UTILIZATION OF FLY ASH FROM BIOMASS ENERGY PLANT WASTE AS FILLER IN FLUTING PAPER PRODUCTION

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This study explores the utilization of fly ash, a by-product from biomass energy plants, as a filler in the production of fluting paper. The integration of fly ash into fluting paper aims to enhance sustainability by reducing dependence on traditional fillers like calcium carbonate and kaolin. Fluting paper samples were produced with varying fly ash contents, and their physical, mechanical, and optical properties were thoroughly analyzed. The findings reveal that while fly ash contributes to improvements in bulk and optical properties, such as whiteness and brightness, it results in a reduction in mechanical strength, notably in tensile and burst strength. Despite these reductions, fly ash offers significant economic and environmental advantages by lowering production costs and diverting waste from landfills. Additionally, SEM imaging confirmed the uniform distribution of fly ash within the paper matrix, ensuring compatibility with existing production processes. This study demonstrates the potential of fly ash as a sustainable and cost-effective filler in fluting paper production, presenting opportunities for both resource optimization and environmental impact reduction in the paper industry.

Keywords: fly ash, fluting paper, filler, sustainability

INTRODUCTION

The recycling of paper has turned into the backbone of environment-friendly strategies,[1,2] as reducing recovered paper not only conserves natural resources, but also limits industrial waste recovery. The impact of recycling goes much farther than helping conserve the environment; it is a key part of the economic and operational benefits for major industries like the corrugated cardboard sector. Most of the paperboard used in the production of corrugated cardboard comes from recovered paper. Test liner and fluting papers are the most important grades used in this production. Test liner papers, mostly found on the surface of corrugated cardboard boxes, contribute to the packaging's mechanical strength and resilience against external forces like impact and moisture.[2–6] By contrast, fluting papers, which form the inner layers of the corrugated structure, provide a cushioning effect and protection from vertical compression; flutes also contribute to strength from top to bottom. Test liner and fluting work together as an effective combination, with the test liner providing external strength to the box, while the fluting ensures that the box withstands compressive forces, both internally and externally.

In the context of paper production, the application of fillers has enabled a change in how manufacturing can be undertaken to improve product quality and cost reduction.[7–10] Fillers have two major functions in papermaking. First, they enhance the surface of the paper, making it more regular and smoother, which is critical as it facilitates better properties for printing and writing applications, thereby improving the final appearance and quality. Second, fillers help make the material more competitively priced and environmentally sound by minimizing reliance on virgin raw materials. Most fillers, usually calcium carbonate, kaolin, and talc, are mined from natural deposits. However, increased demand for paper products has driven up the price of recovered paper as a raw material, leading manufacturers to seek cheaper alternatives. While lower-cost fillers are appealing, they often affect negatively final product quality and performance. Thus, due to the trade-off between cost savings and product performance, a balance that must be found in the paper industry.[10–13] This is why the choice and application of fillers continue to be among the most important decisions producers must make in paper manufacturing in order to succeed in both economically sustainable and environmentally friendly processes.

Bioenergy power plants are a significant cornerstone of the global transition to renewable energy sources,[14–16] widely used for electricity production by converting organic materials into energy. Using biomass, such as waste wood, agricultural residues, and organic waste, these facilities generate power and provide a greener alternative to fossil fuels. Biomass is primarily converted into energy through thermal processes like gasification and combustion. When organic matter combusts, the carbon contained within reacts with oxygen, releasing energy used to generate electricity. One of the by-products of this process is fly ash, composed mainly of mineral oxides, which is released through the plant's chimneys.[17–20] Managing fly ash is a critical issue concerning both environmental and energy sector sustainability.

In the context of paper production, the innovative use of fly ash as a filler material represents a forward-thinking approach to resource optimization and waste reduction. Collaborations between recovered paper mills and biomass energy plants have identified fly ash as a valuable by-product that can be repurposed as a filler material in paper production. Using fly ash as a filler not only improves the surface properties of paper by reducing roughness and enhancing bulk, but also offers significant environmental benefits by reducing the reliance on traditional mineral fillers, such as calcium carbonate and kaolin. This shift towards the use of industrial by-products, such as fly ash, aligns with the broader goals of resource efficiency and sustainability. Additionally, fly ash is available at a lower cost compared to conventional fillers, providing a competitive edge for manufacturers while simultaneously promoting eco-friendly practices.

Recent research has investigated the reuse of industrial by-products, such as fly ash, as alternative fillers in papermaking. Satriawan *et al.* demonstrated that unmodified fly ash can increase the bulk and opacity of paper, but negatively affects brightness and mechanical strength.[21] In an effort to overcome these limitations, Fan *et al.* applied a carbonation treatment to fly ash particles, forming composite fillers coated with calcium carbonate.[22] This method improved compatibility with pulp fibers and enhanced brightness and retention. Similarly, Zhao *et al.* synthesized a fly ash-based calcium silicate (FACS) material, with high surface area and porosity, which yielded improved filler retention and tensile strength compared to traditional PCC, although optical performance remained suboptimal.[23]

Later, Song *et al.* examined the printability of FACS-filled paper and concluded that it provided excellent bulk and mechanical strength, albeit with higher ink consumption.[24] Zhao *et al.* further investigated FACS in cardboard production, utilizing interlayer filling and surface sizing techniques to reduce performance loss at high filler levels.[23]

Although these studies provide valuable insights, most focus on modified fly ash used in virgin or mixed pulp systems, with extensive chemical or physical treatments, such as carbonation, surface coating, or sintering. In contrast, our study employs untreated fly ash (used in its raw form with only sieving) directly as a filler in the production of fluting paper from recycled fibers. The fly ash used in our study is obtained from the biomass-based energy unit of the same paper factory, which eliminates both transport and acquisition costs, making it a zero-cost additive and a highly practical solution for industrial-scale application.

Furthermore, unlike earlier studies that primarily target fine paper or newsprint, this research is specifically tailored to fluting-grade paper, where optical properties are of secondary importance and bulk and strength are prioritized. By comparing key physical and mechanical parameters of fly ash-filled recycled paper with those of conventional fillers (via literature references, such as Fan *et al*., and Song *et al*.),[22,24] this study reveals the real-world feasibility and potential of valorizing fly ash directly within the production line. The integration of this material not only promotes resource circularity, but also enhances sustainability in paper manufacturing.

This study seeks to evaluate both the environmental and economic benefits of integrating fly ash from biomass energy plants into fluting paper production at recovered paper mills. The repurposing of fly ash as a filler not only reduces waste destined for landfills, but also lowers production costs, contributing to the economic sustainability of the industry. Moreover, this approach fosters innovation in paper manufacturing and aligns with future industrial policies focused on sustainability, resource efficiency, and waste minimization. The findings of this study have the potential to influence future environmental and industrial practices, offering a model for other sectors seeking to integrate circular economy principles into their operations.

EXPERIMENTAL

Materials

The pulp used in this study was obtained following the pulping process at the Kahramanmaraş Paper Industry Inc. Fly ash, a by-product from the biomass energy plant of the same facility, was used as a filler material after being sieved through a 200-mesh screen to ensure uniform particle size. To improve fiber retention, polyacrylamide was sourced commercially and incorporated into the paper production process. All paper manufacturing experiments were carried out in Paper and Board Production Laboratory of Kahramanmaraş Sütçü İmam University, Faculty of Forestry. This controlled laboratory environment ensured precision in each stage of the production process, facilitating reliable and replicable results.

Fluting paper production

The pulps were progressively beaten in a laboratory-scale Hollander beater until a freeness degree of 35±5 SR° was achieved, ensuring optimal fiber consistency for fluting paper production. This precise control over the refining process was critical for producing fluting papers with grammages of 120 g/m² and 150 g/m², which meet industry standards for strength and performance. Fly ash, serving as the filler material, was added to the pulp mixtures in varying proportions, as outlined in Table 1. The integration of fly ash was carefully calibrated to enhance the paper's bulk and surface properties, without compromising structural integrity. Paper production was carried out using a laboratory-scale Rapid Köthen RK-21 papermaking machine.

A total of ten test papers were produced from each mixture to evaluate the physical, mechanical, and optical properties in relation to the varying ash content. Before testing, the paper samples were conditioned for 24 hours in a climate-controlled chamber, maintained at a temperature of 23±1 °C and a relative humidity of 50±2%, in strict accordance with the TAPPI T402 om-88 standard. This standardized conditioning process ensured that the papers reached equilibrium moisture content, eliminating any variability in test results due to environmental factors, thus providing accurate and reliable data on the impact of ash content on the paper's performance characteristics.

Determination of physical, mechanical, and optical properties

The fluting papers produced with ash filler content at varying ratios of 0%, 5%, 10%, and 15% were subjected to a comprehensive series of tests, as detailed in Table 2. These tests were meticulously conducted, following recognized industry standards, to ensure the accuracy and reliability of the results. The physical properties, including thickness and density, the mechanical properties, such as tensile and burst strength, and the optical properties, including brightness and opacity, were thoroughly evaluated. This thorough assessment provided critical insights into how the varying levels of ash filler influenced the overall performance and quality of the fluting papers, particularly in terms of their suitability for industrial applications.

SEM analysis

Images of the test papers were captured using a Scanning Electron Microscope (SEM) to analyze the distribution of the ash filler material incorporated into the fluting papers. These high-resolution images were obtained from the advanced laboratories at Kahramanmaraş Sütçü İmam University's ÜSKİM Research Center.

Table 1
Production conditions for fluting paper

No	Grammage (g/m^2)	Fiber charge (%)	Fly ash charge (%)
1	120	100	0
2	120	95	5
3	120	90	10
4	120	85	15
5	150	100	0
6	150	95	5
7	150	90	10
8	150	85	15

Table 2
Physical, mechanical, and optical tests and standards applied to the fluting papers

Tests	Standards
Basis weight (g/m^2)	ISO 536
Thickness (μ)	ISO 534
Breaking length (m)	ISO 1924-2
Burst index (kPa.m^2.g^{-1})	ISO 2759
Tear index (mN.m^2.g^{-1})	ISO 1974
Air permeability (s)	ISO 5636
SCT – short span compression test (kN/m)	ISO 9895
Ash content (%)	ISO1762
Whiteness (%ISO)	ISO 2469
Brightness (%ISO)	ISO/DIS 2470
Yellowness (E313)	ASTM E313

A detailed comparison of the SEM images allowed for a thorough examination of how the ash filler material was dispersed within the paper matrix, providing insights into the uniformity of the distribution and its potential effects on the physical and mechanical properties of the paper. This microscopic analysis was critical in understanding the interaction between the fibers and the ash filler, further enabling the assessment of its impact on paper performance.

Statistical analyses

To ensure the accuracy and reliability of the results, each test listed in Table 2 was performed with a minimum of three repeated measurements on the fluting papers. The resulting data were then analyzed using statistical methods, including analysis of variance (ANOVA) and Duncan's multiple range test, through the SPSS statistical program. These statistical tools were employed to identify significant differences among the ash filler inclusion ratios and to determine which levels of ash provided the optimal physical, mechanical, and optical properties.

RESULTS AND DISCUSSION

Ash content of fluting papers

The impact of incorporating fly ash waste from biomass power plants as a filler material on the ash content of fluting papers has been thoroughly investigated. The ash contents of the fluting papers produced with varying proportions of fly ash are presented in Table 3, illustrating the effects of fly ash addition on overall ash retention.

Upon examining Table 3, it was determined that fluting papers produced without the addition of fly ash at 120 gsm exhibited an ash content of approximately 7%. This aligns with findings from Kawanobe and Okayama, and Monte *et al*., who noted that recovered papers, which often contain inorganic filler materials, typically have an ash content ranging between 1-15%.[1,4] In contrast, when fly ash was added at varying proportions (5%, 10%, and 15%), the total ash content increased to as high as 35%, indicating significant retention of the filler within the paper matrix.

This increase in ash content reflects the efficient integration of fly ash as a filler material, as no substantial loss of filler material was observed during the papermaking process. Such retention efficiency is crucial in papermaking, where poor retention can lead to inconsistent paper properties and reduced production efficiency.[25,26] Moreover, the ash analyses revealed that fly ash was uniformly distributed within the pulp, ensuring a homogenous product. This uniform distribution positively influences the interaction between cellulose fibers and fillers, indicating that fly ash enhances the stability of the paper pulp, without negatively impacting fiber-filler bonding.

The use of fly ash as a filler in fluting paper production represents a notable advancement, as it does not introduce retention challenges, which are commonly encountered with traditional fillers, such as calcium carbonate or kaolin.[27] This highlights a key advantage of fly ash, as it maintains the structural integrity and mechanical properties of the paper, while offering substantial cost and environmental benefits. Retention is a critical factor in fluting paper production, directly influencing the paper's thickness, strength, and overall quality. Therefore, the positive impact of fly ash on retention efficiency underscores its potential for enhancing both production efficiency and the final product's performance characteristics.

These findings emphasize the critical role that alternative materials, such as fly ash, can play in improving industrial processes, while simultaneously reducing environmental impact. The successful integration of fly ash not only aids in waste management by repurposing by-products from biomass energy plants, but also paves the way for more resource-efficient manufacturing practices within the paper industry. By reducing reliance on traditional fillers and utilizing waste materials, the paper industry can move towards more sustainable production models that align with circular economy principles, ultimately contributing to environmental and economic sustainability.[2]

In conclusion, the incorporation of fly ash as a filler material in fluting paper production offers a promising solution for enhancing sustainability in the paper industry. It enables the production of high-quality paper, while minimizing environmental impacts and production costs, positioning fly ash as a viable alternative to traditional fillers in the context of modern industrial processes.

Table 3
Ash content of the fluting papers

No	Gsm (g/m^2)	Fly ash charge (%)	Ash content (%)	Diff.*
1	120	0	20.19	-
2	120	5	27.12	6.93
3	120	10	31.50	11.3
4	120	15	34.77	14.6
5	150	0	20.51	-
6	150	5	25.60	5.08
7	150	10	29.63	9.12
8	150	15	34.42	13.9

*The difference between the control samples at 120 and 150 gsm (experiments 1 and 5) and the samples with added fly ash is indicated

Physical properties of fluting papers

Some physical properties of fluting papers filled with fly ash are presented in Table 4. When filler materials, such as fly ash, are incorporated into the spaces between the cellulose fibers that form the paper structure, they effectively fill the gaps, leading to a thicker and denser paper.[7,8,26,28] This observation is consistent with He *et al*., who demonstrated that filler materials typically enhance paper thickness and bulk due to their ability to occupy void spaces between fibers.[9] This results in a tighter, more compact structure, which can enhance certain physical characteristics, such as bulk and opacity, while influencing other properties like flexibility and porosity.

Table 4 presents the physical properties of fluting papers produced with different fly ash content. According to the Duncan test results, there are statistically significant differences in the physical properties of the samples at varying filler levels, especially in thickness, air permeability, and bulk. For instance, the 120 g/m^2 sample with 15% fly ash (No. 4) showed a significant increase in thickness (235 microns), compared to the control sample (No. 1), with a thickness of 214 microns. Similarly, the air permeability values decreased substantially with increased fly ash content, indicating that the filler particles create more pathways for air transmission. This trend aligns with Koivunen *et al.*, who observed that filler particles can disrupt the fiber matrix, thus increasing the material's porosity.[28]

From a comparative perspective, Bown, and Chauhan *et al*. highlighted similar findings, where filler addition reduced paper density, primarily due to the replacement of high-density cellulose fibers with lower-density fillers.[7,8] In this study, a reduction in density is evident as fly ash content increases, confirming that the replacement of fibers with fly ash lowers the overall density of the paper. For example, in the 120 g/m^2 fluting paper, density decreased from 0.56 g/cm^3 in the control sample to 0.51 g/cm^3 in the 15% fly ash sample (No. 4).

This reduction in density leads to an increase in bulkiness values, as bulk is inversely related to density. As suggested by He *et al*., increasing bulk is advantageous for certain paper applications, where lightweight and voluminous materials are preferred. In this case, the bulkiness of the paper improved progressively with higher fly ash content.[9] For instance, bulkiness values increased from 1.78 cm^3/g in the control sample (No. 1) to 1.96 cm^3/g in the 15% fly ash sample (No. 4), which is statistically significant according to Duncan's test.

Furthermore, air permeability values decreased with increasing fly ash content, confirming that fly ash particles create more porous pathways for air.

This is in line with findings from Katsuzawa *et al.*, who demonstrated that fillers generally increase the paper's porosity by altering the fiber structure.[12] For example, air permeability decreased from 11.9 seconds in the control sample (No. 1) to 5.48 seconds in the 15% fly ash sample (No. 4), which is a considerable change and statistically supported by Duncan's test.

These results confirm that fly ash, as a filler material, significantly enhances the physical properties of fluting papers, particularly in terms of thickness, bulk, and air permeability, while reducing density. These changes are important for applications where bulk and porosity are desired, providing valuable insights for industries aiming to optimize paper properties while reducing production costs. Additionally, the statistical validation from Duncan's test underscores the reliability of the observed trends, making fly ash a viable alternative to traditional fillers like kaolin or calcium carbonate in the production of fluting papers.

Table 4
Some physical properties of fluting papers

No	Gsm (g/m^2)	Fly ash charge (%)	Air permeability (s)	Thickness (micron)	Density (g/cm^3)	Bulkiness (cm^3/g)
1	120	0	11.9^{a}	214^{a}	0.56^{a}	1.78^{a}
2	120	5	7.08^{b}	231^{b}	0.52^{b}	1.93^{b}
3	120	10	5.34^{c}	222^{ab}	0.54^{a}	1.85^{a}
4	120	15	5.48^{c}	235^{b}	0.51^{b}	1.96^{b}
5	150	0	15.8^{a}	274^{b}	0.55^{b}	1.83^{b}
6	150	5	10.3^{b}	253^{c}	0.61^{a}	1.68^{a}
7	150	10	4.84^{c}	258^{c}	0.59^{ab}	1.72^{ab}
8	150	15	5.05^{c}	293^{a}	0.51^{c}	1.95^{c}

*According to Duncan's test, mean values with similar lower-case letters are not statistically different at 95% confidence level

Table 5
Some mechanical properties of fluting papers

No	Gsm (g/m^2)	Fly ash charge (%)	Breaking length (m)	Burst index ($kPa.m^2/g$)	Tear index ($mN.m^2/g$)	SCT (kN/m)
1	120	0	1924^{a}	1.21^{a}	4.58^{ab}	1.93^{a}
2	120	5	1443^{b}	0.98^{b}	4.25^{c}	1.50^{b}
3	120	10	1252^{c}	0.84^{bc}	4.58^{ab}	1.32^{c}
4	120	15	1118^{c}	0.78^{c}	4.91^{a}	1.29^{c}
5	150	0	1869^{a}	1.58^{a}	6.80^{a}	2.52^{a}
6	150	5	1646^{b}	0.99^{b}	5.49^{b}	1.87^{b}
7	150	10	1255^{c}	0.77^{c}	4.84^{c}	1.80^{b}
8	150	15	1056^{d}	0.44^{d}	4.05^{d}	1.52^{c}

*According to Duncan's test, mean values with similar lower-case letters are not statistically different at 95% confidence level

Mechanical properties of fluting papers

Detailed analyses have been conducted on the tensile, burst, tear, and SCT (short span compression) strengths of the fluting papers, and the findings reveal that fly ash has a significant impact on the mechanical properties of these papers. The addition of fly ash at different ratios influences the overall strength and durability, providing valuable insights into its effect on the structural integrity of the paper. As previously noted by Bown, and Shen *et al.*, filler materials generally have the dual effect of reducing mechanical strength while improving other properties like surface smoothness or cost-efficiency.[7,29] Table 5 presents key mechanical properties of fluting papers produced with varying proportions of fly ash, highlighting the relationship between ash content and mechanical performance.

Table 5 shows that, as the fly ash content increases, mechanical properties, such as breaking length, burst index, and SCT strength, tend to decrease. Specifically, at 120 g/m^2, papers containing 5%, 10%, and 15% fly ash exhibited reductions in breaking length by 25%, 34.9%, and

41.9%, respectively. Similarly, the addition of fly ash to 150 g/m² fluting papers resulted in reductions in burst strength by 11.9%, 32.9%, and 43.5%. These findings are consistent with Koivunen *et al.* and Larsson *et al.*, who also observed that increased filler content tends to weaken the bonding between fibers, leading to diminished mechanical performance.[28,30] Significant decreases were also observed in SCT (short span compression) strengths with increasing fly ash content. This suggests that the filler disrupts the fiber-to-fiber contact points that are essential for mechanical integrity, as noted in studies by Hirn and Schennach, and Li *et al*.[31,32]

The Duncan test results confirm that there are statistically significant differences in mechanical properties, particularly between the control samples (0% fly ash) and those with higher fly ash content. For example, breaking length and burst index values for papers with 15% fly ash were significantly lower than those for the control group, indicating that the presence of fly ash negatively affects the structural integrity of the paper. This reinforces the need for careful optimization of filler content to maintain a balance between the economic advantages of fly ash and the mechanical performance required for industrial applications.

The primary disadvantage of using filler materials like fly ash is their low binding potential, which weakens the inter-fiber bonds. During paper manufacturing, the formation of strong fiber bonds is critical to ensuring the paper's mechanical durability. However, filler particles can interfere with this bonding process by obstructing fiber-to-fiber connections, as previously discussed by Tanaka *et al.* and Shen *et al*.[27,29] As fly ash content increases, the reduced bonding potential leads to lower mechanical properties, such as tensile strength, burst resistance, and SCT strength.

Despite these drawbacks, it is important to note that the addition of fillers like fly ash does not have a direct negative impact on tear strength, which is primarily determined by the fiber structure and inter-fiber connections rather than the presence of filler materials.[11,31] As shown in Table 5, no significant changes in tear strength were observed between the samples with varying levels of fly ash. This indicates that while fly ash affects other mechanical properties, it does not notably weaken tear resistance, which remains largely unaffected by the filler.

While the use of fly ash as a filler offers substantial cost and environmental benefits, it requires careful management to avoid compromising the mechanical properties of fluting papers. The observed reductions in breaking length, burst index, and SCT strength underscore the importance of maintaining an optimal balance between filler content and the desired mechanical performance. The results of this study align with existing literature, reinforcing the understanding that filler materials must be used judiciously to maintain paper strength, while capitalizing on their economic and environmental advantages.

Optical properties of fluting papers

In paper production, fillers are primarily employed to optimize optical properties, particularly in white papers, where their influence on parameters, such as whiteness and brightness, is critical. However, in the context of corrugated board paper production, fillers are introduced predominantly for cost-saving purposes, with minimal emphasis placed on enhancing optical characteristics. This is consistent with previous studies by Bown, and Song *et al.*, which highlighted that in packaging-grade papers, optical properties are typically secondary considerations compared to cost and mechanical performance.[7,13] Consequently, improvements in optical properties, such as whiteness and brightness, are often secondary considerations in such applications.

Table 6 illustrates the optical properties of fluting papers with varying levels of fly ash content. The data indicate that the inclusion of fly ash, in both 120 g/m² and 150 g/m² fluting papers, resulted in modest increases of 1-2 units in brightness, alongside slight reductions of 3-4 units in yellowness. This finding aligns with Shen *et al.*, who noted that the incorporation of fillers, particularly mineral-based, tends to increase brightness while reducing yellowness, due to the smoothing effects of fillers on paper surface topography.[29] These effects suggest that fly ash, as a filler, aids in creating a smoother surface that improves light reflection, consequently affecting the paper's optical performance. The impact of filler type and concentration is a decisive factor in shaping the optical properties of the paper, underscoring the importance of careful control over filler selection and usage during production.[7,13,26,29]

When comparing this study's findings with similar studies, it is evident that fly ash, as a by-product from biomass energy plants, offers comparable benefits to traditional fillers, such as kaolin or calcium carbonate, in terms of optical improvements, albeit at a lower cost.[17] This positions fly ash as a viable alternative in industries where cost reduction is a primary driver, while moderate optical improvements are acceptable.

The Duncan test results (Table 6) reveal statistically significant differences in the optical properties between the control samples and those with added fly ash. Specifically, the whiteness and brightness values between different levels of fly ash content (5%, 10%, 15%) are significantly different at the 95% confidence level, indicating that even small additions of fly ash can result in measurable changes in optical performance. For instance, at the 120 g/m² grammage, the papers with 15% fly ash content exhibited the highest brightness and whiteness values, which were statistically different from the control samples and those with lower filler content. This suggests that fly ash has a consistent impact on optical properties, and its effects increase progressively with higher filler content. This trend is crucial for manufacturers aiming to balance optical enhancements with cost savings, as fly ash allows for subtle improvements, without compromising budgetary constraints.

While the primary role of fillers in fluting paper production is economic, this study confirms that fly ash contributes positively to optical properties, particularly in brightness and whiteness, even though these enhancements are not the main focus in packaging-grade papers. Given its cost-effectiveness and availability as a waste by-product, fly ash not only presents an eco-friendly alternative to conventional fillers, but also offers modest improvements in optical qualities, providing a dual benefit for sustainable and cost-efficient production.

Table 6
Some optical properties of the fluting papers

No	Gsm (g/m^2)	Fly ash charge (%)	Whiteness (ISO)	Brightness (ISO)	Yellowness (E313)
1	120	0	35.50^{a}	27.53^{a}	32.56^{a}
2	120	5	36.96^{b}	28.04^{b}	34.61^{b}
3	120	10	37.35^{c}	27.70^{a}	36.85^{c}
4	120	15	37.79^{c}	28.26^{b}	35.80^{bc}
5	150	0	35.74^{a}	27.61^{a}	32.87^{a}
6	150	5	37.05^{b}	27.48^{a}	36.88^{b}
7	150	10	38.11^{c}	28.32^{b}	36.53^{b}
8	150	15	37.98^{c}	28.22^{b}	36.32^{bc}

*According to Duncan's test, mean values with similar lower-case letters are not statistically different at 95% confidence level

SEM images of fluting papers

Scanning electron microscopy (SEM) images were obtained for both unfilled papers and papers filled with 15% fly ash, captured at 1000x magnification. The results are displayed in Figure 1, providing a detailed comparison of the fiber structure and the distribution of fly ash particles within the paper matrix.

The SEM images clearly reveal the structural differences between unfilled and 15% fly ash-filled papers. In the unfilled 120 gsm control papers (Fig. 1a), the fiber structure appears open and well-organized, with ample gaps between the fibers, promoting effective inter-fiber bonding. This supports the paper's mechanical properties, as unimpeded fiber contact typically enhances tensile and burst strength.[27,29] In contrast, the 120 gsm paper filled with 15% fly ash (Fig. 1b) shows that the fly ash particles occupy the spaces among the fibers, reducing direct fiber-to-fiber contact. This could explain the observed decline in mechanical properties, as filler particles often act as barriers, weakening inter-fiber bonds.[28,32] The images also reveal a more compact structure, which contributes to an increase in bulk, but may compromise strength due to the reduced contact between cellulose fibers.

A similar pattern emerges in the 150 gsm papers. In the unfilled 150 gsm paper (Fig. 1c), the fibers appear thicker and more closely packed, providing a strong, cohesive structure that enhances the paper's mechanical durability. The uniformity of the fiber network in the unfilled samples is indicative of stronger inter-fiber bonds, which is critical for maintaining tensile strength and compression resistance. However, in the 150 gsm papers with 15% fly ash (Fig. 1d), the fly ash particles are again seen filling the voids between fibers, contributing to a more compact structure, but simultaneously reducing fiber bonding potential. This tighter structure increases the physical properties, such as bulk and density, but the reduction in direct fiber bonding weakens mechanical performance, particularly in terms of tensile and burst strength. This is consistent with previous studies, which have shown that while fillers increase paper bulk, they tend to reduce mechanical properties due to the lower binding potential between fibers and fillers.[7,8]

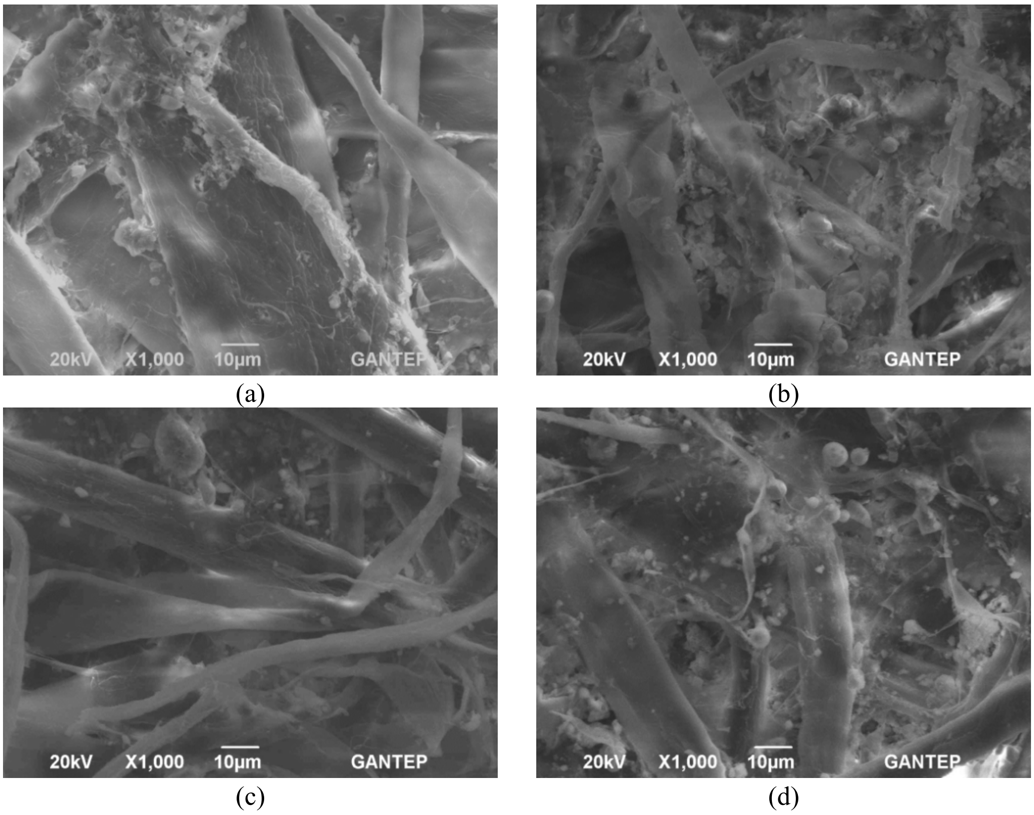

Figure 1: SEM images of unfilled and fly ash filled papers, (a) unfilled at 120 gsm, (b) 15% fly ash filled at 120 gsm, (c) unfilled at 150 gsm, (d) 15% fly ash filled at 150 gsm

The SEM analysis confirms that the incorporation of fly ash as a filler results in a more compact paper structure with enhanced bulk, but the reduced direct bonding between fibers weakens key mechanical properties. This trade-off highlights the need for careful optimization of filler content in paper production, particularly in balancing the benefits of increased bulk and cost savings with the mechanical strength requirements for industrial applications.

CONCLUSION

This study demonstrated that unmodified fly ash, sourced directly from the biomass-based thermal power plant of the same paper facility, can be effectively utilized as a filler in the production of recycled fluting paper. Unlike previous studies that relied on chemically modified or synthetically prepared fillers, this research employed fly ash without any surface treatment – only after sieving – making it a practical, zero-cost alternative for industrial applications.

The experimental findings confirmed that fly ash addition at levels of 5–10% improves paper bulk and maintains mechanical performance within acceptable ranges for packaging-grade applications. Specifically, while a moderate decrease in breaking length and tear index was observed, these values remained functionally adequate for fluting paper, where extreme strength is not always required. As expected, optical properties, such as brightness, were lower than those of papers filled with PCC or clay; however, this limitation is not critical in applications where visual quality is secondary to structural function.

Although a full economic analysis was not conducted, the absence of processing, acquisition, and transportation costs for the in-house fly ash implies potential for cost reduction. The results also suggest that incorporating fly ash contributes positively to circular production systems by valorizing industrial by-products within the same facility. Compared with data from existing literature on conventional fillers, the fly ash-filled papers in this study exhibited competitive performance in terms of bulk and filler retention.

Overall, this study offers a practical and sustainable approach for utilizing untreated fly ash in recycled paper production, particularly in fluting grades. It bridges a gap in the literature by demonstrating the real-world feasibility of directly integrating biomass-derived fly ash into the papermaking process, thereby contributing to waste reduction, cost efficiency, and the advancement of industrial symbiosis in the pulp and paper sector.

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