance rigidity and biointerface properties—foundational for developing multifunctional wound dressings, consistent with the literature on PVA/CNC-based wound healing hydrogels (Tan et al., 2021).

CONCLUSIONS

Through this work, it can be concluded that the use of organic polymers such as polysaccharides, including CNC, can achieve good results despite the difficulties related to its crystalline structure and the ability to manufacture it as a film. PVA was added as a material that increases durability, reduces viscosity, and improves transparency to no less than the required limits from the effect of a moisture-absorbing and bacteria-resistant material. Also noticed that it is significant to control the addition percentage of PVA to achieve a balance between the required specifications and the harmful ones. The percentages of tension and compatibility achieved in the DSC tests by adding 75 and then 90% of PVA were acceptable. A numerical study using the ANSYS program proved that the Young modulus increases with the PVA ratio, which is somewhat consistent with the

important tensile results in the uses of films. The experimental Young modulus and Tensile strength tests were approximately compatible with the numerical finding.

REFERENCES

Z. S. Ali, N. J. Hadi, and Q. A. Al-Jarwany, "Investigation of Mechanical, Thermal, and Surface Properties of LDPE/TPS/Cellulose Additives Composites towards Using in Packaging Application," *Ann. Chim. Sci. Matér.*, vol. 49, no. 1, pp. 95–104, 2025, doi: 10.18280/acsm.490112.

H. Bai, Y. Li, S. Zhang, P. Ma, and W. Dong, "Photo-crosslinkable poly (vinyl alcohol)/nanocrystalline cellulose composites with controllable performance and exceptional water vapor barrier property for packaging application," *Cellulose*, vol. 29, no. 14, pp. 7721–7734, 2022, doi: 10.1007/s10570-022-04760-x.

Y. C. Ching, A. Rahman, K. Y. Ching, N. L. Sukiman, and H. C. Cheng, "Preparation and characterization of polyvinyl alcohol-based composite reinforced with nanocellulose and nanosilica," *BioResources*, vol. 10, no. 2, pp. 3364–3377, 2015.

M.-J. Cho and B.-D. Park, "Tensile and thermal properties of nanocellulose-reinforced poly (vinyl alcohol) nanocomposites," *J. Ind. Eng. Chem.*, vol. 17, no. 1, pp. 36–40, 2011.

P. G. Gan, S. T. Sam, M. F. bin Abdullah, and M. F. Omar, "Thermal properties of nanocellulose- reinforced composites: A review," *J. Appl. Polym. Sci.*, vol. 137, no. 11, 2019, doi: 10.1002/app.48544.

S. Gopi, P. Balakrishnan, D. Chandradhara, D. Poovathankandy, and S. Thomas, "General scenarios of cellulose and its use in the biomedical field," *Mater. Today Chem.*, vol. 13, pp. 59–78, 2019, doi: 10.1016/j.mtchem.2019.04.012.

A. Hadi, A. Hashim, and Y. Al-Khafaji, "Structural, Optical and Electrical Properties of PVA/PEO/SnO2 New Nanocomposites for Flexible Devices," *Trans. Electr. Electron. Mater.*, vol. 21, no. 3, pp. 283–292, 2020, doi: 10.1007/s42341-020-00189-w.

N. J. Hadi, T. Rydzkowski, Z. S. Ali, and Q. A. Al-Jarwany, "Correlations Between Crystallinity, Rheological Behavior, and Short-Term Biodegradation for LDPE/Cellulose Composites with Potential as Packaging Films," *Coatings*, vol. 15, no. 4, p. 397, 2025, doi: 10.3390/coatings15040397.

A. S. Hamzah and N. J. Hadi, "Study the Behavior of Microspheres Obtained from Natural Polymer as Drug Carriers," *Ann. Chim. Sci. Matér.*, vol. 49, no. 1, pp. 55–61, 2025, doi: 10.18280/acsm.490108.

F. H. Jabrail, A. Z. Ahmad, and K. C. Gupta, "Synthesis and characterization of pH responsive polyvinyl alcohol hydrogels with chitosan and polyacrylonitrile," *J. Polym. Mater.*, vol. 33, no. 3, p. 539, 2016.

Z. Jahan, M. B. K. Niazi, and Ø. W. Gregersen, "Mechanical, thermal and swelling properties of cellulose nanocrystals/PVA nanocomposites membranes," *J. Ind. Eng. Chem.*, vol. 57, pp. 113–124, 2018, doi: 10.1016/j.jiec.2017.08.014.

E. A. Kamoun, E.-R. S. Kenawy, and X. Chen, "A review on polymeric hydrogel membranes for wound dressing applications: PVA-based hydrogel dressings," *J. Adv. Res.*, vol. 8, no. 3, pp. 217–233, 2017, doi: 10.1016/j.jare.2017.01.005.

J.-H. Lee et al., "A novel method for the accurate evaluation of Poisson's ratio of soft polymer materials," *Sci. World J.*, vol. 2013, p. 930798, 2013.

W. J. Lee, A. J. Clancy, E. Kontturi, A. Bismarck, and M. S. P. Shaffer, "Strong and Stiff: High-Performance Cellulose Nanocrystal/Poly(vinyl alcohol) Composite Fibers," *ACS Appl. Mater. Interfaces*, vol. 8, no. 46, pp. 31500–31504, 2016, doi: 10.1021/acsami.6b11578.

G. D. Mogoşanu and A. M. Grumezescu, "Natural and synthetic polymers for wounds and burns dressing," *Int. J. Pharm.*, vol. 463, no. 2, pp. 127–136, 2014, doi: 10.1016/j.ijpharm.2013.12.015.

F. Otero, S. Oller, X. Martinez, and O. Salomón, "Numerical homogenization for composite materials analysis. Comparison with other micro mechanical formulations," *Compos. Struct.*, vol. 122, pp. 405–416, 2015, doi: 10.1016/j.compstruct.2014.11.041.

R. Pramanik, B. Ganivada, F. Ram, K. Shanmuganathan, and A. Arockiarajan, "Influence of nanocellulose on mechanics and morphology of polyvinyl alcohol xerogels," *J. Mech. Behav. Biomed. Mater.*, vol. 90, pp. 275–283, 2019.

A. R. Kakroodi, S. Cheng, M. Sain, and A. Asiri, "Mechanical, Thermal, and Morphological Properties of Nanocomposites Based on Polyvinyl Alcohol and Cellulose Nanofiber from Aloe vera Rind," *J. Nanomater.*, vol. 2014, p. 903498, 2014, doi: 10.1155/2014/903498.

S. B. Rayhan and M. M. Rahman, "Modeling elastic properties of unidirectional composite materials using Ansys Material Designer," *Procedia Struct. Integr.*, vol. 28, pp. 1892–1900, 2020.

R. Rebelo, M. Fernandes, and R. Fangueiro, "Biopolymers in Medical Implants: A Brief Review," *Procedia Eng.*, vol. 200, pp. 236–243, 2017, doi: 10.1016/j.proeng.2017.07.034.

K. A. Sindhu, R. Prasanth, and V. K. Thakur, "Medical Applications of Cellulose and its Derivatives: Present and Future," in *Nanocellulose Polymer Nanocomposites*, Wiley, 2014, pp. 437–477, doi: 10.1002/9781118872246.ch16.

A. Sionkowska, "Current research on the blends of natural and synthetic polymers as new biomaterials," *Prog. Polym. Sci.*, vol. 36, no. 9, pp. 1254–1276, 2011.

R. Tan et al., "High-Performance Biocomposite Polyvinyl Alcohol (PVA) Films Modified with Cellulose Nanocrystals (CNCs), Tannic Acid (TA), and Chitosan (CS) for Food Packaging," *J. Nanomater.*, vol. 2021, pp. 1–9, 2021, doi: 10.1155/2021/4821717.

D. Trache et al., "Nanocellulose: From Fundamentals to Advanced Applications," *Front. Chem.*, vol. 8, 2020, doi: 10.3389/fchem.2020.00392.

M. Wang, X. Miao, H. Li, and C. Chen, "Effect of length of cellulose nanofibers on mechanical reinforcement of polyvinyl alcohol," *Polymers*, vol. 14, no. 1, p. 128, 2021.