



# Development of Cymbopogon nardus-Derived Nanocellulose-Reinforced PVA Composite Films for Sustainable Packaging Applications

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## ABSTRACT :

The increasing demand for sustainable alternatives to petroleum-derived polymers has encouraged the development of biodegradable polymer composites reinforced with renewable nanomaterials. In this study, *Cymbopogon nardus* leaves were investigated as a sustainable precursor for nanocellulose production and its application as a reinforcing filler in PVA-based composite films. Nanocellulose was isolated through acid hydrolysis followed by neutralization and characterized using FTIR, SEM, and EDS to evaluate its structural and morphological characteristics. The isolated nanocellulose was subsequently incorporated into PVA films containing glycerol as a plasticizer at different loading levels. The resulting composite films were evaluated in terms of tensile strength and thermal conductivity. Incorporation of glycerol reduced the tensile strength of pristine PVA from 21.8 to 14.61 MPa, whereas the addition of 100  $\mu$ L nanocellulose dispersion increased the tensile strength to 28.0 MPa, attributed to enhanced hydrogen-bonding interactions between nanocellulose and the PVA matrix. Further increases in nanocellulose loading resulted in reduced tensile strength, likely due to nanocellulose aggregation and associated stress-concentration regions. Nanocellulose incorporation also modified the thermal transport behaviour of the films, with appropriate loadings providing increased thermal resistance. These findings demonstrate the potential of *C. nardus*-derived nanocellulose as a renewable reinforcing filler for PVA-based biodegradable films with tunable mechanical and thermal properties, offering promising opportunities for sustainable packaging applications.

**Keywords:** Nanocellulose, *Cymbopogon nardus*, Tensile strength, Thermal conductivity, Biodegradable packaging

## INTRODUCTION

The increasing utilization of petroleum-derived chemicals and polymeric materials has raised significant environmental and ecological concerns owing to the depletion of non-renewable resources and the generation of persistent waste. Consequently, increasing attention has been directed toward renewable and biodegradable materials capable of reducing the environmental burden associated with petroleum-based products. Cellulose is considered one of the most abundant and renewable biopolymers in the biosphere and has emerged as a promising precursor for the development of bio-based materials with reduced environmental impact (Bejoy Thomas, 2018 ). In particular, lignocellulosic biomass, which constitutes a major structural component of plant matter and woody materials, represents an attractive and widely available source of cellulose. The conversion of lignocellulosic biomass into value-added cellulose-based materials therefore provides an opportunity to utilize renewable resources while reducing dependence on petroleum-derived materials (Guddu Kumar Gupta, 2020).

Nanocellulose, obtained through the structural modification of bulk cellulose into nanoscale dimensions, has received considerable attention owing to its distinctive physicochemical characteristics. The nanoscale dimensions of cellulose provide a high specific surface area and a high aspect ratio, while retaining the intrinsic mechanical strength of the cellulose backbone. These characteristics make nanocellulose particularly attractive as a reinforcing filler for polymer matrices (Prabhpreet Kaur, 2021). In addition, the abundance of hydroxyl groups on the nanocellulose surface provides reactive sites for interfacial interactions and surface functionalization. The hydroxyl groups can also participate in hydrogen-bonding interactions with neighbouring cellulose structures and compatible polymer chains, facilitating the formation of interconnected hydrogen-bonded networks. Such interactions can improve interfacial adhesion and contribute to the mechanical and physical performance of nanocellulose-containing composites. Furthermore, nanocellulose combines low density, renewability, biocompatibility, biodegradability, and relatively high mechanical and thermal stability, making it a promising reinforcing material for sustainable polymer composites. Accordingly, nanocellulose has been investigated for applications in polymer films, packaging materials, coatings, membranes, biomedical materials, and other functional composite systems (Danish Tahir, 2022).

The increasing interest in nanocellulose has also encouraged the exploration of non-conventional lignocellulosic biomass resources, including

agricultural residues, plant leaves, grasses, and other underutilized plant components. Lignocellulosic biomass generally consists of cellulose as the major structural polysaccharide together with varying proportions of hemicellulose and lignin. The relative abundance and accessibility of these components depend strongly on the plant species and anatomical part used as the feedstock. Among potential plant-based resources, *Cymbopogon nardus*, commonly known as Ceylon citronella or citronella grass, is a perennial grass species associated with the Indian subcontinent and Sri Lanka and is also cultivated commercially in several tropical and subtropical regions. In addition to its economic importance as an aromatic plant, *C. nardus* has been associated with several traditional and medicinal applications (Harneet Kaur, 2021). Importantly, its lignocellulosic biomass provides a potential source of cellulose for the preparation of value-added cellulose-based materials. Fabiani et al. reported the utilization of citronella waste as a cellulose source for the preparation of microcrystalline cellulose, which was subsequently used in the fabrication of graphene-based electrode materials. Their compositional analysis also demonstrated the presence of substantial cellulose and lignin fractions in the investigated citronella biomass (V A Fabiani, 2023). These findings indicate the potential of citronella-derived biomass as a precursor for cellulose-based materials. Nevertheless, the utilization of *C. nardus* leaves specifically as a source for nanocellulose and its subsequent incorporation into polymer composite films remains comparatively underexplored.

Poly(vinyl alcohol) (PVA) is a synthetic, water-soluble polymer that has attracted considerable interest for the fabrication of sustainable polymer films owing to its biodegradability, biocompatibility, low toxicity, hydrophilicity, and excellent film-forming ability (Zainab Waheed Abdullah, 2017). PVA contains a large number of hydroxyl groups along its polymer backbone, which facilitate strong intermolecular interactions and hydrogen bonding with hydrophilic reinforcing materials such as nanocellulose. These interactions can influence polymer-chain mobility, interfacial adhesion, filler dispersion, and the resulting mechanical properties of the composite films (Kirtiraj K. Gaikwad, 2016). Previous studies have demonstrated that incorporation of nanocellulose into PVA matrices can enhance tensile strength and stiffness when an appropriate filler concentration and dispersion state are achieved. For example, nanocellulose-reinforced PVA films have demonstrated improvements in tensile properties through efficient stress transfer between the polymer matrix and the rigid nanocellulose phase. However, excessive nanocellulose loading may promote particle aggregation and generate stress-concentration sites, resulting in a reduction in the mechanical performance at higher filler concentrations. The hydrophilic nature of PVA also makes its properties sensitive to environmental moisture, and therefore modification with suitable reinforcing phases can provide an effective approach for tailoring its functional performance (Geethanjali Bijoy, 2026). These characteristics make PVA/nanocellulose composite films attractive candidates for applications requiring a combination of mechanical performance, renewable content, and biodegradability.

In addition to mechanical reinforcement, the thermal transport characteristics of nanocellulose-based polymer composites are of interest for applications in which controlled heat transfer is required. The thermal conductivity of cellulose-based materials is influenced by several factors, including the intrinsic properties of the constituents, filler loading, moisture content, interfacial interactions, orientation, density, and the microstructure of the composite (N. J. R. Kojiro Uetani, Mayumi Hatakeyama, Takuya Kitaoka, 2021). Although cellulose and nanocellulose have frequently been considered thermally insulating or low-thermal-conductivity materials, studies have demonstrated that the thermal transport behaviour of nanocellulose-containing films can be strongly affected by nanoscale organization and filler orientation. For example, Murugarren et al. investigated the thermal conductivity of bacterial nanocellulose-based thin films and demonstrated that the thermal conductivity could vary with the direction relative to the orientation of the nanocellulose network (Nerea Murugarren, 2022). Similarly, studies on cellulose nanocrystal/PVA composite films have demonstrated that thermal conductivity is strongly dependent on the processing conditions and structural organization of the nanocellulose phase. Therefore, understanding the simultaneous influence of nanocellulose incorporation on the mechanical and thermal transport properties of PVA films is important for developing multifunctional cellulose-based materials (Mathis Antlauf, 2021).

To the best of our knowledge, the use of *Cymbopogon nardus* leaves specifically as a precursor for the synthesis of nanocellulose and its subsequent incorporation into PVA composite films has received limited attention, particularly with respect to the combined investigation of tensile properties and thermal conductivity. Therefore, the present study focuses on the preparation of nanocellulose from *C. nardus* leaves and its incorporation into PVA to fabricate nanocellulose-reinforced composite films. The prepared nanocellulose was characterized in terms of its particle-size characteristics, structural features, surface morphology, and elemental composition using dynamic light scattering (DLS), Fourier-transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), and energy-dispersive X-ray spectroscopy (EDS), respectively. The resulting PVA/nanocellulose composite films were subsequently evaluated for their tensile properties and thermal conductivity as a function of nanocellulose incorporation. The relationships between the characteristics of the plant-derived nanocellulose and the mechanical and thermal transport properties of the resulting PVA composite films were investigated to assess their potential for sustainable packaging and other functional film applications.

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## 2. Materials and Methods

### *Materials*

All chemicals and reagents used in this study were of analytical grade and were used as received without further purification. Sodium hydroxide (NaOH), sulfuric acid (H<sub>2</sub>SO<sub>4</sub>, 98%), and hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) were used for the synthesis of nanocellulose from *Cymbopogon nardus* fibers. Partially hydrolysed poly (vinyl alcohol) (PVA) and glycerol were subsequently employed as the polymeric matrix and plasticizer, respectively, for the development of nanocellulose-reinforced composite films.

### *Methods*

#### **Preparation of *Cymbopogon nardus* fibers**

Fresh *Cymbopogon nardus* leaves were initially washed three times with an excess of deionized (DI) water to remove adhering dirt and other surface

impurities. The cleaned leaves were subsequently cut into approximately 1 cm lengths and mechanically processed until a fine, uniform pulp was obtained. The resulting pulp was washed three times with DI water until the green coloration was substantially removed. The resulting pale-yellow fibers were then dried in a hot-air oven at 60 °C for 12 h to obtain the dried fibers, which were subsequently used as the starting material for nanocellulose synthesis.

#### **Synthesis of *Cymbopogon nardus* Nanocellulose**

The dried *Cymbopogon nardus* fibers were first ground into a fine powder. Subsequently, 1 g of the fiber powder was subjected to acid hydrolysis using 10 mL of 60% H<sub>2</sub>SO<sub>4</sub> at 40 °C for 45 min under continuous stirring. Following hydrolysis, the reaction was quenched by adding ten times the reaction volume of ice-cold DI water. The resulting suspension was then subjected to probe sonication for 15 min using a 100 Hz pulse setting to facilitate the dispersion and fibrillation of the cellulose material. The sonicated suspension was centrifuged at 3500 rpm for 15 min to remove residual acid and other unwanted particles. The resulting nanocellulose suspension was repeatedly washed/centrifuged until a neutral pH was achieved and subsequently stored for further characterization and film fabrication.

#### **Fabrication of *Cymbopogon nardus* nanocellulose-PVA composite films**

Oven-dried nanocellulose powder (1000 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 plasticized by incorporating glycerol at 10 wt. % relative to the mass of PVA. The resulting PVA/glycerol solution was subsequently mixed 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 and the nanocellulose–PVA composite film exhibiting the highest tensile strength were 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<sup>-1</sup>.

##### **Particle Size Distribution Analysis**

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

##### **Thermal Conductivity analysis**

The Thermal conductivity characteristics of the prepared nanocellulose–PVA thin films were investigated using a Thermtest GHFM 01.

##### **Tensile Strength analysis**

The tensile properties of the fabricated nanocellulose–PVA thin films were evaluated using a 10 N load cell with Haida universal tensile tester. The film specimens were cut into dimensions of 60 mm × 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.

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## **RESULTS AND DISCUSSION**

### **Structural characterization**

Figure 1 presents the FTIR spectrum of the oven-dried nanocellulose derived from *Cymbopogon nardus*. The spectrum exhibits the characteristic vibrational bands associated with the cellulose structure, with prominent peaks observed at 3313, 2888, 1607, 1425, 1314, 1161, 1022, and 889 cm<sup>-1</sup> (Maida Salah Ud Din, 2026). The broad and intense band at 3313 cm<sup>-1</sup> is attributed to the O–H stretching vibrations of hydroxyl groups present in the cellulose chains (Dongyang Sun, 2020). The band at 2888 cm<sup>-1</sup> corresponds to C–H stretching vibrations associated with the pyranose ring structure (N. S. Lani, 2014). A relatively weak band at 1607 cm<sup>-1</sup> can be associated with the bending vibration of absorbed water, with possible contributions from residual lignin-related structures (Ekaterina I. Kashcheyeva, 2022).

The absence of distinct bands within the 1500–1600  $\text{cm}^{-1}$  region, together with the weak intensity of the band around 1730  $\text{cm}^{-1}$ , indicates the limited presence of lignin and hemicellulose in the isolated nanocellulose (Raffaella Lettieri, 2025). This spectral behaviour suggests that the alkaline treatment and subsequent bleaching effectively removed a substantial fraction of the non-cellulosic components from the *C. nardus* fibers. The remaining characteristic cellulose bands further support the successful isolation of the cellulose-rich fraction (Forough Momayez, 2019).

The band at 1425  $\text{cm}^{-1}$  is assigned to  $\text{CH}_2$  symmetric bending vibrations and is commonly associated with the crystalline structure of cellulose (Forough Momayez, 2019). The peaks observed at 1314 and 1161  $\text{cm}^{-1}$  correspond to  $\text{CH}_2$  wagging and asymmetric C–O–C stretching vibrations of the glycosidic bonds, respectively (Stefan Cichosz, 2020). These bands further confirm the preservation of the cellulose backbone in the isolated nanocellulose. At lower wavenumbers, the bands at 1022 and 889  $\text{cm}^{-1}$  are attributed to C–O–C skeletal vibrations of the pyranose ring and  $\beta$ -glycosidic linkages, respectively (Dileswar Pradhan, 2024). Overall, the FTIR spectrum confirms the characteristic chemical structure of cellulose and provides evidence for the effective removal of lignin and hemicellulose during the chemical treatment of *C. nardus* fibers (Rafidah Md Salim, 2021).

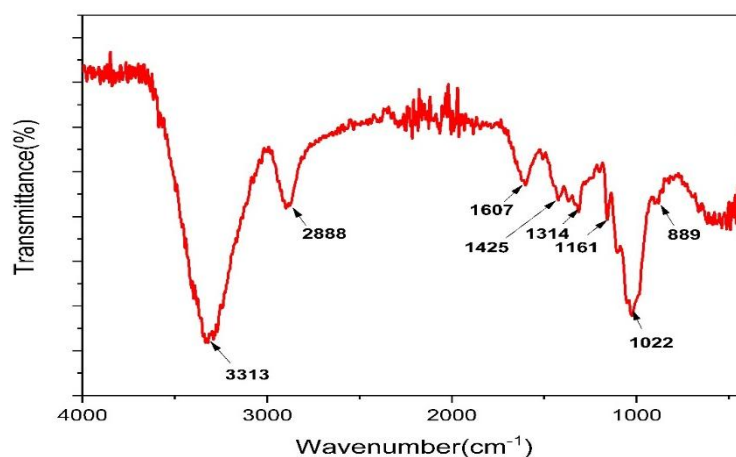


Figure 1: FTIR spectrum obtained for the *Cymbopogon nardus* leaves derived nanocellulose

## Morphological analysis

Figure 2(a) and (b) present the SEM micrographs of the oven-dried *Cymbopogon nardus*-derived nanocellulose at low and high magnifications, respectively. The oven-dried nanocellulose exhibits an irregular, crumpled, and heterogeneous morphology, which can be attributed to the aggregation of individual nanocellulose structures during drying. At lower magnification, the sample displays dense, folded, sheet-like structures containing aggregated ridges and localized voids. This morphology suggests substantial association and fusion of the nanocellulose structures during water removal (Qianqian Wang, 2019). At higher magnification, the surface reveals layered and highly crumpled features, with overlapping flake-like structures and distributed pore regions. Such morphological characteristics are consistent with the strong aggregation tendency of nanocellulose during drying, which arises from the extensive intermolecular hydrogen bonding between the hydroxyl-rich cellulose surfaces. As water evaporates, capillary forces bring adjacent nanocellulose structures into close contact, promoting their association and formation of compact structures. This irreversible aggregation during drying is commonly referred to as hornification and can result in dense, sheet-like morphologies rather than individually distinguishable nanocellulose structures (Laleh Solhi, 2023).

In contrast, the PVA–nanocellulose composite film shown in Figure 2(c) and (d), which exhibited the highest tensile strength and favourable thermal conductivity among the prepared films, demonstrates a comparatively smooth and homogeneous surface morphology. The SEM micrographs reveal a relatively continuous film structure without pronounced large-scale aggregates or extensive surface defects, suggesting effective incorporation and dispersion of nanocellulose throughout the PVA matrix (Melbi Mahardika, 2024). At higher magnification, only isolated and localized particulate features can be observed on the film surface, indicating that the nanocellulose did not undergo substantial macroscopic aggregation within the polymer matrix. This relatively uniform morphology is notable considering the highly hydrophilic nature of nanocellulose and may be attributed to favourable interactions between the hydroxyl groups of PVA and those present on the nanocellulose surface. These interactions can promote compatibility between the two components and facilitate more uniform distribution of nanocellulose throughout the polymer matrix during film formation (Fauzi Handoko, 2021).

The relatively homogeneous surface morphology is also favourable for stress transfer across the polymer–nanocellulose interface, which may contribute to the enhanced tensile performance observed for the composite film. Furthermore, the absence of large aggregates and extensive voids suggests the formation of a more continuous composite structure, which may contribute to the comparatively stable thermal conductivity of the nanocellulose-containing PVA film (Adel Ramezani Kakroodi, 2014). The well-dispersed nanocellulose structures can introduce additional interfaces within the polymer matrix and potentially increase the number of barriers to heat transport, thereby influencing the propagation of vibrational energy through the composite. This behaviour contrasts with the more heterogeneous morphology associated with aggregated structures and large void regions, where discontinuities within the matrix can substantially influence thermal transport. Overall, the SEM observations support the favourable dispersion and interfacial compatibility of nanocellulose within the PVA matrix and provide morphological evidence that is consistent with the observed mechanical and thermal properties of the composite films.

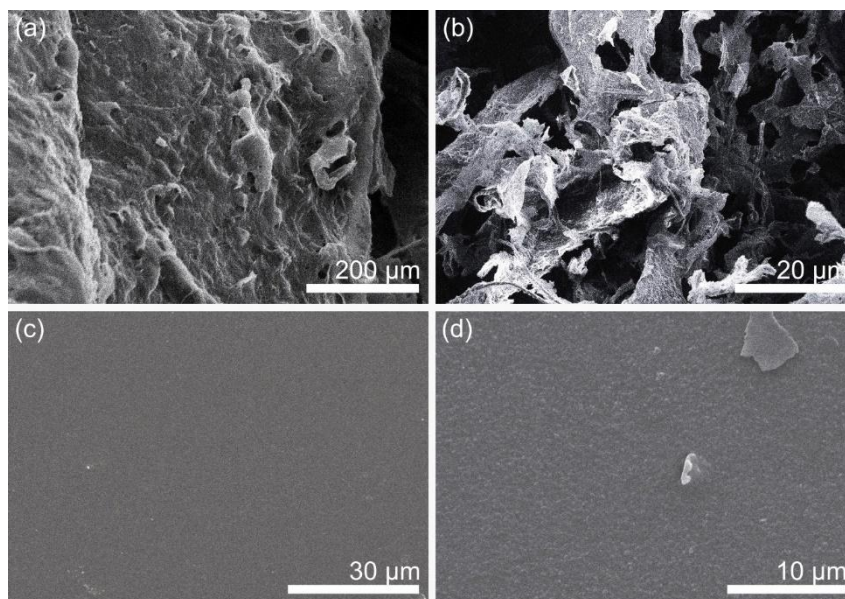


**Figure 2: SEM micrographs of *Cymbopogon nardus*-derived nanocellulose and the PVA/nanocellulose composite film with the highest tensile strength.**

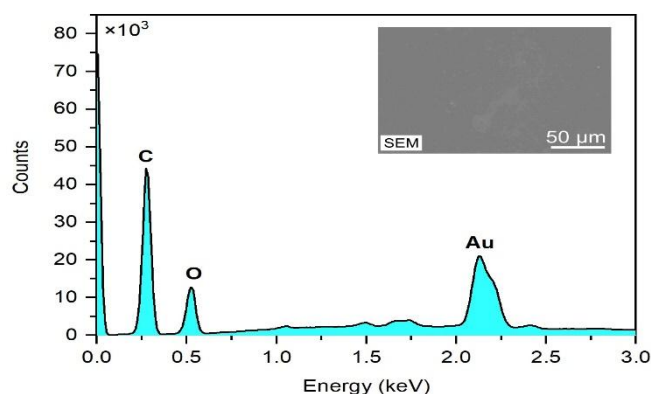


**Figure 3: EDS spectrum and corresponding SEM scan area of nanocellulose derived from *Cymbopogon nardus* plant leaves.**

The dominant carbon signal in EDS spectrum is consistent with the carbon-rich glycopyranose backbone of cellulose, while the oxygen distribution corresponds to the abundant oxygen-containing functional groups present within the cellulose structure (Beatris L. Mello 2024). The relatively homogeneous distribution of both elements across the scanned region indicates that the isolated nanocellulose does not exhibit pronounced compositional heterogeneity at the investigated scale.

The corresponding EDS spectrum presented in Figure 3 exhibits two prominent peaks at approximately 0.277 and 0.528 keV, which are attributed to carbon and oxygen, respectively. The predominance of these two signals confirms that carbon and oxygen are the major elemental constituents of the isolated nanocellulose, as expected for a cellulose-based material (Beatris L. Mello 2024). A distinct gold signal is also observed in the spectrum, which originates from the conductive gold coating applied to the non-conductive nanocellulose sample prior to SEM-EDS analysis.

In addition to the dominant carbon and oxygen signals, several weak peaks are observed within the approximately 1–1.8 keV region and around 2.4 keV. These minor signals can be associated with trace amounts of sodium, aluminium, silicon, and sulphur. The detected sodium, aluminium, and silicon may originate from residual processing impurities or contributions from the sample substrate or holder, and therefore should not necessarily be considered intrinsic constituents of the nanocellulose. In contrast, the detection of sulphur is of particular interest because the nanocellulose was prepared through sulfuric acid hydrolysis. Sulfuric acid treatment can introduce sulphate ester groups onto the cellulose surface through esterification of accessible hydroxyl groups, resulting in sulphur-containing surface functionalities.

Although the sulphur peaks are relatively weak, their presence suggests that sulphur-containing functionalities are associated with the nanocellulose surface rather than arising solely from a localized contaminant. Therefore, the EDS spectrum confirms the predominance of carbon and oxygen and their relatively uniform distribution throughout the isolated nanocellulose. In addition, the presence of a minor sulphur signal provides supporting

evidence of surface functionalization associated with the sulfuric acid hydrolysis treatment.

#### Tensile strength analysis

| Composition                            | Mean maximum Force of three film samples (N) | Mean thickness of three film samples (mm) | Mean Tensile strength of three film samples (MPa) |
|----------------------------------------|----------------------------------------------|-------------------------------------------|---------------------------------------------------|
| PVA                                    | 12                                           | 0.11                                      | 21.8                                              |
| PVA+Glycerol                           | 9.5                                          | 0.13                                      | 14.61                                             |
| PVA+Glycerol+100 $\mu$ l NC dispersion | 14                                           | 0.10                                      | 28                                                |
| PVA+Glycerol+250 $\mu$ l NC dispersion | 16                                           | 0.12                                      | 26.6                                              |
| PVA+Glycerol+500 $\mu$ l NC dispersion | 13                                           | 0.12                                      | 21.6                                              |

**Table 1: Mean Maximum Force, Film Thickness, and Tensile Strength of PVA-based films with different nanocellulose dispersion contents**

Table 1 presents the tensile strength of the PVA/nanocellulose composite films. The pristine PVA film exhibited a tensile strength of 21.8 MPa, which decreased to 14.61 MPa following the incorporation of glycerol at 10 wt. % relative to the PVA content. This reduction was accompanied by a decrease in the maximum force sustained by the film before failure, from 12 N to 9.5 N. The observed reduction can be attributed to the plasticizing effect of the relatively small glycerol molecules, which can interact with the hydroxyl groups of PVA and reduce intermolecular polymer–polymer interactions. Consequently, the polymer chains become more mobile and the overall film rigidity decreases, resulting in a reduction in tensile strength.

Interestingly, incorporation of nanocellulose into the PVA/glycerol matrix reversed this strength reduction. The composite containing 100  $\mu$ L of nanocellulose dispersion exhibited a tensile strength of 28.0 MPa, representing the highest value among the investigated compositions. This enhancement can be attributed to the reinforcing effect of the nanocellulose crystals, which possess a high aspect ratio and abundant surface hydroxyl groups capable of forming hydrogen-bonding interactions with both PVA and glycerol. The resulting interconnected hydrogen-bonded network can facilitate more efficient stress transfer throughout the polymer matrix and compensate for the mechanical strength reduction induced by glycerol plasticization (Mengxia Wang, 2022).

However, further increasing the nanocellulose dispersion volume resulted in a gradual reduction in tensile strength, with values of 26.6 MPa and 21.6 MPa obtained for 250 and 500  $\mu$ L additions, respectively. This decline may be associated with increasing nanocellulose–nanocellulose interactions and the formation of agglomerated regions at higher loadings, which can act as stress-concentration sites and hinder uniform stress transfer. Since the film thickness remained relatively constant within 0.10–0.12 mm, the observed variations in tensile strength are predominantly attributed to compositional effects rather than differences in film geometry. Overall, the 100  $\mu$ L nanocellulose loading provided the most effective balance between reinforcement and dispersion, resulting in the highest tensile strength, which is also consistent with the morphology observed in the SEM images (Sheng Xu, 2020).

#### Thermal conductivity and thermal resistivity behaviour

| Composition                            | Thermal conductivity (W/m.K) | Thermal resistivity (m.K/W) | Film thickness (mm) |
|----------------------------------------|------------------------------|-----------------------------|---------------------|
| PVA                                    | 0.633                        | 1.580                       | 0.11                |
| PVA+Glycerol+100 $\mu$ l NC dispersion | 0.403                        | 2.481                       | 0.13                |
| PVA+Glycerol+250 $\mu$ l NC dispersion | 0.361                        | 2.770                       | 0.19                |
| PVA+Glycerol+500 $\mu$ l NC dispersion | 0.101                        | 9.901                       | 0.11                |

**Table 2: Thermal Conductivity, Thermal Resistivity, and Thickness of PVA -Based Films with different nanocellulose dispersion contents**

Table 2 presents the thermal conductivity and thermal resistivity of the pristine PVA and PVA/nanocellulose composite films. The pristine PVA film exhibited the highest thermal conductivity of 0.633 W/m·K and the corresponding lowest thermal resistivity of 1.580 m·K/W. Following the incorporation of glycerol and nanocellulose, the thermal conductivity decreased to 0.403, 0.361, and 0.101 W/m·K for nanocellulose dispersion volumes of 100, 250, and 500  $\mu$ L, respectively, with corresponding increases in thermal resistivity. The reduction in thermal conductivity can be associated with the heterogeneous structure introduced by the nanocellulose phase, which increases the number of internal interfaces and phase boundaries within the polymer matrix (Ana Fernandes, 2023). Since heat transport in polymeric materials is largely governed by vibrational energy propagation, these interfaces can act as additional scattering sites and consequently impede heat transfer through the composite (Reaz A. Chowdhury, 2019).

The lowest thermal conductivity was observed for the composite containing 500  $\mu$ L of nanocellulose dispersion, indicating that this composition provided the greatest resistance to heat transport. As the nanocellulose content decreased, the thermal conductivity exhibited an increasing trend, indicating that the thermal response of the composite films is governed not only by the nanocellulose loading but also by its dispersion and distribution within the polymer matrix (K. H. Kojiro Uetani, 2017). At higher loading, the formation of nanocellulose-rich regions or agglomerates may introduce structural discontinuities and alter the continuity of heat-transfer pathways, consistent with the agglomeration tendency discussed in the tensile-strength analysis.

Overall, the incorporation of nanocellulose modified the thermal transport characteristics of the PVA-based films and, at suitable loading levels, enhanced their thermal resistance compared with pristine PVA. This combination of reduced thermal conductivity and improved mechanical reinforcement demonstrates the potential of PVA/nanocellulose composites for applications where thermal insulation is required without substantially

compromising structural integrity.

## CONCLUSION

This study demonstrated the successful extraction of nanocellulose from *Cymbopogon nardus* leaves and its application as a reinforcing and thermal-property-modifying filler in glycerol-plasticized PVA composite films. FTIR and EDS analyses confirmed the formation of a cellulose-rich structure following acid hydrolysis, while SEM revealed the aggregated morphology of the air-dried nanocellulose and its structural characteristics after incorporation into the PVA matrix. Glycerol plasticization reduced the tensile strength of pristine PVA; however, the incorporation of nanocellulose effectively restored and enhanced the mechanical performance of the composite films. The addition of 100  $\mu\text{L}$  of nanocellulose dispersion produced the highest tensile strength of 28 MPa, which can be attributed to the formation of an extensive hydrogen-bonded network between nanocellulose and the PVA matrix, promoting efficient stress transfer. Further increases in nanocellulose loading resulted in a reduction in tensile strength, likely due to nanocellulose agglomeration and the formation of stress-concentration regions. Moreover, nanocellulose incorporation altered the thermal transport behaviour of the composite films, with higher loadings increasing thermal resistivity, indicating increased structural discontinuities that hinder heat transport. Overall, *C. nardus*-derived nanocellulose shows considerable potential as a renewable multifunctional filler for PVA-based films, offering mechanical reinforcement and tunable thermal insulation properties for sustainable packaging and thermal-management applications.

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