Evaluation of Sorghum Residues Valorization as an Alternative Non-Wood Raw Material for Soda Pulp Production

Orrawan Panichjarern [a,*], Phungjai Tinnasulanon[a], Samart Khamthawee[b] and Somkid Sitichai[b]
[a]*Innovation and Product Development /Plantation and Bioproduct, SCG Packaging PLC, Ratchaburi 70110, Thailand*
[b]*Research Laboratory and Services, SCG Packaging PLC, Ratchaburi 70110, Thailand*

Abstract

This study investigated soda-anthraquinone (soda-AQ) pulping of Thai Sorghum bicolor residues in two forms: whole stalks with leaves and stalks only. Whole stalks with leaves were pulped at NaOH charges of 12–24%, whereas stalks only were evaluated at 8–18%, with NaOH charge expressed as Na_2O on an oven-dry raw-material basis and AQ maintained at 0.1%. Increasing NaOH charge reduced kappa number and screen rejects but also decreased screened pulp yield. At 12% NaOH, whole stalks with leaves gave a screened yield of 37.71% and a kappa number of 28.80. For stalks only, increasing NaOH to 18% reduced the reject to 0.30%, with a screened yield of 37.54% and a kappa number of 10.44. Ring crush values reached 431 N (vs. 296 N for reference eucalyptus handsheets), and corrugating medium strength reached 398 N (vs. 384 N). The whole-stalk-with-leaves pulp exhibited a tensile index of 91.1 N·m/g, approximately 41.9% higher than the 64.2 N·m/g of the eucalyptus reference pulp. These results support the technical potential of undepithed sorghum residues as an alternative non-wood fiber source for unbleached packaging-paper applications. Further studies are required to establish multi-response criteria for selecting pulping conditions and to evaluate industrial, economic, and environmental performance.

Keywords*: Sorghum bicolor, Soda-Anthraquinone Pulping, Non-Wood Fiber, Agricultural Residues, Packaging Paper*

1. Introduction

The pulp and paper industry relies heavily on lignocellulosic biomass as a raw material for fiber production [1–3]. Recent literature emphasizes growing interest in non-wood lignocellulosic resources and agricultural residues as complementary fiber sources and as feedstocks for circular biomass utilization [11–16,28–30,32]. Sorghum residues generated after grain harvesting consist primarily of stalks and leaves and have been investigated as feedstocks for chemical pulp and other bioproducts [4–6,8,10,17–21,31]. Previous sorghum studies demonstrate that cooking conditions and raw-material preparation can influence pulp yield, delignification, fiber characteristics, and paper properties [5,6,8,10,17,18,28,29,31]. Soda-anthraquinone (soda-AQ) pulping is a sulfur-free alkaline pulping process that is technically distinct from kraft pulping [2,3,7]. Soda and soda-AQ processes are widely

* Corresponding author. Tel.: +66-32-913-111; fax: +66-032-339842
E-mail address: orrawanp@scg.com

Manuscript History:
Received 26 May, 2026, Revised 30 September, 2026, Accepted 7 October, 2026, Published 31 October, 2026
Copyright © 2026 UNIMAS Publisher. This is an open access article under the CC BY-NC-SA 4.0 license.
https://doi.org/10.33736/jaspe.13204.2026

e-ISSN: 2289-7771

discussed for non-wood lignocellulosic materials, although heterogeneous anatomy, ash and mineral content, fiber dimensions, raw-material handling, and process integration remain relevant technical considerations [11–16,22,30,32]. Sorghum stalks contain fibrous tissue together with parenchymatous pith, and depithing or physical fractionation has been investigated before processing [5,9,19]. Recent work on sorghum bagasse and other herbaceous residues also demonstrates continuing interest in their pulping and papermaking potential [17,18,20–26,28,29,31,32]. However, limited information is available on the comparative soda-AQ pulping behavior of undepithed whole stalks with leaves and stalks only, particularly with respect to pulping response, fiber morphology, and handsheet properties.

This study investigated soda-anthraquinone (soda-AQ) pulping of Thai *Sorghum bicolor* residues collected after grain harvesting, using two raw-material fractions defined as whole stalks with leaves and stalks only. Both fractions were processed without depithing under different NaOH charges. The resulting pulps were evaluated in terms of chemical composition, pulping performance, fiber morphology, and handsheet properties, and compared with a eucalyptus reference pulp. The objective was to assess the technical potential of undepithed sorghum residues as an alternative non-wood fiber source for unbleached packaging-paper applications.

2. Research methodology

The experimental methodology employed a laboratory-scale digester to investigate soda-anthraquinone (soda-AQ) pulping of two fractions of Thai *Sorghum bicolor* residues: whole stalks with leaves and stalks only. Both fractions were processed without depithing. Unbleached pulp samples were produced at different NaOH charges, and the resulting pulps were evaluated for pulping performance, fiber morphology, optical properties, and handsheet strength properties. An eucalyptus reference pulp from an internal SCGP laboratory experiment was used for comparative evaluation of pulping response, fiber characteristics, and handsheet properties.

2.1. Research processes

Unbleached sorghum pulp was prepared from two fractions, whole stalks with leaves and stalks only, using the soda-AQ process. The NaOH charge was varied independently for each raw-material fraction, while the AQ dosage, liquor-to-raw-material ratio, cooking temperature, and cooking time were kept constant. After cooking, the pulps were disintegrated and screened. Selected pulps were subsequently refined and formed into laboratory handsheets for optical and strength testing using standard TAPPI and ISO methods. The eucalyptus reference used for comparison was obtained from an internal SCGP laboratory experiment at 18% NaOH as Na_2O; a 14% NaOH eucalyptus cook was excluded from quantitative comparison because of high reject and uncooked chips.

2.2. Raw material collection and preparation

Air-dry stalks of *Sorghum bicolor* together with attached leaves were collected from the Siam Forestry Company in Chonburi, Thailand (Figure 1). The material was manually chopped into 2–5 cm lengths for pulp preparation. Two fractions were prepared: whole stalks with leaves (leaves attached; Figure 2) and stalks only (leaves removed; Figure 3). For chemical composition analysis, dried samples of each fraction were ground into meal and passed through a 200-mesh sieve.

2.3. Chemical composition analysis

Solvent extractives (alcohol-benzene) were determined according to TAPPI T 204 cm-17, and acetone extractives were measured following TAPPI T 280 pm-99. Pentosan content was analyzed using

TAPPI T 223 cm-23. Ash content was determined by combustion at 525 °C in accordance with TAPPI T 211 om-22. Cellulose and lignin contents were not determined in the present study; therefore, interpretation of delignification and carbohydrate retention was limited to the measured pulping responses and is acknowledged as a limitation of the chemical composition analysis.

2.4. Soda-AQ pulping

For pulp preparation, chopped sorghum residues (2–5 cm) were processed in a six-batch laboratory digester equipped with heating and temperature control. Whole stalks with leaves and stalks only were processed without depithing. In each cook, 350 g of oven-dry sorghum material was pulped with 0.1% soluble anthraquinone based on oven-dry raw material at a liquor-to-raw-material ratio of 4:1. Whole stalks with leaves were cooked at 12, 14, 16, 18, 22, and 24% NaOH, whereas stalks only were cooked at 8, 10, 12, 14, 16, and 18% NaOH. All NaOH charges were expressed as Na_2O on an oven-dry raw-material basis. The material was impregnated with cooking liquor under nitrogen pressure (6.5 kg/cm²) for 40 min, heated to 165 °C over 60 min, and maintained at 165 °C for 60 min. After cooking, the spent cooking liquor (black liquor) was separated from the pulp, which was then disintegrated according to TAPPI T 205 sp-02 and screened using a Somerville fractionator equipped with a 0.15-mm slotted plate. Screened pulp yield and screen reject were determined on an oven-dry basis. The black liquor contained dissolved organic material from the sorghum raw material, including lignin-derived material and dissolved or degraded carbohydrates, together with residual inorganic cooking chemicals; these components were not quantified separately. A representative black liquor sample was oven-dried, and the dry residue was weighed gravimetrically. The black liquor dry-solids load was calculated as the mass of oven-dried black liquor solids divided by the oven-dry mass of screened pulp produced from the corresponding cook and was expressed as t dry solids/t pulp. This parameter therefore represents total black liquor dry solids normalized to screened pulp production and not the quantity of any individual dissolved component.

Black liquor dry-solids load (t dry solids/t pulp) = Mass of oven-dried black liquor solids / Mass of oven-dry screened pulp

2.5. Pulp property evaluation

Kappa number was measured on the screened pulp according to TAPPI T 236 om-99. Selected screened pulps used for handsheet evaluation were refined in a PFI mill following TAPPI T 248 sp-00. Pulp freeness was measured according to TAPPI T 227 om-21, and laboratory handsheets were prepared according to TAPPI T 205 sp-02. Handsheets used for comparison were prepared at a target freeness of 300 mL CSF.

The handsheets were conditioned at 27 ± 2 °C and 65 ± 2% relative humidity in accordance with ISO 187:2022 prior to testing for optical and physical properties.

Handsheet strength properties were evaluated following TAPPI standard methods:

Burst index: TAPPI T 403 om-23

Tear index: TAPPI T 414 om-21
Tensile properties (tensile index, stretch %, tensile stiffness index): TAPPI T 494 om-22

Ring crush: TAPPI T 822 om-22

Corrugating medium test: TAPPI T 809 om-21

Handsheets for optical testing were prepared according to ISO 3688:1999, and pulp brightness was measured following ISO 2470-1:2016 (ISO brightness).

2.6. Fiber morphology analysis

Average fiber length and fines content of the selected sorghum pulps were compared with those of the eucalyptus reference pulp from SCG Packaging Public Company Limited (SCGP). The eucalyptus pulping response used for reference was obtained at 18% NaOH as Na_2O; a 14% NaOH eucalyptus cook produced high reject and uncooked chips and was therefore excluded from quantitative comparison. These comparisons are used as reference benchmarks rather than as evidence of equivalent pulping severity across raw materials.

2.7. Statistical analysis

Pulping experiments and chemical composition analyses were performed in triplicate, and results are reported as mean ± standard deviation (n = 3), where replicate measurements were available. No inferential statistical test was applied; therefore, differences among treatments and between sorghum and eucalyptus are described descriptively and are not interpreted as statistically significant.

3. Results and Discussion

The measured chemical composition of the two sorghum residue fractions is presented in Table 1. Whole stalks with leaves contained 18.74% alcohol-benzene extractives, 14.49% acetone extractives, 26.89% pentosans, and 5.74% ash, whereas stalks only contained 23.22%, 15.78%, 28.02%, and 4.57%, respectively. The eucalyptus reference contained lower extractives, pentosans, and ash than either sorghum fraction. Because no inferential statistical tests were performed, these differences are described descriptively rather than as statistically significant. Cellulose and lignin contents were not determined; consequently, the chemical-composition data cannot be used to quantify delignification or carbohydrate retention.



Figure 1. *Sorghum bicolor* plantation in Chonburi, Thailand (Siam Forestry Company).



Figure 2. Whole stalks with leaves used as sorghum raw material.



Figure 3. Stalks only used as sorghum raw material.



Figure 4. (A) Sorghum residues in the laboratory digester and (B) pulp after cooking before washing.

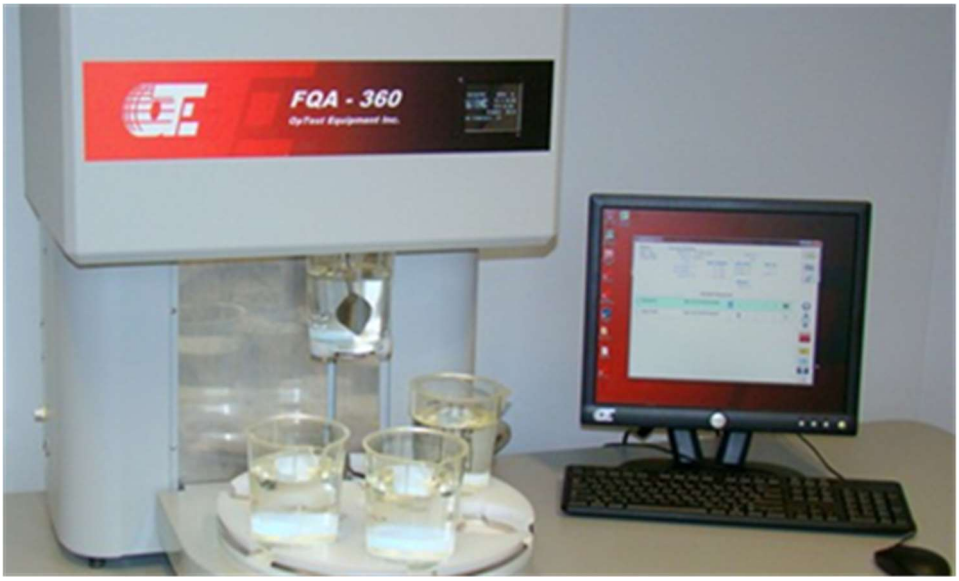


Figure 5. Fiber Quality Analyzer (FQA model 360).

Table 1. Chemical composition (%, oven-dry basis) of whole stalks with leaves, stalks only, and eucalyptus reference woodchips. Values are mean ± standard deviation (n = 3).

Test item, % oven-dry raw material	**Whole stalks with leaves**	**Stalks only**	**Eucalyptus reference woodchips**
Solvent extractive (alcohol-benzene)	18.74±0.05	23.22±0.05	1.80±0.06
Solvent extractive (Acetone)	14.49±0.05	15.78±0.05	0.93±0.04
Pentosans	26.89±0.20	28.02±0.10	12.30±0.25
Ash content at 525 ˚C	5.74±0.5	4.57±0.30	0.30±0.05

The sorghum fractions contained higher measured solvent extractives than the eucalyptus reference. Alcohol-benzene extractives were 18.74% for whole stalks with leaves and 23.22% for stalks only, compared with 1.80% for eucalyptus; acetone extractives were 14.49%, 15.78%, and 0.93%, respectively. These compositional differences may influence pulping and downstream liquor handling; however, their specific effects were not evaluated in the present study, and the contribution of individual plant fractions was not separately determined.

Pentosan contents were 26.89% for whole stalks with leaves and 28.02% for stalks only, compared with 12.30% for the eucalyptus reference. Hemicelluloses can contribute to fiber swelling, inter-fiber bonding, and paper-strength development [1–3,14,22,23]; nevertheless, the present data do not isolate the contribution of pentosans to the measured handsheet properties.

Ash contents were 5.74% for whole stalks with leaves and 4.57% for stalks only, compared with 0.30% for the eucalyptus reference. Higher mineral contents are commonly reported for many non-wood and agricultural-residue feedstocks and represent an additional consideration in their processing [11–16,22]. However, silica was not measured separately in the present study. Accordingly, no conclusion

is made regarding the specific contribution of leaves to silica content or the magnitude of potential recovery-system impacts.

Overall, the measured extractives, pentosans, and ash demonstrate compositional differences between the sorghum fractions and the eucalyptus reference. Because cellulose and lignin were not analyzed, interpretation of delignification and carbohydrate retention is restricted to the observed pulping responses, including screened yield, reject content, and kappa number.

Table 2. Soda-AQ pulping results for whole stalks with leaves at NaOH charges of 12–24% (expressed as Na_2O on oven-dry sorghum residues) and 0.1% AQ.

Batch	**1**	**2**	**3**	**4**	**5**	**6**
NaOH charge, % as Na_2O on oven-dry raw material	12	14	16	18	22	24
Screened pulp yield, %	37.71±0.21	35.92±0.20	35.62±0.30	34.90±0.22	31.90±0.11	30.82±0.12
Reject, %	1.70±0.10	0.60±0.05	0.50±0.06	0.20±0.05	0.10±0.03	0.10±0.03
Kappa number	28.80±0.50	16.05±0.41	11.30±0.30	10.35±0.41	9.50±0.20	9.30±0.22
Black liquor dry-solids load, t dry solids/t pulp	1.10±0.01	1.41±0.01	1.63±0.02	1.76±0.02	1.85±0.02	2.29±0.05

Note: Values are presented as mean ± standard deviation of triplicate experiments (n = 3). Black liquor dry-solids load (t dry solids/t pulp) was calculated as the mass of oven-dried black liquor solids divided by the oven-dry mass of screened pulp produced from the corresponding cook.

Table 3. Soda-AQ pulping results for stalks only at NaOH charges of 8–18% (expressed as Na_2O on oven-dry sorghum residues) and 0.1% AQ.

Batch	**1**	**2**	**3**	**4**	**5**	**6**
NaOH charge, % as Na_2O on oven-dry raw material	8	10	12	14	16	18
Screened pulp yield, %	52.70±0.50	45.71±0.42	40.00±0.52	38.03±0.30	37.92±0.41	37.54±0.22
Reject, %	19.60±0.40	13.00±0.40	3.90±0.10	2.30±0.12	0.50±0.02	0.30±0.01
Kappa number	52.71±0.60	45.70±0.40	40.02±0.50	31.62±0.50	16.01±0.20	10.44±0.40
Black liquor dry-solids load, t dry solids/t pulp	1.11±0.01	1.10±0.03	1.15±0.08	1.24±0.07	1.33±0.02	1.50±0.05

Note: Values are presented as mean ± standard deviation of triplicate experiments (n = 3). Black liquor dry-solids load (t dry solids/t pulp) was calculated as the mass of oven-dried black liquor solids divided by the oven-dry mass of screened pulp produced from the corresponding cook.

Table 4. Fiber morphology of selected sorghum pulps compared with the eucalyptus reference pulp.

Test items	Whole stalks with leaves	Stalks only	Eucalyptus reference
Fiber length, mm	0.86	1.04	0.58
Fines, %	17.4	10.5	2.7

Table 5. Optical and handsheet strength properties of selected sorghum pulps and the eucalyptus reference pulp.

Property	Whole stalks with leaves	Stalks only	Eucalyptus reference
Brightness, % ISO	21.5	19.5	24.9
Burst index, kPa·m²/g	7.38	4.34	4.22
Tear index, mN·m²/g	8	7.5	9.4
Tensile index, N·m/g	91.1	56.1	64.2
Stretch, %	3.04	2.84	3.09
Tensile stiffness index, N·m/g	4379	3203	–
Ring crush, N	431	349	296
Corrugating medium test, N	398	393	384

Note: Brightness and handsheet strength values are comparative laboratory measurements for the selected sorghum pulps and eucalyptus reference pulp at the stated test conditions. Inferential statistical significance was not evaluated.

The effects of NaOH charge on soda-AQ pulping were evaluated separately for the two sorghum fractions. Whole stalks with leaves were cooked at 12, 14, 16, 18, 22, and 24% NaOH, whereas stalks only were cooked at 8, 10, 12, 14, 16, and 18% NaOH; all charges were expressed as Na_2O on an oven-dry raw-material basis, with AQ fixed at 0.1%. For whole stalks with leaves, increasing NaOH charge from 12 to 24% decreased kappa number from 28.80 to 9.30 and screened yield from 37.71 to 30.82%, while reject decreased from 1.70 to 0.10%. These trends indicate greater delignification and lower screening losses at higher NaOH charge, accompanied by lower screened pulp yield. Because cellulose and lignin contents were not measured, the yield reduction cannot be quantitatively assigned to carbohydrate degradation.

For whole stalks with leaves, the black liquor dry-solids load increased from 1.10 ± 0.01 t dry solids/t pulp at 12% NaOH to 2.29 ± 0.05 t dry solids/t pulp at 24% NaOH (Table 2). This parameter represents black liquor dry solids normalized to pulp production and should be distinguished from black liquor solids content expressed as wt.%. The increasing dry-solids load with NaOH charge was interpreted as an experimental pulping response rather than direct evidence of differences in recovery energy or operating cost.

The observed decrease in kappa number and screened yield with increasing alkali charge is consistent with alkaline pulping responses reported for non-wood lignocellulosic materials, where stronger cooking conditions promote delignification but may also increase dissolution of carbohydrate-derived material [13,17,18,23,28,29,31,32]. In the present experiments, however, cellulose, lignin, and individual dissolved-organic components were not quantified; therefore, the screened-yield decrease and higher black-liquor dry-solids load are interpreted only as overall pulping responses rather than direct measurements of specific degradation mechanisms.

The internal SCGP eucalyptus laboratory experiment at 18% NaOH as Na_2O produced a screened pulp yield of 46.38%, reject of 0.15%, kappa number of 26.04, and black liquor dry-solids load of 1.40 t dry solids/t pulp (Table 6). A 14% NaOH eucalyptus cook was also evaluated, but it produced high reject and substantial uncooked chips that could not be reliably separated from the fiber fraction; consequently, the 14% condition was excluded from quantitative comparison. Relative to the 18% eucalyptus reference, the selected sorghum conditions used lower NaOH charges, although the comparison is interpreted descriptively because the raw materials exhibited different cooking responses.

Comparison at the common NaOH charge of 12% showed different pulping responses between the two fractions. Whole stalks with leaves gave a screened yield of 37.71%, reject of 1.70%, and kappa number of 28.80, whereas stalks only gave 40.00%, 3.90%, and 40.02, respectively. The lower kappa number of whole stalks with leaves indicates a greater extent of delignification under this common cooking condition. However, because the leaves and stalk tissues were not characterized separately for lignin, cellulose, or anatomical accessibility, the mechanism responsible for this difference cannot be established from the present data. The effect of leaves on liquor penetration and delignification should therefore be regarded as a hypothesis requiring further investigation.

For whole stalks with leaves, 12% NaOH provided the highest screened yield within the tested range (37.71%) with a kappa number of 28.80 and a reject level of 1.70%. Increasing the charge to 14% reduced kappa number markedly to 16.05, with a screened yield of 35.92%. For stalks only, 14% NaOH gave a screened yield of 38.03%, reject of 2.30%, and kappa number of 31.62, while 18% NaOH further reduced reject and kappa number to 0.30% and 10.44, respectively, with a screened yield of 37.54%. These results demonstrate trade-offs among screened yield, reject content, and delignification. Accordingly, the 12% NaOH whole-stalk-with-leaves condition and the 14% NaOH stalks-only condition were selected for comparative handsheet evaluation; no formal multi-response optimization was performed.

Table 6 provides a direct comparison of the selected sorghum conditions with the internal SCGP eucalyptus reference. Whole stalks with leaves at 12% NaOH gave a screened yield of 37.71%, reject of 1.70%, kappa number of 28.80, and black liquor dry-solids load of 1.10 t dry solids/t pulp. Stalks only at 14% NaOH gave corresponding values of 38.03%, 2.30%, 31.62, and 1.24 t dry solids/t pulp. The eucalyptus reference at 18% NaOH gave a screened yield of 46.38%, reject of 0.15%, kappa number of 26.04, and black liquor dry-solids load of 1.40 t dry solids/t pulp. These data demonstrate different trade-offs among chemical charge, screened yield, reject, delignification, and dry-solids generation. They do not establish differences in industrial chemical cost, recovery-energy demand, or operating cost by themselves.

The brightness values of the selected sorghum pulps were 21.5% ISO for whole stalks with leaves and 19.5% ISO for stalks only, compared with 24.9% ISO for the eucalyptus reference (Table 5; Table 6; Figure 6). Fiber morphology and handsheet properties are therefore presented as comparative laboratory benchmarks. Although Table 6 also includes pulping data from the internal SCGP eucalyptus experiment, differences among the three materials should be interpreted descriptively because the selected conditions were not established at equivalent cooking severity.

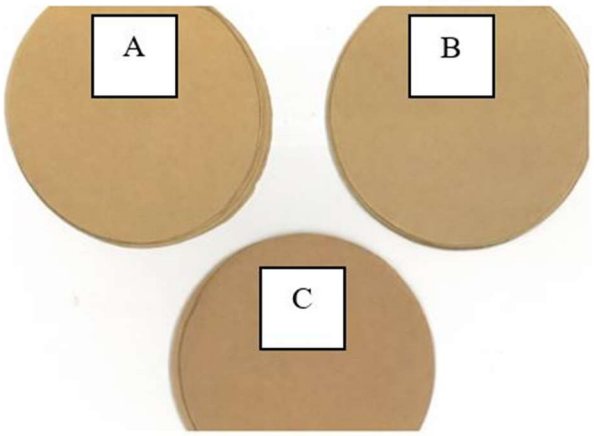


Figure 6. (A) Eucalyptus reference pulp handsheet, (B) stalks-only sorghum pulp handsheet, and (C) whole-stalk-with-leaves sorghum pulp handsheet.

Fiber quality analysis showed average fiber lengths of 0.86 mm for whole-stalk-with-leaves pulp and 1.04 mm for stalks-only pulp, compared with 0.58 mm for the eucalyptus reference (Table 4). Fines contents were 17.4, 10.5, and 2.7%, respectively. The higher fines contents of the sorghum pulps are consistent with the presence of heterogeneous fibrous and parenchymatous tissues reported for sorghum and other herbaceous non-wood feedstocks [5,8,9,17,23]. Recent studies also emphasize that fiber morphology, fines generation, refining, and fiber-network consolidation can influence laboratory-sheet properties [22–24,27,30,32]. However, this study did not experimentally isolate pith-derived fines or determine their causal contribution to handsheet properties. The observed fines contents should therefore be regarded as associated fiber-morphology characteristics rather than a demonstrated mechanism for the measured strength differences. At higher fines levels, drainage, retention, and sheet formation may also be affected; these effects require direct evaluation before industrial conclusions can be drawn.

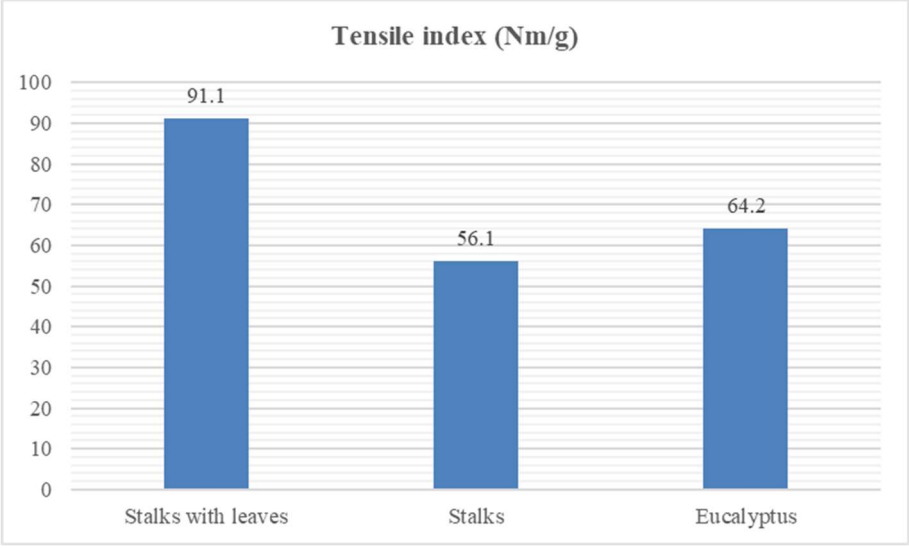


Figure 7. Tensile index of sorghum pulp handsheets compared with the eucalyptus reference pulp handsheet.

Table 5 compares optical and handsheet strength properties of the selected sorghum pulps with the eucalyptus reference at a target freeness of 300 mL CSF. Whole-stalk-with-leaves pulp gave a tensile index of 91.1 N·m/g, compared with 56.1 N·m/g for stalks only and 64.2 N·m/g for eucalyptus. Thus, the tensile index of the whole-stalk-with-leaves pulp was approximately 41.9% higher than that of the eucalyptus reference. Ring crush values were 431, 349, and 296 N, and corrugating medium test values were 398, 393, and 384 N for whole stalks with leaves, stalks only, and eucalyptus, respectively. Recent investigations of non-wood pulps likewise show that fiber morphology, refining, and sheet consolidation can support strong paper-related properties, although performance remains strongly feedstock- and process-dependent [22–24,27]. These comparisons therefore indicate promising laboratory handsheet performance of the sorghum pulps but do not establish compliance with commercial packaging specifications or demonstrate a causal relationship between fines content and compression-related properties.

Taken together, the fiber morphology and handsheet data indicate that undepithed sorghum soda-AQ pulps have technical potential for unbleached packaging-paper applications. However, the present results are based on laboratory handsheets and should not be interpreted as a demonstration of industrial paper-machine performance. Additional studies should evaluate drainage, retention, formation, refining response, blend ratios with wood pulp, and performance under pilot- or mill-scale papermaking conditions.

For concise comparison, Table 6 summarizes the selected sorghum pulping conditions and the eucalyptus reference condition obtained from an internal SCG Packaging Public Company Limited (SCGP) laboratory experiment. The eucalyptus reference was cooked at 18% NaOH, expressed as Na_2O, and produced a screened pulp yield of 46.38%, reject of 0.15%, kappa number of 26.04, and black liquor dry-solids load of 1.40 t dry solids/t pulp. A 14% NaOH eucalyptus cook was also examined; however, the cook produced high reject and a substantial amount of uncooked chips that could not be reliably separated from the fiber fraction. Therefore, the 14% eucalyptus condition was excluded from quantitative comparison.

Table 6. Comparison of selected sorghum soda-AQ pulps with the eucalyptus reference pulp.

Property	Whole stalks with leaves	Stalks only	Eucalyptus reference
NaOH charge, % as Na_2O	12	14	18
Screened pulp yield, %	37.71	38.03	46.38
Reject, %	1.70	2.30	0.15
Kappa number	28.80	31.62	26.04
Black liquor dry-solids load, t dry solids/t pulp	1.10	1.24	1.40
Brightness, % ISO	21.5	19.5	24.9
Fiber length, mm	0.86	1.04	0.58
Fines, %	17.4	10.5	2.7
Burst index, kPa·m²/g	7.38	4.34	4.22
Tear index, mN·m²/g	8.0	7.5	9.4
Tensile index, N·m/g	91.1	56.1	64.2
Ring crush, N	431	349	296
Corrugating medium test, N	398	393	384

Note: Sorghum values correspond to the 12% NaOH whole-stalk-with-leaves condition and the 14% NaOH stalks-only condition used for comparative discussion and handsheet evaluation. Eucalyptus pulping values were obtained from an internal SCGP laboratory experiment at 18% NaOH as Na_2O. The 14% NaOH eucalyptus cook was excluded from quantitative comparison because of high reject and uncooked chips that could not be reliably separated from the fiber fraction. Handsheet and fiber-morphology values are reported for the eucalyptus reference pulp under the stated laboratory comparison conditions.

4. Conclusion

This study demonstrated that undepithed Thai *Sorghum bicolor* residues can be converted to unbleached pulp by soda-AQ pulping. For whole stalks with leaves, 12% NaOH provided the highest screened pulp yield within the tested range (37.71%) with a kappa number of 28.80, while increasing NaOH charge enhanced delignification but reduced screened pulp yield. Stalks only also responded to increasing NaOH charge; at 18% NaOH, reject was reduced to 0.30%, with a screened pulp yield of 37.54% and a kappa number of 10.44. The results therefore indicate trade-offs among screened yield, reject content, kappa number, and black liquor dry-solids load. The 12% NaOH whole-stalk-with-leaves condition and 14% NaOH stalks-only condition were selected for comparative handsheet evaluation rather than identified as formally optimized cooking conditions. The internal SCGP eucalyptus reference at 18% NaOH produced a screened yield of 46.38%, reject of 0.15%, kappa number of 26.04, and black liquor dry-solids load of 1.40 t dry solids/t pulp; these values are used as a descriptive reference because the raw materials exhibited different cooking responses. Under the laboratory handsheet conditions used, the whole-stalk-with-leaves pulp exhibited a tensile index of 91.1 N·m/g, approximately 41.9% higher than the eucalyptus reference value of 64.2 N·m/g, together with ring crush and corrugating medium test values of 431 and 398 N, respectively. The higher fines content of the sorghum pulps was associated with differences in handsheet properties, but its causal contribution to compression strength was not established. Overall, the results demonstrate the technical potential of undepithed sorghum soda-AQ pulp as an alternative non-wood fiber source for unbleached packaging-paper applications. Further work should establish defined multi-response criteria for selecting cooking conditions and evaluate refining response, drainage, formation, wood-pulp blending, chemical recovery, process economics, and environmental performance at pilot or industrial scale.

Acknowledgements

The authors would like to express their sincere gratitude to Siam Forestry Company for providing the sorghum residues used in this study, collected after harvesting from plantations in Chonburi, Thailand. The authors also gratefully acknowledge the Innovation and Product Development Center at SCG Packaging Public Company Limited (SCGP) for providing the commercial unbleached eucalyptus pulp used as a reference material, as well as for their support in providing laboratory facilities, experimental equipment, and analytical instruments necessary for conducting the pulping experiments and material characterization. Their valuable support greatly contributed to the successful completion of this research.

Conflict of Interest

The authors declare no conflict of interest.

References

[1] Gullichsen, J., & Paulapuro, H. (2000). *Papermaking science and technology: Chemical pulping*. Finnish Paper Engineers' Association, TAPPI. ISBN: 9525216004

[2] Kocurek, M. J. (1989). *Pulp and paper manufacture: Alkaline pulping*. TAPPI Press, Atlanta USA.

[3] Sixta, H. (2006). *Handbook of pulp*. Wiley-VCH.

[4] Belayachi, L., & Delmas, M. (1995). Sweet sorghum: A quality raw material for the manufacturing of chemical paper pulp. *Biomass and Bioenergy*, 8(6), 411–417. https://doi.org/10.1016/0961-9534(95)00046-1

[5] Belayachi, L., Delmas, M., & Gosse, G. (1997). Sweet sorghum bagasse: A raw material for the production of chemical paper pulp: Effect of depithing. *Industrial Crops and Products*, 6(3–4), 229–232. https://doi.org/10.1016/S0926-6690(97)00012-5

[6] Saeed, H. A. M., Liu, Y., Lucia, L. A., & Chen, H. (2017). Evaluation of Sudanese sorghum and bagasse as a pulp and paper feedstock. *BioResources*, 12(3), 5212–5222. https://doi.org/10.15376/biores.12.3.5212-5222

[7] Monot, N., Grelier, S., Brosse, N., & Navard, P. (2015). The use of a sulfur-free process for the production of cellulose fibers from mixed softwood species [Conference presentation]. Annual Convention of the Society of Wood Science and Technology. https://www.swst.org/meetings/AM15/pdfs/presentations/monot.pdf

[8] Khristova, P., & Gabir, S. (1990). Soda-anthraquinone pulping of sorghum stalks. *Biological Wastes*, 33(4), 243–250. https://doi.org/10.1016/0269-7483(90)90128-F

[9] Wilson, J. R., Mertens, D. R., & Hatfield, R. D. (1993). Isolates of cell types from sorghum stems: Digestion, cell wall and anatomical characteristics. *Journal of the Science of Food and Agriculture*, 63(4), 407–417. https://doi.org/10.1002/jsfa.2740630406

[10] Gençer, A., & Şahin, M. (2015). Identifying the conditions required for the NaOH method for producing pulp and paper from sorghum grown in Turkey. *BioResources*, 10(2), 2850–2858. https://doi.org/10.15376/biores.10.2.2850-2858

[11] Haile, A., Gebino, G., Tesfaye, T., Mengie, W., Ayele, M., Abuhay, A., & Yilie, D. (2023). Utilization of non-wood biomass for pulp manufacturing in paper industry: case of Ethiopia. *Biomass Conversion and Biorefinery*, *13*(9), 7441-7459. https://doi.org/10.1007/s13399-021-01424-x

[12] Jahan, M. S., Rahman, M. M., & Ni, Y. (2020). Alternative initiatives for non-wood chemical pulping and integration with the biorefinery concept: A review. *Biofuels, Bioproducts and Biorefining*, 15(1), 100–118. https://doi.org/10.1002/bbb.2143

[13] Worku, L. A., Bachheti, A., Bachheti, R. K., Rodrigues Reis, C. E., & Chandel, A. K. (2023). Agricultural residues as raw materials for pulp and paper production: Overview and applications on membrane fabrication. *Membranes*, 13(2), 228. https://doi.org/10.3390/membranes13020228

[14] Li, P., Xu, Y., Yin, L., Liang, X., Wang, R., & Liu, K. (2023). Development of raw materials and technology for pulping: A brief review. *Polymers*, 15(22), 4465. https://doi.org/10.3390/polym15224465

[15] Danielewicz, D. (2023). Industrial hemp as a potential nonwood source of fibres for European industrial-scale papermaking—A review. *Materials*, 16(19), 6548. https://doi.org/10.3390/ma16196548

[16] Abdallah, A. F., Jawaid, M., Mohamed, A. Z., Tahir, P. M., Osman, F. A., & Abdullah, U. H. (2024). A review on alkaline sulfite anthraquinone methanol as an alternative pulping process for non-woody biomass. *Biomass Conversion and Biorefinery*, 14(24), 30861–30880. https://doi.org/10.1007/s13399-023-05006-x

[17] Wistara, N. J., & Fatriasari, W. (2023). Pulping and papermaking of sorghum bagasse. In *Pulping and Papermaking of Nonwood Plant Fibers* (pp. 213–231). Academic Press. https://doi.org/10.1016/B978-0-323-91625-7.00013-8

[18] Karimah, A., Solihat, N. N., Hastuti, N., Ismayati, M., Ermawar, R. A., Sohail, A., Iswanto, A. H., Ariyanta, H. A., Ilyas, R. A., Dungani, R., & Fatriasari, W. (2023). The effect of active alkali and sulfidity loading on

the kraft pulp properties of sweet sorghum bagasse. *Sugar Tech*, 25(5), 1196–1210. https://doi.org/10.1007/s12355-023-01291-y

[19] Li, M., Yan, G., Bhalla, A., Maldonado-Pereira, L., Russell, P. R., Ding, S.-Y., Mullet, J. E., & Hodge, D. B. (2018). Physical fractionation of sweet sorghum and forage/energy sorghum for optimal processing in a bio-refinery. *Industrial Crops and Products*, 124, 607–616. https://doi.org/10.1016/j.indcrop.2018.07.002

[20] Silva, T. N., Thomas, J. B., Dahlberg, J., Rhee, S. Y., & Mortimer, J. C. (2022). Progress and challenges in sorghum biotechnology, a multipurpose feedstock for the bioeconomy. *Journal of Experimental Botany*, 73(3), 646–664. https://doi.org/10.1093/jxb/erab450

[21] Panichjarern, O. (2026). Potential of sorghum for pulp, paper and bioenergy industries. *Journal of Applied Science and Innovation*, 1(2), Article 26205. https://li02.tci-thaijo.org/index.php/jasi/article/view/1881

[22] Lee, C. L., Chin, K. L., H'ng, P. S., Hafizuddin, M. S., & Khoo, P. S. (2022). Valorisation of underutilized grass fibre (stem) as a potential material for paper production. *Polymers*, 14(23), 5203. https://doi.org/10.3390/polym14235203

[23] Lemma, H. B., Steffen, F., Ali, A. Y., & Saake, B. (2024). Production of long-fiber pulp from Enset plant residues by soda pulping. *Molecules*, 29(20), 4874. https://doi.org/10.3390/molecules29204874

[24] Iglesias, A., Cancela, Á., Soler Baena, A., & Sánchez, Á. (2023). Characterization of cellulose derived from invasive alien species plant waste for application in the papermaking industry: Physic-mechanical, optical, and chemical property analysis. *Applied Sciences*, 13(20), 11568. https://doi.org/10.3390/app132011568

[25] Divya, R., Indumathi, T. R., Venugopal, T., & Prakash, C. (2024). Investigation on potential application of non-wood pulp for hygiene products as absorbent core substantial. *Biomass Conversion and Biorefinery*, 14(14), 16363–16368. https://doi.org/10.1007/s13399-022-03725-1

[26] Said, A. E. A. A., Aly, A. A., Mostafa, A. H., Ahmed, H. S., & Goda, M. N. (2023). An approach for application of ozone bleaching and nano-filler loading on quality of papermaking from sorghum bagasse as a promise alternative non-wood fiber. *Environmental Progress & Sustainable Energy*, *42*(5), e14159. https://doi.org/10.1002/ep.14159

[27] Jurado, J., Huilcapi, V., Suarez, I., & Lopez, A. (2026). A sustainable approach to paper production from Eichhornia crassipes to strengthen the non-wood fiber industry. *Fibers*, 14(6), 68. https://doi.org/10.3390/fib14060068

[28] Melesse, E. Y., Bedru, T. K., & Meshesha, B. T. (2022). Production and characterization of pulp from banana pseudo stem for paper making via soda anthraquinone pulping process. *International Journal of Engineering Research in Africa*, 58, 63–76. https://doi.org/10.4028/www.scientific.net/JERA.58.63

[29] Worku, L. A., Bachheti, R. K., Tadesse, M. G., Bachheti, A., Alshammari, A., Albekairi, N. A., Kabra, A., & Alemu, W. K. (2024). Exploring Oxytenanthera abyssinica as a sustainable alternative for pulp and paper production: A response surface methodology approach for optimized soda pulping. *Journal of King Saud University - Science*, 36, 103230. https://doi.org/10.1016/j.jksus.2024.103230

[30] Khan, M. U., Rehman, A., Khan, M. A., Khan, A. R., Ali, S., & Ahmad, Z. (2024). Utilization of non-wood fibers as raw materials for pulp and paper production in Pakistan: A review. *Pakistan Journal of Forestry*, 74(2), 53–62. https://doi.org/10.17582/journal.PJF/2024/74.2.53.62

[31] Kanbar, A., Lemma, H. B., Saake, B., Stolzenburg, K., & Nick, P. (2026). Potential of sorghum stalk as climate resilient resource for paper production. *BioResources*, 21(3), 7247–7263. https://doi.org/10.15376/biores.21.3.7247-7263

[32] Hájková, K., Bárta, J., Filipi, M., & Sikora, A. (2026). Comparative evaluation of soda and nitrate-alkaline pulping of hemp, flax, and sisal post-harvest biomass. *ChemistryOpen*, 15(3). https://doi.org/10.1002/open.202500614