

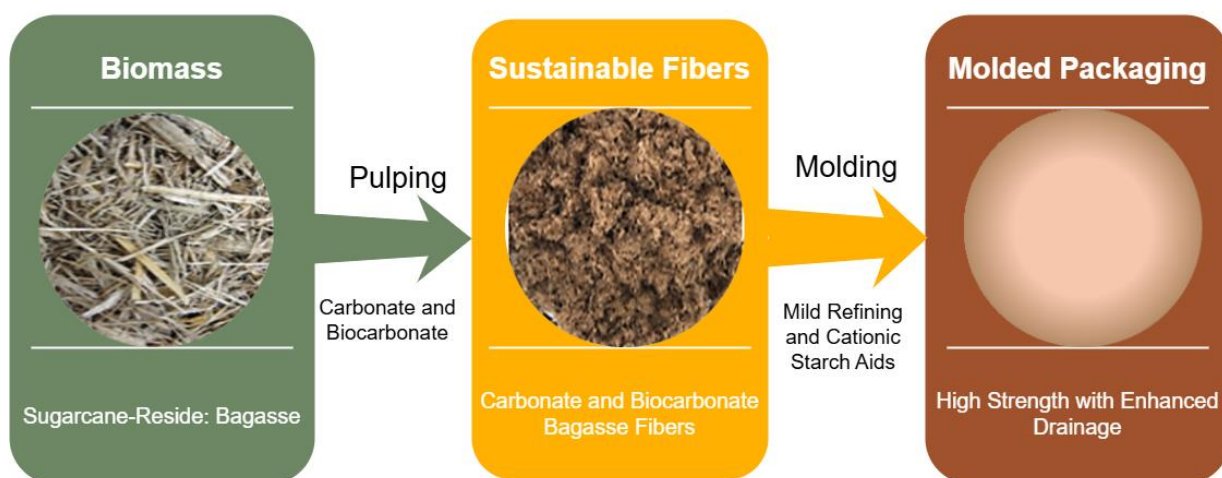
Development of Molded Fibers-Based Packaging from Sugarcane Bagasse for Sustainable Alternatives to Single-Use Plastics

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GRAPHICAL ABSTRACT



Development of Molded Fibers-Based Packaging from Sugarcane Bagasse for Sustainable Alternatives to Single-Use Plastics

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Molded fiber-based packaging has recently surged in popularity as a replacement for single-use plastics (SUPs). However, key challenges include the lack of low-cost, high-yield sustainable fibers that provide adequate strength and moldability while reducing drying energy consumption, which is essential for widespread adoption. Therefore, this study explores high-yield, sustainable fiber development for molded packaging applications through carbonate and bicarbonate pulping, as well as oxygen delignification. Furthermore, it examines mild refining and cationic starch treatments to balance strength and drainage properties during the molding process. Results show that carbonate and bicarbonate pulping of sugarcane bagasse achieved yields of approximately 72%, while oxygen delignification reduced yield by 2% but improves mechanical performance by 25%. Mild refining decreased dryness by 10%, whereas adding 1% cationic starch enhanced dryness by 9% and increased mechanical strength by up to 60%. These alternative fibers from sugarcane bagasse present a viable solution for replacing SUP packaging, helping to mitigate pollution and reduce waste accumulation.

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Keywords: Sugarcane bagasse; Molded packaging; Single-use-plastics; Bicarbonate pulping; Agro-residues; Alternative fibers

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INTRODUCTION

Packaging plays a vital role in the modern economy, offering essential protection for the products while enhancing perceived value and ease of handling (Gutta *et al.* 2013). In 2022, the total value of the global packaging market was ~1 trillion dollars, with a compounded annual growth rate (CAGR) of 2.9% (Smithers 2018). However, a major portion of this market is composed of non-biodegradable and non-renewable materials such as plastics, glass, and metals. The widespread use of plastics, particularly single-use plastic/packaging (SUP) has adverse effects on ecosystems. The excessive use of SUP has raised environmental sustainability concerns (Viera *et al.* 2020; Yates *et al.* 2021; Debnath *et al.* 2022; Lo *et al.* 2024). Since 1950, approximately 60% of the 8.3 billion MT of plastic produced globally has ended up in landfills or natural environment (MacArthur *et al.* 2016; Schneiderman and Hillmyer 2017; Horejs 2020; Ashraf *et al.* 2021; MacLeod *et al.* 2021).

Molded fiber-based packaging products are three-dimensional in nature and have garnered a growing level of interest as a potential substitute for expanded polystyrene (EPS or Styrofoam) (Didone *et al.* 2017; Su *et al.* 2018; Debnath *et al.* 2022; Zhang *et al.* 2022).

Molded fibers are a type of packaging material that have gained recent popularity due to their versatility, sustainability, and eco-friendliness (Wever and Twede 2007; Zhang *et al.* 2022). A molded fibers packaging item typically has low density, moderate compression resistance, and favorable insulating properties, particularly in the dry state (Abhijith *et al.* 2018; Didone and Tosello 2020).

Fibers produced through kraft pulping exhibit greater flexibility and conformability when exposed to moisture, resulting in a greater degree of compression and subsequent reduction in thickness (Kirwan 2013). In terms of strength properties, it has been observed that the mechanical properties of kraft fibers tend to decrease with each successive reprocessing cycle. This can be attributed to the resistance of fiber swelling when rewet after undergoing drying (Hubbe *et al.* 2007). This poses a significant challenge for incorporating 100% recycled fibers in molded packaging. In this context, low-cost non-wood fibers specifically from sugarcane bagasse can be used as a sustainable alternative to high-cost virgin wood fibers for molded packaging (Lo *et al.* 2024). Sugarcane bagasse fiber has emerged as a viable raw material because of its high specific strengths and modulus, low cost, low density, and lightweight compared to other virgin fibers (Mustapa *et al.* 2015).

The two most common methods of fiber development are chemical and mechanical pulping. Both possess advantages as well as limitations. For example, chemical pulping generates low yield and high capital cost fibers, while fibers are optically stable and have high strength properties (Debnath *et al.* 2022). Chemical pulping processes such as kraft pulping can dissolve most or all lignin and a sizeable portion of the hemicellulose, but the yield can go as low as 40% (Su *et al.* 2018). In contrast, mechanical pulping generates high-yield fibers, but the process requires high electrical energy, and the resulting fibers are optically unstable and low in mechanical strength (Debnath *et al.* 2022).

There are some other limitations in the current practice of fiber development and barrier performance of the products that hinder their widespread applications despite their popularity. Unlike traditional paper-based packaging, molded packaging is defined as having a three-dimensional shape which limits conventional drying. Another challenge is their low barrier properties. Unlike plastic and paper-based packaging, molded fiber-based packaging does not provide the same level of protection against moisture, oxygen, and other external factors. This can limit the range of products that can be packaged using molded paper, as some products require a higher level of protection. Additionally, molded fibers can also tend to stick together, making it difficult to separate and leading to issues during production.

Hence, the current study aims to develop high-yield sustainable fibers from sugarcane bagasse through low-chemical pulping techniques such as carbonate and bicarbonate cooking, followed by evaluation of fiber properties. An oxygen delignification step with bicarbonate pulping was also performed to evaluate fiber properties and packaging paper. A mild mechanical refining and bio-based additive (cationic starch, St) treatment was conducted to improve molded packaging dryness and mechanical strength. Finally, the molded fiber product exemplified as handsheet were developed from bagasse fibers were further evaluated for mechanical performance for the potential replacement of single-use plastic molding, such as clamshells, trays, or protective inserts, where moisture resistance is not a primary concern.

EXPERIMENTAL

Materials

Sugarcane (*Saccharum officinarum*) bagasse (BG) of dimensions 4 to 9 mm wide and 20 to 40 mm long was used. The chemicals utilized in the pulping process, namely sodium carbonate (Na_2CO_3) and sodium bicarbonate (NaHCO_3), as well as the paper-making additive cationic starch, were acquired from Fisher Scientific and Ingredion.

Methods

Compositional analysis of sugarcane bagasse

Raw BG was soaked in tap water at a 4:1 (water-to-solid) ratio for 2 h. After 2 h, the wet BG was taken out and air dried until reaching a solid consistency of 90%, and then it was utilized for the chemical composition analysis. The compositional analysis followed the procedures of Sluiter *et al.* (2008) and ASTM E1758-01 (2015), as previously reported in the literature (Stevulova *et al.* 2014; Naithani *et al.* 2020; Salem *et al.* 2020).

Chemical (carbonate and bicarbonate) pulping of sugarcane bagasse

Before pulping, BG was washed to remove any dirt or contaminants. Carbonate and bicarbonate pulping was done in a digester with BG at a high liquor-to-solid ratio of 8:1 due to the lower bulk density of BG compared to softwoods and hardwoods. The bicarbonate pulping was done at 4% and 8% active alkali charge with and without oxygen, while carbonate pulping was done at 4% and 8% active alkali charge without any oxygen. All the active alkali chemical charge was calculated based on the oven dry weight of the BG. A schematic representation of the process is shown in Fig. 1. A total of six different chemical pulping (shown in Table 1) were done to compare fiber quality and its effect on molded fiber.



Fig. 1. Schematic representation of carbonate and bicarbonate pulping, refining and screening of the sugarcane bagasse

Table 1. Different Chemical (Carbonate and Bicarbonate) Pulping, Active Alkali Concentrations, and Reaction Conditions Used for Sugarcane Bagasse

Sample ID	Chemical Treatment ^a		Reaction Conditions ^b		
	Active Alkali	Active Alkali Concentration (%)	O ₂ (Presence/Absence)	Time (hr)	Pressure (psi)
BG-SB8	NaHCO ₃	8	No	-	-
BG-SB8O	NaHCO ₃	8	Yes	1	100
BG-SB4	NaHCO ₃	4	No	-	-
BG-SB4O	NaHCO ₃	4	Yes	1	100
BG-SC8	Na ₂ CO ₃	8	No	-	-
BG-SC4	Na ₂ CO ₃	4	No	-	-

a: Chemical treatment was done at 160 °C and H- factor 1200, b: Temperature was 100 °C.

Molded paper handsheet preparation

All prepared pulps were utilized to prepare molded handsheets of 100 g/m² basis weight were prepared following the TAPPI T205 sp-02 (2006) method, with modifications to better represent the higher basis weight structures typical of molded pulp products. A mild PFI refining and cationic starch (1%) treatment was performed in the fiber slurry to optimize the paper properties. There were 15 handsheets prepared for each condition. Specifically, handsheets with a basis weight of approximately 100 g/m² (compared to the standard 60 g/m²) were formed using a standard TAPPI handsheet mold. Following sheet formation, an alternative drum drying method was employed instead of conventional ambient drying, to better simulate industrial molded fiber processing. These modifications made it possible to assess both drying efficiency and fiber surface stickiness under more practical conditions. The physical properties of the molded fiber sheets were measured after drying with a drum dryer at 105 °C.

Determination of Pulp and Fiber Quality

To evaluate the quality of the pulp and fiber analysis, several tests were conducted for all prepared pulps. The pulp yield, kappa number, freeness, and brightness were performed according to TAPPI T222 om-21 (2021), TAPPI T236 om-99 (2006), TAPPI T227 om-99 (1999), and ISO brightness (ISO-2470-1 2016), respectively. Weighted fiber length (l_w), fines level, and other physical parameters of the pulp samples were calculated using a high-resolution fiber quality analyzer (HiRes FQA, OpTest Equipment Inc, Hawkesbury, ON, Canada).

Determination of Molded Papersheet Properties

The performance of prepared molded paper was evaluated in terms of dryness, tensile strength, and air resistivity. The effects of mechanical refining and cationic starch were also evaluated and compared to unrefined and no-starch samples. The air resistivity was performed as per TAPPI T460 om-02 (2006) while tensile strength was performed as per TAPPI T494 om-01 (2006).

X-Ray Diffraction (XRD) Analysis

A Rigaku SmartLab X-Ray Diffractometer was used to measure the crystallinity indices (C.I.) of the variously processed BG. X-Ray source was run at 45 kV and 40 mA to generate Ni-filtered CuK α radiation. X-Ray diffractograms were captured between the range of 5 to 60° at 0.02°/s for every two scans. The handsheets of molded fiber were dried completely overnight and then utilized for crystallographic analysis. The percentage

crystallinity index (% C. I.) of the samples was determined using the Segal Peak height method (Segal *et al.* 1959),

$$\text{Crystallinity Index (\% C.I.)} = \left[\frac{(I_{002} - I_{AM})}{I_{002}} \right] \times 100 \quad (1)$$

where I_{002} is the intensity of the diffraction peak of the crystalline plane at 22° , and I_{AM} is the minimum intensity between the crystalline peak (I_{002}) and the amorphous background (typically evaluated at 18°).

Scanning Electron Microscopy (SEM)

A Hitachi S3200N variable pressure scanning electron microscope (VPSEM) was used to characterize the morphological nature of the prepared samples. The molded paper samples were analyzed for surface and cross-sectional microstructure. All of the samples were sputter coated with gold-palladium for 5 min to create a 10 nm coating layer. SEM micrographs were acquired at 10 kV for 250 to 2500 magnifications.

RESULTS AND DISCUSSION

Chemical Composition of Sugarcane Bagasse

The chemical composition of raw materials is indeed an important factor in determining their suitability for fiber sources and their applications. When comparing the chemical composition of BG to wood and non-wood biomass sources, there were similarities and differences in their chemical components, based on the present findings and previously published data as cited in Table 2. The contents of hemp hurd (cellulose - 43.0%, hemicellulose - 29.0%, lignin - 24.4%, ash - 3.6%), softwood (cellulose - 42.0%, hemicellulose - 27.5%, ash - 2.8%), and BG (cellulose - 41.8%, hemicellulose - 28.1%, lignin - 22.8%, ash - 3.6%) were similar.

Table 2. Chemical Composition of Sugarcane Bagasse and Other Wood (Softwood and Hardwood) and Non-Wood (Rice Straw, Wheat Straw, Bamboo, and Hemp Hurd) Biomasses

Biomass	Cellulose (%)		Hemicellulose (%)		Lignin (%)		Ash (%)		References
	Avg.	Std.	Avg.	Std.	Avg.	Std.	Avg.	Std.	
Sugarcane Bagasse	41.8	2.6	28.1	2.9	22.8	1.6	3.6	1.4	Current work
Hardwood	44.1	1.9	24.0	1.2	20.0	3.4	4.1	2.6	Heinze <i>et al.</i> (2018)
Softwood	42.0	1.5	27.5	2.5	28.7	3.1	2.8	2.1	Heinze <i>et al.</i> (2018)
Rice Straw	44.3	2.4	33.5	2.3	20.4	2.5	Not recorded		Chen <i>et al.</i> (2011)
Wheat Straw	45.0	2.0	21.3	1.8	19.0	3.1	Not recorded		Asghar <i>et al.</i> (2015)
Bamboo	43.2	1.2	27.1	1.8	26.7	2.0	3.0	1.3	Salem <i>et al.</i> (2020)
Hemp Hurds	43.0	2.4	29.0	1.1	24.4	2.2	3.6	2.3	Salem <i>et al.</i> (2020)

One notable difference was lignin content of BG (20.8%) was less compared to widely used softwood (28.7%) for fiber production and paper making. The chemical

compositions of BG and some other wood and non-wood biomass are provided in Table 2. BG is a waste or low-value by-product of the sugarcane industry. The high cellulose and low lignin content in the BG shows that it can be mildly treated for defibrillation or high-value cellulose production and can be considered a sustainable and excellent source of fiber production and/or paper making.

Pulp Yield and Residual Lignin Content

The yields of bicarbonate and carbonate pulps were calculated and are presented in Fig. 2. The yields ranged from 67% to 72%, depending on active alkali charge and whether the pulping process included oxygen delignification. These yields were significantly higher than the pulp yield produced by conventional soda pulping methods (Ferdous *et al.* 2020). The pulp yield of oxygen delignified bicarbonate BG at 4% and 8% active alkali charge were 68.5% and 67.9%, respectively, which was 3.2% and 2.0% less than the pulp yield of bicarbonate pulping at 4% and 8% active alkali charge without oxygen delignification. The low yield at oxygen delignified fibers is due to the removal of higher amount of lignin by oxygen delignification. In contrast, 4% and 8% active alkali treated carbonate pulping showed 71.7% and 66.6% yields, respectively. The reason for the lower pulp yield is because high pH facilitates the peeling reaction while concomitantly removing a higher amount of lignin (Lusby and Maass 1937; Naithani *et al.* 2020). The removal of the higher amount of lignin represents a low kappa number as shown in Fig. 2.

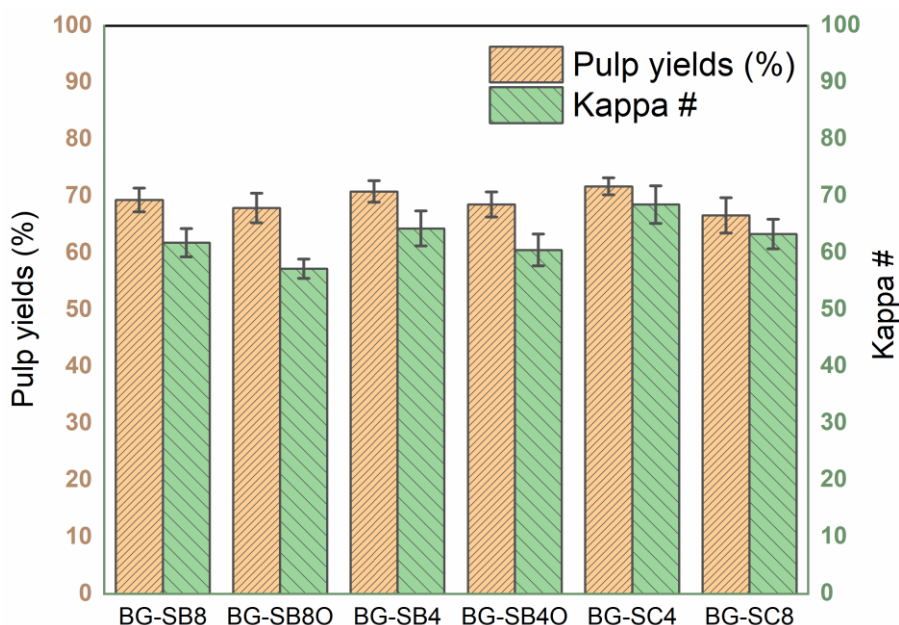


Fig. 2. Effect of carbonate and bicarbonate (with and without oxygen) pulping on fiber yield (%) and kappa number of the pulp produced from sugarcane bagasse

Fiber Quality and Pulp Properties

The investigation of fiber structure was extended through a comparative analysis of the fiber morphology of the pulps generated by six distinct processes. The morphology of fibers is intricately linked to structure, which is predominantly governed by the feedstocks and pulping conditions. The fiber quality is typically characterized by fiber length, coarseness, kink, curl, and fine content, as shown in Table 3.

The carbonate and bicarbonate processes made the fiber softer and caused it to defibrillate with a high degree of fibrillation, which ultimately resulted in the production of fewer fines and longer fibers (Lyytikäinen *et al.* 2011; Naithani *et al.* 2020). Oxygen delignified bicarbonate fibers at both conditions (4% and 8% AA) generated fewer fines, less coarse fibers, and relatively high brightness than the other two bicarbonate fibers. In contrast, high charge (8% AA) carbonate pulping generated fewer fines, less coarse and longer fibers than low charge (4% AA) carbonate fibers. Research on fiber properties has demonstrated that longer fibers exhibit better strength characteristics, particularly in terms of resistance to tearing. This is because longer fibers possess a greater surface area for bonding, which enables them to form a more robust network than shorter fibers. Fibers that are longer and slender, possessing greater fibrillation and reduced coarseness, exhibit a propensity for facile collapse and formation of a robust network characterized by low bulk and high density, as observed from the scanning electron microscopy in Fig. 6 (Belle and Odermatt 2016). Oxygen delignified bicarbonate fibers generate relatively higher yield, lower fines, and less coarse fibers. As expected, the brightness of the oxygen delignified bicarbonate and high alkali charged carbonate fibers are higher than other conditions. The parameter of freeness holds significant importance in the process of paper manufacturing. It is an indicator of the pulp fibers' capacity to exhibit fluidity and facilitate water drainage during paper production. The degree of fiber separation or fibrillation, the amount of fine content, coarseness, and the surface charge of the fibers are the determining factors for freeness. The value of freeness exhibited a positive correlation with lignin present, as well as with lower levels of fibrillation and higher degrees of coarseness. As shown in Table 2, all fibers produced through different pulping methods exhibited high freeness. This is attributable to retention of most of the lignin and hemicellulose as the fibers were developed through mild chemical pulping techniques (Naithani *et al.* 2020; Salem *et al.* 2020).

Table 3. Fiber Quality Parameters (Length, Width, Fines, and Coarseness), Freeness, and Brightness Values of the Sugarcane Bagasse at Different Pulping Conditions

Pulp Type	Length, l_w (mm)	Width (μm)	Fines (%)	Coarseness ($\text{mg}\cdot\text{m}^{-1}$)	Freeness (CSF, mL)	Brightness (ISO)
BG-SB8	1.17	22.4	10.47	0.18	714	12.61
BG-SB8O	0.84	22.8	8.35	0.13	679	14.30
BG-SB4	0.68	21.7	15.37	0.22	667	9.58
BG-SB4O	0.84	19.7	10.22	0.16	635	12.63
BG-SC4	0.77	20.8	13.67	0.19	709	10.36
BG-SC8	1.05	22.6	6.86	0.14	704	16.35

X-Ray Diffraction (XRD) and Crystallinity Index

X-ray diffraction (XRD) analysis was employed to assess the impact of pulping conditions on the crystallinity indices of BG fibers. The crystallinity of the cellulosic fibers was observed through the presence of three distinct characteristic peaks at $2\theta = 16^\circ$, 22° , and 35° (Verma *et al.* 2023). These peaks were observed in all fibers, although their intensity varied. Fibers generated through high chemical charge and oxygen delignification exhibited a higher crystallinity index, as evidenced by the greater intensity of the observed peaks. The amorphous nature of fibers can be attributed to the presence of hemicellulose, which is characterized by short, linear, and highly branched sugar side chains (Scheller and

Ulvskov 2010). These chains are extensively crosslinked with lignin and cellulose through cinnamate ester linkages and hydrogen bonding, respectively (Hendriks and Zeeman 2009). The crystalline indices of fibers processed by bicarbonate and carbonate pulping with and without oxygen delignification range from 45 to 57% as shown in Fig. 3.

The higher crystallinity indexes ~57, 52, and 55% were observed for fibers prepared by 8% and 4% bicarbonate pulping with oxygen delignification and 8% carbonate pulping, respectively. These higher values may be attributed not only to the mild chemical pulping's minimal impact on the peeling reaction and amorphous cellulose removal but also to the partial delignification and potential loss of hemicellulose also, hence increasing the relative proportion of the crystalline cellulose in the fibers.

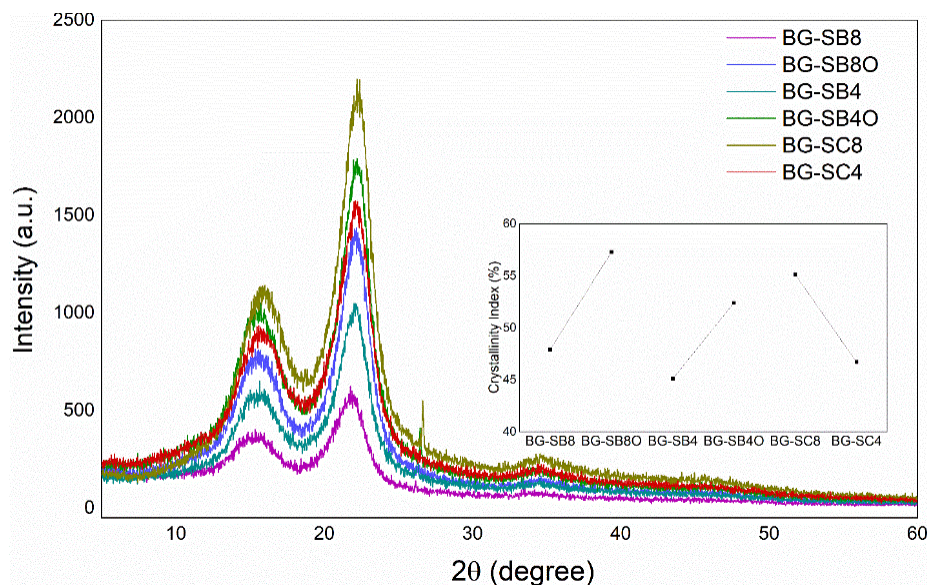


Fig. 3. X-Ray diffractogram and % crystallinity of fibers after carbonate and bicarbonate (with and without oxygen) pulping

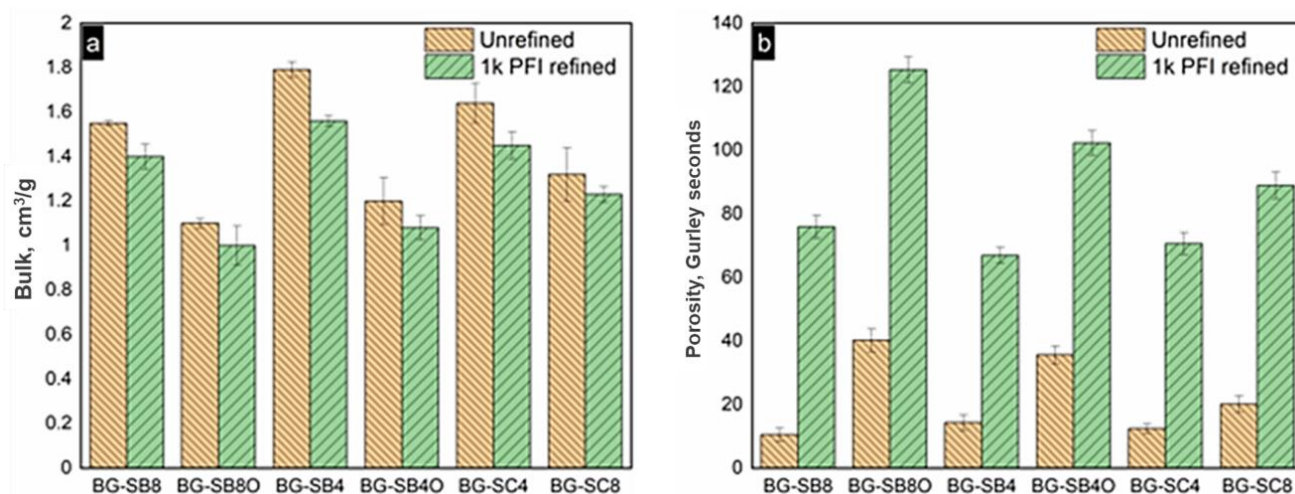


Fig. 4. Effect of refining on bulk (a) and porosity (b) of the molded paper sheets produced from carbonate and bicarbonate (with and without oxygen) pulping

Molded Paper Properties

Effect of refining on bulk and air permeability

Bulk is a crucial characteristic for product packaging. Porosity, pore volume, thickness, liquid absorption, and air/gas permeability can all be impacted by it (Kartovaara *et al.* 1985). The fiber processing and mechanical refining significantly affect the bulkiness of the molded paper. Figure 4(b) shows that fibers processed with oxygen delignified bicarbonate methods possessed low bulk due to higher fibrillations and low lignin, which allows a denser hydrogen bonding network by fiber collapsing. In contrast, BG-SB4 and BG-SC4 fibers were coarser and retained high lignin content, which will resist fiber collapse and thus form a bulkier paper with less mechanical strength.

Mild mechanical refining of the fibers enhances fibrillations and thus facilitates fiber-fiber bonding and ease of fiber collapsing which reduces bulkiness. It was observed that 1000 revolutions (1k) of PFI refining resulted in a 9 to 12% reduction of the bulkiness of molded paper. SEM images in Fig. 5 show the overall bulkiness and reduced thickness in refined paper. Oxygen delignified bicarbonate paper had lower thickness (as measured by ImageJ software), while the fibers were densely agglomerated, thereby forming a higher density and less porous paper. This has been also reflected in the air permeability data where BG-SB4O and BG-SB8O paper with mild refining showed high Gurley seconds value due to the low permeability of the air through paper surface. Gas barrier is an important parameter for food packaging measured using a Gurley seconds tester (higher Gurley seconds → lower permeable), where all the unrefined samples showed below 100 Gurley seconds in Fig. 4(b). While the 1k-PFI refined samples significantly improved the air resistance due to the increased number of hydrogen bonds and formation of a denser network in the paper web which was also proven by showing lower bulkiness. The effect of refining increases the hydrogen bonding and makes a denser network in paper is supported by several other studies (Barrios *et al.* 2024; Debnath *et al.* 2021, 2025; Motamedian *et al.* 2019; Salem *et al.* 2022; Starkey *et al.* 2021; Upadhyay *et al.* 2023).

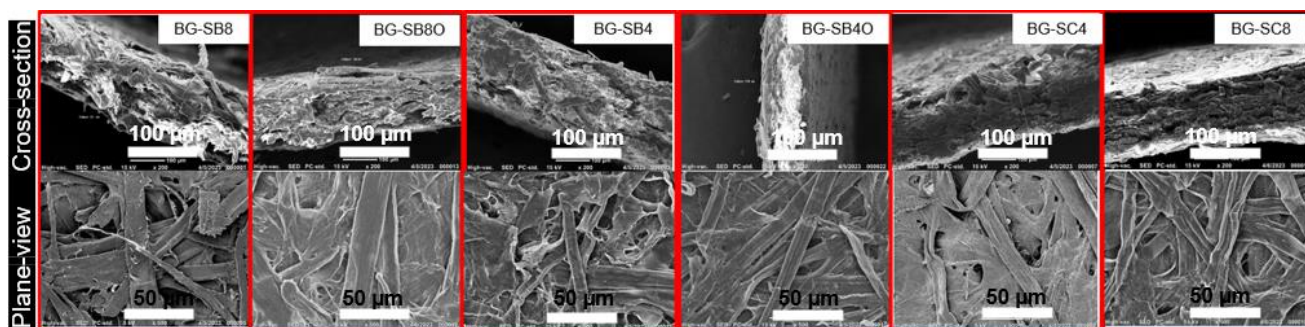


Fig. 5. Surface and Cross-sectional SEM micrographs of the molded paper sheet produced through carbonate and bicarbonate (with and without oxygen) pulping

Effect of refining and cationic starch on dryness

The dryness of molded packaging is a critical factor in its production process and overall quality. It was observed that unrefined paper exhibited faster drying compared to refined paper, with a decrease in dryness of approximately 10% after the refining process, as shown in Fig. 6. This decrease can be attributed to the higher degree of fibrillation and increased fiber-water bonding resulting from refining.

In contrast, when 1% cationic starch was added to the paper slurry, it led to a significant enhancement in dryness by approximately 9%. This improvement can be

attributed to the interaction between the cationic starch and the fine particles. The cationic starch acts as a flocculating agent causing fine particles to aggregate and form larger flocks. These larger flocks have less interaction with water compared to individual fines, thereby increasing the drainage rate and ultimately enhancing the dryness of the molded packaging (Nachtergaele 1989). The findings highlight the influence of refining and the addition of cationic starch on the dryness of molded packaging. Refining can decrease dryness due to increased fiber-water bonding, while the inclusion of cationic starch can improve dryness by facilitating the formation of larger flocks and promoting efficient water drainage.

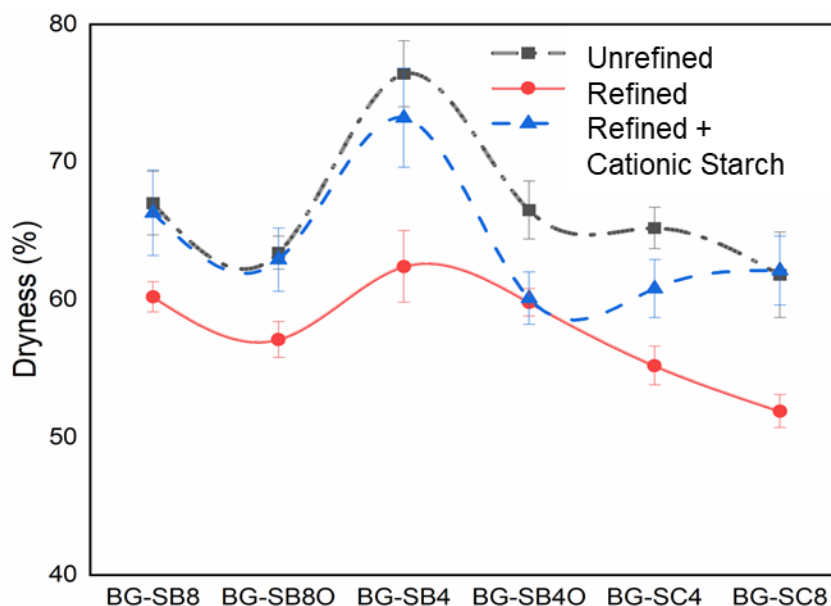


Fig. 6. Effect of refining and cationic starch on dryness of molded papersheets prepared through carbonate and bicarbonate (with and without oxygen) pulping

Tensile strength

The tensile strength of molded paper is a crucial parameter in assessing strength properties, particularly for packaging. It is largely dependent on various factors including fiber strength, fiber length, and bonding. Figure 7 compares three types of fibers: oxygen-delignified bicarbonate, fibers and bicarbonate fibers, and carbonate fibers. The oxygen-delignified bicarbonate fibers exhibited approximately 25% higher tensile strength compared to fibers prepared by bicarbonate pulping. This increase in tensile strength can be attributed to less lignin and a higher degree of fibrillation in oxygen-delignified fibers. The reduction in lignin content allows for better inter-fiber bonding and collapse, resulting in the formation of a stronger paper.

Additionally, the study revealed that refining of the fibers led to a significant increase in tensile strength by 40 to 60%. Refining increases the surface area and promotes fibrillation of the fibers, thereby facilitating hydrogen bonding. This improved bonding contributes to enhanced tensile strength in the molded paper. Furthermore, the addition of starch was found to improve tensile strength by 10 to 20% because addition of starch improves inter-fiber bonding (Tajik *et al.* 2018).

Comparing the two types of fibers, it was observed that both oxygen delignified carbonate/bicarbonate pulps demonstrated superior tensile performance compared to fibers prepared without oxygen delignification, with BG-SB8O showing a 26% improvement and

BG-SB4O showing a 16% improvement in tensile strength. Overall, the findings highlight the significant impact of oxygen delignification pulping techniques, refining, and starch addition on the tensile strength of molded paper.

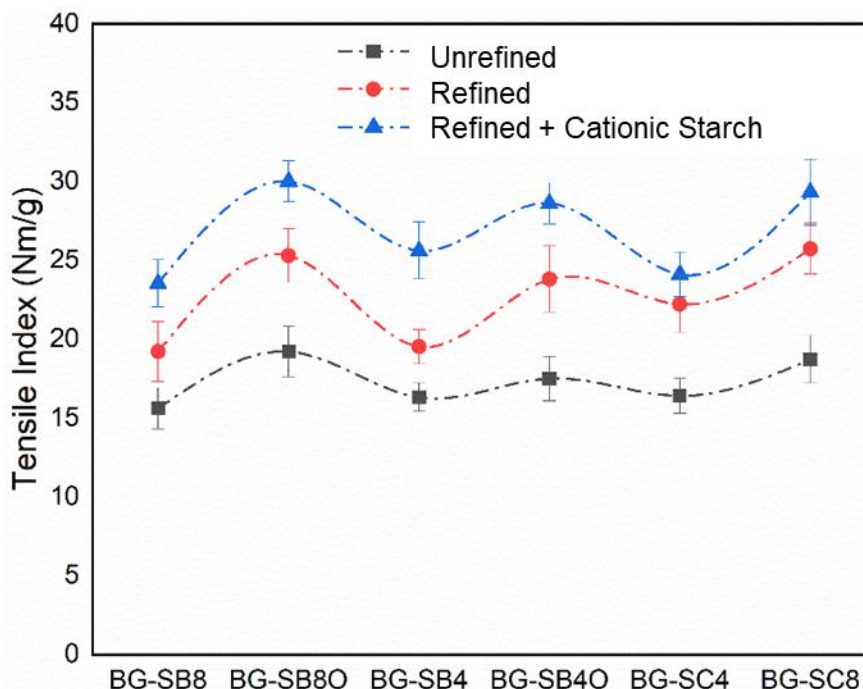


Fig. 7. Effect of mechanical refining and cationic starch on the tensile index of the molded paper sheets prepared using carbonate and bicarbonate (with and without oxygen) pulping

CONCLUSIONS

1. Utilizing sodium bicarbonate and sodium carbonate pulping processes, which are environmentally friendly, enabled the efficient production of high-yield fibers, with pulping yields of ~72%.
2. The incorporation of oxygen delignification, through slightly lowering yields by 2%, significantly improved fiber quality, enhancing mechanical performance by 25%.
3. Furthermore, mild refining decreased dryness by 10%, but the addition of 1% cationic starch offset this, enhancing dryness by 9% and mechanical strength by up to 60%.
4. The mild chemicals used in the pulping processes align with green chemistry principles, ensuring minimal environmental impact.
5. The valorization of sugarcane bagasse, an agricultural residue, not only reduces pollution and waste accumulation, but it also supports a circular economy by creating high value sustainable packaging solutions.
6. Future work could explore the addition of barrier layers to the molded packaging material to enhance its suitability for water-based product applications, as well as conduct a life cycle assessment and techno-economic analysis to evaluate the process and environmental impact of the developed material.

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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