American Journal of Chemical Engineering
2025, Vol. 13, No. 5, pp. 101-110
https://doi.org/10.11648/j.ajche.20251305.12

Research Article

Recycling Pineapple Leaf (Ananas Comosus) Agro-Waste as an Alternative Raw Material to Produce Eco-Friendly Paper

Isaac Yongai, Sahr Emmanuel Lebbie*, David Conteh, Umaru Kanneh, Issa Turay, Tamba Patrick Komba

Chemistry Department, Njala University, Moyamba, Sierra Leone

Abstract

This study investigates the viability of recycling pineapple leaf agro-waste (PALF) as a sustainable and eco-friendly alternative to wood-based pulp for paper production in Sierra Leone. The research addresses the dual challenges of heavy reliance on imported paper products and the environmental problem of agricultural waste mismanagement. An experimental design was employed to compare two distinct pulping techniques: a chemical method using an 11% Sodium Hydroxide (NaOH) solution and a traditional method using a locally sourced wood ash lye solution. Fibers were extracted from pineapple leaves, converted into pulp, and then formed into handmade paper sheets. The physical and mechanical properties of the resulting papers, including thickness, water absorbency, writing quality, tensile strength, and tearing resistance, were systematically analyzed. The findings indicate that the NaOH pulping method produced higher quality paper, exhibiting superior tensile strength (500 N/m breaking force), a smoother finish, and minimal ink feathering, making it suitable for writing and printing applications. In contrast, the wood ash lye method yielded a functional but lower-grade paper that was thicker, coarser, and possessed lower mechanical strength (410 N/m breaking force). The study concludes that pineapple leaf agro-waste is a highly promising non-wood fiber source for paper production. While the NaOH method is technically superior, the wood ash lye method presents a compelling, low-cost, and accessible alternative for small-scale, rural enterprises in resource-limited settings like Sierra Leone. This research demonstrates a practical model for waste valorization that aligns with circular economic principles, promoting environmental sustainability, green entrepreneurship, and import substitution. The study recommends scaling up production for pilot testing, optimizing chemical usage, and developing training programs to support local adoption of these sustainable technologies. This study, therefore, recommends that future researchers should explore optimal NaOH concentrations and environmentally friendly alternatives to reduce chemical use without compromising quality, and combining PALF pulp with other fibers (e.g., recycled paper, banana pseudo-stem pulp) could improve paper properties and reduce costs.

Keywords

Pineapple Leaf, Tearing Resistance, Agro-Waste, Tensile Strength, Paper, Handmade, Sustainable, Fibers, Recycling, Eco-Friendly, Physical and Mechanical Properties, Environmental Impact

*Corresponding author: sahremmanuellebbie17@gmail.com (Sahr Emmanuel Lebbie)

Received: 10 September 2025; **Accepted:** 19 September 2025; **Published:** 10 October 2025

1. Introduction

Paper is essential to our everyday existence because it allows us to record, store, and distribute information [27]. 225 million tons of recycled paper, 176 million tons of wood pulp, and 12 million tons of other fiber pulp are used to produce the 406 million tons of paper and paper board that are produced annually worldwide [7]. As the population of the globe continues to grow, so does the need and consumption of paper [9]. Around 402 million tons of pulp, paper, and paperboard are needed annually worldwide [3]. The pulp and paper sectors are the fourth largest industrial energy consumer in the world, accounting for around 5.6% of global industrial energy consumption [21]. Traditionally, wood-free materials such as silk cotton, banana fibers, cotton, kenaf, mat grass, bagasse, and agricultural waste are used to make handmade papers [18]. Handmade papermaking was reportedly first done in China, but many European and Asian nations are now adopting it as well because of its great potential [18]. Raw materials made from agro-waste have a high fiber content and may be easily pulped to produce high quality paper [23]. The most environmentally friendly type of paper is handmade. The primary advantage of producing handmade paper is a twofold reduction in environmental loading, also referred to as an environmental impact reduction. From the primary perspective, natural resources are preserved alongside the inputs used in the manufacturing process, and from the secondary perspective, the quantity of harmful compounds that leak into the environment decreases alongside the outputs of the manufacturing process [18]. About 90% of the conventional raw materials used to produce pulp and paper worldwide come from wood, but the environment has suffered greatly because of the depletion of forest resources for wood production [3]. Because local wood supplies in many parts of the world are insufficient to meet the demand for pulp, the paper-making industry has focused more on finding non-wood raw materials because of the growing need for wood resources [30]. According to [6], pineapple (Ananas comosus) is the third most important tropical fruit in the world, behind citrus and bananas. A popular fruit in tropical and subtropical regions, pineapples are noted for their abundance. However, only around 25% of the produce may be sold in the food industry, with the other 75% of the peel, stem, leaves, and crown being thrown away as agro-waste [10]. Very little pineapple leaf fiber is used as feedstock or to produce electricity [10]. Strong, white, silky fibers from pineapple leaves may be spun into fine textile-grade yarn using cotton or jute spinning equipment [10]. An underappreciated part of the plant, the leaves offer a chance for extensive commercial utilization [12]. Pineapple leaf fibers are one of the six main types of plant fibers [17], along with bass, bast, seed, straw, and wood fibers. These fibers are becoming more common in a variety of applications these days. About 15 tons of PALF can be produced annually from a hectare of pineapple plantations [10]. Each pineapple leaf fiber (PALF) has a same number of hexagonal areas on its outer layer, regardless of its size or shape [25]. Pineapple leaf fiber is one of the many natural fibers that could be used as a plentiful and practical substitute for the pricey synthetic fibers due to its high tensile strength, ease of extraction from the leaves, and environmental friendliness [2, 16]. The quality of PALF is comparable to that of numerous leaf fibers; it exhibits noteworthy qualities including strength, length, and bright white color, making it a premium option among the widely used leaf fibers. This natural fiber is frequently used in the composite industry because of its high cellulose content (70-80%) and relatively low microfibrillar angle, which give it a high specific strength and stiffness [10]. Its high fineness index makes it preferable to other vegetable fibers. This special characteristic makes PALF ideal for a variety of industrial uses, including woven yarn and cloth [1]. Many farmers also consider PALF to be a waste after harvest. However, it also gives them new money to spend. Farm owners will be encouraged to employ pineapple leaves by PALF's growing awareness of its benefits over synthetic fibers, which will help the textile sector [10]. The optimal time to harvest pineapple leaves to obtain high-quality fibers is being investigated [15]. Making the most of pineapple leaf fiber through increased industrial usage is essential to minimizing the waste of renewable resources. Instead of treating it as waste, evaluating its potential in the paper and textile industries requires a lot of work [11]. Because they contain lignocellulosic fibers, these pineapple leaves are high in cellulose, hemicellulose, and lignin all essential components to produce paper [14]. Making paper from pineapple leaves is a sustainable alternative that can reduce these negative environmental effects [20]. This approach also supports the principles of a circular economy, which reduces overall environmental damage and creates revenue for the communities who harvest and prepare pineapple leaves by reducing waste and reusing it into new products [20]. Fibers from pineapple leaves can produce paper with desired physical attributes, such as durability, strength, and texture [21].

Agriculture, which is crucial to the country's economy, employs more than 60% of people in Sierra Leone [31]. The nation's agricultural industry is dominated by crops including rice, cassava, and pineapple, which are grown primarily in the country's eastern and southern regions. These crops not only provide food security for the local population but also play a crucial role in export markets. Efforts to improve agricultural practices and infrastructure could significantly enhance productivity and livelihoods in rural communities.

Considering growing environmental concerns, resource shortages, and the adverse effects of climate change, it is now essential to pursue sustainable alternatives in industrial production. Particularly, the paper sector has come under fire for its high energy consumption, substantial environmental pollution, and unsustainable reliance on wood-based raw materials [24]. Recycling agricultural waste, particularly underutilized materials like pineapple leaves, into useful goods like paper is a sensible and environmentally responsible approach that supports the UN Sustainable Development Goals and other global sustainability objectives [29]. In tropical and subtropical areas, pineapples are widely grown, and the resulting agro-waste is mainly the leaves are frequently thrown away or burned, degrading the environment [5]. Because of their high cellulose and lignin content, these leaves are a good source of raw materials for pulp and paper manufacturing [13]. The study intends to advance a circular economy model that eliminates deforestation, lowers environmental pollution, and increases the economic worth of agricultural byproducts by turning this waste into paper.

The introduction of local, environmentally friendly paper production using pineapple leaf waste not only provides a sustainable material alternative but also promotes job creation, supports rural livelihoods, and contributes to national development through import substitution [28]. In Africa, and especially in Sierra Leone, there is a great reliance on imports due to a significant gap in local paper production capabilities, which raises costs and exposes the nation to global market volatility [26] additionally, this study tackles the need for creative waste management approaches in Sierra Leone, where most agricultural residues are not effectively used, and offers a research-based solution that combines environmental preservation with socioeconomic growth. As a result, the study is supported by its potential to impact policy, encourage green entrepreneurship, and support sustainable industrial development in other low-resource nations [29].

Globally, the growing demand for paper goods has increased the strain on forest resources, resulting in increased carbon emissions, deforestation, and biodiversity loss [4]. Therefore, it is imperative that the paper industry find sustainable alternatives. An environmentally benign and renewable resource that can lessen reliance on wood pulp and support sustainable manufacturing methods is provided by using agricultural waste, such as pineapple leaves [24]. By investigating the use of pineapple leaf fibers, a rich source of cellulose, as a feasible substitute for raw material for paper manufacture, this work supports international initiatives to promote bio-based circular economies [13]. Additionally, it supports several Sustainable Development Goals (SDGs) of the UN, such as climate action (SDG 13) and responsible consumption and production (SDG 12) [29]. Given Sierra Leone's present reliance on imported paper goods, which exacerbates trade imbalances and foreign exchange limits, the study is especially pertinent there (Statistics Sierra Leone, 2021). However, pineapple cultivation produces large amounts of unused leaf waste, particularly in areas like Bo and Kenema [5]. The study presents a sustainable waste management approach by turning this garbage into environmentally friendly paper, which also creates opportunities for green entrepreneurship and rural jobs. Additionally, by producing reasonably priced, locally produced paper goods, the invention could help achieve national environmental objectives and educational needs [22].

Therefore, the study aimed to explore the viability of recycling pineapple leaf agro-waste as an alternative raw material for the production of eco-friendly paper, and the specific objectives of the study are as follows: to extract fibers from pineapple leaf agro-waste, to convert extracted pineapple leaf fibers into pulp, to produce handmade paper sheets from pineapple leaf pulp, and to test the physical and mechanical properties of the handmade paper. Additionally, the research will evaluate the environmental impact of using pineapple leaf fibers compared to traditional wood-based paper production. This comprehensive analysis will contribute valuable insights into sustainable practices within the paper industry.

2. Data and Methods

2.1. Study Area

The districts of Bonthe to the south, Bo to the east, Port Loko and Tonkolili to the north, and the Atlantic Ocean to the west all about Moyamba District, which is in the Southern Province. Moyamba Town is its largest city and capital. With 14 chiefdoms and a combined area of 6,902 km2, the district is the largest in the Southern Province in terms of geographic extent. The Mende people make up most of the population, with Sherbro, Temne, and Loko being among the other ethnic groups. Mining (bauxite and rutile) and agriculture (crop farming, fishing, rice cultivation, and oil palm plantations) are the primary economic activities [19]. The mining industry of Lower Banta chiefdom depends heavily on the port of Nitti. In the south, it offers the only deep-water port that may be used for mechanical loading and unloading directly. Njala University, located in Moyamba District, has the capacity to produce highly skilled human resources, particularly in the fields of environmental and agricultural science. For more than 71% of the population, agriculture continues to be the primary source of income and the district's largest economic sector. Oil palm, starch food crops (yam, cassava, and cocoa), and cereals (maize, rice, sorghum, and millet) are among the crops cultivated in the district. Additionally, the district's most popular agricultural products include cashew, sugarcane, pineapple, ginger, black pepper, and cashew. Most farmers operate smallholdings, which are basic subsistence food production and Kori chiefdom has a population of 33,981 people (51.13/km^2 Population Density) and total area of 662.9km2 [21].

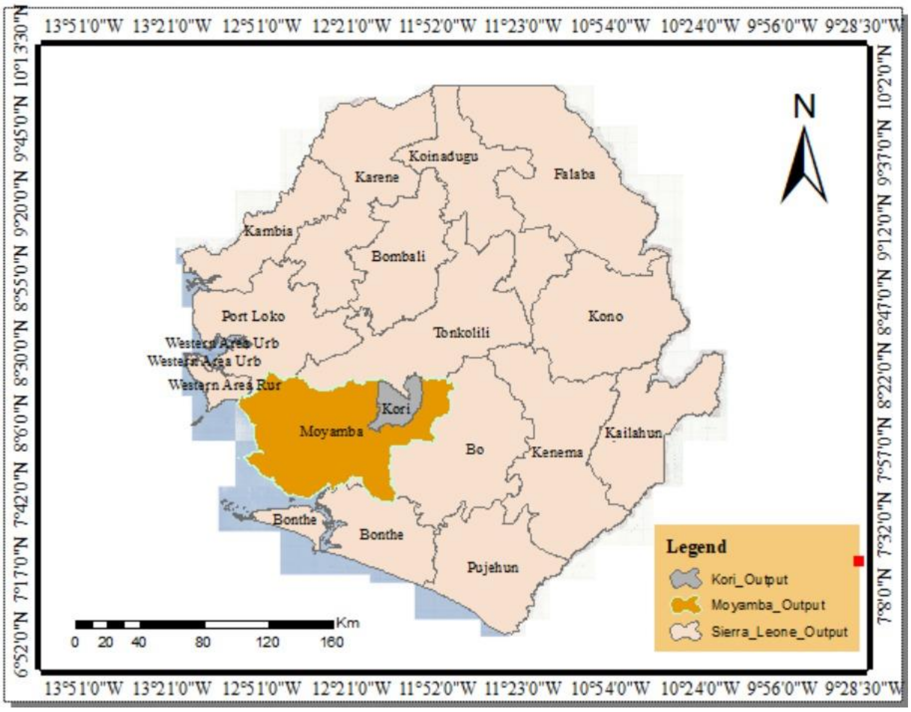

Figure 1. *Map showing the study area in Sierra Leone (Source: Author, 2025).*

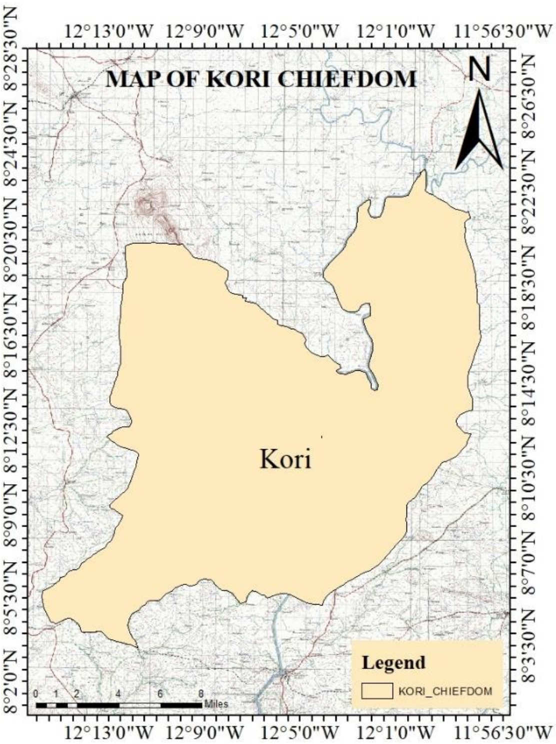

Figure 2. *Sample Area (Source: Author, 2025).*

2.2. Research Design

This study adopted an experimental research design, focusing on controlled laboratory processes to ensure the reliability and validity of the finding comparison between the two proposed pulping methods. The entire experiment was conducted in a laboratory setting at the Department of Chemistry, Njala University, Mokonde Campus, to ensure control over process conditions such as temperature, chemical concentration, and time. Every step was meticulously documented to ensure transparency and replicability. The primary independent variable was the pulping agent (sodium hydroxide vs. wood ash), while the dependent variables were the physical and mechanical properties of the resulting paper sheets.

2.3. Research Materials and Chemicals

Materials: Fresh pineapple leaves (Variety: Smooth Cayenne).

Chemicals: Sodium Hydroxide (NaOH): Analytical grade, in pellet form (99% purity).

Wood Ash: Sourced locally for the preparation of alkaline lye.

Fuel (Charcoal): Used as a heat source for boiling the pineapple leaves.

Water: Distilled water was used for all solution preparations and final pulp washing. Tap water was used for initial leaf cleaning.

Preparation & Pulping: Machete, scissors, cutting board, non-reactive stainless steel boiling pot, charcoal stove, and a long stirring stick.

Processing: Electric blender, fine-mesh sieve, beakers, reagent bottles, wash bottles, weighing boat, spatula, funnel, and a volumetric flask.

Papermaking: A4-sized mould and deckle, couching sheets (felt), and sponges.

Drying: Solar sun-dryer and drying racks.

Safety: Laboratory coat, safety goggles, and heavy-duty rubber gloves.

Measurement & Analysis: Weighing scale (beam balance), Spring balance, pH meter/litmus paper, ruler, and a micrometer screw gauge.

2.4. Experimental Procedures

The experimental work was divided into four main stages: (1) Raw Material Preparation, (2) Chemical Fiber Extraction and Pulping, (3) Pulp Processing and Paper Sheet Formation, and (4) Analysis of the Physical and Mechanical Properties of the Paper.

2.4.1. Raw Material Preparation

Cleaning: Collected leaves were thoroughly washed under running tap water to remove soil, dust, and other surface contaminants.

Sizing: The thorny edges of the leaves were trimmed. The leaves were then manually cut into uniform lengths of approximately 10 cm.

Scraping: The outer green epidermal layer (cuticle) was manually scraped from the leaves using a sharp knife to help reduce lignin content and improve the efficiency of chemical pulping.

2.4.2. Chemical Fiber Extraction and Pulping

Two different pulping methods were employed to extract cellulose fibers.

METHOD A: Sodium Hydroxide (NaOH) Method

Liquor Preparation: An 11% (w/v) solution of Sodium Hydroxide was prepared by dissolving 440g of sodium hydroxide (NaOH) pellets in distilled water to make a final volume of 4000 mL (4 L). This was achieved by dissolving 110 g of sodium hydroxide (NaOH) into distilled water and adjusting the volume to 1000 mL, a process repeated four times.

Digestion: A 2000g sample of prepared pineapple leaves was placed in a stainless-steel pot. The 4 L sodium hydroxide (NaOH) solution was added, ensuring the leaves were fully submerged. The mixture was heated to boiling (approx. 100 ℃) and maintained for 40 minutes with intermittent stirring.

Washing and Screening: After boiling, the slurry was allowed to cool. The fibers were washed with fresh water over a fine-mesh screen until the filtrate reach a neutral pH (≈ 7.0).

This step was critical for removing residual sodium hydroxide (NaOH) and dissolved lignin. The washed fibers were then screened to remove uncooked leaf fragments.

Calculations and Preparation of Sodium Hydroxide (NaOH)

To prepare an 11% (w/v) solution of sodium hydroxide (NaOH) using 4 liters of distilled water, implies regarding the final volume.

Volume Calculation of Sodium Hydroxide (NaOH)

Target final volume: 4 liters.

1liter → 1000mL

4liters → x

X = 4 x 1000mL X = 4000mL

Mass Calculation of Sodium Hydroxide (NaOH)

A 11% (w/v) solution means 11 g of solute per 100 mL of solution.

Mass of sodium hydroxide (NaOH) = 11g/100mL x 4000mL

Mass of sodium hydroxide (NaOH) = 0.11g/mL x 4000mL

Mass of sodium hydroxide (NaOH) = 440g for the 4 liters

Now for each 1 liter, I divide the total mass by 4

Mass of each 1 liter of sodium hydroxide (NaOH) = 440g/4

Mass of each 1 liter of sodium hydroxide (NaOH) = 110g

Preparations Of Sodium Hydroxide (NaOH) Solution

Therefore, 110 g of sodium hydroxide (NaOH) pellets were carefully weighed and dissolved in distilled water, with the final volume being made up to 1000 mL in a volumetric flask.

This process was done four consecutive times to reach the exact mass of sodium hydroxide (NaOH), and the exact volume of distilled water for the entire process.

METHOD B: Wood Ash Lye Method

Lye Preparation: A wood ash lye solution was prepared by mixing 240g of wood ash with 4 liters of distilled water, based on a ratio of 60g of wood ash per liter of water. The mixture was stirred and allowed to settle for 24 hours. The clear, alkaline supernatant liquid (lye) was decanted for use, and its pH was recorded.

First Digestion: A 2000g sample of prepared pineapple leaves was placed in the stainless-steel pot. Three liters of the prepared wood ash lye solution were added, and the mixture was boiled at approximately 100 ℃ for 40 minutes with stirring.

Washing and Drying: The resulting fibers were washed over a fine mesh screen until the filtrate was neutral. The washed fibers were then dried under the sun for four days. The final weight of the dried fibers was 1000g.

Second Digestion: The 1000g of dried fibers were boiled again with the remaining 1 liter of wood ash lye solution, following the same washing and screening process as before.

Calculations of Wood Ash (Lye)

A wood ash lye solution was prepared based on a fixed mass to volume ratio.

Total mass of wood ash weighed = 240g

Total volume of distilled water used = 4 liters

Mass of wood ash to be dissolved in 1L = 240g/4

Mass of wood ash to be dissolved in 1L = 60g. So, each 1L of distilled water contained 60g of wood ash (lye).

2.4.3. Pulp Processing and Paper Sheet Formation

Mechanical Refining: For both methods, the clean fibers were mechanically refined using an electric blender. A fixed quantity of fibers was blended with water for a consistent duration of 7 minutes to fibrillate the cellulose fibers and increase their bonding potential.

Slurry Preparation: The final pulp was mixed with water in a large basin to form a thin, uniform slurry.

Sheet Formation: An A4-sized mould and deckle was submerged into the slurry and lifted out horizontally to capture a layer of fibers. The wet sheet was transferred onto a piece of damp felt (couching).

Pressing and Drying: A stack of sheets, alternated with felts, was manually pressed with a sponge to remove excess water. The pressed sheets were then air dried on drying racks or in a solar dryer for 24-48 hours.

2.4.4. Analysis of Physical and Mechanical Properties of Paper

Thickness (Caliper): The thickness of a single sheet of paper was measured using a micrometer screw gauge. Measurements were taken at five different points on the sheet, and the average was calculated and reported in millimeters (mm).

Water Absorbency: A single drop of water was placed on the paper surface, and the time taken for the drop to be fully absorbed was measured with a stopwatch.

Writing Quality: A standard ink pen was used to write on the paper surface. The surface was then observed to assess ink feathering (spreading) and bleed-through.

Tensile Strength: Paper strips of a standard 15 mm width were cut. The breaking force was determined by clamping one end of the strip and attaching incremental weights to the other end until the strip failed.

Tearing Resistance: An initial cut was made in the paper sample. The force required to propagate this tear was then assessed qualitatively by hand.

2.5. Data Analysis

All quantitative tests (thickness, tensile strength) were performed on at least three replicate samples for each pulping method. The mean and standard deviation were calculated for each property. The results from the sodium hydroxide (NaOH) pulping method and the wood ash lye solution method were then compared to determine which process yielded paper with more desirable characteristics. Qualitative assessments were used to supplement and support the quantitative data.

3. Results and Discussion

3.1. Fiber Extraction and Pulp Characteristics

The initial stage of the experiment involved the extraction of fibers from the prepared pineapple leaves and their conversion into pulp. The two methods yielded fibers with distinct characteristics in terms of yield, color, and texture.

Fiber Yield: From an initial raw material weight of 2000g of scraped pineapple leaves, the sodium hydroxide (NaOH) method (Method A) produced approximately 820g of moist fiber, resulting in a yield of 41%. The Wood Ash Lye method (Method B), which involved a two-stage digestion process, produced approximately 740g of dried fiber from the same initial weight, corresponding to a yield of 37%.

Qualitative Observations:

Method A [sodium hydroxide (NaOH, Pulp)]: The pulp produced was light tan in color, relatively uniform, and had a soft texture. The digestion process appeared to be highly effective, breaking down most of the non-fibrous material and resulting in well-separated fibers.

Method B (Wood Ash Lye Pulp): The pulp was darker, appearing medium brown. The texture was slightly coarser compared to the sodium hydroxide (NaOH) pulp, with some smaller, unrefined fiber bundles remaining after the two-stage boiling process. This suggests that the wood ash lye solution was less aggressive in delignification compared to the commercial grade sodium hydroxide (NaOH).

3.2. Physical Properties of the Handmade Paper

Handmade paper sheets were successfully produced from both pulp types. The physical properties, including thickness, water absorbency, and writing quality, were evaluated to determine their suitability for practical use. The results are summarized in Table 1.

Table 1. Physical Properties of Handmade Paper from Pineapple Leaf Agro-Waste.

Property	Method A (NaOH) Paper	Method B (Wood Ash) Paper
Thickness (mm)	0.13(±0.02)	0.22 (±0.04)
Water Absorbency	Fully absorbed in 35 seconds (avg)	Fully absorbed in 30 seconds (avg)
Writing Quality	Minimal ink feathering, no bleed-through	Moderate ink feathering, slight bleed-through

Physical Properties: The paper produced using the sodium hydroxide (NaOH) method was thinner and more uniform, which can be attributed to the complete breakdown and separation of fibers, allowing for a more compact sheet formation. In contrast, the paper from the wood ash lye solution method was thicker and showed greater variability, likely due to the presence of residual lignin and hemicellulose, which hindered tight packing of the cellulose fibers.

The high-water absorbency of both paper types is characteristic of unsized paper. The slightly faster absorption rate of the wood ash paper (30 seconds vs 35seconds) correlates with its course, more porous structure. For writing applications, the sodium hydroxide (NaOH) paper performed better, showing minimal ink feathering. This indicates a denser, less porous surface, which is more desirable for writing and printing. The moderate feathering on the wood ash paper suggests it would be better suited for applications where high ink absorption is not a critical issue, such as for craft materials or packaging.

3.3. Mechanical Properties of the Handmade Paper

The mechanical strength of the paper is crucial for its durability. Tensile strength and tearing resistance were assessed to compare the structural integrity of the papers produced by the two methods. The results are presented in Table 2.

Table 2. Mechanical Properties of Handmade Paper from Pineapple Leaf Agro-Waste.

Property	Method A (NaOH) Paper	Method B (Wood Ash) Paper
Tensile Strength	High (Avg. Breaking Force: 500N/m)	Moderate (Avg. Breaking Force: 410N/m)
Tearing Resistance	High resistance to tearing	Moderate resistance to tearing

Mechanical Properties: The paper produced via the sodium hydroxide (NaOH) method exhibited significantly higher tensile strength and tearing resistance. This is a direct result of more effective delignification. As established in the literature review, lignin acts as a binder in the plant but hinders the formation of strong hydrogen bonds between cellulose fibers during papermaking. The 11% sodium hydroxide (NaOH) solution effectively removed a larger portion of this lignin, allowing the long cellulose fibers of the pineapple leaf to bond more tightly, resulting in a stronger, more durable sheet.

The paper from the wood ash lye solution method, while still possessing functional strength, was weaker. This indicates that the alkaline lye, while effective, was not as potent as the concentrated sodium hydroxide (NaOH) solution, leaving more residual lignin in the pulp. This interfered with fiber-to-fiber bonding, leading to lower mechanical strength.

3.4. Discussion

This study successfully met its specific objectives. Fibers were extracted from pineapple leaf agro-waste, converted into pulp, and used to produce handmade paper sheets (Objectives 1, 2, and 3). The physical and mechanical properties of this paper were then tested (Objective 4), allowing for a direct comparison between the two pulping methods.

The results clearly indicate that the Sodium Hydroxide (NaOH) method is superior in producing paper with more desirable physical and mechanical properties. The resulting paper was stronger, smoother, and better for writing. This aligns with findings in the literature [8] that highlight the effectiveness of soda pulping for non-wood fibers. The high cellulose content of PALF, as noted in methodology, is the key contributor to the impressive strength of the paper produced, especially when delignification is effective.

However, the Wood Ash Lye method presents a compelling alternative, particularly within the context of Sierra Leone. While the paper quality was lower, this method successfully produced a functional paper product using a readily available, low-cost, and traditional material (wood ash). This addresses the problem of import dependency and lack of industrial infrastructure. For rural communities, this method represents a more accessible and economically feasible approach to waste valorization and green entrepreneurship. It transforms agricultural waste and cooking by-products (ash) into a valuable commodity without the need for expensive, imported chemicals.

The study has demonstrated effective techniques for fiber extraction and pulping, confirmed that pineapple leaf pulp can create durable paper, and quantified the properties of this paper, comparing it across two different production methods.

3.5. Summary of Findings

The following are the summary of findings of the research.

1) Both Sodium Hydroxide and wood ash lye solution can be used to successfully produce pulp and handmade paper from pineapple leaf agro-waste.
2) The sodium hydroxide (NaOH) method yielded a higher quality paper with superior strength (500N/m breaking force), a smoother finish, and better writing characteristics.
3) The wood ash lye solution method produced a functional but lower-grade paper that was thicker, coarser, and had lower mechanical strength (410N/m breaking force).
4) The study confirms that pineapple leaf fiber is a viable, sustainable alternative to wood pulp, aligning with global efforts to promote a circular economy.
5) The wood ash lye solution method, despite its technical inferiority to the sodium hydroxide (NaOH) method, holds significant potential for small-scale, low-cost, and sustainable paper production in resource-limited settings like Sierra Leone.

3.6. Conclusion

The findings of this research confirm that pineapple leaf agro-waste is a promising non-wood fiber resource for handmade paper production. The NaOH method demonstrated superior results in terms of paper quality and mechanical strength, aligning with prior studies on soda pulping efficiency for agro-waste fibers. However, the wood ash lye method, though technically inferior, presents a valuable, low-cost solution for small-scale and rural paper production, especially in countries like Sierra Leone where access to industrial chemicals is limited. This research supports the feasibility of turning agricultural waste into commercially viable paper products, contributing to environmental sustainability, waste management, and green entrepreneurship.

Based on the findings, the researcher recommends the following; Future studies should focus on scaling the process from laboratory to semi-industrial levels to determine technical and economic viability, future Researchers should explore optimal NaOH concentrations and environmentally friendly alternatives to reduce chemical use without compromising quality, Combining PALF pulp with other fibers (e.g., recycled paper, banana pseudo stem pulp) could improve paper properties and reduce costs, and government and NGOs should invest in agro-waste valorization initiatives, especially in rural areas, to create employment and promote sustainability.

Abbreviations

FAO	Food and Agriculture Organization
LCA	Life Cycle Assessment
NaOH	Sodium Hydroxide
PALF	Pineapple Leaf Fiber
SDGs	Sustainable Development Goals
UNCTAD	United Nations Conference on Trade and Development
UNDP	United Nations Development Programme
WWF	World Wide Fund for Nature
SEM	Scanning Electron Microscopy
TGA	Thermogravimetric Analysis
DSC	Differential Scanning Calorimetry
OH	Hydroxyl
FTIR	Fourier Transform Infrared Spectroscopy
SGW	Stones Groundwood
RMP	Refiner Mechanical Pulp
TMP	Thermomechanical Pulping
Na_2S	Sodium Sulfide
pH	Potential of Hydrogen
NGOs	Nongovernmental Organizations

Author Contributions

Isaac Yongai: Data curation, Formal Analysis, Investigation, Methodology, Project administration, Software

Sahr Emmanuel Lebbie: Conceptualization, Resources, Visualization, Writing – original draft

David Conteh: Resources, Visualization, Writing – review & editing

Umaru Kanneh: Funding acquisition, Resources, Validation

Issa Turay: Resources, Visualization, Writing – review & editing

Tamba Patrick Komba: Resources, Supervision, Visualization, Writing – review & editing

Conflicts of Interest

The authors declare no conflict of interest.

References

[1] Aisyah, H. A., Paridah, M. T., Sapuan, S. M., Ilyas, R. A., Khalina, A., Nurazzi, N. M.,... & Lee, C. H. (2021). A comprehensive review on advanced sustainable woven natural fibre polymer composites. *Polymers*, *13*(3), 471.

[2] Ameer, K., Shahbaz, H. M., & Kwon, J. H. (2017). Green extraction methods for polyphenols from plant matrices and their byproducts: A review. *Comprehensive reviews in food science and food safety*, *16*(2), 295-315.

[3] Chauhan, S., & Meena, B. L. (2021). Introduction to pulp and paper industry: Global scenario. *Physical Sciences Reviews*, *6*(5), 81-109.

[4] Food and Agriculture Organization. (2020). *Forests and sustainable cities: Inspiring stories from around the world*.

[5] Food and Agriculture Organization. (2023). *Pineapple market and production reports: Sierra Leone*. [Internal or local publication]

[6] Gil, C. R., & Bolivar, C. (2020). *Ananas comosus*.

[7] Haile, A., Gebino, G., Tesfaye, T., Mengie, W., Ayele, M., Abuhay, A., & Yilie, D. (2021). Utilization of non-wood biomass for pulp manufacturing in paper industry: case of Ethiopia. *Biomass Conversion and Biorefinery*, 1-19.

[8] Kaur, H., Dutt, D., & Tyagi, C. H. (2017). Optimization of soda pulping of pineapple leaf (Ananas comosus) fibres for paper making. Journal of Scientific & Industrial Research, 76(1), 45-50.

[9] Kaur, N., Sharma, I., Kirat, K., & Pati, P. K. (2016). Detection of reactive oxygen species in Oryza sativa L.(rice). *Bio-protocol*, *6*(24), e2061-e2061.

[10] Lalhruaitluangi, N., & Mandal, D. (2024). Utilization of pineapple leaf: an alternative for paper and textile industries. *Journal of Postharvest Technology*, *12*(3), 1-10.

[11] Madhav, S., Ahamad, A., Singh, P., & Mishra, P. K. (2018). A review of textile industry: Wet processing, environmental impacts, and effluent treatment methods. *Environmental Quality Management*, *27*(3), 31-41.

[12] Mofokeng, M. M., Du Plooy, C. P., Araya, H. T., Amoo, S. O., Mokgehle, S. N., Pofu, K. M., & Mashela, P. W. (2022). Medicinal plant cultivation for sustainable use and commercialization of high-value crops. *South African Journal of Science*, *118*(7-8), 1-7.

[13] Mokhothu, T. H., & John, M. J. (2015). Review on pineapple leaf fiber and its composites. Express Polymer Letters, 9(10), 857-880. https://doi.org/10.3144/expresspolymlett.2015.79

[14] Nathan, V. K. (2023). Pulping and papermaking using pineapple leaves. In *Pulping and Papermaking of Nonwood Plant Fibers* (pp. 233-243). Academic Press.

[15] Pandit, R., Chen, L., & Götz, J. (2020). The blood-brain barrier: Physiology and strategies for drug delivery. *Advanced drug delivery reviews*, *165*, 1-14.

[16] Rafiqah, A., Abdan, K., Nasir, M., & Asim, M. (2020). Effect of extraction on the mechanical, physical and biological properties of pineapple leaf fibres. *Pineapple leaf fibers: Processing, properties and applications*, 41-54.

[17] Ramamoorthy, S. K., Skrifvars, M., & Persson, A. (2015). A review of natural fibers used in biocomposites: Plant, animal and regenerated cellulose fibers. *Polymer reviews*, *55*(1), 107-162.

[18] Rather, M. A., Dolley, A., Hazarika, N., Ritse, V., Sarma, K., Jamir, L.,... & Namsa, N. D. (2022). Glycome Profiling and Bioprospecting Potential of the Himalayan Buddhist Handmade Paper of Tawang Region of Arunachal Pradesh. *Frontiers in Plant Science*, *13*, 831589.

[19] Republic of Sierra Leone (2021): Population and Housing Census: Analytical Report on Population Distribution, Migration and Ur banisation in Sierra Leone. Ibrahim Mohamed Sesay, Andrew A. Karam, Jinnah J. Ngobeh. Published November 2006.

[20] Sarangi, P. K., Singh, A. K., Srivastava, R. K., & Gupta, V. K. (2023). Recent progress and future perspectives for zero agriculture waste technologies: Pineapple waste as a case study. *Sustainability*, *15*(4), 3575.

[21] Sethupathi, M., Khumalo, M. V., Skosana, S. J., & Muniyasamy, S. (2024). Recent Developments of Pineapple Leaf Fiber (PALF) Utilization in the Polymer Composites, A Review. *Separations*, *11*(8), 245.

[22] Shabbir, I., Mirzaeian, M., & Sher, F. (2022). Energy efficiency improvement potentials through energy benchmarking in pulp and paper industry. *Cleaner Chemical Engineering*, *3*, 100058.

[23] Sholokhova, A., Varžinskas, V., & Rutkaitė, R. (2024). Valorization of Agro-waste in Bio-based and Biodegradable Polymer Composites: A Comprehensive Review with Emphasis on Europe Perspective. *Waste and Biomass Valorization*, 1-35.

[24] Singh, R. P., Shukla, A., & Tiwari, S. (2018). Environmental consequences of paper waste and potential of alternative fiber sources. Environmental Progress & Sustainable Energy, 37(1), 45-52. https://doi.org/10.1002/ep.12727

[25] Singha, N., Gautam, S. B., Sawood, G. M., Yadav, V. L., Mishra, G., Dixit, S., & Gupta, S. K. (2024). Bioenergy from agro-waste: a sustainable solution for energy needs. In Sustainable Clean Energy Production Using Waste Biomass: Sustainable Energy Production and Utilization (pp. 207-249). Singapore: Springer Nature Singapore.

[26] Statistics Sierra Leone. (2021). *Annual trade report*.

[27] Tyagi, A. K., Dananjayan, S., Agarwal, D., & Thariq Ahmed, H. F. (2023). Blockchain Internet of Things applications: Opportunities and challenges for industry 4.0 and society 5.0. *Sensors*, *23*(2), 947.

[28] United Nations Conference on Trade and Development. (2019). Economic development in Africa report: Made in Africa Rules of origin for enhanced intra-African trade. https://unctad.org/webflyer/economic-development-africa-report-2019

[29] United Nations Development Programme. (2022). Sustainable Development Goals. https://www.undp.org/sustainable-development-goals

[30] Waham, S. (2015). Sing for Me.

[31] World Bank Publications. (2019). *The Economics of the Belt and Road Initiative: Opportunities and Risks of Transport Corridors*. World Bank Publications.

Biography

Isaac Yongai, a well profound and deep-rooted science student cultivated from high school, nurtured as an environmental Chemist, Innovative leader, Scientific researcher, Field worker, and an Author in the University. Soon to own a degree of Bachelor of Science in Basic Sciences with Honors in Environmental Chemistry on 20th, December 2025. My desire is to move beyond traditional education and equip myself with practical skills, creative mindset, and unwavering confidence to build my career. I always count it joy when, I find myself in my critical zone (Environmental & Climate stuffs, Innovations, Scientific research and Field work), because it creates for me more learning environment, and executing what, I have learned so far. Always willing and ready to give my all in such environments.

Sahr Emmanuel Lebbie is a renowned Sierra Leonean environmentalist, an articulate and creative person with good organizational and industrial managerial skills, competent in chemical analysis, quality control, human resource development, and administrative and research work at Njala University, Department of Chemistry. Presently, he is pursuing his PhD in Environmental Sciences and Engineering at Harbin Institute of Technology, China. Mr. Lebbie completed his master's in environmental chemistry from Njala University in 2021 and his bachelor's degree in environmental chemistry from the same university in 2019. In addition, he holds a French Certificate from IMATT College, Freetown, in 2023, and a Generic Research Competency License Supervising Certificate for the Postgraduate Supervision Course, Editorial Assistant and Technical Editing, APA Referencing, and Canons of Research from Njala University in 2024. Recognized for his exceptional skills and academic excellence, he was employed as a lecturer at Njala University and as an associate lecturer in the Health Sciences Department, Central University, Sierra Leone. He has participated in multiple international research collaboration projects recently and he has published several publications in the field of Environmental Sciences. Mr. Lebbie is dedicated to advancing environmental issues and research in Sierra Leone.

David Conteh was born and raised in Makeni City. Currently, the CEO of the International College of Makeni. He owns a BSc. Honors degree in Chemistry from Fourah Bay College, University of Sierra Leone. Conteh acquired his MSc. in Chemistry from Njala University in 2005. He worked as a laboratory analyst at the Pharmacy Board Quality Control Laboratory in 2006 and worked as a technical manager in the chemical laboratory at the Sierra Leone Standards Bureau till 2016. Has been working on environmental impact assessments as a consultant for companies. Currently pursuing a PhD in Environmental Chemistry at Njala University.

Umaru Kanneh is a lecturer at Njala University Sierra Leone. 80% of his time is allocated to teaching, research and community service. He was born in Daru Town Eastern Sierra Leone on the 14th of April 1984. He grew up in Daru Town, at the age of ten He was enrolled in Junior Secondary School (JSS1) at Wesley Secondary School Segbwema, seven miles from Daru, during this period there was rebel war in Sierra Leone, and Kailahun District was the headquarter of the rebels. As a result, their schooling was frequently interrupted. In 1999. He transferred to the regional head quarter town Kenema to pursue his Senior Secondary School (SSS1). He both have BSc. Chemistry Education (2002) and MSc. in Environmental Chemistry, (2013) both from Njala University.

Issa Turay has B.Sc. (HONS) in Environmental Chemistry and M.Sc. in Environmental Chemistry. Mr. Issa Turay worked in various schools around Sierra Leone for the period 2004-2016. He joined Njala University in 2016 and has since risen to Lecturer II and has held different positions in the Department of Chemistry. His research interests include Wastes Management, Water Resources Management, Physicochemical Parameters of Soil, and other related areas. Outside of his professional life, Mr. Issa Turay engages in construction work, sports, gardening, and community service.

Tamba Patrick Komba is a dedicated final-year honors student completing his Bachelor of Science in Environmental Chemistry at Njala University, Sierra Leone. An active member of his university community, Tamba serves as the Public Relations Officer for the Njala University Volunteers for the 2024/2025 academic year. His commitment to university life is further demonstrated by his volunteer work in organizing major academic ceremonies, including Matriculation and Convocation programs. His skill set is complemented by a foundation in graphic design from the Laton Impression Institution and proficiency in computer skills, making him a well-rounded and engaged student prepared for the challenges of scientific research and communication.