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Proceeding Paper

Development and Performance Analysis of Coconut Coir Waste-Based Recycle Papers for Cooling Pad Applications †

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Abstract: Paper is an essential material in daily life, yet its widespread use contributes significantly to waste, which poses environmental hazards. In Indonesia, paper waste is one of the most substantial types of solid waste. Recycling waste paper into new, usable products offers both environmental and economic benefits. This study investigates the tensile strength, tearing strength, and microstructure of recycled paper produced using 70 g HVS waste paper, coconut husk fibers, NaOH as a chemical treatment, and tapioca powder as an adhesive. NaOH concentrations were varied at 2%, 4%, 6%, and 8% to assess their effects on the mechanical properties of the recycled paper. Results from tensile strength tests indicated that the highest tensile strength, 2.2774 MPa, was achieved with a 6% NaOH concentration, while the lowest tensile strength, 1.1065 MPa, was observed at a 4% NaOH concentration. Tearing strength tests showed that the highest tearing strength of 2.6145 MPa was obtained with a 4% NaOH concentration, whereas the lowest tearing strength of 1.8481 MPa was observed at an 8% NaOH concentration. Microstructural analysis of the fracture and tear zones revealed non-uniform fiber pullout, highlighting the influence of NaOH concentration on fiber bonding. These findings provide insights into optimizing NaOH concentration for improved mechanical properties in recycled paper products.

Keywords: recycled paper; NaOH concentration; tensile strength; tearing strength; coconut husk fiber

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1. Introduction

Cooling pads are a fundamental component in evaporative cooling systems that are widely used in various applications, from residential air coolers to industrial climate control systems [1]. Their principal function is to enhance cooling efficiency by enabling air to pass through a wetted medium, typically made from materials that can hold and distribute water evenly. As air flows through the wetted pad, water evaporates, absorbing heat from the surrounding air, which leads to a significant drop in temperature [2]. This process, known as evaporative cooling, is both cost-effective and energy-efficient compared to conventional refrigeration-based air conditioning systems [3].

Traditionally, cooling pads are manufactured from materials such as cellulose, wood wool, and synthetic fibers [4]. These materials, while effective, have several limitations, including high production costs, non-biodegradability, and poor performance in terms of water retention and mechanical strength under prolonged use [3]. These challenges necessitate the exploration of alternative materials that are environmentally friendly, cost-effective, and offer better performance characteristics [5].

The primary material challenges associated with conventional cooling pads include their limited durability, low resistance to microbial growth, and significant environmental impact due to the non-renewable nature of synthetic fibers [6]. Cellulose-based pads, for example, are prone to degradation when exposed to water for extended periods, leading to a decrease in cooling efficiency and the need for frequent replacements [7]. Furthermore, the environmental footprint of producing synthetic fibers and the energy-intensive process of manufacturing cellulose pads highlight the need for more sustainable materials [7].

Given these challenges, there is a growing interest in natural fiber composites, which offer the dual benefits of sustainability and enhanced performance. One such promising material is coconut coir, a natural fiber derived from the husk of coconuts, which is being increasingly recognized for its potential in various composite applications, including cooling pads [8,9].

Coconut coir is an abundant, biodegradable, and renewable resource. The coir fiber, obtained from the outer shell of coconuts, is composed of lignocellulosic materials that exhibit excellent mechanical properties, including high tensile strength, elasticity, and durability [10,11] Coir fibers are also known for their resistance to saltwater, making them particularly suitable for use in humid and wet conditions, which are common in evaporative cooling applications [4,12].

Coconut coir waste-based composites are typically manufactured by combining coir fibers with a polymer matrix, such as unsaturated polyester resin, to form a strong and durable material. The coir fibers serve as the reinforcement phase, while the polymer matrix provides structural support and helps distribute stress across the composite [7,13]. In the context of cooling pads, the water retention capability of coir fibers, coupled with their mechanical resilience, makes them an ideal candidate for replacing conventional materials [4,14].

The use of coconut coir waste-based composites in cooling pads offers several advantages over traditional materials. Firstly, coir fibers are highly absorbent, allowing for better water distribution across the pad, which enhances the efficiency of the evaporative cooling process [3,15]. Additionally, coir composites are more durable and resistant to microbial growth compared to cellulose-based pads, which are prone to decay in moist environments [16]. This increases the lifespan of the cooling pads and reduces the frequency of replacement, thereby lowering maintenance costs [3].

Furthermore, the environmental benefits of using coconut coir are significant. As a byproduct of coconut harvesting, coir fibers are abundantly available, particularly in tropical regions. Utilizing coconut coir for composite manufacturing not only reduces agricultural waste but also promotes sustainability by decreasing reliance on non-renewable synthetic materials [17]. This aligns with global trends toward the use of eco-friendly materials in industrial applications [18].

In comparing coconut coir waste-based composites to conventional materials like cellulose and synthetic fibers, coir-based composites exhibit superior properties in several areas. Coir fibers have a higher tensile strength than many natural fibers, which translates into better mechanical performance under load-bearing conditions [19]. The natural porosity of coir fibers also allows for efficient water absorption and distribution, making them ideal for use in evaporative cooling systems [4]. Additionally, the durability of coir-based composites ensures that the cooling pads can withstand prolonged exposure to water without significant degradation [20,21].

Despite their many advantages, coconut coir waste-based composites are not without limitations. One of the primary challenges is the variability in fiber quality, which can affect the consistency of the composite material [7]. Coir fibers, being a natural material, are subject to variations in size, strength, and water retention capacity depending on factors such as geographic origin and processing techniques [3]. Additionally, the bonding between the coir fibers and the polymer matrix can be a limiting factor, as poor interfacial adhesion may lead to a reduction in mechanical properties over time [22].

Another limitation is the susceptibility of coir-based composites to thermal degradation. While coir fibers have good mechanical properties, their thermal stability is lower compared to synthetic fibers, which may limit their use in high-temperature applications [7].

This study aims to address several gaps in the current research on natural fiber composites, particularly in the context of cooling pad applications. While previous studies have demonstrated the potential of coir fibers in various composite materials, there is limited research on the specific performance of coir-based composites in evaporative cooling systems [3]. This study seeks to fill this gap by investigating the tensile strength, water absorption, and durability of coir waste-based composites when used as a cooling pad material [7].

The main objective of this research is to develop a coconut coir waste-based composite material that can effectively replace conventional cooling pad materials. By optimizing the volume fraction of coir fibers within the composite, the study aims to achieve a balance between mechanical strength and water retention capacity [4]. The results of this research are expected to contribute to the development of more sustainable, efficient, and cost-effective cooling pads for evaporative cooling systems [3].

2. Materials and Methods

This study utilizes several materials and follows a detailed process for the preparation and fabrication of composite specimens aimed at assessing mechanical properties and microstructural characteristics. The primary materials include used recycled paper, coconut fiber, NaOH as a chemical treatment, and tapioca flour as an adhesive. Each material serves a specific function, enhancing the overall properties of the composite.

2.1. Materials

Recycled paper is utilized as the primary pulp component. Coconut fiber, prepared as reinforcing material, is first washed and sun-dried, and then cut into fibers of 1 cm length. This fiber provides tensile reinforcement, contributing to the structural integrity of the composite. NaOH (sodium hydroxide), supplied in flake form, serves as a solvent material to dissolve lignin in the coconut fibers, aiding in fiber treatment and improving fiber–matrix adhesion. Tapioca flour, a natural starch powder, acts as an adhesive, binding the paper pulp and coconut fibers effectively when mixed into the pulp.

To prepare the paper pulp, the recycled paper is cut into small pieces and soaked in water for 24 h, allowing it to soften. After soaking, the paper is blended until a smooth, homogenous pulp is achieved. This pulp is then dried thoroughly under sunlight, ensuring it reaches the desired consistency before being weighed according to the requirements of the composite mixture.

The coconut fiber undergoes a specific preparation process to optimize its properties for composite use. Initially, NaOH is weighed according to the desired concentration to ensure effective lignin dissolution. The fiber is then treated by boiling it in a 1 L solution of water and NaOH for one hour at 100 °C. After boiling, the fibers are rinsed with clean water until no residual NaOH remains, ensuring a clean and treated fiber surface. The fibers are then air-dried at room temperature for two days. Finally, they are cut into 10 mm lengths and weighed as per the composite design specifications.

2.2. Fabrication of Paper Specimens

The manufacturing of the composite specimens involves multiple stages to ensure uniform mixing, shaping, and drying. Initially, the prepared paper pulp and treated coconut fibers are combined in a tub containing 2 L of water. To this mixture, 5% tapioca flour by volume is added and stirred until all components achieve a homogenous consistency. The mixture is then ready for molding.

A clean specimen mold is submerged into the tub, capturing the pulp and fiber blend. Upon lifting, the mold is allowed to drain momentarily until water ceases to drip. The filled mold is then transferred onto a piece of plywood, where it is pressed to expel excess water from the specimen. The specimen, now on plywood, is set to dry under sunlight for one day.

Once fully dried, the specimens are cut according to the SNI 1924-2:2016 [23] standard specifications, preparing them for both tensile and tear testing. Following these tests, microstructural analysis is conducted on intact specimens and those fractured from testing, using micro-photography to examine fiber pullout, bonding, and fiber distribution within the composite structure. This multi-step methodology ensures that the composite specimens are consistently prepared, allowing for accurate and reliable testing of their mechanical and structural properties.

2.3. Tensile and Tear Strength Test

For evaluating the mechanical performance of the recycled paper composite material reinforced with coconut fiber, both tensile and tear strength tests are conducted in accordance with the SNI 1924-2:2016 standard as depicted in Figure 1. The tensile strength test measures the material's ability to withstand a uniaxial pulling force, providing insights into its structural integrity and resistance under tension. This test is crucial for understanding the overall durability of the composite, especially in applications where tensile loads may be encountered. Complementing this, the tear strength test assesses the material's resistance to tearing forces. While similar in principle to the tensile test, the tear test focuses on the specimen's ability to resist propagation of a tear under stress, a property particularly relevant for materials exposed to puncture or high-stress environments. Together, these tests offer a comprehensive view of the mechanical resilience of the composite, allowing for optimization in applications that require high durability and tear resistance.

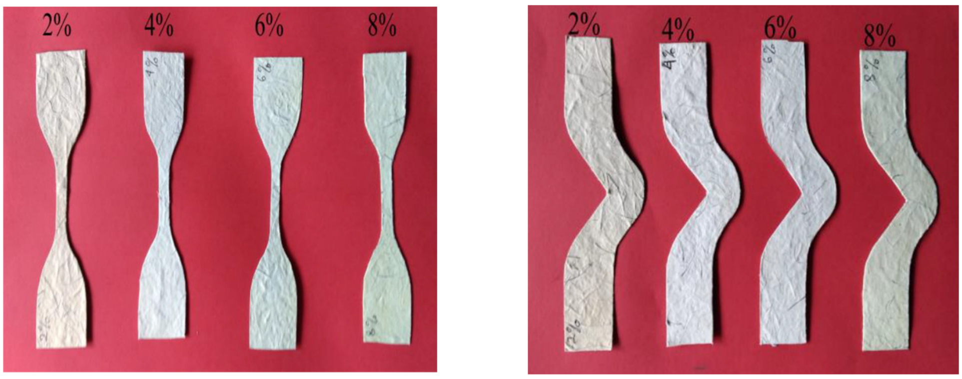

Figure 1. Tensile and tear strength specimens.

Tensile and tear strength testing was conducted using the Shimadzu AGS-X Universal Testing Machine, equipped with a load cell capacity of 5 kN and precision control software, ensuring the accurate measurement of tensile properties. This test assesses the material's ability to endure a uniaxial pulling force, providing insights into its structural resilience and maximum load-bearing capability under tension. The machine's precision load cell and extensometer measure both force and elongation, offering valuable data on the composite's elasticity, strength, and durability.

2.4. Testing Environment

All mechanical tests were performed in a controlled laboratory environment at a temperature of 23 °C and a relative humidity of 50%. The environmental conditions were monitored throughout the testing process to ensure that the results were not affected by external factors such as temperature fluctuations or humidity variations.

2.5. Microstructural Analysis

After the mechanical tests, a detailed microstructural analysis was performed on the fractured specimens using an Olympus BX53M optical microscope, equipped with a 1000× magnification capability and a high-resolution CCD camera for precise imaging. This analysis focused on examining the fiber–matrix interface and evaluating the distribution of fibers within the composite, providing crucial insights into the material's failure mechanisms and overall structural integrity. The analysis helped to identify any defects, such as voids or fiber pullout, that may have contributed to the mechanical behavior of the composite.

Micrographs were used to evaluate the quality of the fiber–matrix bonding and the extent of damage in the composite after tensile testing. The microstructural observations were correlated with the mechanical test results to explain the performance of the composite, particularly in terms of how the fiber content and water absorption influenced the tensile properties.

3. Results and Discussion

This section presents a comprehensive analysis of the mechanical properties of recycled paper composites reinforced with coconut coir, treated with varying concentrations of NaOH. This study specifically examines how NaOH concentration affects the tensile strength, tear resistance, and microstructure of the composite material. By exploring these properties, the study aims to identify the optimal NaOH concentration that maximizes both strength and durability.

3.1. Tensile Strength Analysis

The tensile strength tests revealed notable variations across the different NaOH concentrations applied to the recycled paper composite. Figure 2 shows the results of the specimens' tensile tests. Specimens treated with 6% NaOH achieved the highest tensile strength at 2.2774 MPa, whereas the 4% NaOH concentration showed the lowest tensile strength, measured at 1.1065 MPa. The higher tensile strength in the 6% NaOH concentration suggests improved inter-fiber bonding due to the optimized alkali treatment, which aids in lignin removal and enhances fiber surface roughness, thus improving the adhesion between coconut coir fibers and the pulp matrix [24].

Previous studies have documented the benefits of alkali treatment in enhancing the mechanical properties of natural fiber composites. Lertwattanaruk and Suntijitto [25] demonstrated that alkali-treated coconut coir in cement composites increased tensile and compressive strength due to better fiber–matrix adhesion. The current study aligns with these findings, where the 6% NaOH concentration enhanced tensile properties in a similar manner. However, increasing NaOH concentration to 8% resulted in reduced tensile strength, indicating that excessive alkali might damage the fiber structure, thus reducing its effectiveness as a reinforcement [25].

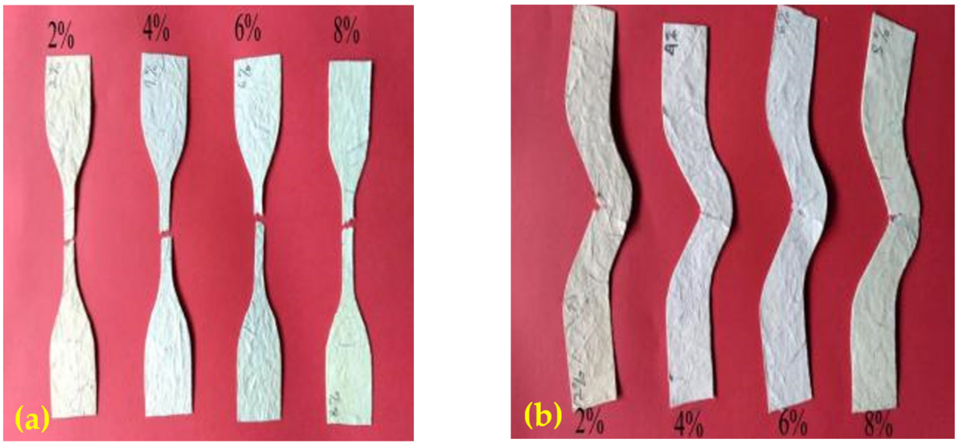

Figure 2. Tensile (**a**) and tear (**b**) test results for variations in NaOH treatment.

Figure 2a displays the fracture patterns of tensile-tested recycled paper composites reinforced with coconut coir, treated with NaOH concentrations of 2%, 4%, 6%, and 8%. The 2% specimen shows a brittle break, indicating weaker bonding, while the 4% specimen exhibits slightly better cohesion. The 6% NaOH specimen achieves the cleanest and most uniform fracture, reflecting optimal fiber–matrix bonding and the highest tensile strength, likely due to effective lignin removal. In contrast, the 8% specimen displays an irregular fracture, suggesting fiber damage from excessive NaOH, which weakens structural integrity. These results suggest that a 6% NaOH concentration provides the best balance of strength and bonding without fiber degradation.

3.2. Tear Strength Analysis

The tear strength analysis provided insights into the composite's resistance to tearing forces. The highest tear strength was recorded in specimens treated with 4% NaOH, reaching 2.6145 MPa, while the lowest tear strength of 1.8481 MPa was observed in the 8% NaOH-treated specimens. This trend indicates that an optimal concentration of NaOH can improve tear resistance, likely due to enhanced bonding between fibers at this concentration. However, further increases in NaOH concentration weaken the composite structure, resulting in reduced tear resistance. This finding is consistent with the work of Mahmud, et al. [26], who noted that moderate alkali treatment effectively enhances fiber-reinforced composite properties, while excessive alkali treatment may lead to fiber damage and weakened composite integrity.

The differences in tensile and tear strength suggest that while a higher NaOH concentration benefits tensile strength due to increased inter-fiber bonding, tear resistance relies on fiber flexibility, which is reduced with overly aggressive chemical treatments. Mahmud et al. [26] observed similar behavior in coir-based composites, where moderate alkali treatment produced optimal mechanical properties without compromising fiber integrity. This finding emphasizes the importance of balancing chemical treatment to achieve a composite with balanced mechanical properties suitable for different applications.

Figure 2b shows tear test fracture patterns for recycled paper composites with coconut coir treated with NaOH concentrations of 2%, 4%, 6%, and 8%. The 2% and 8% NaOH specimens exhibit relatively straight tears, indicating weaker tear resistance due to inadequate bonding at 2% and fiber damage at 8%. In contrast, the 4% and 6% NaOH specimens show more irregular tear paths, suggesting stronger fiber–matrix bonding and improved tear resistance. This implies that moderate NaOH concentrations (4–6%) optimize tear resistance by enhancing fiber adhesion without causing fiber degradation, while lower or higher concentrations compromise performance.

3.3. Microstructure Analysis

Microstructural examination through micrographs provided further insight into the fiber distribution and bonding within the composite matrix. The micrographs revealed that at lower NaOH concentrations (2% and 4%), fiber distribution was less uniform, and bonding between fibers and the pulp matrix was weaker. In contrast, the 6% NaOH concentration exhibited a more cohesive structure, with fewer voids and better inter-fiber bonding. This enhanced microstructural cohesion explains the higher tensile strength at this concentration, as stronger fiber–matrix adhesion contributes to load transfer efficiency in the composite [27].

In specimens treated with 8% NaOH, micrographs showed evidence of fiber damage, characterized by fiber fraying and fragmentation. This result supports the mechanical test data, where the 8% concentration led to a reduction in both tensile and tear strength. Excessive alkali exposure can degrade lignocellulosic fibers, leading to weaker structural integrity. Similar findings were reported by Stelte et al. [27], where high NaOH concentrations led to fiber deterioration in coir fiberboard composites. The visual representation of fiber damage in the micrographs correlates well with the observed decline in mechanical properties, affirming the need for optimized alkali concentrations to preserve fiber integrity while enhancing inter-fiber bonding.

The micrographs depict coconut coir composite samples treated with varying NaOH concentrations (2%, 4%, 6%, and 8%), revealing differences in fiber appearance, bubble formation, and fiber dimensions, as shown in Figure 3. NaOH treatment generally aims to improve fiber–matrix adhesion by removing impurities and increasing surface roughness. The observed variations in fiber appearance could indicate that the different NaOH concentrations altered the fiber surface, potentially removing surface lignin and hemicellulose to varying extents. This could influence the bonding between the fibers and the methyl ethyl matrix, with higher concentrations possibly resulting in a more pronounced surface roughness.

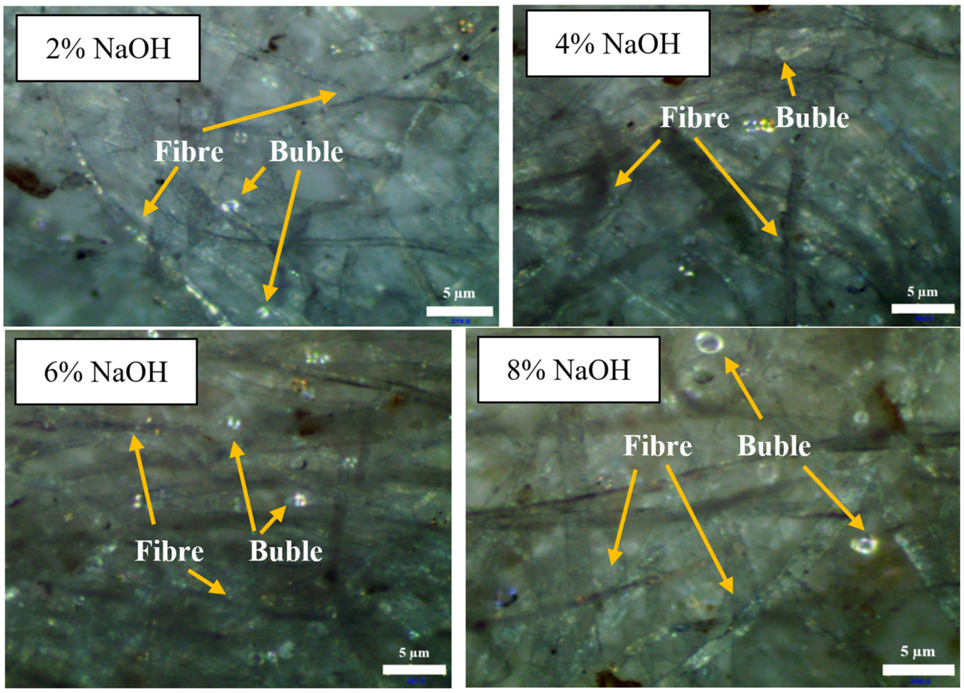

Figure 3. Micrograph of the specimen with varying NaOH treatments.

The color differences among fibers might suggest varying degrees of chemical interaction between the NaOH and fiber material. Higher concentrations of NaOH could lead to more extensive fiber modification, possibly contributing to a lighter or darker fiber appearance. This change could be due to alterations in the fiber's natural components or the removal of surface impurities. The presence of bubbles could indicate micro-voids or air entrapment during the mixing process. Bubbles can occur if the fiber surface is not adequately wetted by the resin, or if there are impurities left on the fibers despite treatment. The NaOH concentration may impact the wettability of the fibers, with certain concentrations leading to either more or fewer bubbles depending on how well the resin adheres to the treated fiber surface.

Different NaOH treatments could affect fiber size indirectly by causing partial fragmentation or fiber swelling. A higher NaOH concentration may increase the fiber's susceptibility to structural breakdown or swelling, which can affect the apparent fiber size in the composite. If the treatment is too aggressive, it may even weaken the fibers, leading to reduced fiber integrity.

The combination of these factors (surface roughness, bonding characteristics, and fiber integrity) significantly influences the mechanical properties of the composite. Higher NaOH concentrations are likely to enhance fiber–matrix adhesion up to an optimal level, after which fiber degradation might negatively affect the material's mechanical performance. Properly balanced NaOH treatment can lead to improved tensile strength and durability by promoting better load transfer between fibers and the matrix.

Figure 4 shows the tensile test fracture surfaces of recycled paper composites reinforced with coconut coir, treated with NaOH concentrations of 2%, 4%, 6%, and 8%. Each micrograph provides insights into the fiber pullout behavior, fracture characteristics, and bonding quality between the recycled paper, coconut coir fibers, and the tapioca binder.

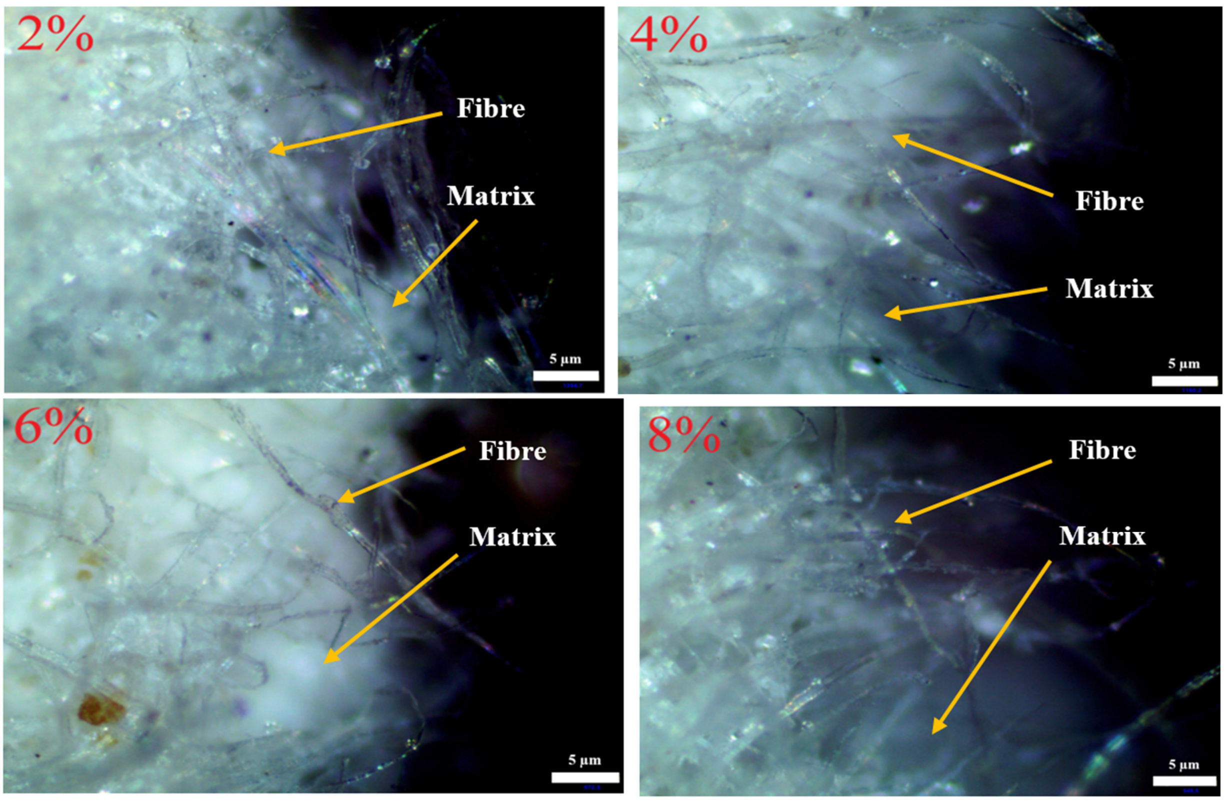

Figure 4. Micrograph of fractured tensile test specimens with varying NaOH treatments.

The micrograph for the 2% NaOH concentration shows noticeable fiber pullout, with fibers appearing loosely bonded to the matrix. This indicates that the low concentration of NaOH may be insufficient for effective lignin removal, resulting in weaker bonding between the coconut coir fibers and the recycled paper matrix. The lack of strong fiber–matrix adhesion likely contributes to early fiber pullout and a brittle fracture pattern, limiting the composite's tensile strength.

At 4% NaOH, the microstructure shows improved bonding with slightly less fiber pullout compared to the 2% sample. The fibers appear more integrated into the matrix, suggesting that this concentration facilitates better fiber–matrix bonding, likely through moderate lignin dissolution. The improved bonding enhances load transfer between fibers and the matrix, which contributes to increased tensile strength, though some fiber pullout is still visible, indicating that the bonding is not yet optimal.

The 6% NaOH micrograph reveals the best fiber–matrix integration among all samples, with minimal fiber pullout observed. The fibers are well-embedded within the matrix, suggesting strong interfacial bonding due to effective lignin removal at this concentration. This enhanced bonding improves load distribution across the composite, reducing fiber pullout and resulting in a more cohesive fracture. The strong fiber–matrix adhesion observed at 6% NaOH concentration corresponds with the highest tensile strength, as the fibers effectively reinforce the recycled paper matrix without detachment.

The 8% NaOH micrograph shows signs of fiber degradation and increased fiber pullout, similar to the 2% concentration. Excessive NaOH appears to damage the coconut coir fibers, weakening the composite structure. This damage results in poor fiber–matrix adhesion, as fibers are more prone to detachment from the matrix under stress. Consequently, the composite with 8% NaOH displays a weaker bond, which decreases tensile strength and leads to premature failure with more extensive fiber pullout.

The micrographs highlight that a moderate NaOH concentration, specifically 6%, provides optimal bonding within the composite by enhancing fiber–matrix adhesion while avoiding fiber degradation. Lower (2%) and higher (8%) concentrations are less effective, either due to inadequate lignin removal or excessive fiber damage, resulting in increased fiber pullout and reduced tensile strength.

This study's results align with several previous studies on coconut coir and natural fiber composites. For instance, Kaliappan and Natrayan [28] reported that hybrid composites incorporating coconut fibers and moderate NaOH treatment improved mechanical properties, demonstrating the effectiveness of controlled chemical treatments. Similarly, Pereira et al. [29] found that coconut coir composites with optimal chemical treatments exhibited increased strength and durability, supporting the effectiveness of the alkali treatment observed in this study at a 6% concentration.

In comparison to synthetic fiber composites, natural fiber composites, such as those reinforced with coconut coir, offer a more sustainable and environmentally friendly alternative, though often with lower mechanical properties. This study's composite tensile strength falls below that of typical synthetic composites, but its performance is adequate for lightweight, eco-friendly applications, particularly where biodegradability and sustainability are prioritized. Demirdağ et al. [29] also highlighted the ecological advantages of using coconut coir in polymer composites, noting that while natural fibers may not match the absolute strength of synthetic counterparts, their environmental benefits are substantial.

This study contributes to the growing body of knowledge on optimizing alkali treatment for natural fiber composites. It confirms that while alkali treatment can enhance fiber–matrix bonding and mechanical properties, there exists an optimal concentration beyond which fiber integrity is compromised. These findings underscore the need for balanced chemical treatments, providing a foundation for future research in eco-friendly composite materials.

4. Conclusions

Based on the results and analysis in this study, it can be concluded that the NaOH concentration significantly affects the mechanical properties and structural integrity of recycled paper composites reinforced with coconut coir. The optimal NaOH concentration was found to be 6%, which provided the highest tensile strength due to improved fiber–matrix bonding, as evidenced by a cohesive fracture pattern during tensile testing. For tear resistance, 4% and 6% NaOH concentrations exhibited better performance, suggesting that moderate NaOH treatment strengthens fiber adhesion without compromising fiber integrity. Conversely, lower (2%) and higher (8%) NaOH concentrations resulted in weaker performance; insufficient NaOH led to poor bonding, while excessive NaOH caused fiber degradation, reducing both tensile and tear strength. These findings highlight that a balanced NaOH treatment is crucial for maximizing the mechanical properties of eco-friendly composites and demonstrate that a 6% concentration is ideal for applications requiring enhanced tensile strength and durability. This study reinforces the potential of recycled paper and coconut coir composites as sustainable materials with optimized chemical treatment, offering an environmentally friendly alternative for various industrial applications.

Author Contributions: The following are the author's contributions: A.Y. prepared the materials and instruments, A.S.D. analyzed the data, A.D.A. composed the text, and carried out the experimental methods. All authors have read and agreed to the published version of the manuscript.

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