



Effect of alkali surface treatments on mechanical and morphology of natural galangal fibers

Sukanya Petchsirivej^{1,*}, Pornsiri Wanarattikan¹ and Noppamas Akarachantachote²

¹Physical Department, Faculty of Science and Technology, Huachiew Chalermprakiet University, Thailand

² Computing Science and Digital Technology Department, Faculty of Science and Technology, Huachiew Chalermprakiet University, Thailand

*Corresponding author: sukanya.pet@hcu.ac.th

Received 29 January 2026

Revised 5 May 2026

Accepted 5 May 2026

Abstract

This study addresses the value-addition to agricultural residues by investigating the effects of alkali treatment on the physical and mechanical properties of *Alpinia galanga* (L.) Willd (AG) and *Alpinia siamensis* K. Schum (AS) pseudo-stem fibers. The fibers were extracted from pseudo-stem segments with an initial length of 25-30 cm. The untreated fiber diameters were $131.96 \pm 38.42 \mu\text{m}$ for AG and $172.50 \pm 42.94 \mu\text{m}$ for AS. To evaluate treatment efficiency, both a thermal-assisted at low concentration route and a conventional room-temperature process were compared. Morphological and surface roughness analyses (R_q and R_a) revealed that alkali treatments effectively dissolved surface impurities, reduced fiber diameters (reaching minimums of $107.99 \pm 20.90 \mu\text{m}$ for AG at 10% wt. NaOH and $62.75 \pm 11.77 \mu\text{m}$ for AS at 15% wt. NaOH), and induced distinct fibrillation. Regarding mechanical performance, the treated fibers showed enhanced tensile strength and elongation. The maximum tensile strength for AG was $147.67 \pm 53.47 \text{ MPa}$ (at 5% wt. NaOH), while AS peaked at $215.64 \pm 95.57 \text{ MPa}$ (at 0.5% wt. NaOH). Although extreme concentrations (15% wt. NaOH) yielded maximum elongation for both AG ($7.25 \pm 1.74\%$) and AS ($5.93 \pm 1.30\%$), they triggered cellulose degradation and reduced tensile strength. These findings highlight that optimized, low-chemical alkali treatments can successfully tailor galangal fibers into sustainable reinforcing materials, advancing circular economy principles in composite engineering.

Keywords: Alkali-Treatment, Elongation at break, Galanga fiber, Surface roughness, Tensile strength

1. Introduction

Currently, agricultural waste, such as stems and leaves, is often disposed of through natural decomposition or open burning, which significantly contributes to environmental degradation and air pollution. However, these biomass residues are rich in natural fibers that can be utilized in various functional applications. The utilization of such agricultural waste not only reduces environmental burdens but also creates added value, directly promoting a circular economy. In recent years, natural fibers have gained significant attention as sustainable alternatives to synthetic fibers, particularly as reinforcing fillers in composite materials, owing to their acceptable specific mechanical properties, low density, and biodegradability [1, 2]. Consequently, extensive research efforts have been directed toward extracting natural fibers from plants such as bamboo, flax, hemp, jute, palm, pineapple, and galangal for structural and engineering applications [2-7].

Despite their potential, the structural application of natural fibers is often limited by their inherent complex composition, primarily consisting of cellulose, hemicellulose, pectin, and lignin. To enhance the interfacial adhesion between natural fibers and polymer matrices, various surface modifications are required. Among these, chemical treatment, particularly alkaline processing is one of the most widely used and effective methods. The application of alkaline solvents such as sodium hydroxide (NaOH) facilitates the breakdown and partial removal of amorphous lignin and hemicellulose. This process alters the surface topography, removes impurities, and promotes fiber fibrillation, which ultimately improves the mechanical strength and fiber-resin interaction [7-9].

Alpinia galanga (L.) Willd. (family Zingiberaceae), locally known in Thailand as Kha, is widely cultivated for its culinary and medicinal rhizomes [10, 11]. Following the harvest of valuable rhizomes, the pseudo-stems (1 - 3.5 meters in height) are typically discarded as agricultural waste [12-14]. Under the framework of the circular economy, valorizing this abundant biomass into functional natural fibers offers a promising sustainable solution. According to previous studies, galangal pseudo-stems contain approximately 14% natural fibers, alongside moisture (5.43%) and essential minerals [15]. In terms of chemical composition, galangal fibers contain moderate levels of amorphous binding materials, specifically hemicellulose (16.52%) and lignin (11.21%) [16]. While its hemicellulose content is lower than that of other agricultural residues like corn husk, its lignin content is significantly lower than that of woody biomass. This moderate chemical profile is particularly favorable, as it allows for the effective removal of non-cellulosic binders through chemical treatments, such as the sodium hydroxide (NaOH) processes employed in this study. Such modifications facilitate an increase in the relative cellulose proportion and mechanical integrity, positioning galangal fibers as a competitive, eco-friendly reinforcement for lightweight composites compared to traditional fibers like jute or sisal.

Therefore, the present study aims to investigate the effects of different alkaline treatment routes on the morphological and mechanical properties of natural fibers extracted from galangal pseudo-stems. Specifically, the experimental design compares a conventional high concentration NaOH treatment at room temperature with a thermal-assisted low-concentration NaOH treatment. This comparative approach was selected to evaluate the optimal balance between chemical consumption, processing time, and the resulting fiber quality. The surface morphology and diameter of the treated fibers were observed using a scanning electron microscope (SEM) and an optical microscope (OM), respectively. Furthermore, the tensile properties were measured according to ISO 5079 - 1955(E) standard [17]. Statistical analysis of the experimental data was conducted using the Shapiro-Wilk test, the Kruskal-Wallis test, and Dwass-Steel-Critchlow-Fligner pairwise comparisons to ensure the reliability of the findings.

2. Materials and methods

2.1 Materials

Galangal pseudo-stems from two distinct species were utilized in this study: *Alpinia galanga* (L.) Willd. (AG), obtained from a local farmer in Bang Sao Thong District, and *Alpinia siamensis* K. Schum. (AS), sourced from Bang Bo District, Samutprakarn Province, Thailand. Sodium hydroxide (AR grade) was purchased from Pine Chemical.

2.2 Fiber Extraction and Alkali Treatments

The pseudo-stems were cut into segments 25-30 cm in lengths and thoroughly washed. To facilitate initial fiber separation, the outer layers of the stems were mechanically crushed using a hammer. Following repeated rinsing with deionized (DI) water, the raw fibers were randomly assigned to two distinct alkali treatment routes:

1. Thermal-Assisted Route: Fibers were immersed in low-concentration NaOH solutions (0.5%, 1.0%, and 2.0% wt.) and heated at 90 °C for 1 hour.
2. Room-Temperature Route: Fibers were submerged in NaOH solutions of varying concentrations (0%, 5%, 10%, and 15% wt.) and maintained at ambient temperature for 40 days.

After the treatment process, all fibers were vigorously washed with DI water until the rinse water reached a neutral pH (~7.0) to eliminate any residual alkali. The treated fibers were subsequently air-dried and stored in a desiccator to prevent moisture absorption prior to further characterization.

2.3 Diameter and Morphologies measurement

The diameter of galangal fibers was measured 50 times using the optical microscope, Leica DM750 from Germany. The surface morphology of the fibers was observed using a Hitachi SU8020 scanning electron microscope, which offers a magnification range of 0.020K-800K and an acceleration voltage between 0.1-30kV. The platinum was sputtering with Quorum Sputter Coater (Q150RES). The surface roughness was quantified by the arithmetic average roughness (R_a) and the root mean square roughness (R_q) by following equations 1 and 2.

$$R_a = \frac{1}{n} \sum_{i=1}^n |z_i - \bar{z}| \quad (1)$$

$$R_q = \sqrt{\frac{1}{n} \sum_{i=1}^n (z_i - \bar{z})^2} \quad (2)$$

When z_i = the intensity value (gray value) at each point, and $\bar{z}$ = the mean intensity value., n = the number of data points.

2.4 Tensile stress and elongation measurement

A single galangal fiber was tested by the single fiber tensile test following ISO 5079 - 1955(E) [17] by an Autograph (AGS5kN) from Shimadzu Japan. The tests were conducted at a constant crosshead speed of 3 mm/min, and a total of 50 replicate samples were tested for each condition to ensure statistical reliability. Tensile stress and elongation values are measured automatically by the equipment by following equations 3 and 4 for the tensile stress and the elongation respectively.

$$\sigma_{max} = \frac{F_{max}}{A} \quad (3)$$

$$\varepsilon = \left(\frac{L_i - L_0}{L_0} \right) \times 100\% \quad (4)$$

When σ_{max} = maximum tensile strength (MPa), ε = elongation at break, and A = a cross-section area of fiber (mm^2).

2.5 Statistical method

In the quantitative data analysis, descriptive statistics including the mean $\pm$ standard deviation (SD) and the median were calculated to summarize the dataset and provide an overview of the main variables of interest, which are diameter, tension strength, and elongation of the fibers. The Shapiro-Wilk test was performed to verify the assumption of normality in the data distribution. As the data failed to satisfy the assumptions of normality, as evidenced by the Shapiro-Wilk test, the Kruskal-Wallis test was employed to compare the diameter, tensile strength, and elongation of fiber across different methods. Additionally, Dwass-Steel-Critchlow-Fligner pairwise comparisons were performed to identify specific differences between the methods.

3. Results and discussion

3.1 Statistical Analysis

Fiber diameters were measured using an optical microscope (OM), while the tensile strength and elongation were determined using an Autograph (AGS-5kN) universal testing machine in accordance with the ISO 5079-1995 standard. Descriptive statistics for all parameters are summarized in Table 1. Due to the non-normal distribution of the data, the Kruskal-Wallis test was applied to evaluate the overall differences among the treatment methods, followed by Dwass-Steel-Critchlow-Fligner (DSCF) post hoc analyses to identify specific group differences (Table 2 and Table 3). Kruskal-Wallis analysis was performed to evaluate the effect of various treatments on fiber. The results indicated statistically significant differences among the groups at a 0.05 significance level for both AG and AS fibers.

Table 1 Descriptive statistics of diameter, tensile strength and elongation.

Variable	Method	AG Fiber		AS Fiber	
		Mean±SD	Median	Mean±SD	Median
Diameter (µm)	Untreated (Water)	131.96 ± 38.42	136.69	172.50 ± 42.94	177.35
	0.5% wt. NaOH 90°C	158.33 ± 42.80	156.36	123.85 ± 28.69	122.11
	1% wt. NaOH 90°C	109.49 ± 25.54	109.30	139.27 ± 36.43	137.59
	2% wt. NaOH 90°C	177.82 ± 31.13	177.91	117.00 ± 17.87	113.24
	5% wt. NaOH	138.87 ± 30.47	144.87	96.59 ± 27.55	87.67
	10% wt. NaOH	107.99 ± 20.90	111.95	78.78 ± 19.28	72.72
	15% wt. NaOH	120.81 ± 26.42	118.49	62.75 ± 11.77	60.11
Tensile strength (MPa)	Untreated (Water)	68.51 ± 31.06	64.41	110.49 ± 41.62	113.06
	0.5% wt. NaOH 90°C	96.58 ± 44.67	93.97	215.64 ± 95.57	210.78
	1% wt. NaOH 90°C	132.09 ± 48.74	129.33	201.13 ± 77.81	187.67
	2% wt. NaOH 90°C	145.71 ± 52.53	142.11	192.72 ± 64.60	176.88
	5% wt. NaOH	147.67 ± 53.47	142.34	212.27 ± 87.72	197.52
	10% wt. NaOH	130.59 ± 41.74	128.04	214.75 ± 76.34	193.60
	15% wt. NaOH	97.58 ± 41.52	93.34	199.88 ± 77.28	177.30
Elongation (%)	Untreated (Water)	1.22 ± 0.40	1.16	2.02 ± 0.35	2.04
	0.5% wt. NaOH 90°C	2.23 ± 0.70	2.12	2.84 ± 0.47	2.74
	1% wt. NaOH 90°C	2.51 ± 0.68	2.43	2.76 ± 0.40	2.83
	2% wt. NaOH 90°C	3.19 ± 0.67	3.22	2.28 ± 0.33	2.26
	5% wt. NaOH	2.76 ± 0.65	2.71	2.24 ± 0.52	2.32
	10% wt. NaOH	6.73 ± 1.36	7.01	4.10 ± 1.03	4.18
	15% wt. NaOH	7.25 ± 1.74	7.41	5.93 ± 1.30	5.97

These untreated fibers diameter frequently demonstrated significant differences compared to the treated samples, particularly in AS fibers where $p < 0.001$ for most comparisons. In contrast, AG fiber's diameter showed fewer significant in diameter between treatment pairs, although specific comparisons such as Water vs. 1% wt. NaOH 90°C, Water vs. 2% wt. NaOH 90°C, and 1% wt. NaOH 90°C vs. 2% wt. NaOH 90°C, did yield statistical significance.

Table 2 Kruskal–Wallis test of median differences in diameter, tensile strength, and elongation for AG fiber and the AS fiber

Variable	AG Fiber		AS Fiber	
	χ^2	p-value	χ^2	p-value
Diameter (µm)	122.72	<0.001*	217.17	<0.001*
Tensile strength (MPa)	94.40	<0.001*	62.56	<0.001*
Elongation (%)	279.71	<0.001*	238.17	<0.001*

Table 3 Dwass-Steel-Critchlow-Fligner pairwise comparisons.

Method (1)	Method (2)	p-value (AG)			p-value (AS)		
		Diameter	Tensile strength	Elongation	Diameter	Tensile strength	Elongation
		(µm)	(MPa)	(%)	(µm)	(MPa)	(%)
Untreated (Water)	0.5% wt. NaOH 90°C	0.079	0.030*	<0.001*	<0.001*	<0.001*	<0.001*
	1% wt. NaOH 90°C	0.030*	<0.001*	<0.001*	0.006*	<0.001*	<0.001*
	2% wt. NaOH 90°C	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	0.022*
	5% wt. NaOH	0.989	<0.001*	<0.001*	<0.001*	<0.001*	0.146
	10% wt. NaOH	0.013*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*
	15% wt. NaOH	0.582	0.008*	<0.001*	<0.001*	<0.001*	<0.001*
0.5% wt. NaOH 90°C	1% wt. NaOH 90°C	<0.001*	0.012*	0.442	0.319	0.994	0.996
	2% wt. NaOH 90°C	0.174	<0.001*	<0.001*	0.950	0.983	<0.001*
	5% wt. NaOH	0.381	<0.001*	0.006*	<0.001*	1.000	<0.001*
	10% wt. NaOH	<0.001*	0.006*	<0.001*	<0.001*	1.000	<0.001*
	15% wt. NaOH	<0.001*	1.000	<0.001*	<0.001*	1.000	<0.001*
	2% wt. NaOH 90°C	<0.001*	0.854	<0.001*	0.010*	1.000	<0.001*
1% wt. NaOH 90°C	5% wt. NaOH	<0.001*	0.845	0.567	<0.001*	0.999	<0.001*
	10% wt. NaOH	1.000	1.000	<0.001*	<0.001*	0.964	<0.001*
	15% wt. NaOH	0.393	0.012*	<0.001*	<0.001*	1.000	<0.001*
	5% wt. NaOH	<0.001*	1.000	0.062	0.006*	0.993	1.000
2% wt. NaOH 90°C	10% wt. NaOH	<0.001*	0.714	<0.001*	<0.001*	0.803	<0.001*
	15% wt. NaOH	<0.001*	<0.001*	<0.001*	<0.001*	1.000	<0.001*
5% wt. NaOH	10% wt. NaOH	<0.001*	0.828	<0.001*	0.019*	0.999	<0.001*
	15% wt. NaOH	0.042*	<0.001*	<0.001*	<0.001*	0.997	<0.001*
10% wt. NaOH	15% wt. NaOH	0.196	0.005*	0.674	<0.001*	0.921	<0.001*

*Statistically significant difference $p < 0.05$.

The tensile strength of untreated AS fiber differed significantly from all other groups. In contrast, no significant differences were found among the NaOH treated AS samples. For AG fibers, the tensile strength varied

significantly between 5% and 10% wt. NaOH, whereas comparisons between the 1% or 2% wt. NaOH 90°C and 5% wt. NaOH treatments showed no statistical significance. The elongation of the most treatment of AS fibers shows significantly different. For the AG fibers, most pairs were significantly different, except 10% vs. 15% wt. NaOH ($p > 0.05$).

3.2 Diameter and Morphologies Analysis

The surface morphology of untreated and treated fibers is shown in the SEM images (Figure 1 and 2). The SEM micrographs of the untreated AG. (Figure 1a) and AS. (Figure 2a) show relatively smooth topographies, as the fibers are fully enveloped by a binding layer of wax, pectin, and other non-cellulose impurities [18]. Following the sodium hydroxide treatments, the morphologies resulting from the thermal assisted low concentration process (0.5%, 1% and 2% at 90°C) for both galangal pseudo-stems are shown in Figures 1b–d and Figure 2b–2d respectively. The high concentration process at room temperature (5%, 10%, and 15%) are shown in Figures 1e–1g and Figure 2e–2g. The SEMs of the treated samples exhibit distinct axial grooves along the fiber axis and the clear separation of the fiber bundles into individual microfibrils (fibrillation). That is a result of the alkaline treatment process effectively removes amorphous components such as hemicellulose, lignin, waxes, and other surface impurities [17–20].

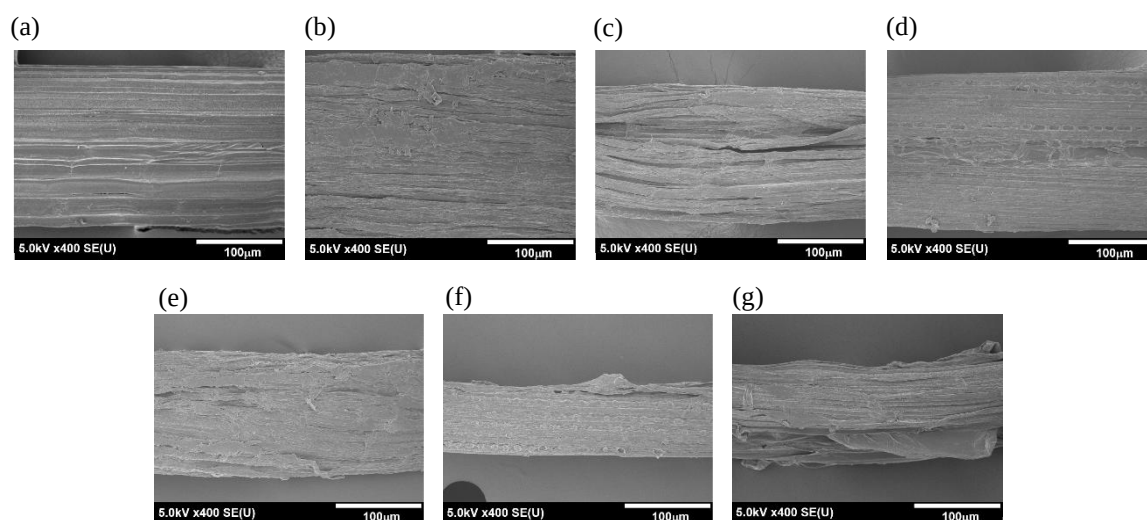


Figure 1 Surface of the galanga fiber with *Alpinia galanga* (L) Willd. (a) untreated surface, in alkali treatment at 90°C (b) 0.5% wt. NaOH, (c) 1% wt. NaOH, (d) 2% wt. NaOH, in alkali treatment at room temperature (e) 5% wt. NaOH, (f) 10% wt. NaOH and (g) 15% wt. NaOH.

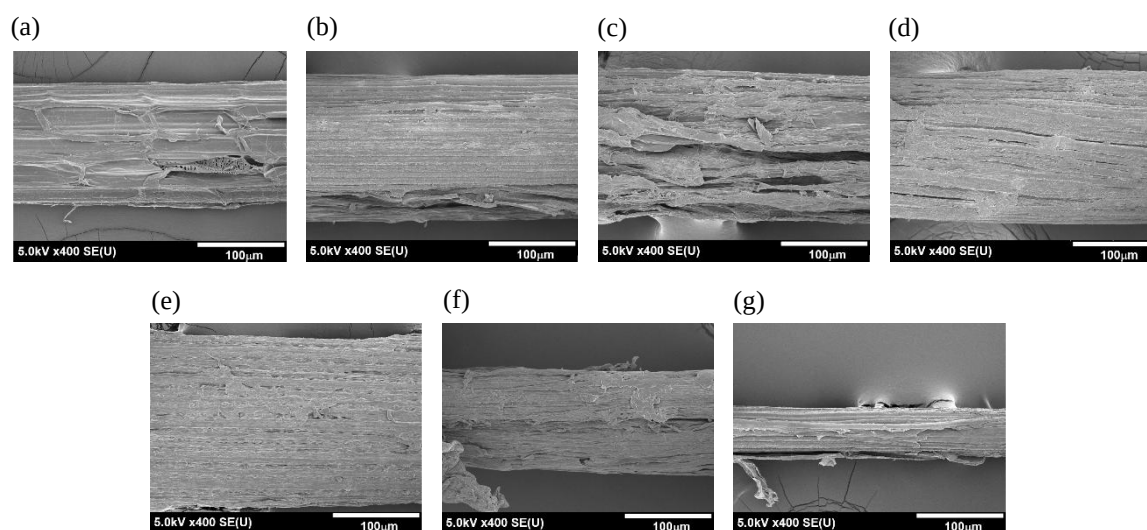


Figure 2 Surface of the galanga fiber with *Alpinia siamensis* K. Schum. (a) untreated surface, in alkali treatment at 90°C (b) 0.5% wt. NaOH, (c) 1% wt. NaOH, (d) 2% wt. NaOH, in alkali treatment at room temperature (e) 5% wt. NaOH, (f) 10% wt. NaOH and (g) 15% wt. NaOH.

The diameter of untreated pseudo-stem fibers is $131.96 \pm 38.42 \mu\text{m}$ for AG and $172.50 \pm 42.94 \mu\text{m}$ for AS. The diameters of treated fibers were generally smaller than those of the untreated samples as shown in Figure 3. Specifically, the diameter of AS fibers decreased as the NaOH concentration increased. The minimum diameters were recorded at $107.99 \pm 20.90 \mu\text{m}$ for AG fibers treated with 10% wt. NaOH, and $62.75 \pm 11.77 \mu\text{m}$ for AS fibers treated with 15% wt. NaOH. This substantial reduction in diameter is closely related to the surface modifications observed in the SEM images and the quantitative roughness analysis. Compared to the aggressive etching of the high-concentration process, the heating treatment at low concentration preserved larger fiber diameters. This indicates that heat effectively removes outer layers without compromising the structural bulk. The quantitative surface roughness analysis, expressed as R_a and R_q values, is presented in Table 4.

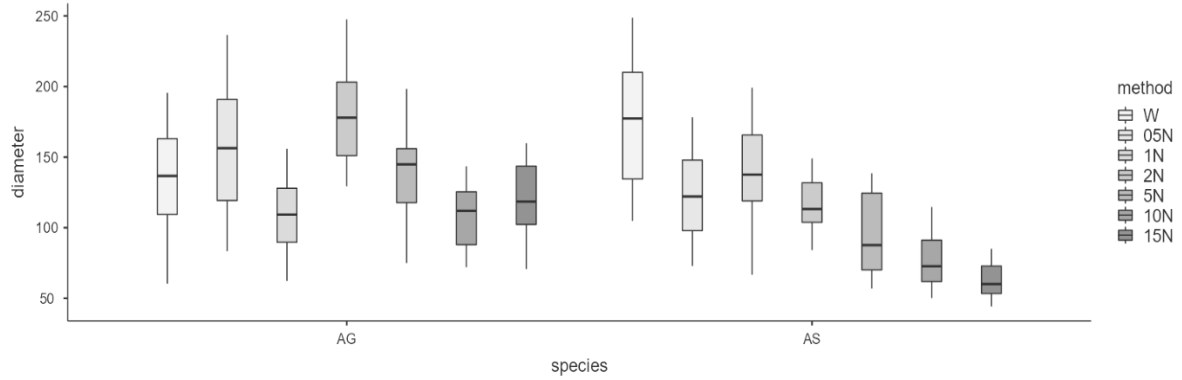


Figure 3 Boxplot comparison of fiber diameter (μm) in the AG fibers and the AS fibers under seven extraction methods

*Where W means Untreated (Water), 05N means 0.5% wt. NaOH 90°C, 1N means 1% wt. NaOH 90°C, 2N means 2% wt. NaOH 90°C, 5N means 5% wt. NaOH, 10N means 10% wt. NaOH, 15N means 15% wt. NaOH.

This strongly correlates with the SEM observations and provides a clear mechanistic explanation for the morphological changes. Initially, the untreated fibers exhibited high roughness values (R_a 6.38 for AG and 6.15 for AS) due to the uneven presence of wax, pectin, and impurities forming lumps on the surface [21]. Upon low-concentration alkali treatment (0.5% wt. NaOH), the roughness significantly dropped as these surface impurities were efficiently dissolved, revealing a smoother fiber surface. The application of heat effectively reduces the chemical concentration required for surface cleaning. However, as the NaOH concentration increased to 10%, a consistent upward trend in surface roughness was observed (R_a reaching 6.55 for AG and 4.97 for AS) [19].

As observed, the R_q values are consistently higher than the R_a values across all treated samples, with this divergence becoming particularly different at the 10% wt. NaOH concentration (R_q peaking at 7.38 for AG and 6.36 for AS). This substantial spike confirms that the heightened roughness is not merely a uniform texture. Rather, it signifies the extensive formation of localized deep axial grooves and extensive microfibril separation (fibrillation). This quantitative statistical evidence perfectly corroborates the severe structural modifications observed in the corresponding SEM micrographs. At the highest concentration (15% wt. NaOH), the roughness decreased, suggesting excessive cellulose degradation where the severe chemical attack led to the collapse and flattening of the microfibril structures.

Table 4 Quantitative surface roughness parameters: Arithmetic Average Roughness (R_a) and Root Mean Square Roughness (R_q)

Variable	Method	AG Fiber		AS Fiber	
		R_a	R_q	R_a	R_q
Surface Roughness parameters *	Untreated (Water)	6.38	7.39	6.15	7.01
	0.5% wt. NaOH 90°C	3.01	3.62	2.57	3.09
	1% wt. NaOH 90°C	3.69	4.46	3.39	3.99
	2% wt. NaOH 90°C	3.25	4.04	4.49	5.51
	5% wt. NaOH	5.12	6.01	3.80	4.65
	10% wt. NaOH	6.55	7.38	4.97	6.36
	15% wt. NaOH	5.24	6.59	4.12	4.90

* The roughness parameters (R_a and R_q) were calculated based on grayscale intensity profiles from SEM micrographs and are expressed in arbitrary units to represent relative surface modifications.

3.3 Mechanical properties

These structural changes directly affected the mechanical properties. The untreated fibers exhibited the lowest tensile strengths ($68.51 \pm 31.06 \text{ MPa}$ for AG and $110.49 \pm 41.62 \text{ MPa}$ for AS) as shown in Figures 4. After

treatment, the tensile strength significantly improved, reaching a maximum at 5% wt. NaOH for AG (147.67 ± 53.47 MPa) and at 0.5% wt. NaOH (90°C) for AS (215.64 ± 95.57 MPa). The removal of hemicellulose, lignin, and wax allowed the cellulose fibrils to pack closer together, which improved the fibers' ability to withstand higher loads [22-25]. However, at an excessive concentration of 15% wt. NaOH, a marked reduction in tensile strength was observed. This reduction is due to cellulose degradation and the structural collapse of microfibrils, as evidenced by the decreased surface roughness (R_q) at this concentration. This is consistent with previous findings indicating that higher alkali concentrations can deteriorate fiber strength, leading to greater structural damage [21, 26-28]

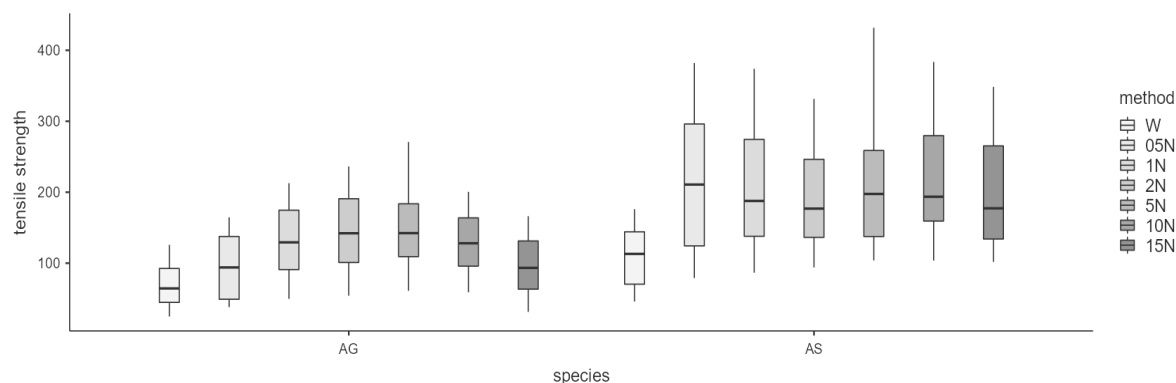


Figure 4 Boxplot comparison of fiber tensile strength (MPa) in the AG fiber and the AS fiber under seven extraction methods

*Where W means Untreated (Water), 05N means 0.5% wt. NaOH 90°C , 1N means 1% wt. NaOH 90°C , 2N means 2% wt. NaOH 90°C , 5N means 5% wt. NaOH, 10N means 10% wt. NaOH, 15N means 15% wt. NaOH.

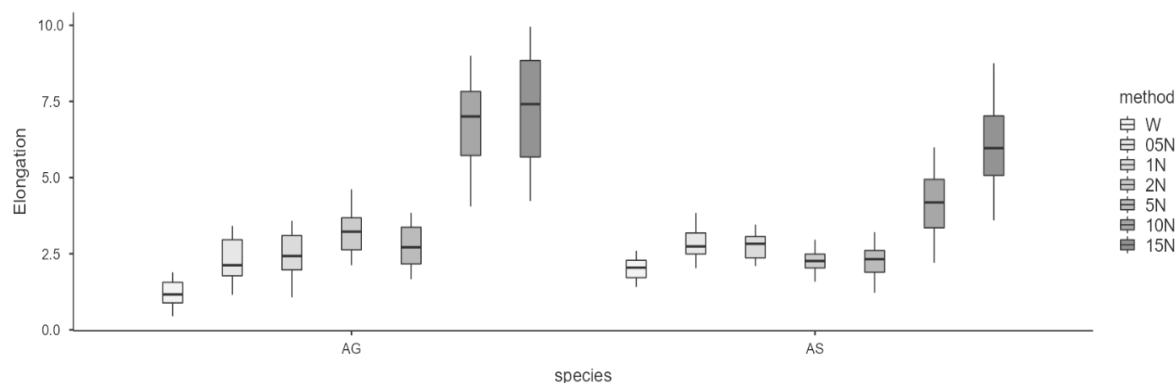


Figure 5 Boxplot comparison of fiber Elongation (%) in the AG fiber and the AS fiber under seven extraction methods

*Where W means Untreated (Water), 05N means 0.5% wt. NaOH 90°C , 1N means 1% wt. NaOH 90°C , 2N means 2% wt. NaOH 90°C , 5N means 5% wt. NaOH, 10N means 10% wt. NaOH, 15N means 15% wt. NaOH.

The elongation at break, the untreated fibers showed the lowest values, measured at $1.22 \pm 0.40\%$ for AG and $2.02 \pm 0.35\%$ for AS. Following the alkali treatments, a significant increase in elongation was observed for both fiber types (Figure 5). The maximum elongation was recorded at 15% wt. NaOH for both AG ($7.25 \pm 1.74\%$) and AS fibers ($5.93 \pm 1.30\%$). Interestingly, this peak in elongation occurred alongside a decrease in tensile strength at the highest concentration. This trend is due to the effective removal of non-cellulosic binders, such as lignin and hemicellulose, which enhances the overall flexibility of the fiber structure. This modification allows the treated fibers to undergo greater deformation under tension, resulting in the observed increase in ductility compared to the untreated fibers [28, 29]. Therefore, at higher NaOH concentrations, a clear trade-off mechanism emerges: while the severe alkaline environment causes cellulose degradation that diminishes tensile strength, it simultaneously removes structural constraints, maximizing fibrillation and chain mobility, thereby resulting in peak elongation.

4. Conclusions

Alkali treatment significantly modified the physical and mechanical properties of galanga fibers (AG and AS). The treatment effectively reduced fiber diameters while enhancing surface roughness. Importantly, R_q was found to be more sensitive than R_a in identifying localized surface changes, such as deep grooves and fibrillation induced by higher alkaline concentrations. For AG fibers, the 10% wt. NaOH treatment resulted in the smallest diameter, while the highest tensile strength and elongation were achieved at 5% and 0.5% wt. NaOH, respectively. On the other hand, AS fibers reached their smallest diameter and maximum elongation at 15% wt. NaOH, with the maximum tensile strength observed at 0.5% wt. NaOH. These results confirm that excessively high alkali concentrations (15%) lead to cellulose degradation and structural collapse, causing a decline in tensile strength despite an increase in ductility. Furthermore, the inclusion of thermal – assisted treatment (90°C) was shown to be a significant factor in accelerating surface modification and altering fiber properties more efficiently than the room temperature process. These findings suggest that optimized alkali treatment is crucial for tailoring galanga fibers for specific composite applications. Based on the enhanced mechanical properties and surface fibrillation achieved through the optimized alkali treatments, galanga fibers demonstrate significant potential as eco-friendly reinforcements in polymer composites requiring lightweight and moderate strength. Additionally, they can be utilized in sustainable packaging and non-structural building materials (such as insulation boards or partition walls), and textile application (such as eco-friendly fabrics or non-woven materials). Utilizing galanga pseudo-stems not only provides a high-performance alternative to synthetic fibers but also promotes a circular bio-economy by upcycling agricultural waste into value-added industrial products.

5. Acknowledgements

This work was supported by Research Program supported by Faculty of Science and Technology, Huachiew Chalermprakiet University.

6. Author Contributions

Sukanya Petchsirivej: Conceptualization, Methodology, Investigation, Validation, Data curation, Formal analysis, Project administration, Writing – original draft; Pornsiri Wanarattikan: Methodology, Investigation, Validation, Resources, Data curation, Writing – review & editing; Noppamas Akarachantachote: Data curation, Writing – review & editing. All authors have read and agreed to the published version of the manuscript.

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