



Sansevieria zeylanica-Derived Nanocellulose as a Green Reinforcement for PVA Composite Films with Enhanced UV-Shielding and Mechanical Properties

H.P.U.Kalhara^b , W.A.C.N.Kariyawasam^b , Thimira Madhusankha^a , Lasitha Madhusanka^b, G.D.K.V.Madhuwantha^{a,b}, H.D.C.N. Gunawardana^{a,b*}, K.R. Koswattage^{a,b}

^aFaculty of Technology, Sabaragamuwa University of Sri Lanka, Belihuloya 70140, Sri Lanka

^bCenter for Nanodevice Fabrication and Characterization (CNFC), Faculty of Technology, Sabaragamuwa University of Sri Lanka, Belihuloya 70140, Sri Lanka

DOI : <https://doi.org/10.55248/gengpi.06.1226.2841>

ABSTRACT :

Sansevieria zeylanica (Ceylon bowstring hemp) fibers were investigated as a sustainable source for nanocellulose synthesis. The fibers were subjected to sequential alkaline treatment and hydrogen peroxide bleaching, followed by sulfuric acid hydrolysis and neutralization. The resulting nanocellulose was incorporated into a glycerol-plasticized polyvinyl alcohol (PVA) matrix to fabricate composite films. Fourier-transform infrared (FTIR) spectroscopy confirmed the successful isolation of nanocellulose through characteristic bands of cellulose, with only weak residual signals associated with lignin and hemicellulose. Dynamic light scattering (DLS) measurements confirmed nanoscale hydrodynamic dimensions with moderate polydispersity, consistent with the fibrillar morphology and aggregation of nanocellulose through hydrophilic surface interactions. Scanning electron microscopy (SEM) revealed that oven drying promoted nanocellulose aggregation, forming microscale aggregates. Energy-dispersive spectroscopy (EDS) confirmed carbon and oxygen as the dominant elements, while sulfur detected in elemental mapping indicated the presence of sulfate ester groups introduced during sulfuric acid hydrolysis. Nanocellulose incorporation enhanced light scattering and UV-shielding capacity, while tensile strength increased with nanocellulose loading and reached a maximum at 1500 μL . These findings demonstrate the potential of *Sansevieria zeylanica*-derived nanocellulose as a sustainable reinforcing material for PVA-based composite films.

Keywords: *Sansevieria zeylanica*, Nanocellulose, PVA, Composite films; UV shielding

INTRODUCTION

Cellulose is the most abundant natural biopolymer on Earth and constitutes the primary structural component of plant cell walls. It can be obtained from a wide range of lignocellulosic biomass sources, including forest resources, agricultural residues, grasses, and aquatic plants (Sanjit Acharya, 2021). Owing to its renewability, biodegradability, low density, and availability, cellulose-based materials have been extensively utilized in applications such as textiles, packaging, and other industrial products (Antony Allwyn Sundarraj, 2018). However, conventional cellulose materials may not always provide the mechanical performance and functional characteristics required for advanced engineering applications (Tariq Aziz, 2022).

The development of nanocellulose has created new opportunities for the utilization of cellulose in high-performance materials. Nanocellulose generally refers to cellulose-based materials with at least one dimension in the nanometer range, typically between 1 and 100 nm (Aiswarya Poulouse, 2022), depending on the classification and preparation method. It consists of crystalline and amorphous domains and possesses several attractive properties, including a high specific surface area, high aspect ratio, low density, and excellent mechanical characteristics (Djalal Trache, 2020). The reduction of cellulose dimensions to the nanoscale significantly increases its available surface area (Dufresne, 2019), thereby enhancing the interaction between nanocellulose and surrounding matrices. In addition, the abundant hydroxyl groups present on the surface of nanocellulose enable strong intermolecular interactions and provide opportunities for further chemical modification (Haiyu Xu, 2019). These characteristics make nanocellulose an attractive reinforcement material for the development of polymer-based composites.

Among synthetic polymers, poly (vinyl alcohol) (PVA) has received considerable attention for the fabrication of thin films because of its good film-forming ability, mechanical properties, optical transparency, and biodegradability (Mohammad Mizanur Rahman Khan, 2024). The hydrophilic nature of PVA facilitates strong interactions with nanocellulose through hydrogen bonding between the hydroxyl groups present in both materials (Mohamad Nurul Azman Mohammad Taib, 2024). Consequently, the incorporation of nanocellulose into PVA matrices can potentially improve the mechanical properties of the resulting composite films while influencing their optical characteristics. The effectiveness of nanocellulose as a reinforcing material is strongly dependent on factors such as particle size, aspect ratio, surface characteristics, dispersion, and interfacial interactions with the polymer matrix (Eduardo Espinosa, 2019).

Natural plant fibers represent an attractive and sustainable source for nanocellulose production due to their renewable nature, low density, biodegradability, and relatively high cellulose content (Filipe V. Ferreira, 2019). Among the available lignocellulosic resources, *Sansevieria zeylanica*, commonly known as Ceylon bowstring hemp, is a plant indigenous to coastal regions and dry-zone areas of Sri Lanka. The leaves of this plant contain bundles of fine, tough, and elastic fibers that have previously attracted attention as potential reinforcement materials. Previous studies have reported that *S. zeylanica* fibers possess a relatively high cellulose content. For example, P. Pannu Krishnan et al. reported cellulose, hemicellulose, and lignin contents of approximately 76.12%, 9.32%, and 4.28%, respectively. Furthermore, the fibers demonstrated promising mechanical properties, with a reported tensile strength of approximately 359 MPa and a Young's modulus of approximately 8 GPa (P. Pannu Krishnan, 2016).

Despite the promising cellulose content and mechanical properties of *S. zeylanica* fibers, their potential as a precursor for nanocellulose production and as a reinforcing material in PVA-based films remains insufficiently explored. Therefore, the present study investigates the extraction and synthesis of nanocellulose from *Sansevieria zeylanica* fibers and its subsequent incorporation into PVA films. The prepared nanocellulose was characterized in terms of particle size distribution using dynamic light scattering (DLS), while its structural characteristics were investigated using Fourier-transform infrared spectroscopy (FTIR). The morphological features of the freeze-dried nanocellulose were examined using scanning electron microscopy (SEM), and energy-dispersive X-ray spectroscopy (EDS) was employed to evaluate its elemental composition. Furthermore, the influence of nanocellulose incorporation on the tensile properties and UV-visible absorbance characteristics of the prepared PVA-based composite films was investigated. The findings of this study are expected to demonstrate the potential of *S. zeylanica*-derived nanocellulose as a sustainable reinforcement material for the development of polymer-based composite films.

2. Materials and Methods

Materials

All chemicals and reagents used in this study were of analytical grade and used as received without further purification. Hand-decorticated, washed, and sun-dried *Sansevieria zeylanica* fibers were used as the lignocellulosic precursor for nanocellulose extraction. Sodium hydroxide (NaOH), sulfuric acid (H₂SO₄, 98%), hydrogen peroxide (H₂O₂), and glycerol were used during the fiber treatment and film preparation processes. Partially hydrolysed poly (vinyl alcohol) (PVA) was used as the polymer matrix for the fabrication of nanocellulose-reinforced composite films. Deionized (DI) water was used throughout the experimental procedures.

Methods

Extraction and Preparation of Nanocellulose

The hand-decorticated, washed, and sun-dried *Sansevieria zeylanica* fibers were initially subjected to alkaline treatment using a 5% (w/v) sodium hydroxide solution at 55 °C for 1 h. The alkali-treated fibers were subsequently washed thoroughly with deionized water to remove residual sodium hydroxide. The washed fibers were then dried in an air oven at 60 °C for 8 h.

The alkali-treated and defibrillated fibers were subsequently subjected to bleaching using a 10% hydrogen peroxide solution at 55 °C for 1 h. The bleaching treatment was continued until the fibers exhibited a white appearance, indicating the removal of a substantial portion of the non-cellulosic components. The purified cellulose fibers were then dried in an air oven at 60 °C for 8 h.

Nanocellulose was subsequently prepared through sulfuric acid hydrolysis of the purified cellulose. Briefly, 1 g of purified cellulose was treated with 10 mL of 55% sulfuric acid solution and maintained under hydrolysis for 45 min. Following hydrolysis, the reaction was terminated by diluting the resulting suspension with a ten-fold volume of ice-cold water. The acid-treated cellulose suspension was subsequently washed repeatedly with deionized water until a neutral pH was obtained.

The resulting nanocellulose suspension was subjected to sonication for 10 min to promote the dispersion and separation of the cellulose nanoparticles. Finally, the prepared nanocellulose dispersion was oven-dried to obtain nanocellulose in powder form for further characterization and composite film fabrication.

Fabrication of Nanocellulose-Reinforced PVA Films

Oven-dried nanocellulose powder (900 mg) was initially dispersed in 50 mL of deionized water by continuous stirring for 5 h. A 5% (w/v) PVA solution was prepared separately and subsequently combined with varying volumes of the prepared nanocellulose dispersion to obtain PVA/nanocellulose composite films with different nanocellulose contents.

To maintain the flexibility of the prepared films, glycerol was incorporated into the polymer mixture at 10 wt.% relative to the PVA content. The resulting PVA/nanocellulose mixtures were stirred until homogeneous dispersions were obtained. Subsequently, the prepared solutions were cast onto Petri dishes and dried at 45 °C for 12 h to obtain the nanocellulose-reinforced PVA composite films (Each composite film was fabricated using 15 mL of the polymer-NC solution).

Characterization

Morphological Characterization and Elemental Analysis

The surface morphological characteristics of the prepared oven-dried nanocellulose was examined using a SEC-SNE-ALPHA tabletop scanning electron microscope (SEM). Prior to SEM analysis, the samples were gold sputter-coated to enhance their surface conductivity and minimize charging effects, thereby improving the quality and resolution of the obtained micrographs. The elemental composition of the prepared samples was further investigated using a Bruker energy-dispersive X-ray spectroscopy (EDS) analyser.

Structural Characterization

The functional groups and chemical structural characteristics of the prepared samples were analysed using a Thermo Scientific Fourier-transform infrared (FTIR) spectrometer. The spectra were recorded over the wavenumber range of 400–4000 cm^{-1} .

Particle Size Distribution Analysis

The particle size distribution of the prepared nanocellulose was determined using an Anton Paar Litesizer 500 particle size analyser.

UV–Visible Absorbance Characterization

The UV–visible absorbance characteristics of the prepared nanocellulose–PVA thin films were investigated using a Shimadzu UV-2600i Plus UV–visible spectrophotometer.

Tensile Strength analysis

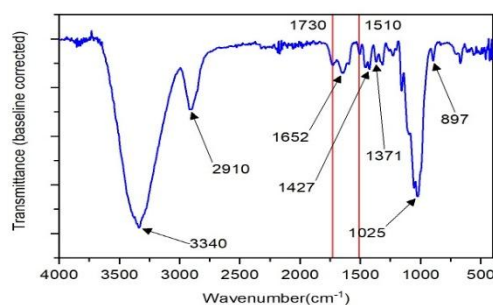
The tensile properties of the fabricated nanocellulose–PVA thin films were evaluated using a 10 N load cells with Haida universal tensile tester. The film specimens were cut into dimensions of 60 mm $\times$ 5 mm prior to testing. For each film composition, three separate specimens were tested under identical conditions. The tensile strength values reported for each sample represent the mean value obtained from the three independent measurements.

RESULTS AND DISCUSSION

Structural characterization

The chemical structure of the prepared nanocellulose was investigated using FTIR spectroscopy over the wavenumber range of 400–4000 cm^{-1} . The obtained spectrum (Figure 02) exhibited the characteristic functional groups associated with the cellulose backbone. The broad absorption band at 3340 cm^{-1} was attributed to O–H stretching vibrations of the hydroxyl groups in cellulose and hydrogen-bonded water molecules (Oluyamo Sunday Samuel, 2019). The band at 2910 cm^{-1} corresponded to C–H stretching vibrations of the cellulose chains, whereas the absorption at 1652 cm^{-1} was mainly associated with the O–H bending vibration of adsorbed moisture (M. El Achaby, 2018). The bands at 1427 and 1371 cm^{-1} were assigned to CH_2 and C–H bending vibrations, respectively (Daniel Tavares de Farias 2014). Furthermore, the distinct band at 1025 cm^{-1} was attributed to C–O stretching vibrations, while the band near 897 cm^{-1} was associated with the β -(1 $\rightarrow$ 4)-glycosidic linkage of cellulose. Collectively, these characteristic absorptions confirm the predominance of the cellulose structure in the prepared material.

In addition to the characteristic cellulose bands, relatively weak absorptions were detected at 1730 and 1510 cm^{-1} , indicating the possible presence of minor residual non-cellulosic components after the bleaching and isolation process. The band at 1730 cm^{-1} can be associated with C=O stretching vibrations arising from residual hemicellulosic components and/or oxidized functional groups, while the band at 1510 cm^{-1} can be attributed to aromatic skeletal vibrations associated with residual lignin (Maida Salah Ud Din, 2026). The relatively low intensity of these bands compared with the



dominant

cellulose-associated absorptions suggests that these components were present only in minor quantities. Therefore, despite the possible retention of small amounts of hemicellulose, lignin, or oxidized groups, the FTIR spectrum was predominantly characterized by the functional groups of cellulose, confirming the successful formation of a cellulose-rich nanocellulose material following the isolation process.

Particle Size distribution analysis

The synthesized nanocellulose was characterized using dynamic light scattering (DLS) at 30 °C. The measured dispersions exhibited hydrodynamic diameters ranging from 418 to 599 nm, with polydispersity values ranging from 32.0 to 37.4%. These moderate polydispersity values indicate a relatively broad particle-size distribution within the nanocellulose dispersion. The variation in hydrodynamic diameter can be associated with the heterogeneous and fibrillar morphology of nanocellulose, differences in particle orientation, and the formation of aggregates through intermolecular hydrogen bonding (Michael Kaszuba 2008). The relatively consistent polydispersity values among the measurements indicate reasonable reproducibility of the dispersion characteristics. However, the hydrodynamic diameter obtained by DLS represents the effective size of dispersed nanocellulose structures or aggregates undergoing Brownian motion and therefore should not be considered as the actual physical dimensions of individual nanocellulose particles (Quim Tarrés 2022). In particular, the anisotropic and fibrillar morphology of nanocellulose can influence the measured hydrodynamic diameter (D. Langevin, 2018).

The transmittance values of the nanocellulose dispersions varied from 24.3% to 31.4%, indicating the interaction and scattering of incident laser light by the suspended nanocellulose structures. The variation in transmittance may be attributed to differences in the local concentration and distribution of nanocellulose within the aqueous medium (Jörg Stetefeld, 2016). Overall, the DLS results indicate the presence of dispersed nanocellulose structures exhibiting sub micrometre hydrodynamic dimensions. Nevertheless, the moderate polydispersity and relatively large hydrodynamic diameters suggest a certain degree of particle-size heterogeneity and aggregation within the dispersion (Felix Sahayaraj Arockiasamy 2025). Such aggregation can occur because of the strong intermolecular hydrogen bonding between the hydroxyl-rich surfaces of nanocellulose, particularly in aqueous media such as deionized water. Therefore, while DLS provides useful information regarding the dispersion behaviour and effective hydrodynamic size of the synthesized nanocellulose, direct morphological techniques such as AFM or TEM would be more appropriate for determining the actual dimensions and aspect ratio of individual nanocellulose structures.

Temperature (°C)	Hydrodynamic diameter (nm)	Polydispersity (%)	Transmittance (%)
30	418	36.1	24.3
30	532	37.4	30.6
30	599	32	31.4

Table 1: Hydrodynamic diameter, polydispersity, and transmittance of Sansevieria zeylanica fiber-derived nanocellulose

Morphological analysis and Elemental analysis

The SEM micrographs of the oven-dried nanocellulose powder revealed irregular and heterogeneous surface morphologies. At lower magnification (500 µm), the sample exhibited sheet-like structures accompanied by localized agglomeration. With increasing magnification, the cellulose structures appeared crumpled, folded, and randomly oriented, while higher-magnification images revealed rough and fibrous features with interconnected ridges, voids, and porous regions. The pronounced aggregation observed in the dried sample can be attributed to the strong intermolecular hydrogen bonding between cellulose chains and the capillary forces generated during water removal (Jie Gong, 2017). In particular, conventional oven drying can promote close association of cellulose fibrils as the water present between the fibrils evaporates, resulting in irreversible or partially irreversible aggregation, commonly referred to as hornification (Laleh Solhi, 2023). Consequently, the dried nanocellulose exhibited relatively dense, flake-like aggregated structures rather than well-separated nanostructured fibrils. The observed morphology may also reflect the preferential removal of amorphous cellulose regions during sulfuric acid hydrolysis, leaving relatively crystalline cellulose domains. Localized shrinkage and micro cracking may further arise from stresses developed during drying.

The EDS spectrum of the sulfuric-acid-treated nanocellulose predominantly revealed carbon and oxygen, which are the principal elements associated with the glucopyranose-based cellulose backbone. The detection of sulphur provides additional evidence for the incorporation of sulfate-containing groups following sulfuric acid treatment. Sulfate ester groups introduced onto the cellulose surface can impart a negative surface charge, which may contribute to electrostatic stabilization of the nanocellulose dispersion and influence its interaction with the PVA matrix. However, the EDS results provide evidence of elemental composition rather than direct confirmation of the chemical bonding or the exact surface concentration of sulfate groups; therefore, the presence and chemical nature of sulfate ester functionalities are more appropriately supported by complementary FTIR and, where available, surface-sensitive spectroscopic analyses. The EDS spectrum confirmed the presence of C, O, Mg, Al, Si, Au, and S, where Mg and Si may

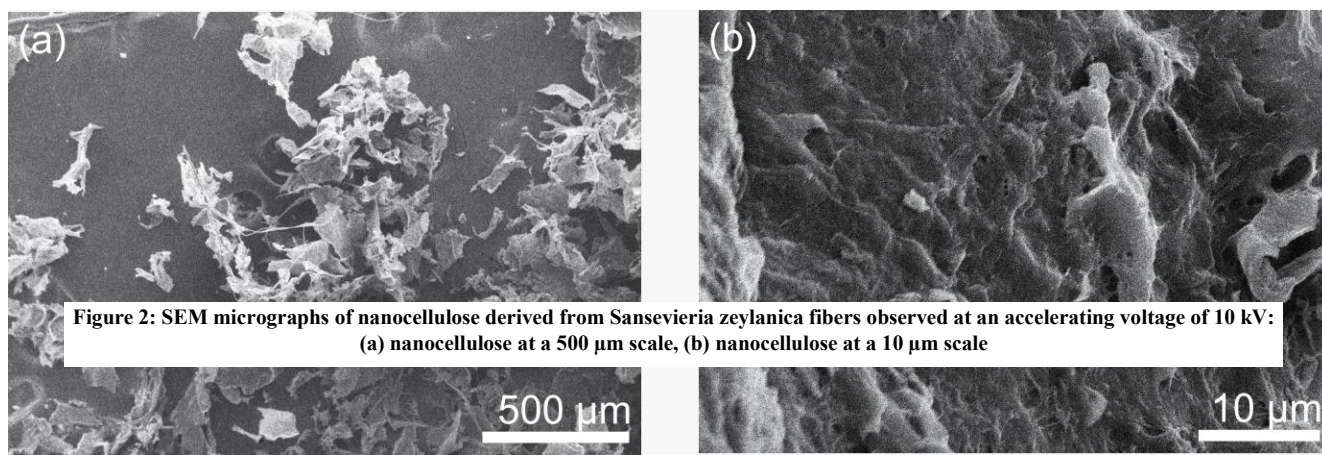
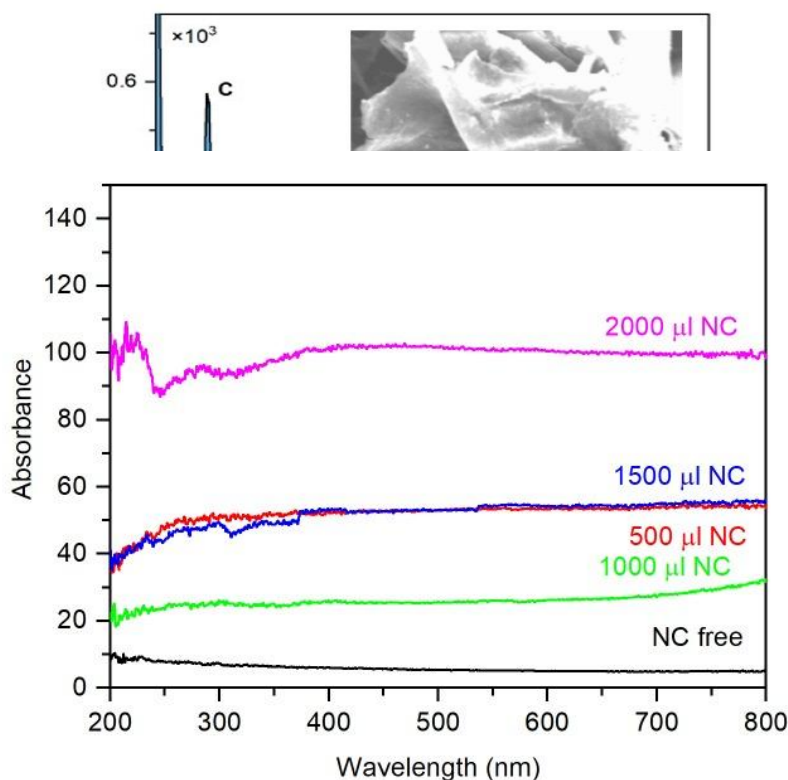


Figure 2: SEM micrographs of nanocellulose derived from Sansevieria zeylanica fibers observed at an accelerating voltage of 10 kV: (a) nanocellulose at a 500 µm scale, (b) nanocellulose at a 10 µm scale

originate from minor impurities, Al from the sample holder, and Au from the sputter-coated gold layer used to enhance SEM imaging conductivity. The detection of S, together with the dominant C and O signals, supports the presence of sulphur-containing functionalities on the cellulose-based structure following sulfuric acid treatment.

Figure 3: EDS spectrum of *Sansevieria zeylanica* fiber-derived nanocellulose, along with the scanned area used for the measurement.

UV-visible absorbance analysis



The UV-Visible absorbance characteristics of the developed PVA films containing different volumes of nanocellulose (NC) dispersion were investigated over the wavelength range of 200–800 nm. A progressive increase in absorbance was generally observed with increasing NC dispersion loading (Melbi Mahardika, 2024). The NC dispersion used for film preparation had a concentration of 18 mg mL^{-1} ; therefore, the addition of 500, 1000, 1500, and 2000 μL corresponded to approximately 9, 18, 27, and 36 mg of NC, respectively. In comparison, the NC-free PVA film exhibited relatively low and nearly featureless absorbance, remaining approximately within 5–10 a.u. across the measured wavelength range.

Figure 4: UV-Visible absorption spectra of nanocellulose-reinforced films with different nanocellulose concentrations

Incorporation of NC resulted in a broad increase in absorbance without the appearance of prominent distinct absorption maxima, indicating that the optical response of the composite films was primarily influenced by enhanced light attenuation rather than the formation of new strong chromophoric absorption bands (Alvarado, 2024). This behaviour can reasonably be associated with increased light scattering arising from the dispersed cellulose nanofibrils within the PVA matrix. The absorbance spectra also exhibited minor spectral features below approximately 260 nm, which became more noticeable at higher NC loadings. These features may be related to residual non-cellulosic constituents present in the extracted NC, although further chemical characterization would be required to confirm their origin.

The absorbance intensity increased from approximately 35–55 a.u. at 500 μ L NC loading to 90–105 a.u. at 1500 μ L, with the highest absorbance observed for the 2000 μ L formulation. The comparatively lower absorbance recorded for the 1000 μ L film, approximately 20–32 a.u., may be related to differences in film thickness, NC dispersion, or microstructural homogeneity during solution casting. Overall, the progressive increase in optical attenuation at higher NC contents indicates that the incorporation of NC substantially reduces the transparency of the PVA films through enhanced light scattering and absorption (Ebise Getacho Bacha, 2022). Therefore, the relatively high NC loading, particularly the 1500 and 2000 μ L formulations, demonstrates potential for improving the UV-shielding capability of PVA-based films. The results further indicate that NC derived from *Sansevieria zeylanica* can effectively modify the optical properties of PVA films, making these composites promising candidates for applications where reduced UV transmission is desirable (Xun Niu, 2018).

Tensile strength analysis of nanocellulose-PVA composite films

The incorporation of nanocellulose (NC) resulted in a non-monotonic variation in the tensile strength of the prepared films. The pristine PVA film exhibited a tensile strength of 20.0 MPa, which decreased to 16.0 MPa following glycerol incorporation. This reduction can be attributed to the plasticizing effect of glycerol, which weakens PVA–PVA intermolecular interactions and increases the segmental mobility of the polymer chains (Zhen-zhen Fu, 2022). With the incorporation of 500 and 1000 μ L of NC dispersion, the tensile strength was 21.3 and 20.0 MPa, respectively. The initial improvement can be associated with enhanced hydrogen-bonding interactions between the hydroxyl groups of NC and PVA (Chousidis, 2024), which strengthen the polymer–nanocellulose interface and promote more effective stress transfer throughout the composite matrix (Fauzi Handoko, 2021). The presence of NC may also influence the organization of PVA chains and contribute to the development of a more mechanically stable polymer network (Xun Niu, 2018).

A pronounced enhancement in tensile strength was observed at 1500 μ L of NC dispersion, reaching a maximum value of 41.8 MPa. This substantial improvement suggests that this composition provided a more effective balance between NC dispersion and interfacial interactions, resulting in efficient load transfer within the PVA matrix. The enhanced strength may be attributed to the formation of a well-dispersed NC–PVA network in which the rigid nanocellulose domains act as reinforcing elements (Melbi Mahardika, 2024). However, further increasing the NC dispersion to 2000 μ L decreased the tensile strength to 24.0 MPa. This reduction may be associated with increased NC–NC interactions and aggregation at higher loading, which can generate localized stress-concentration regions and reduce the effective polymer–NC interfacial area (Mohamad Nurul Azman Mohammad Taib, 2024). Therefore, the 1500 μ L NC-containing film exhibited the highest tensile strength, indicating that an optimum NC loading is required to achieve effective reinforcement of the PVA-based matrix. Additionally, Variations in the thickness of the cast films may have also contributed to the observed differences in tensile strength.

Sample	Maximum Force (N)	Thickness (mm)	Tensile Strength (MPa)
PVA	10	0.1	20
PVA+Glycerol	12	0.15	16
PVA+Glycerol+500 μ l Nanocellulose dispersion	16	0.15	21.3
PVA+Glycerol+1000 μ l Nanocellulose dispersion	21	0.21	20
PVA+Glycerol+1500 μ l Nanocellulose dispersion	23	0.11	41.8
PVA+Glycerol+2000 μ l Nanocellulose dispersion	18	0.15	24

Table 2: Maximum force, film thickness, and tensile strength of PVA-based films containing different concentrations of nanocellulose.

CONCLUSION

This study demonstrated the successful extraction of nanocellulose from *Sansevieria zeylanica* fibers through sequential alkaline treatment, bleaching, and sulfuric acid hydrolysis, followed by its incorporation into PVA composite films to minimize aggregation associated with drying-induced hornification. FTIR analysis indicated effective removal of lignin and hemicellulose, while DLS confirmed the nanoscale dimensions of the isolated nanocellulose with moderate polydispersity, reflecting its fibrillar morphology and aggregation in dispersion. SEM further confirmed the formation of microscale aggregates following oven drying, consistent with the DLS observations. Increasing nanocellulose loading enhanced the UV-shielding capability of the films across 200–800 nm and improved their tensile strength, reaching a maximum value of 41.8 MPa at 1500 μ L loading. Further increases in nanocellulose content reduced tensile strength, likely due to increased aggregation and reduced interfacial efficiency. Overall, the findings demonstrate that *Sansevieria zeylanica* fibers are a viable source of nanocellulose for reinforcing biodegradable polymer films with potential UV-

shielding applications. Future studies should employ AFM and TEM to provide deeper insight into nanocellulose surface morphology and evaluate the influence of different drying methods on its aggregation behavior.

ACKNOWLEDGEMENTS

This research was funded by the Science and Technology Human Resource Development Project, Ministry of Education, Sri Lanka, funded by the Asian Development Bank (Grant No CRG-R2-SB-1).

REFERENCES

- Aiswarya Poullose, J. P., Jinu Jacob George, Jineesh Ayippadath Gopi, Senthilkumar Krishnasamy, Midhun Dominic C. D, Nishar Hameed, Nisa V. Salim, Sabarish Radoor, Natalia Sienkiewicz (2022). Nanocellulose: A fundamental material for science and technology applications. *Molecules*, MDPI.
- Alvarado, M. C. (2024). Recent progress in polyvinyl alcohol (pva)/nanocellulose composite films for packaging applications: A comprehensive review of the impact on physico-mechanical properties. *Food Bioengineering*.
- Antony Allwyn Sundarraj, T. V. R. (2018). A review on cellulose and its utilization from agro-industrial waste. *Drug Invention Today*.
- Chousidis, N. (2024). Polyvinyl alcohol (pva)-based films: Insights from crosslinking and plasticizer incorporation. *Engineering Research Express*.
- D. Langevin, E. R., S. Mariot, A. Knyazev, A. Stocco, A. Salonen, A. Luch, A. Haase, B. Trouiller, C. Relier, O. Lozano, S. Thomas, A. Salvati, K. Dawson. (2018). Towards reproducible measurement of nanoparticle size using dynamic light scattering: Important controls and considerations. *Nanoimpact*.
- Daniel Tavares de Farias , J. L., Cristiane Pedrazzi, Darci Alberto Gatto, Pedro Henrique Gonzalez de Cademartori, Carline Andréa Welter, Gabriela Teixeira da Silva, Tielle Moraes de Almeida. (2014). Acid-hydrolysis-assisted cellulose nanocrystal isolation from acacia mearnsii de wild. Wood kraft pulp. *Polymers*, MDPI.
- Djalal Trache, A. F. T., Mehdi Derradji ,Tuan Sherwyn Hamidon, Nanang Masruchin, Nicolas Brosse, M. Hazwan Hussin. (2020). Nanocellulose: From fundamentals to advanced applications. *Frontiers in Chemistry*.
- Dufresne, A. (2019). Nanocellulose processing properties and potential applications. *Current Forestry Reports*.
- Ebise Getacho Bacha, H. D. D., Lema Deme Shumi, Bune Erre Debesa. (2022). Investigation on reinforcement effects of nanocellulose on the mechanical properties, water absorption capacity, biodegradability, optical properties, and thermal stability of a polyvinyl alcohol nanocomposite film. *Advances in Polymer Technology*.
- Eduardo Espinosa, I.-V., Antonio Rosal, Fernando Pérez-Rodríguez, Gary Chinga-Carrasco, Alejandro Rodríguez. (2019). Pva/(ligno)nanocellulose biocomposite films. Effect of residual lignin content on structural, mechanical, barrier and antioxidant properties. *International Journal of Biological Macromolecules*.
- Fauzi Handoko, Y. Y. (2021). Synthesis and physicochemical properties of poly(vinyl) alcohol nanocomposites reinforced with nanocrystalline cellulose from tea (camellia sinensis) waste. *materials*.
- Felix Sahayaraj Arockiasamy , B. M., Vivek Mariappan Santhi , K. Prakashathan , Diwahar Periasamy , Aravind Dhandapani, Varagunapandian Natarajan, Senthilkumar Krishnasamy, Senthil Muthu Kumar Thiagamani, R.A. Ilyas. (2025). Navigating the nano-world future: Harnessing cellulose nanocrystals from green sources for sustainable innovation. *Heliyon*.
- Filipe V. Ferreira, I. F. P., Sivoney F. de Souza, Lucia H. I. Mei, Liliane M. F. Lona. (2019). Polymer composites reinforced with natural fibers and nanocellulose in the automotive industry: A short review. *Journal of Composite Science*.
- Haiyu Xu, Y. L., Yuanyuan Xie, Enwen Zhu, Zhuqun Shi, Quanling Yang, Chuanxi Xiong. (2019). Doubly cross-linked nanocellulose hydrogels with excellent mechanical properties. *Cellulose*.
- Jie Gong, J. L., Jun Xu, Zhouyang Xiang, Lihuan Mo. (2017). Research on cellulose nanocrystals produced from cellulose sources with various polymorphs. *RSC Advances*.
- Jörg Stetefeld, S. A. M., Trushar R. Patel (2016). Dynamic light scattering: A practical guide and applications in biomedical sciences. *Biophys Rev*.
- Laleh Solhi, V. G., Katja Heise, Iina Solala, Elina Niinivaara, Wenyang Xu, Karl Mihhels, Marcel Kröger, Zhuojun Meng, Jakob Wohler, Han Tao, Emily D. Cranston, and Eero Kontturi. (2023). Understanding nanocellulose–water interactions: Turning a detriment into an asset. *Chemical Reviews*.
- M. El Achaby, N. F., M. C. Figueroa-Espinoza, H. Ben youcef, A. Aboulkas. (2018). New highly hydrated cellulose microfibrils with a tendril helical morphology extracted from agrowaste material: Application to removal of dyes from waste water. *RSC Advances*.
- Maida Salah Ud Din, M. N., Hotaf Hassan Makki, Hotaf Hassan Makki. (2026). Development and characterization of nanocellulose sheets from rice husk through sequential pretreatment and hydrolysis. *Scientific Reports*.
- Melbi Mahardika, N. M., Devita Amelia, Rushdan Ahmad Ilyas, Athanasia Amanda Septevani, Edi Syafri, Novitri Hastuti, Myrtha Karina, Moonis Ali Khan, Byong-Hun Jeon , Nasmi Herlina Sari. (2024). Nanocellulose reinforced polyvinyl alcohol-based bio-nanocomposite films: Improved mechanical, uv-light barrier, and thermal properties. *RSC Advances*.
- Michael Kaszuba , D. M., Malcolm T. Connah, Fraser K. McNeil-Watson, Ulf Nobbmann. (2008). Measuring sub nanometre sizes using dynamic light scattering. *J Nanopart Res*.

-
- Mohamad Nurul Azman Mohammad Taib, T. S. Y., Djalal Trache, M. Hazwan Hussin. (2024). Modification on nanocellulose extracted from kenaf (*hibiscus cannabinus*) with 3-aminopropyltriethoxysilane for thermal stability in poly (vinyl alcohol) thin film composites. *Cellulose*.
 - Mohammad Mizanur Rahman Khan, M. M. H. R., Mobinul Islam. (2024). Synthesis, rheology, morphology, and mechanical properties of biodegradable pva-based composite films: A review on recent progress. *Processes, MDPI*.
 - Oluyamo Sunday Samuel, A. M. A. (2019). Influence of size classifications on the structural and solid-state characterization of cellulose materials. In Intechopen (Ed.), *Cellulose*.
 - P Ponnu Krishnan, J. S. R. (2016). Microscopical, physico-chemical, mineralogical, and mechanical characterization of sansevieria zeylanica fibers as potential reinforcement of composite structures. *Journal of Composite Materials*.
 - Quim Tarrés , R. A., Justin O. Zoppe, Pere Mutjé, Núria Fiol, Marc Delgado-Aguilar (2022). Dynamic light scattering plus scanning electron microscopy: Usefulness and limitations of a simplified estimation of nanocellulose dimensions. *Nanomaterials, MDPI*.
 - Sanjit Acharya, S. L., Prakash Parajuli, Shaïda Sultana Rumi, Julia L. Shamshina, Nouredine Abidi (2021). Utilization of cellulose to its full potential: A review on cellulose dissolution, regeneration, and applications. *Polymers, MDPI*.
 - Tariq Aziz, A. F., Fazal Haq, Fazal Haq, Asmat Ullah, Kechun Zhang, Cheng Li, Shakira Ghazanfar, Hongyue Sun, Roh Ullah, Amjad Ali, Muhammad Muzammal, Muddaser Shah, Nosheen Akhtar, Samy Selim, Nashwa Hagagy, Mennatalla Samy, Soad K. Al Jaouni (2022). A review on the modification of cellulose and its applications. *Polymers, MDPI*.
 - Xun Niu, Y. L., Guigan Fang, Chaobo Huang, Orlando J. Rojas, Hui Pan. (2018). Highly transparent, strong and flexible films with modified cellulose nanofiber bearing uv shielding property. *Bio macromolecules*.
 - Zhen-zhen Fu, Y.-h. Y., Sheng-jie Guo, Ke Wang, Qin Zhang, and Qiang Fu. (2022). Effect of plasticization on stretching stability of poly(vinyl alcohol) films: A case study using glycerol and water. *Macro molecular rapid communications*.