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Production of nanocellulose and biocomposites from kawayan kiling (*Bambusa vulgaris* Schrader ex Wendland) shoots

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ABSTRACT. The study examined the potential of the shoots of a locally grown bamboo species, *kawayan kiling*, as a candidate raw material for nanocellulose production. The low lignin content of bamboo shoots which translates to ease of processing and low chemical and energy consumption, and the advantages of fast growth and wide distribution, altogether represent a favorable scenario for producing nanocellulose from bamboo shoots. Pretreatment of the bamboo shoots to isolate the cellulose consisted mainly of extraction with water, bleaching, and alkali treatment. After several trials under a variety of conditions, rod-like nanocellulose (NC) materials from bamboo shoots were obtained through hydrolysis of the isolated cellulose at 50% v/v H_2SO_4, 50^{o}C, and 45-min reaction time. The resulting NC materials from the bamboo shoots were 5.80 to 8.57 nm in diameter and 82.93 to 170.67 nm in length. The aspect ratios of the NC materials ranged from 11.89 to 21.97, with the ratios decreasing with the severity of hydrolysis conditions. The study also showed the feasibility of using bamboo shoot NC as reinforcement to polyvinyl alcohol (PVA) films. Fabrication of the PVA/NC films involved the addition of the prepared bamboo shoot NC to PVA in an aqueous system, followed by solvent casting. The well-dispersed NC showed good reinforcement effects on the PVA matrix. NC-reinforced PVA films with enhanced mechanical properties were produced at 2% NC loading. The NC-reinforced PVA films exhibited a tensile strength of 32.46 MPa, 53% higher than that of neat PVA film.

Keywords: Bamboo shoots, *Bambusa vulgaris*, nanocellulose, polyvinyl alcohol

INTRODUCTION

Cellulose, considered the most abundant, renewable, and biodegradable polymer, has long been used as key raw material in producing paper, textiles, building materials, and other industrial products. Its applications continue to expand to different fields, mainly driven by the increasing demand for products made from renewable and sustainable non-petroleum-based resources. Cellulose is being forwarded to resolve environmental issues besieging petrochemicals such as pollution, carbon footprint, and sustainability (Nechyporchuk *et al*. 2016). More recently, the design of processes using nanocellulose for the next generation of cellulose-based biomaterials has become a clear trend (Rebouillat & Pla 2013). The term ‘nanocellulose’ (NC) generally refers to cellulosic materials having at least one dimension in the nanometer range. It may be in the form of cellulose nanocrystals (CNC), produced by chemical methods like acid hydrolysis, or cellulose nanofibrils (CNF), which result from the mechanical disintegration of cellulosic fibers (Nechyporchuk *et al*. 2016). By extracting cellulose at the nanoscale, enhanced properties, new functions, and novel applications become possible with the resource. Also, the wide array of options for chemical and material processing of nanocellulose opens a vast range of possibilities in terms of structure and function (Dufresne 2013; Abitbol *et al*. 2016). Owing to its low thermal expansion, high aspect ratio, strengthening effect, and good mechanical and optical properties, nanocellulose finds many applications such as in composites, filtration, membranes, paints, packaging, biomedical sciences, construction, cosmetics, and foods (Abdul Khalil *et al*. 2014; Salas *et al*. 2014).

The main challenges towards the advancement of nanocellulose-based materials include finding new sources, new applications, and new preparation procedures. The properties of cellulose nanostructures depend largely on the cellulose source. Even though all nanocellulose materials are made of the same biopolymer, the use of different raw materials and different extraction methods determine its properties and applications (Moon *et al*. 2011; Garcia *et al*. 2016).

Recent studies have demonstrated the potential of bamboo for nanocellulose production. Bamboo plantations and natural stands exist all over the Philippines, both on government and private lands. Like wood, the cell walls of bamboo culms consist mainly of cellulose, hemicellulose, and lignin. Cellulose from bamboo has been described as having excellent toughness, hygroscopicity, and high crystallinity (Yu *et al*. 2012). Cellulose nanocrystals and nanofibrils have been successfully isolated from mature bamboo culms with the use of different chemical and mechanical methods (Chen *et al*. 2011; Brito *et al*. 2012; Chang *et al*. 2012; Yu *et al*. 2012; Villegas 2015; Wang *et al*. 2015; Hong *et al*. 2016). However, very limited research in the direction of nanocellulose production from bamboo shoots has been carried out to date (Wijaya *et al*. 2019).

It has been established in several studies that the lignin content of bamboo shoots is lower than that of mature bamboo (Shimokawa *et al*. 2009; Yang *et al*. 2014), suggesting that shoots can more easily be defibrillated and hydrolyzed. The ease with which shoots can be processed, with the associated reduction in chemicals and energy consumption, and the advantages of fast growth and wide distribution, altogether represent a favorable scenario for producing nanocellulose from bamboo shoots. This study examined the potential of the shoots of a locally grown bamboo species, *kawayan kiling* (*Bambusa vulgaris* Schrader ex Wendland), as a candidate raw material for NC production to capitalize on these professed advantages. The study also examined the reinforcing capability of the cellulosic nanocrystals from bamboo shoots to polymer matrix by fabricating NC-reinforced polyvinyl alcohol (PVA) films. PVA is a widely-used water-soluble, semi-crystalline, non-toxic, transparent, and petroleum-based biodegradable polymer (Liu *et al*. 2013; Tan *et al*. 2015). However, the low mechanical properties and integrity of PVA necessitate the incorporation of reinforcing materials like cellulose nanofibrils (Liu *et al*. 2013). Since both materials are polar, composites based on PVA and cellulose are likely to turn out into materials with excellent mechanical properties (Tan *et al*. 2015). The use of nanocellulose as reinforcement stemmed from the possibility of capitalizing on the high stiffness and strength of cellulose crystals in composite applications (Dufresne 2013; Lee *et al*. 2014). Incorporating nanocellulose materials into biodegradable polymer matrices is a strategy beneficial not only from a commercial viewpoint but also to the environment.

The development of value-added products such as nanocellulose materials is a potential route to increasing the value of bamboo shoots. Exploring the isolation methods and applications of bamboo shoot nanocellulose could lead to more efficient and valuable utilization of the resource and may also contribute to the development of strategies for establishing bamboo plantations, targeting shoots as the biomass source.

METHODOLOGY

Materials

Bambusa vulgaris shoots, 60 cm in height, were harvested from the Mount Makiling Forest Reserve (MMFR) in Los Baños, Laguna, Philippines. A previous study (Jara *et al*. 2018) revealed the chemical composition of the shoots as follows: 47.91% holocellulose, 27.71% α–cellulose, 11.95% lignin, 7.21% cyclohexane-ethanol extractives, 26.44% hot water extractives, and 11.30% ash.

Reagent grade chemicals, sulfuric acid (H_2SO_4), sodium hydroxide (NaOH), and acetic acid (CH_3COOH), as well as technical grade PVA (Mw = 72,000 g mol^{-1}) were used without further purification. Sodium hypochlorite (NaClO) from ordinary household bleach was utilized for the bleaching experiments.

Isolation of bamboo shoot NC

Initial preparation included removing the coarse sheath from the freshly harvested shoots and washing to remove any adhering dirt. The peeled shoots were cut into matchstick-size strips and blended for one minute for initial size reduction and disintegration of fibers. Pretreatment of the bamboo shoot fibers consisted of water extraction, bleaching, and alkali treatment. Water extraction at 80°C for 4 hrs was carried out to remove the extractives. As the shoots contain low amounts of lignin, mild bleaching was employed. The water-pretreated samples were bleached for 30 min with the use of 1.75% NaOCl solution. For alkali pretreatment, 20 mL of NaOH solution (17.5 g NaOH in 100 mL distilled water) was added to each 1 g bleached sample. The samples were placed in a water bath maintained at a temperature of 20°C for 30 min. The yield and lignin content of the products after each pretreatment stage were monitored. Lignin content determination was performed following the Technical Association of the Pulp and Paper Industry (TAPPI) Standard T222 om–02.

The alkali-insoluble cellulose (AIC) samples obtained from the pretreatment stages were subjected to acid hydrolysis for NC production. The isolated AIC was hydrolyzed with H_2SO_4 at a ratio of 1 g cellulose to 50 mL H_2SO_4. Earlier studies (Brito *et al*. 2012; Yu *et al*. 2012; Villegas 2015; Hong *et al*. 2016) about optimal combinations of acid concentration, temperature, and reaction time for sulfuric acid hydrolysis of bamboo were used as a guide. As shown in **Table 1**, three sets of conditions, mild to more severe, for the acid hydrolysis of the bamboo shoots were employed to yield NC-1, NC-2, and NC-3.

Table 1. Sets of conditions for the acid hydrolysis of bamboo shoot cellulose.

Sample code	Hydrolysis condition		
	H_2SO_4 concentration (% v/v)	Temperature (°C)	Reaction time (min)
NC-1	45	45	30
NC-2	50	50	45
NC-3	55	50	45

The hydrolysis reaction was quenched by adding 10-fold excess deionized water to the reaction mixture. After allowing the mixture to stand for 24 hrs, water was removed, and the sediment was collected. The bamboo shoot NC suspensions were then post-treated by centrifugation, dialysis, and sonication. The NC suspensions were transferred in falcon tubes and repeatedly washed using refrigerated centrifugation at 5°C and 10,000 rpm for 15 min. The samples were then collected in dialysis membranes and dialyzed for 3 days to remove free acid molecules. The dispersions were ultrasonicated using Cole Palmer Ultrasonic cleaner at 50–60 Hz for 30 min.

NC characterization

The samples were characterized in terms of morphology and chemical structure. The resulting NC yield for each treatment was also calculated. Atomic force microscope (AFM) images were taken in tapping non-contact mode using the Park Systems XE-BIO model. From each suspension, 15 uL of the sample was placed on freshly cleaved mica. The droplet was allowed to adsorb for 10 min and dried with pressurized N_2 gas. The sample was washed with 15 uL MQ-H_2O, and dried once again with N_2 gas. The dimensions of the NC materials were measured with the aid of the scanning probe microscopy data visualization and analysis software Gwyddion (http://gwyddion.net/).

The functional groups present in the chemical constituents of the samples at every stage of the treatment/preparation of the nanocellulose were investigated by Fourier-transform infrared spectroscopy (FTIR). The FTIR spectra of the samples were recorded in transmittance mode in the range of 400–4,000 cm^{-1}.

Fabrication and characterization of PVA/NC films

PVA aqueous solution was prepared by dissolving 4 g of PVA (Mw = 72,000 g mol^{-1}) in 200 mL deionized water at 80°C with stirring for 1 hr. After stirring, NC (2 and 4 wt% with respect to the weight of PVA) was added to the PVA solution. The solutions were kept at 80°C with stirring for 2 hrs. The solutions were then placed in an ultrasonic bath for 15 min to remove all bubbles. The PVA-based solutions were poured into non-stick containers and dried at 50°C for 72 hrs. Three films, each with a diameter of about 18 cm per treatment (PVA, PVA/NC–2%, and PVA/NC–4%), were prepared and tested.

The films were characterized in terms of thickness, grammage, and density, as well as mechanical properties. Thickness measurements were obtained with the use of a digital caliper. The grammage of the film was determined by dividing the weight of the film by its area. Density was obtained by dividing the weight by the volume of the film.

The tensile strength of each film was determined using the Instron 4411 universal testing machine. The test specimens consisted of strips of uniform width of 15 mm and length of 150 mm. The test followed ASTM D882, which covers the determination of tensile properties of plastics in the form of thin sheeting, including films with less than 1.0 mm thickness. The test was performed in triplicates for each treatment.

Statistical analysis

Results of analyses were expressed as mean ± standard deviation (SD). Statistical analysis on a completely randomized design was conducted using the analysis of variance (ANOVA) procedure. An α = 0.05 level of significance was applied in all cases. Statistical analyses were performed using SPSS (IBM Corp.) and STATA (StataCorp) software packages.

RESULTS AND DISCUSSION

Lignin content and yield

Pretreatment techniques to produce nanocellulose from lignocellulosic materials involve the complete or partial removal of matrix materials, lignin, and hemicellulose, as well as the isolation of purified cellulosic fibers (Moon *et al*. 2011; Rebouillat & Pla 2013). As the bamboo shoot samples underwent the different pretreatment stages, size reduction and conversion into finer, thread-like fibers were apparent (**Figure 1**). The water-treated fibers became slightly yellowish upon bleaching and then whiter as converted into AIC. The fibers also became softer as bleached, and alkali-treated. These effects of the pretreatment techniques on the fibers were anticipated as each step targeted the removal of other constituents in the fibers apart from cellulose.

Nearly all the lignin in the samples were removed by bleaching and alkali treatments. It was found that the

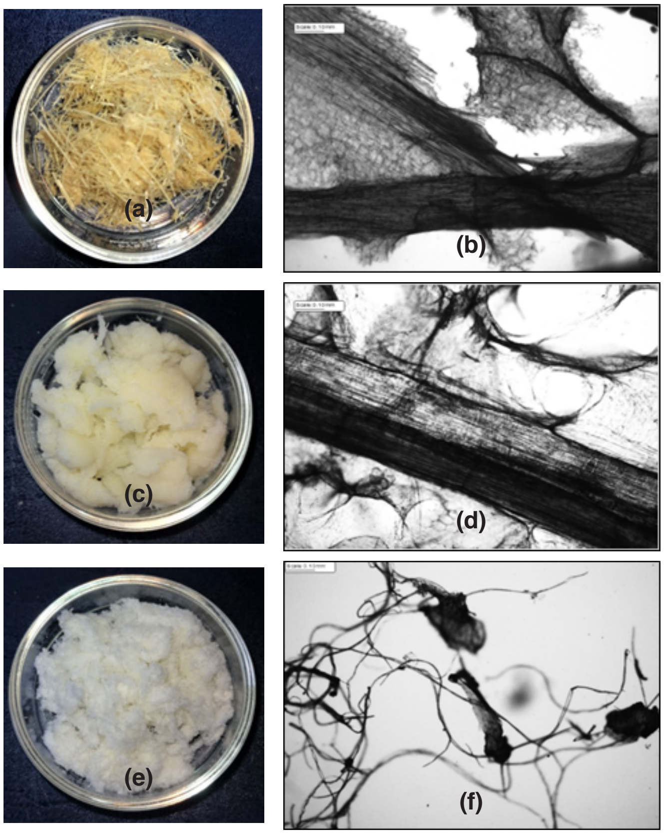


Figure 1. The water-treated fibers (a and b), bleached fibers (c and d), and AIC (e and f) from the bamboo shoots, with corresponding 10x images (scale bar = 0.10 mm).

water-treated, bleached, and AIC samples contained 7.96%, 0.83%, and 0.29% lignin, respectively. Low lignin content, 0.63%, was observed as well in *Dendrocalamus asper* shoot samples produced by Wijaya *et al*. (2019) after alkali treatment and bleaching. The low lignin content of the bamboo shoots and the ease in which lignin could be removed justify the use of a one-step, short-duration bleaching process for the delignification of the fibers from the bamboo shoots in the study. This demonstrates the key advantage of using bamboo shoots as a raw material since lignin is regarded as one of the natural factors contributing to the recalcitrance of lignocellulosic feedstock to chemicals or enzymes. This advantage translates to easier fiber delignification and less harmful purification processes for cellulose (Nechyporchuk *et al*. 2016).

The reduction in non-cellulosic components in the fibers during each pretreatment stage can be inferred from the calculated yield for each step (**Table 2**). The low yield after water treatment may reflect the high water-soluble components present in the samples. Also, subjecting the soft and fragile tissues of the shoots to disintegration via a high-speed blender, albeit for a short duration, may have contributed to the lowering of the yield. During bleaching, other components were possibly removed aside from lignin. These other components may include the extractives not removed by water extraction and possibly some portion of cellulose, as it has been reported that sodium hypochlorite may also attack cellulose aside from removing lignin (Xian *et al*. 2020). The last pretreatment stage, alkali treatment, aims to isolate pure cellulose (AIC) by removing hemicelluloses, pectins, and waxes (Ng *et al*. 2015; Jones *et al*. 2017). The yield values obtained after pretreatment stages translate to an equivalent yield of around 15% based on the moisture-free weight of raw bamboo shoots.

Table 2. Yield at the different stages of NC production from the bamboo shoots.

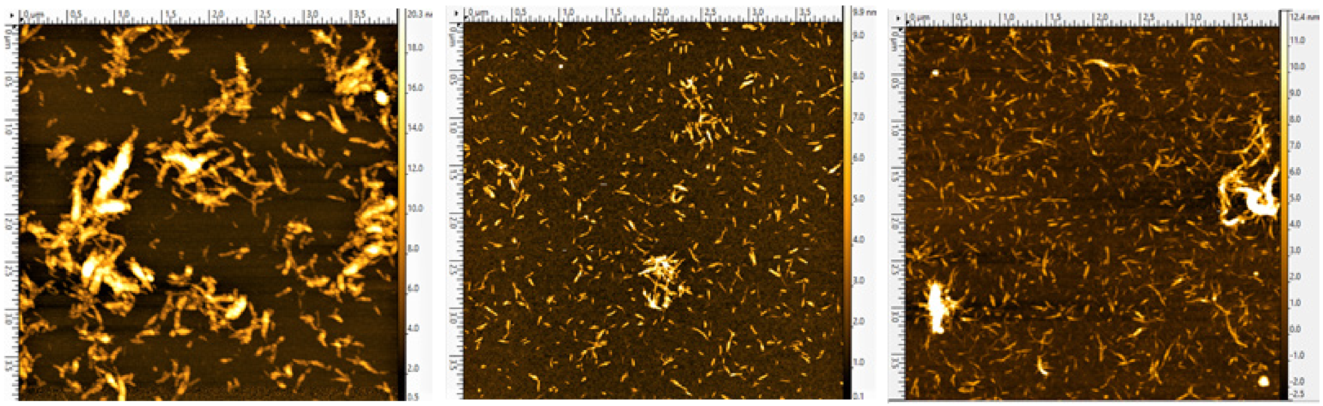
Stage	Yield (%)*
Water treatment	45.62
Bleaching	62.37
Alkali treatment	54.05
Acid hydrolysis:	
NC-1	73.04
NC-2	59.56
NC-3	12.32

**based on the weight of starting material for each stage*

Isolation of NC from the prepared AIC from the bamboo shoots was achieved by subjecting the samples to acid hydrolysis. The amorphous domains of cellulose are susceptible to the attack of acids and may be removed under controlled conditions, leaving the crystalline regions intact (Ng *et al*. 2015; Garcia *et al*. 2016). Significant differences in yield were observed in the different treatments, with NC-1 having the highest yield with respect to the amount of AIC. The results obtained for NC-1 and NC-2 were higher than the optimum yield of 50.67% obtained by Wijaya (2019) from the acid hydrolysis of pretreated bamboo shoots using 54.73 wt% sulfuric acid concentration (1:20 sample mass to acid volume ratio), at 39°C for 60 min. Concerning the moisture-free weight of raw bamboo shoots, the yield values were equivalent to 11.23%, 9.16%, and 1.90% for NC-1, NC-2, and NC-3, respectively. The decreasing trend in yield may be traced to the increasing severity of the hydrolysis conditions. The higher yield obtained for NC-1, supported by the morphology of the NC materials as shown in its AFM images, may indicate that the hydrolysis was inadequate or incomplete. As such, there may have been incomplete removal of the amorphous regions. On the other hand, the low yield for NC-3 suggested that the combination of 55% v/v H_2SO_4, 50°C, and 45 min might have been severe for the material, resulting in cellulose degradation (Yu *et al*. 2012). The yellowish or brownish resultant suspension of NC-3 after hydrolysis may be indicative of degradation.

Morphology

Minimal agglomerations and numerous fine rod-like nanomaterials were found in the AFM images of the cellulose nanocrystals (**Figure 2**). The relatively mild hydrolysis conditions employed to produce NC-1 resulted in coarse, uneven-width nanomaterials, while the more severe combinations for the isolation of NC-2 and NC-3 resulted in fine, rod-like ones typical of NCs reported in



(a) (b) (c)

Figure 2. AFM images (scan area: 4 µm x 4 µm) of (a) NC-1, (b) NC-2 and (c) NC-3.

the literature (Moon *et al*. 2011; Jonoobi *et al*. 2015). As mentioned earlier, the mild conditions for NC-1 production may have resulted in incomplete hydrolysis, hence the coarse and long nanomaterials. On the other hand, the isolation of rod-like NC-2 and NC-3 nanomaterials was likely due to more severe conditions, such as higher acid concentration, higher temperature, and longer hydrolysis time, giving rise to shorter nanomaterials (Rebouillat & Pla 2013).

The average sizes of the nanomaterials as gathered from AFM images fall within the range listed in related reports (Moon *et al*. 2011; Brito *et al*. 2012), with the bamboo shoot NCs having a diameter of 5.80–8.57 nm, and length of 82.93–170.67 nm (**Table 3**). The aspect ratios of the NCs ranged from 11.89 to 21.97. Aspect ratio, which is the ratio of the length to the diameter of the cellulose nanomaterials, is an essential parameter for NCs as it influences the strength and web formation in films and displays (Dufresne *et al*. 2013; Bharimalla *et al*. 2015). A decreasing trend in aspect ratio with the severity of hydrolysis conditions was observed.

Table 3. Dimensions of the bamboo shoot NC based on AFM.

Sample	Diameter (Nm)	Length (Nm)	Aspect ratio
NC-1	8.57 + 3.09a	170.67 + 73.31a	21.97 + 13.52a
NC-2	5.80 + 1.16b	86.29 + 27.23b	15.54 + 6.01b
NC-3	6.90 + 1.08ab	82.93 + 52.27b	11.89 + 6.49c

Mean values listed in columns with different letters indicate statistically significant differences ($P < 0.05$)

Chemical structure

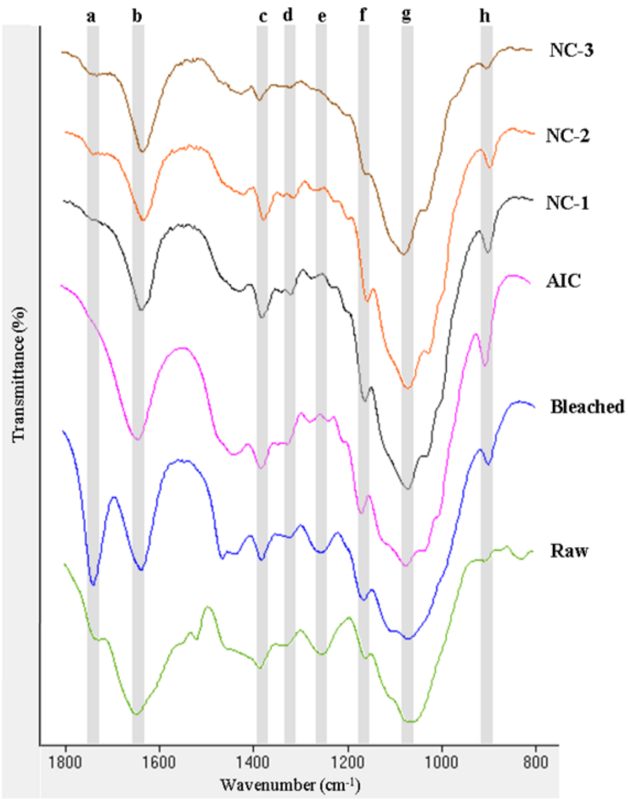
The FTIR spectra of the cellulose nanomaterials revealed two regions typically observed in cellulosic materials, the OH and CH stretching vibrations in the 3800–2700 cm^{-1} region and the "fingerprint" region assigned to stretching vibrations of different functional groups at 1800–800 cm^{-1} (Poletto *et al*. 2012). The dominant peaks of OH-stretching and CH-stretching at approximately 3400 cm^{-1} and 2800 cm^{-1}, respectively, were observed in all spectra. The CH vibrations at around 2800–2900 cm^{-1} are usually not analyzed in detail since cellulose, hemicelluloses, and lignin have similar peak shapes in this region (Carrillo *et al*. 2018; Aguayo *et al*. 2018).

In the fingerprint region (**Figure 3**), the CH and CO stretching peaks at 1375–1385, 1316–1337, 1154–1164, 1063–1074, and 896–898 cm^{-1} represent the cellulose content in all samples. A prominent peak around 1,735 cm^{-1} was detected in the bleached samples. Poletto *et al*. (2012) narrated that this band is assigned to CO stretching v ibrations of the carboxyl and acetyl groups in hemicellulose. A strong peak indicates higher holocellulose content at this band. Therefore, it is not surprising that the bleached sample, which consists mainly of holocellulose, registered the strongest band around 1735 cm^{-1}. After alkali reatment, this prominent peak at 1735 cm^{-1} disappeared completely. Also, the peak near 1260 cm^{-1} in the raw and bleached samples, which represents stretching of OCO and CO groups in guaiacyl lignin (Lehto *et al*. 2018), was not present in the AIC samples. This observation corroborates the results of lignin content determination discussed earlier. The disappearance of the above mentioned peaks suggests that the goal of purifying the samples, leaving cellulose only, was achieved during the pretreatment stages.

The spectra obtained from the NC produced in the study resemble that of the AIC and revealed the presence of IR bands corresponding to neat nanocellulose materials as described in the literature (Foster *et al*. 2018). This result implies that the molecular structure of cellulose was not altered by the chemical treatments.

Properties of PVA/NC films

The reinforcing potential of the NC from bamboo shoots was evaluated by preparing PVA/NC films through solvent-casting technique. Specifically, NC-2 from the previous part of the study was used in the fabrication of films. Thin and transparent NC-reinforced PVA films were fabricated, with 0.1194–0.1217 mm thickness,



(a) 1726-1737 cm-1 CO stretching vibrations of the carboxyl and acetyl groups in hemicellulose
(b) 1630-1646 cm-1 adsorbed water
(c) 1375-1385 cm-1 CH deformation vibration of cellulose
(d) 1316-1337cm-1 CH deformation vibration of cellulose
(e) 1249-1252 cm-1 OCO and CO stretching vibrations of lignin
(f) 1154-1164 cm-1 COC asymmetric stretching of cellulose
(g) 1063-1074 cm-1 CO stretching vibration of cellulose
(h) 896-898 cm-1 CH rock vibration of cellulose

Figure 3. FTIR spectra of raw and bleached fibers, AIC, and NC from *B. vulgaris* shoots.

148.55–156.18 g m^{-2} grammage, and 1.23–1.29 g cm^{-3} density (**Table 4**). The compatibility of PVA and natural fibers is attributed to the formation of the hydrogen bonds between the hydroxyl groups in both PVA and the cellulose in the fibers (Tan *et al*. 2015). The incorporation of NC did not affect the thickness, grammage, and density of the films as statistically insignificant differences were observed in all values for each parameter.

Table 4. Thickness, grammage, and density of the PVA and PVA/NC films.

Film	Thickness (mm)	Grammage (g m^{-2})	Density (g cm^{-3})
PVA	0.1217 + 0.0103a	148.55 + 2.53a	1.23 + 0.08a
PVA/NC-2%	0.1194 + 0.0090a	151.74 + 4.82a	1.27 + 0.06a
PVA/NC-4%	0.1210 + 0.0056a	156.18 + 2.03a	1.29 + 0.06a

Mean values listed in columns with different letters indicate statistically significant differences (P < 0.05).

The addition of 2% and 4% NC improved the tensile strength and Young's modulus of the films (**Table 5**). This improvement in mechanical properties reflects the reinforcing capability of the NC materials. With the grammage, density, and thickness of the films, whether neat or NC-reinforced, statistically equal, the differences in the strength properties of the films can only be traced to the presence of the NC materials in the films.

Table 5. Mechanical properties of the PVA and PVA/NC films.

Film	Tensile Strength (MPa)	Young's Modulus (MPa)
PVA	21.17 + 5.03b	82.45 + 6.79b
PVA/NC-2%	32.46 + 3.62a	146.67 + 20.28b
PVA/NC-4%	29.84 + 1.71a	319.56 + 72.59a

Mean values listed in columns with different letters indicate statistically significant differences (P < 0.05).

Tensile strength was highest (32.46 MPa) at the NC loading of 2 wt%. This value is 53% higher than that of neat PVA film. The intermolecular forces between NC and the base matrix may have enhanced the tensile strength of the PVA composite films (Rahman *et al*. 2014). On the other hand, at 319.56 MPa, a nearly threefold increase in Young's Modulus was recorded for PVA/NC–4%.

Improved mechanical properties at low loading of nanocellulose in PVA films have been reported in the literature (Gonzalez *et al*. 2014; Li *et al*. 2014; Rahman *et al*. 2014). This improvement could be attributed to the crystallinity, surface area, and active interfaces of the nanometer size materials (Panaitescu *et al*. 2008). The formation of strong hydrogen bonds between nanocellulose and PVA contributes to the uniform dispersion of nanofillers in the PVA matrix and results in excellent load transfer from the matrix to the nanocellulose reinforcement (Ching *et al*. 2015). The processing method used in forming the films, evaporation casting, may have also facilitated the development of the high-strength nanocomposites. According to Ramires & Dufresne (2011), slow processes such as casting/evaporation produce materials with the highest mechanical performance compared with other methods. During slow water evaporation, a rearrangement of the nanowhiskers is likely to occur because of Brownian motion in the suspension. The interaction of the nanowhiskers makes possible the formation of a continuous network, which is the foundation of the reinforcing effect.

CONCLUSION AND RECOMMENDATIONS

The study demonstrated the feasibility of producing cellulose nanocrystals from *B. vulgaris* shoots. Pretreatment of the bamboo shoots did not necessitate pulping and consisted mainly of extraction with water, bleaching, and alkali treatment to isolate cellulose. Three sets of conditions, mild to more severe, for the acid hydrolysis of the bamboo shoots were employed, with yield ranging from 1.90% to 11.23% with respect to the moisture-free weight of raw bamboo shoots. NC materials with a diameter of 5.80–8.57 nm and a length of 82.93–170.67 nm were obtained. The aspect ratios of the NCs ranged from 11.89 to 21.97, with the ratios decreasing with the severity of hydrolysis conditions. The best results for the isolation of rod-like NC materials from the bamboo shoots were obtained with the use of moderate hydrolysis conditions of 50% v/v H_2SO_4, 50°C, and 45 min reaction time.

The NC isolated from the bamboo shoots and PVA showed good compatibility when fabricated into films. Fabrication of the PVA/NC films involved adding the prepared bamboo shoot NC at low loading of 2 and 4 wt% to PVA in an aqueous system and solvent casting. The thickness, grammage, and density of the PVA/NC films were comparable to those of pure PVA films. Films of about 0.1194–0.1217 mm thickness, 148.55–156.18 g m^{-2} grammage, and 1.23 to 1.29 g cm^{-3} density were produced. The well-dispersed NC showed good reinforcement effects on the PVA matrix. The study demonstrated that at low loading of the bamboo shoot NC, it is possible to fabricate NC-reinforced PVA films with enhanced mechanical properties. The tensile strength of the NC-reinforced PVA films showed the highest value of 32.46 MPa at the NC loading of 2 wt%, which is 53% higher than that of neat PVA film.

While the study provided evidence and vital information about the potential of the bamboo shoots as raw material for nanocellulose and biocomposite production, many areas for further exploration remain. The wide array of techniques for the processing of nanocellulose presents numerous opportunities and possibilities for the bamboo shoot NC. Further research could open new avenues for tapping the vast potential of this renewable natural product.

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