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CHARACTERIZATION MECHANICAL PROPERTIES OF ALKALI-TREATED OXYTENANTHERA ABYSSINICA BAMBOO FIBER PROPERTIES: CASE STUDY

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ABSTRACT

Ethiopia's indigenous lowland bamboo (Oxytenanthera abyssinica) plant mechanical properties have not been extensively studied in the context of single fibers, which presents significant challenges when considering its applications in various industries such as textiles, fashion, and structural engineering. The lack of comprehensive research has hindered the ability to fully harness the potential of this remarkable natural resource. In light of this gap, the current study aims to systematically investigate a range of critical mechanical properties, including breaking force, tenacity, elongation, work done, and modulus, while examining the individual and interactive effects of various factors such as plant age (ranging from 36 to 54 months), soaking duration (between 5 and 15 minutes), and alkali concentration (from 5% to 15%).

Utilizing Box–Behnken design expert@11 software 2D and 3D plotting techniques, the study provides a clear visualization of these relationships, making it easier to understand how each variable impacts the overall performance of the bamboo fibers.

The findings disclosed that increasing the alkali concentration significantly aids in reducing the fiber's weight by effectively dissolving lignin and hemicellulose, which the primary components are contributing to the fiber's heaviness. Furthermore, as both the alkali concentration and the age of the bamboo plant increase, there are noticeable improvements in the mechanical properties of the fibers, indicating that older fibers may possess enhanced resilience and strength. However, it is noteworthy that this positive trend reaches a plateau or even declines beyond certain thresholds, except for the modulus, which demonstrated a unique response, suggesting that further exploration is warranted. The study not only highlights the potential for optimizing treatment conditions to significantly enhance bamboo fiber performance but also emphasizes the importance of further research in this area. By unlocking the mechanical capabilities of Ethiopian bamboo, we can pave the way for innovative applications in sustainable fashion and structural materials, ultimately contributing to more environmentally friendly practices within these industries. This research serves as a foundational step toward understanding the true potential of bamboo fibers, encouraging further investigation that could lead to the development of new, eco-conscious products that utilize this abundant and versatile natural resource in Ethiopia.

Keywords: Lowland bamboo, Bamboo fiber, Mechanical properties, alkali concentration, Box-Behnken,

1. INTRODUCTION

Natural fibers are gaining attention as promising alternatives to synthetic fibers, especially in textiles, fashion, and structural applications [1]. Their renewable source and biodegradable nature make them environmentally friendly, helping to reduce pollution and waste. Unlike synthetic fibers, which rely on fossil fuels and often cause long-lasting environmental damage, natural fibers offer a low-impact solution with comparable mechanical strength and flexibility [2]. Industries searching for sustainable options are increasingly embracing natural fibers to meet growing consumer demand for eco-conscious products [3]. These fibers can be used in everything from clothing to building materials, offering versatility while supporting a smaller carbon footprint. As innovation continues, natural fibers are driving advancements in green textiles and construction, contributing significantly to sustainability goals and a cleaner future [4], [5].

Natural fibers, such as those from bamboo species like *Oxytenanthera abyssinica*, are attracting growing interest for their renewable and biodegradable qualities. These fibers stand out for their low density, good mechanical strength, and cost-effectiveness, making them ideal for use in textiles, composite materials, and even construction [6], [7]. Their environmental benefits are clear. They help reduce reliance on synthetic fibers derived from fossil fuels. However, natural fibers do present challenges. Their properties can vary depending on growing conditions, and they tend to absorb moisture, which may weaken their structure compared to synthetic alternatives. To address this, scientists are studying their microscopic structure and developing treatments to improve durability and performance. Due to continuous research and innovation, these eco-friendly fibers are becoming more versatile, helping industries develop sustainable products without compromising quality or cost [1], [4], [8].

Ethiopia is home to several important bamboo species that contribute significantly to local ecosystems and economies. The most common is **Yushania alpine (Figure 1)**, known as African alpine bamboo [9]. It thrives in the highland regions at elevations between 2,400 and 3,300 meters, where it forms dense stands. These bamboo groves provide vital habitats for wildlife while supporting soil conservation and water retention [10].

Figure 1: Ethiopian highland bamboo plant [11]

Another key species is **Oxytenanthera abyssinica**, valued for its strong and durable fibers. This bamboo is widely used in construction, furniture making, and local handicrafts, making it an essential resource for many communities. Together, these bamboo species not only sustain biodiversity but also support livelihoods through their versatile uses in everyday life and commerce [7], [12]. Oxytenanthera abyssinica, commonly known as lowland bamboo, is a fast-growing plant native to Ethiopia. It thrives in the country's lowland areas, where it can shoot up rapidly; its culms often reach over 20 meters within just a few years, outpacing many tree species in growth speed. This bamboo plays a vital role in rural communities [13]. Its strong stems and tough fibers are harvested sustainably, allowing the plant to regenerate year after year. Locals use the poles to build houses, roofs, floors, and fences, while artisans craft baskets, mats, and chairs from their flexible fibers. These crafts not only reduce reliance on wood from forests but also help prevent soil erosion [14]. With over one million hectares covered by bamboo in Ethiopia, lowland bamboo fuels economic growth by creating jobs and income, especially for women who often lead weaving projects. This sustainable resource supports both environmental health and community livelihoods across the region [15]. Oxytenanthera abyssinica, a species of bamboo native to Africa, holds promise as a sustainable material for textile and structural uses. However, research into its mechanical properties at the single fiber level is still limited [16]. Most current studies focus on the behavior of composites or bulk materials made from this bamboo, leaving a gap in understanding the strength, elasticity, and durability of individual fibers. To fully solve its potential, it's important to evaluate key parameters such as tensile strength (how much force a fiber can withstand before breaking), Young's modulus (a measure of stiffness), and elongation at break (how much a fiber can stretch). These characteristics are essential for designing high-performance textiles and structural materials that are both strong and flexible. By gaining deeper insights into these properties, researchers and manufacturers can better assess the suitability of Oxytenanthera abyssinica fibers, paving the way for innovative and eco-friendly applications in fashion and construction [17], [18], [19].

This study investigates the mechanical behavior of single fibers from Oxytenanthera abyssinica bamboo, focusing on key properties such as tensile strength, Young's modulus, and elongation at break. These parameters help reveal how the fibers perform under stress and how flexible or stiff they are, essential for their use in textiles and structural materials. The research also explores how different factors influence these properties. Alkali treatment with sodium hydroxide (NaOH) alters the fiber surface and internal structure, potentially enhancing strength and flexibility. Additionally, the age of the plant and the duration of alkali soaking are examined to find the optimal conditions for improving fiber quality. Understanding these variables allows for better optimization of Oxytenanthera abyssinica fibers, making them more suitable for sustainable, high-performance applications in both fashion and construction industries.

2. Methodology

In the present experimental study, the mechanical properties of Ethiopian lowland bamboo fiber were analyzed. The bamboos were acquired from **Benishangul-Gumuz Region (Figure 2), Ethiopia**, containing a massive portion of the country's total lowland bamboo resources, often cited as approximately 55% to 85% of the national total. (Elevation**: 580 to over 2,700 meters above sea level (m.a.s.l.)).** The fiber from the bamboo was extracted mechanically using a rolling machine after being prepared by soaking the bamboo culm in alkali and water.

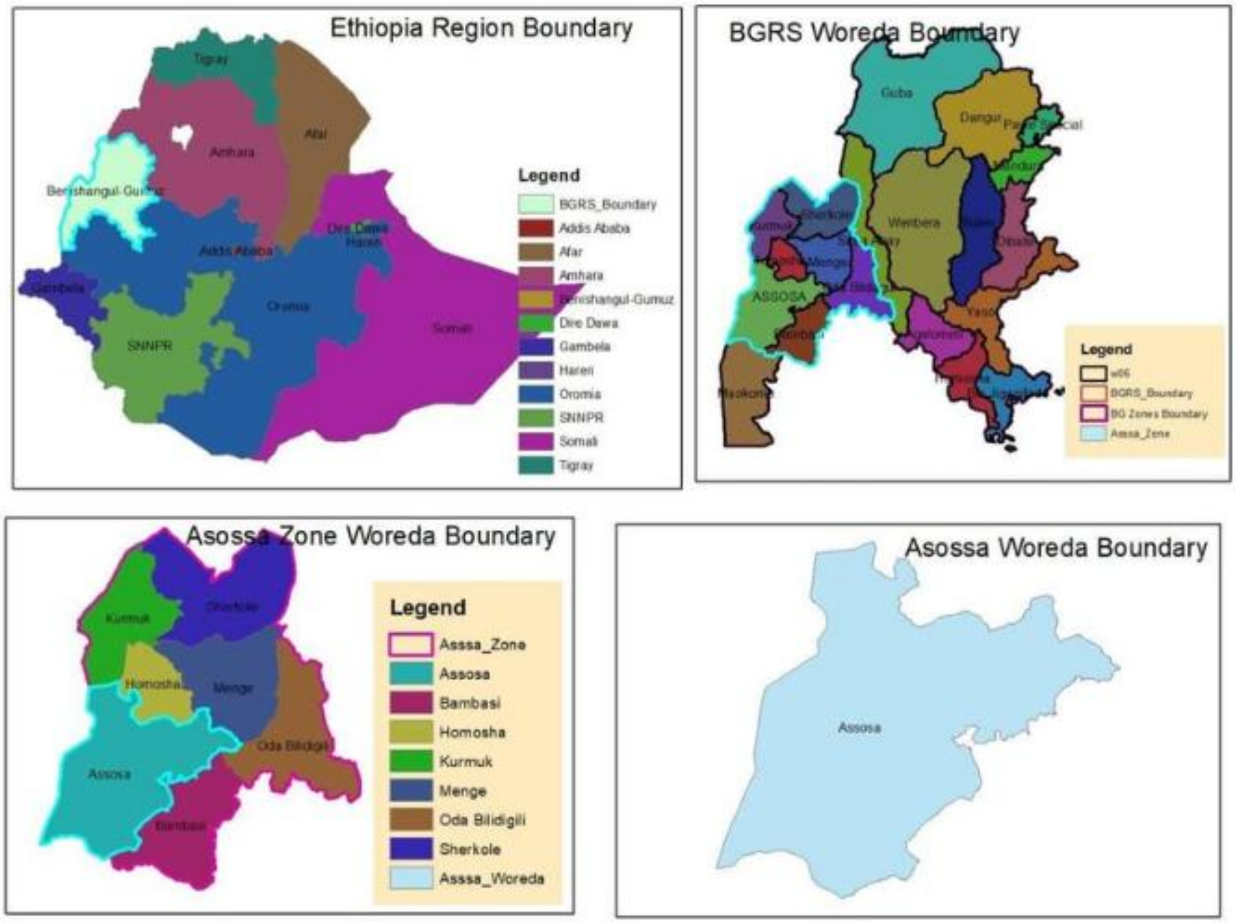


Figure 2: Map of the Study row material(lowland bamboo) area [20].

2.1 Materials

Lowland (Oxytenanthera abyssinica) is the type of bamboo used in the studies. Samples (Figure 3) were taken from plantations that were between 18 and 54months old in **Benishangul-Gumuz Region, Ethiopia**.

Figure 3: Lowland Bamboo in **Bnnishangul-Gumuz Region, Ethiopia [21].**

2.1.1 Chemical

Sodium hydroxide (NaOH, manufacturer: RESEARCH-LAB FINE CHEM INDUSTRIES, Assay: min98%) at different concentration weights by volume of 8, 16, and 24% and soaking duration of 24, 48, and 72 hours.

2.2 Methods

2.2.1 Raw Material Preparation

The middle of the bamboo stem was sliced with a slicer to remove the residual pieces, which were approximately 25–30 cm long and 2.0–2.5mm thick, as shown in Figure 4.

Figure 4: Lowland bamboo plants were chopped with a slicer

2.3 Extraction

The fiber extraction process involved treating bamboo strips with NaOH solutions at concentrations ranging from 8% to 20% (w/v), with plant ages between 18 and 54 months, and soaking durations of 24 to 72 hr. After soaking, the fibers were thoroughly washed with tap water to neutralize the solution, then subjected to mechanical extraction using a roller crusher machine (PHOENIX, Belgium), which produced small fibers from the alkali-treated bamboo strips. The extracted fibers (Figure 5) were subsequently dried in an oven at 105 °C for one hour to ensure moisture removal before further use.

a) Rolling machine b) Alkali-treated fibers

Figure 5: Fiber extraction machine and alkaline-treated lowland bamboo fibers used for experimental studies

2.4 Experimental design

In order to effectively assess the primary effects and interactions of plant age, alkali concentration, and soaking time on fiber properties, the study employed the Box-Behnken design (BBD), a subset of response surface methodology (RSM). This allowed for the creation of model equations for each dependent variable. Compared to standard factorial designs, BBD minimizes the number of experimental runs while preserving accuracy. It focuses on optimizing process parameters, particularly as these factors have a substantial impact on the cellulose content of alkali-treated fibers. To enable a methodical examination of their impacts, the factors were coded as low (-1), medium (0), and high (+1), with Table 1 providing exact levels for each.

Table 1 Design layout of independent variables and coded values

Factors	Symbol	Unit	Range and level		
			Low -1	Middle 0	High 1
Plant age	A	month	18	36	54
NaOH Concentration	B	%	5	10	15
Soaking duration	C	min	5	10	15

The tests, which included 17 runs with five center points per block, were planned, laid out, and analyzed with the aid of Design Expert® 11 software. The tests looked at how reactions, including breaking force, elongation, tenacity, work done, and modulus, related to the independent variables plant age (A), concentration (B), and soaking time (C). A three-factor polynomial equation was used to represent these relationships, enabling the assessment of main impacts and interactions to efficiently optimize fiber qualities.

Design Expert® 11 was utilized to create the plan lattice and analyze the experimental data, ensuring a structured approach to the study. The analysis included conducting 13 experiments, with each block containing 5 central points, as presented in Table 2. This setup allows for precise estimation of experimental effects and interactions, enhancing the reliability of the results. By employing Design Expert® 11, the design and analysis process was streamlined, facilitating efficient interpretation and validation of the findings.

Table 2: Design experimental factors and responses setups of Design Expert 11software

Factor 1	Factor 2	Factor 3	Response 1	Response 2	Response 3	Response 4	Response 5
A: Plant Age	B:NaOH	C:Soaking Duration	Breaking Force	Tenacity	work done	Elongation	Modulus
Month	%	min	N	cN/tex	cNmm	%	cN/mm
36	10	10					
54	10	5					
36	5	15					
18	10	15					
18	8	10					
36	24	5					
18	24	10					
36	16	10					
36	16	10					
36	16	10					
54	24	10					
54	16	15					
54	8	10					
36	8	5					
36	16	10					
18	16	5					
36	24	15					

2.5 Characterization

In compliance with ISO 13934-1: 2013, design expert software was used to examine the mechanical characteristics of 13 samples, including breaking force, elongation, tenacity, work done, and modulus. A semi-automated tensile testing apparatus with load cells ranging from 20 N to 5000 N was used for the tests. The machine had a speed measurement accuracy of ± 0.01% and a force measurement accuracy of ± 0.03%. Samples aligned under an axial tensile load until failure, indicated by cracks or splitting, were tested using a 20 N load cell with a resolution of 0.0002 cN.

3. Results and Discussion

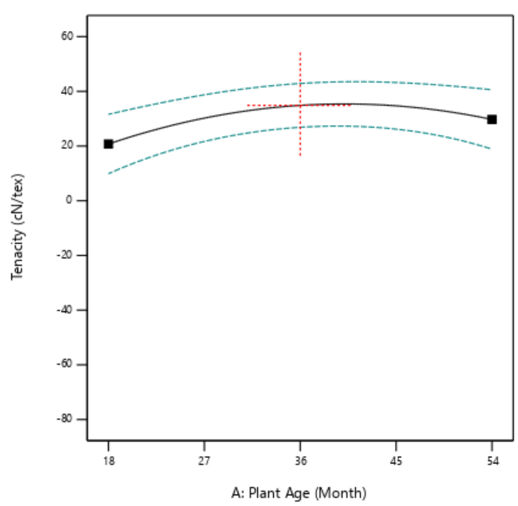
3.1 **Mechanical properties**

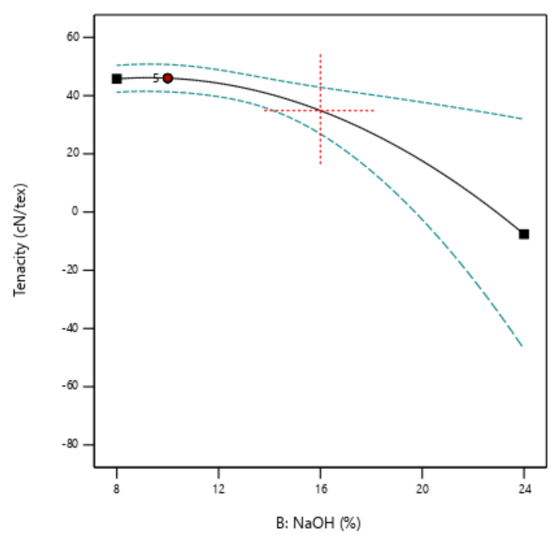
The mechanical properties of alkali-treated Oxytenanthera abyssinica bamboo fibers are affected by several important factors, including the age of the plant, the concentration of alkali used, and the duration of soaking. As the bamboo plant matures, its fibers typically become stronger and stiffer. This increase in strength occurs because older plants contain more lignin and cellulose, which are essential components that provide the fibers with their structure and toughness. When it comes to alkali concentration, using a higher amount can improve the roughness of the fiber's surface and help remove unwanted impurities. This cleaning process can lead to improved tensile strength, allowing the fibers to hold more weight without breaking. However, it is important to be careful with the amount of alkali used, as too much can damage the fibers, making them weaker instead of stronger. Soaking time is another key factor that impacts the effectiveness of the chemical treatment. The right soaking duration is essential to ensure that the fibers are properly purified and their surfaces are modified in a way that enhances their properties. If the soaking time is too short, the treatment may not be effective, but if it is too long, it can harm the fibers. Therefore, finding the right balance among these factors: - plant age, alkali concentration, and soaking time is crucial for improving the mechanical performance of the treated bamboo fibers. This balance is especially important when these fibers are used in various applications, where strong and durable fibers are essential for optimal performance [22].

3.1.1 One-factor effect of the independent variables on the responses

A factor effect refers to the influence that an independent variable has on individual responses in a study or experiment, indicating how changes in that factor can impact the outcome or dependent variable.

In this study, different mechanical properties like breaking force, elongation, work done, modulus, and tenacity of the Ethiopian indigenous bamboo plant fiber (lowland bamboo) were characterized. The description highlights an interesting relationship between the tenacity of lowland bamboo plants and their age. As shown in Figure 6a, the tenacity—which reflects the plant’s strength and durability—increases linearly as the bamboo grows, up to about 36 months old. This means younger bamboo steadily becomes stronger the longer it matures within this period. However, beyond 36 months, there is a slight decline in tenacity, indicating an inverse relationship between age and strength after this peak. In other words, while bamboo initially gains toughness as it ages, after reaching a mature stage, its tenacity gently decreases. This pattern is important for understanding when bamboo is at its strongest, which can inform decisions in cultivation and harvesting for uses that require optimal durability. This study is in line with the previous study on the bamboo plant fiber [19], [22]. Figure 6c shows that soaking duration has a clear impact on tenacity, increasing it linearly up to 10 minutes. Beyond this point, the tenacity starts to decline, indicating that prolonged soaking may weaken the material. On the other hand, Figure 6b reveals that base concentration has little to no effect on tenacity up to 10%. However, when the concentration exceeds 10%, there is a significant drop in tenacity. These findings align well with previous studies, confirming that both soaking time and chemical concentration play critical roles in determining material strength, but only within certain limits [23]. Understanding these relationships helps in optimizing processing conditions to achieve the best mechanical properties without compromising durability.





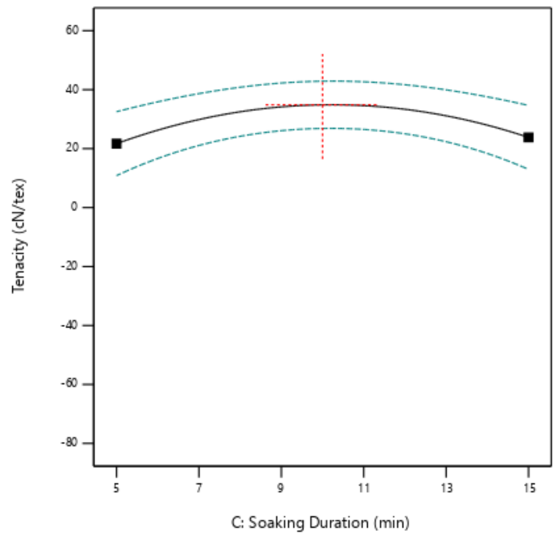
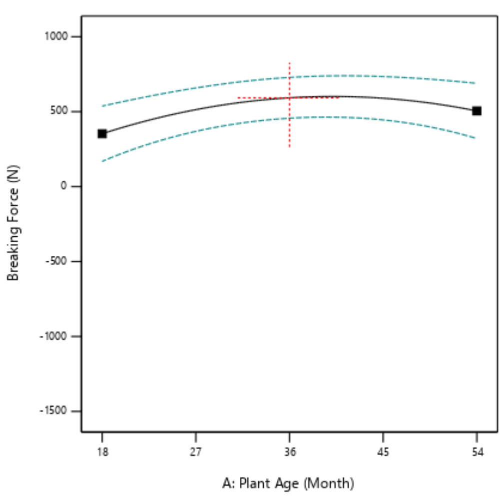


Figure 6 One factor effect of independent variables on Tenacity. a) Plant age vs Tenacity, b) Concentration vs Tenacity, c) Soaking duration vs Tenacity

Figures 7a and 7c demonstrate that both plant age and soaking duration initially have a positive effect on breaking force, meaning the force increases proportionally up to a mid-point value. Beyond this middle value, however, their influence reverses, causing a decrease in breaking force. Meanwhile, Figure 7b focuses on concentration levels and their impact on breaking force. It shows that concentrations up to around 10% tend to increase the breaking force, but beyond this point, there is a sharp decline. Notably, concentrations below 8% appear optimal for enhancing breaking force, although this finding still requires further experimental validation. Overall, these results suggest that careful control of plant age, soaking time, and concentration can improve material strength, but exceeding certain thresholds may weaken it.



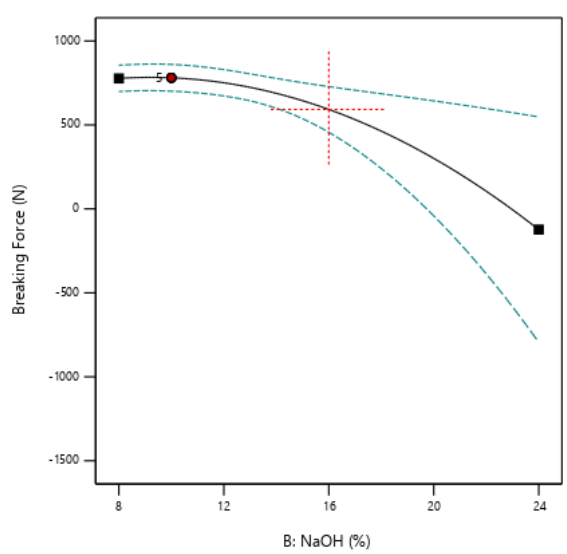


Figure 7 One factor effect of independent variables on breaking force, a) Plant age vs Breaking force, b) Concentration vs Breaking force, c) Soaking duration vs Breaking force

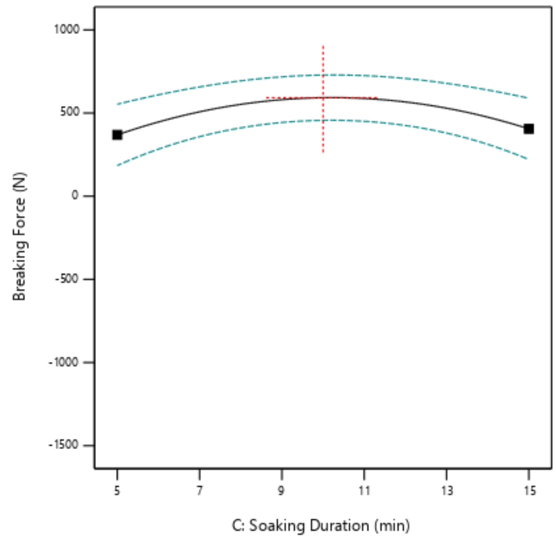
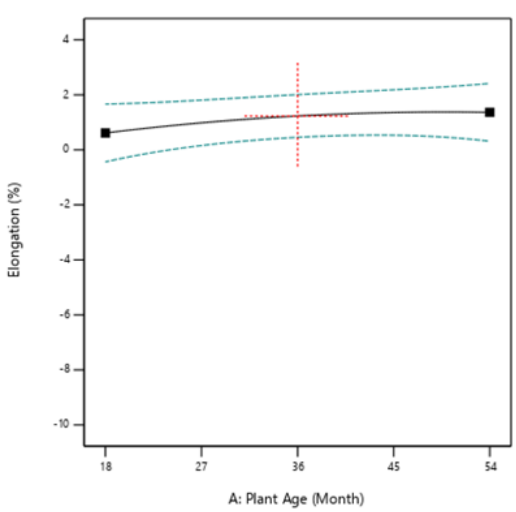


Figure 8a reveals a clear trend: elongation increases steadily as the plant ages, showing a proportional relationship throughout the study period. This suggests that older plants naturally develop greater elongation. In contrast, Figure 8c highlights the effect of soaking duration on elongation. Elongation increases up to a midpoint in soaking time, but beyond that, it begins to decline, implying that too long a soak can negatively impact growth. Figure 8b explores the impact of alkali concentration, showing a slight increase in elongation up to a 10% concentration. After this point, elongation levels off and then drops sharply, indicating that excessive alkali can be harmful. Together, these figures illustrate how plant age, soaking time, and alkali concentration each play a critical role in influencing elongation, highlighting the importance of balancing these factors for optimal growth outcomes.



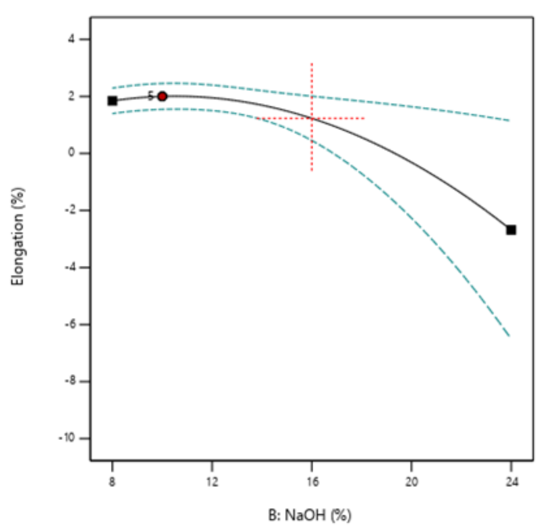
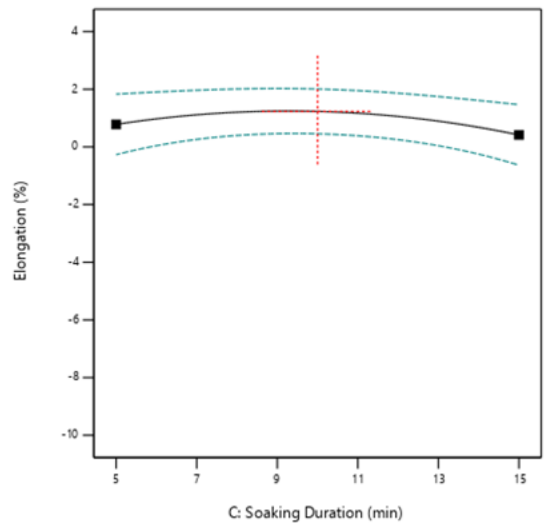
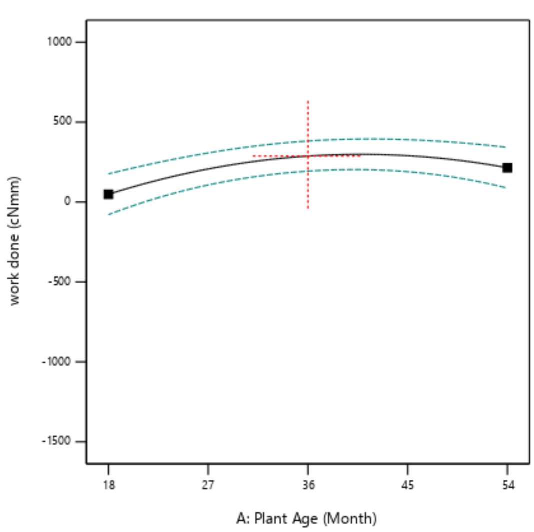
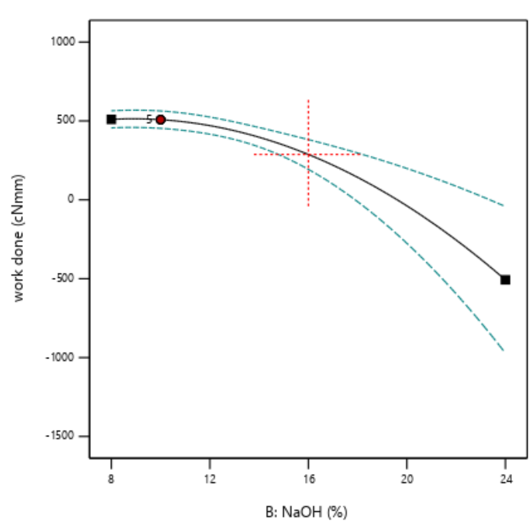


Figure 8 One factor effect of independent variables on elongation, a) Plant age vs Elongation, b) Concentration vs Elongation, c) soaking duration vs Elongation



This study investigates how plant age and soaking duration influence a specific response, work done. Showing mostly linear effects up to a middle point. Initially, both plant age and soaking duration have strong positive impacts. After reaching that middle level, the influence of plant age slightly decreases, while the effect of soaking duration declines more noticeably. Additionally, the concentration factor plays an important role. At a low concentration level of 8%, the positive effect is at its peak. Beyond this point, from about 8% to 11%, the effect remains relatively stable, but when the concentration rises above 11%, it begins to negatively affect the outcome. These trends are illustrated clearly in Figures 9a, 9b, and 9c, providing a visual summary of how these variables interact and influence the studied parameter.





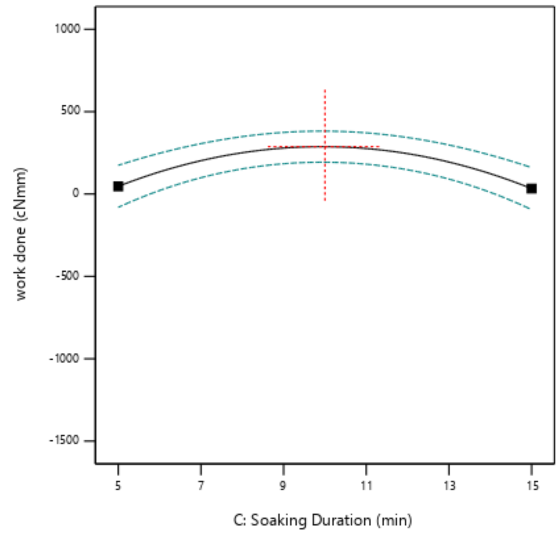
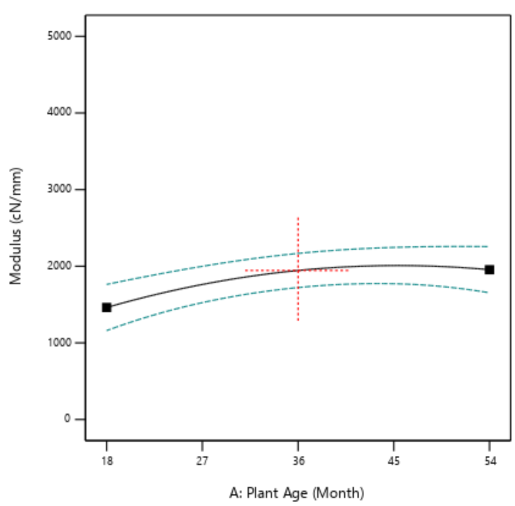
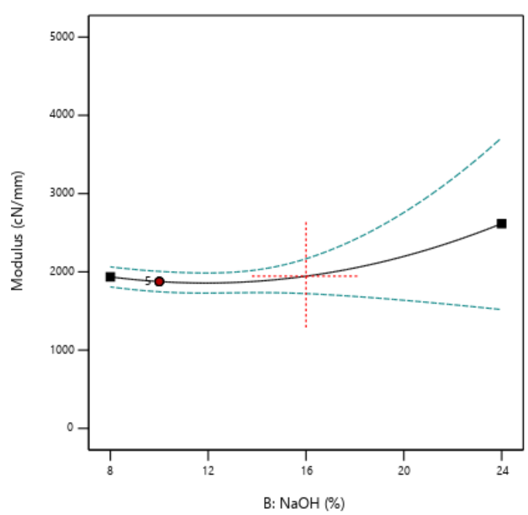


Figure 9 One factor effect of independent variables on work done, a) Plant age vs Work done, b) Concentration vs Work done, c) Soaking duration vs Work done

Plant age and soaking duration both influence the modulus in a similar pattern: they increase it linearly up to a certain midpoint, after which their effects decline and eventually become negative. This means that while moderate plant age and soaking times can strengthen the material, too much can weaken it. On the other hand, concentration behaves differently. It causes a decrease in modulus up to about 10%, but beyond this point, the effect shifts dramatically and positively, leading to a significant increase in modulus. These trends, illustrated in Figures 10a, 10b, and 10c, show key relationships between these factors and material properties. Understanding these patterns helps optimize conditions for the best mechanical performance.





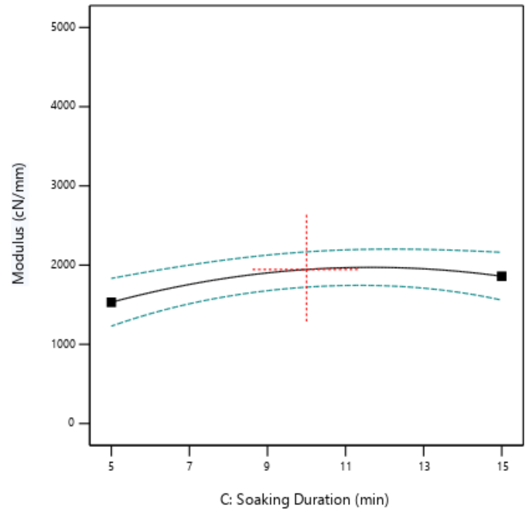


Figure 10 One factor effect of independent variables on modulus, a) Plant age vs Modulus, b) Concentration vs Modulus, c) Soaking duration vs Modulus

3.1.1 Two factor Interaction effect of the independent variables on the responses

This study investigates how the interaction of three key factors, plant age, alkali concentration, and soaking duration, affects various mechanical properties of fibers. These properties include breaking force, tenacity, elongation, work done, and modulus, all critical for understanding fiber strength and flexibility.

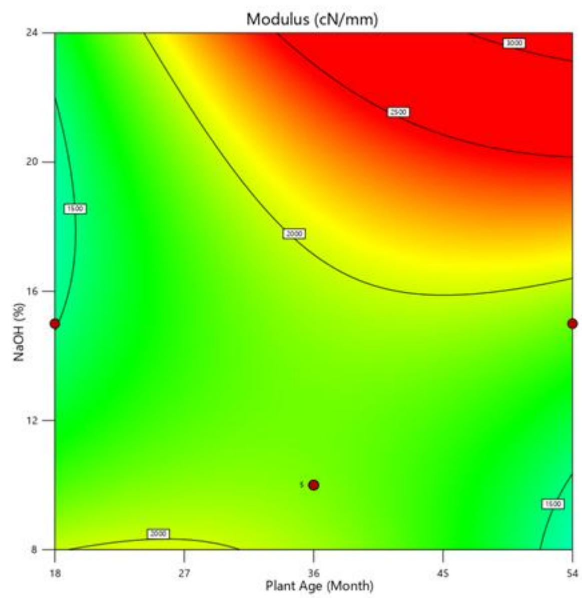
The research highlights that changes in plant age, levels of alkali used during treatment, and the soaking time together influence the fibers' performance in complex ways. For example, older plants might yield fibers with different breaking forces compared to younger ones, and varying the alkali concentration can either improve or weaken fiber strength depending on duration.

Interestingly, this study both supports and challenges findings from previous research, showing positive correlations in some cases and negative in others. This nuanced insight adds depth to our understanding of fiber processing, emphasizing the importance of optimizing all three variables to achieve desired mechanical qualities.

When analyzing how independent variables interact, visualization can make all the difference. Both 2D and 3D plots offer clear and intuitive ways to see these interactions at a glance. A 2D plot (Figures 11, 13, 15, 17, and 19 from a to c) often uses lines or bars to show how one variable changes with another, which helps spot trends quickly. However, when more complexity is involved, especially with two independent variables influencing a dependent outcome. A 3D plot (Figures 12, 14, 16, 18, and 20 from a to c) adds depth by representing all three dimensions visually. This allows you to observe how the combination of variables affects results, making patterns and interaction effects easier to understand. Using these plots together gives a fuller picture: In short, these graphical tools transform raw data into insightful visual stories, helping both beginners and experts grasp interactions more easily and effectively.

Interaction effects occur when the combined impact of two or more factors is different from the sum of their individual effects. Recognizing these effects is key to fully understanding how variables work together in experiments or processes. To grasp interaction effects easily, visualization methods such as interaction plots are invaluable. These plots help highlight when and how factors influence each other, making the patterns clear at a glance. By identifying interaction effects early, it becomes possible to adjust variables more effectively and streamline the optimization process. This means better decision-making, improved product quality, and more efficient use of resources. In practice, attention to interaction effects ensures that solutions are not just good in isolation but perform optimally in combination. In short, understanding interaction effects leads directly to smarter, targeted optimization strategies that unlock the full potential of any system or process.

In this study, color-coded 2D and 3D plots were used to illustrate how independent variables interact and affect dependent variables or responses. The red sections on the plots indicate a strong interaction effect, meaning that the independent variables have a significant impact on the response. Blue areas, on the other hand, show little to no effect, suggesting weak or negligible interaction. Meanwhile, orange and yellow regions represent medium levels of influence, highlighting moderate interactions. This clear color gradient helps researchers quickly identify which factors play crucial roles and which do not, enhancing data interpretation and decision-making. Using such visual tools makes complex relationships easier to understand and communicate.



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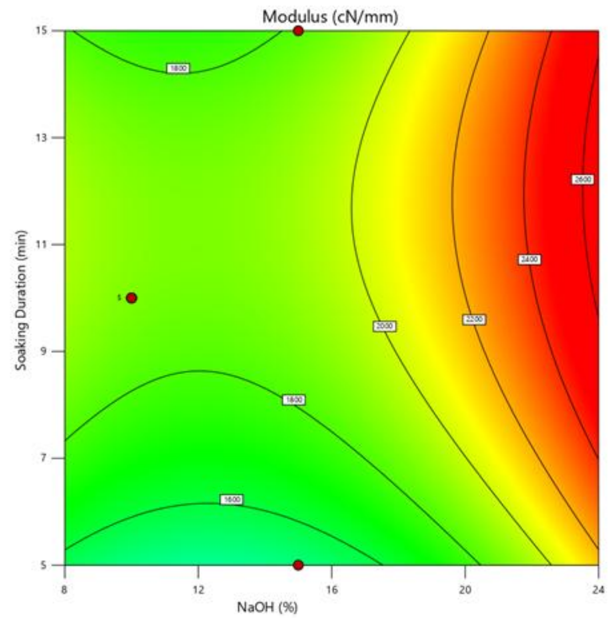
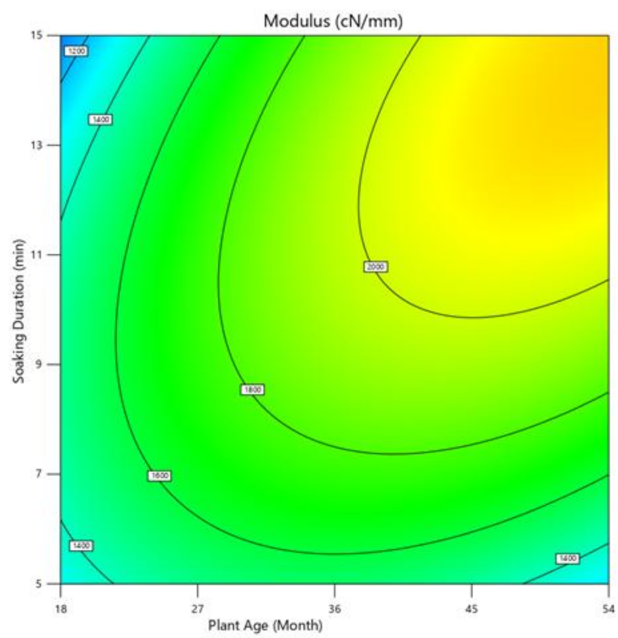
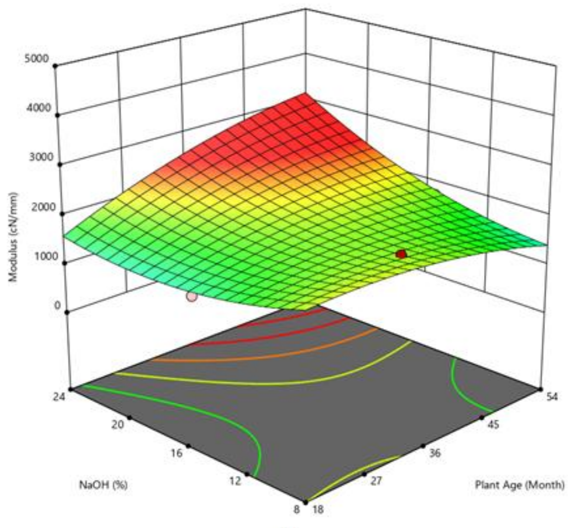


b)

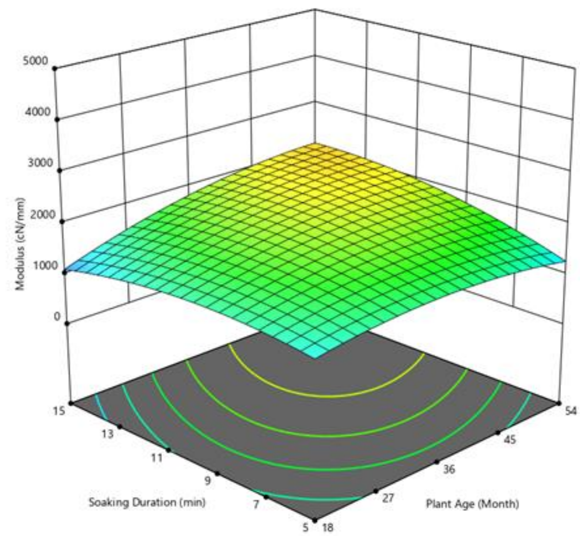
Figure 11 2D- Plot of two-factor interaction effect on modulus, a) Plant age vs Concentration, b) Concentration vs soaking duration, c) Soaking duration vs Plant age



c)

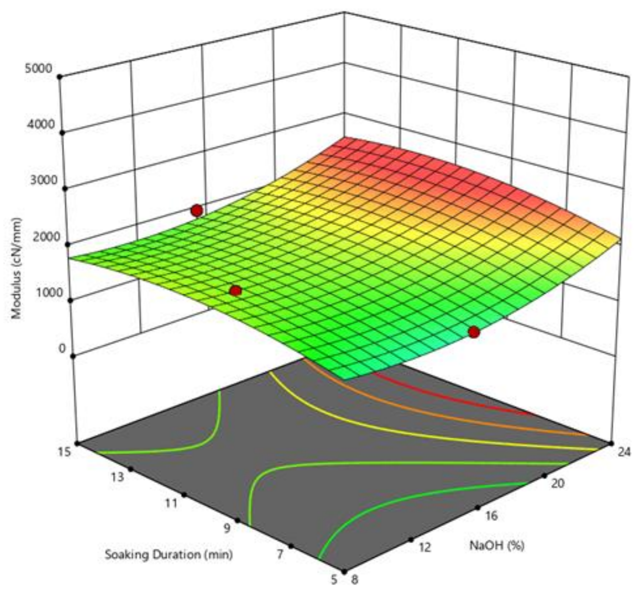


a)

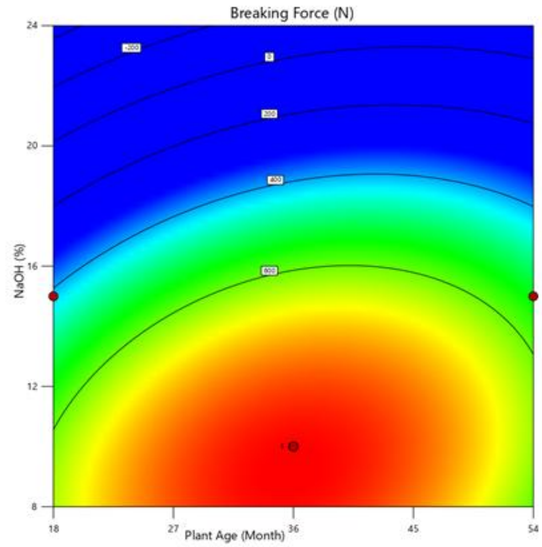


b)

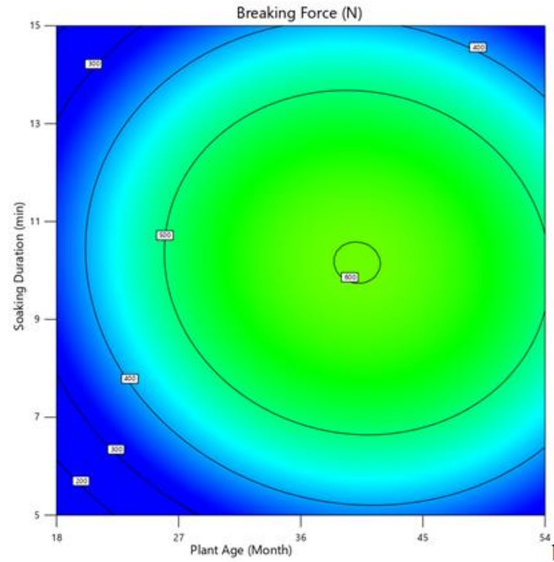
Figure 12 3D- Plot of two-factor interaction effect on modulus, a) Plant age vs Concentration, b) Concentration vs soaking duration, c) Soaking duration vs Plant age



c)

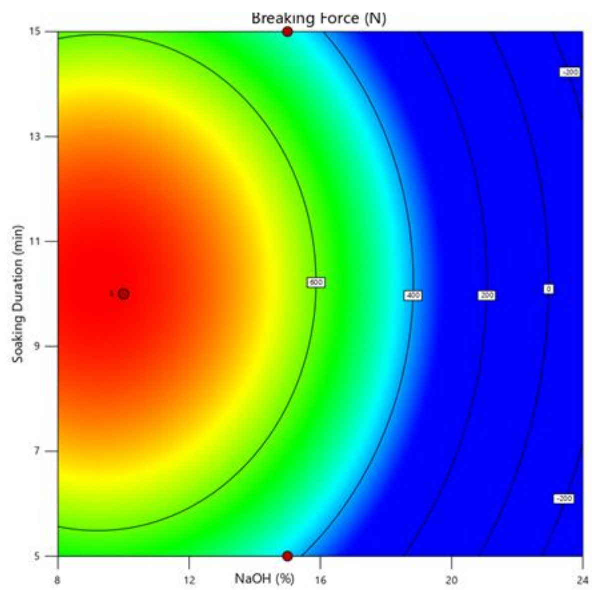


a)

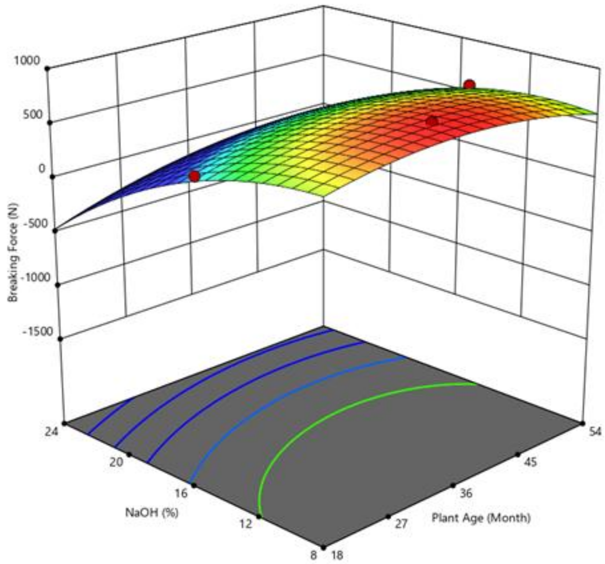


b)

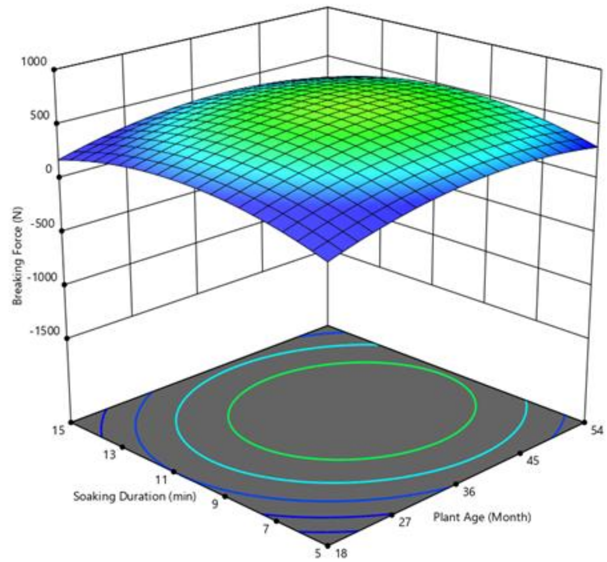
Figure 13 2D- Plot of two-factor interaction effect on Breaking Force, a) Plant age vs Concentration, b) Soaking duration vs Plant age , c) Concentration vs soaking duration



c)

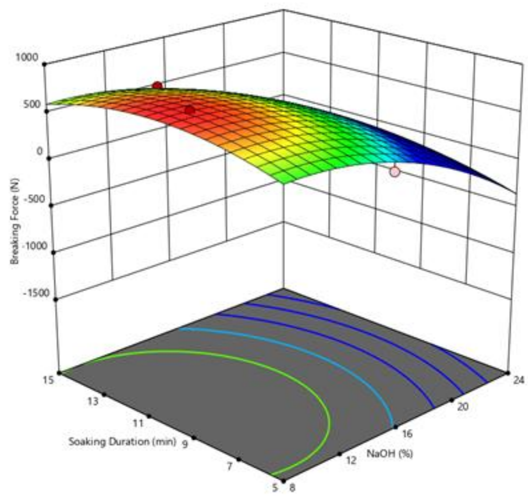


a)



b)

Figure 14 3D- Plot of two-factor interaction effect on Breaking Force, a) Plant age vs Concentration, b) Soaking duration vs Plant age , c) Concentration vs soaking duration



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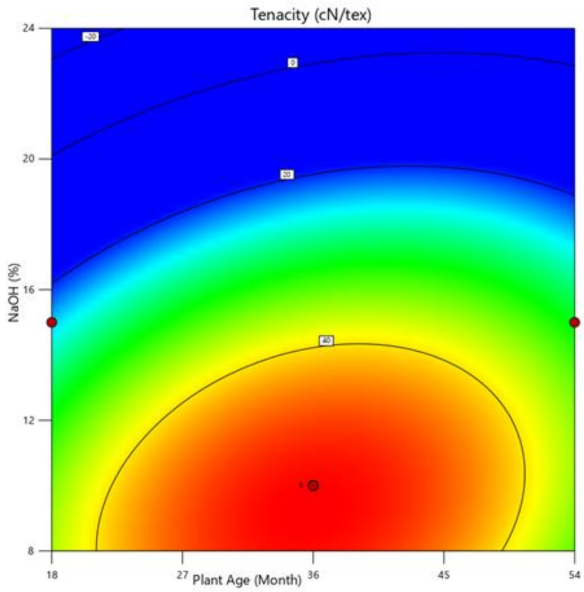
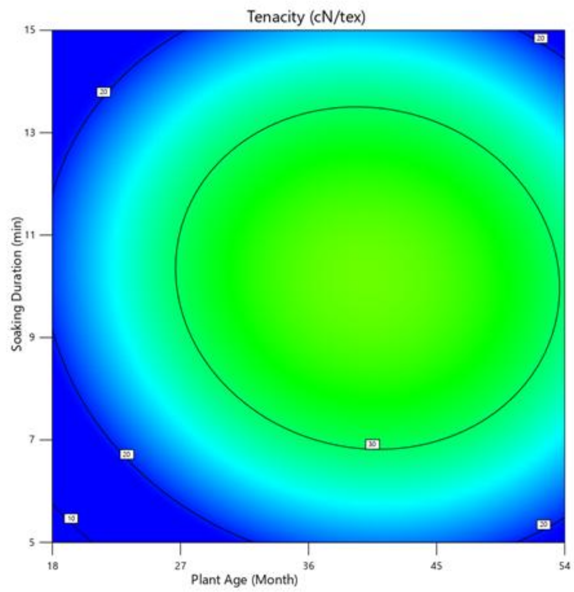


a)



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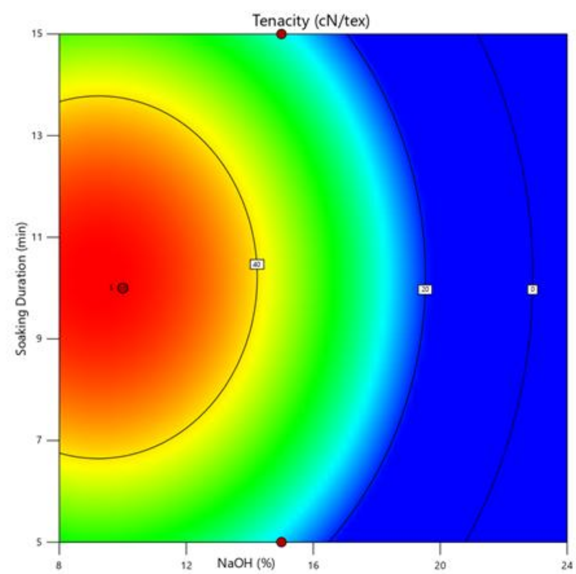
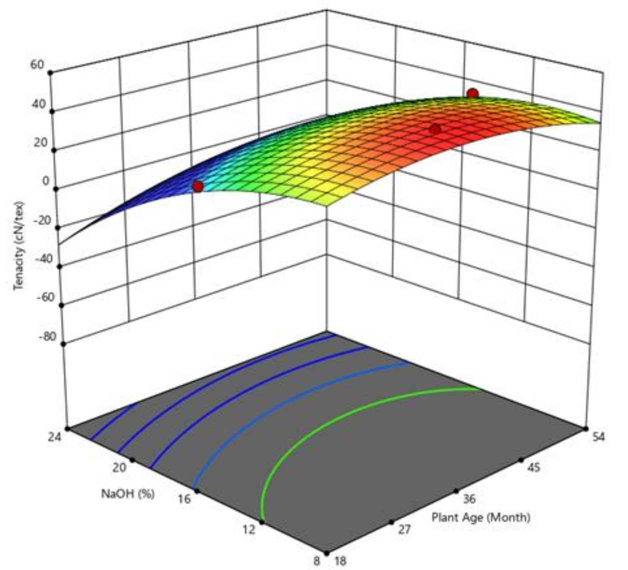
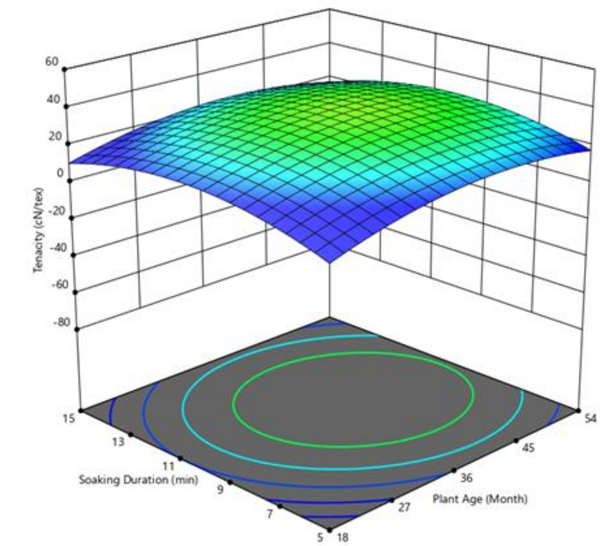


c)

Figure 15 2D- Plot of two-factor interaction effect on Tenacity, a) Plant age vs Concentration, b) Soaking duration vs Plant age , c) Concentration vs soaking duration

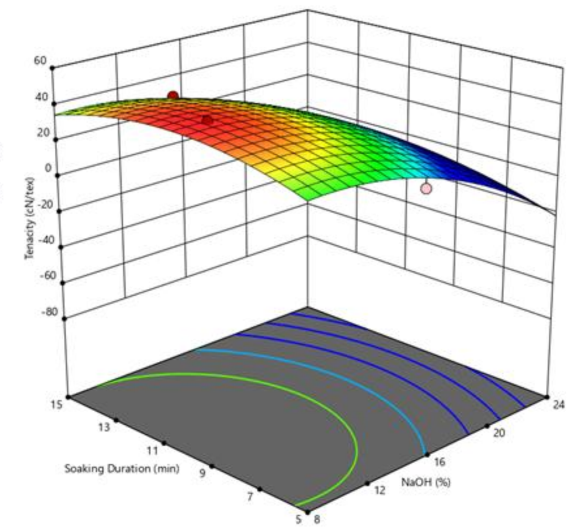


a)

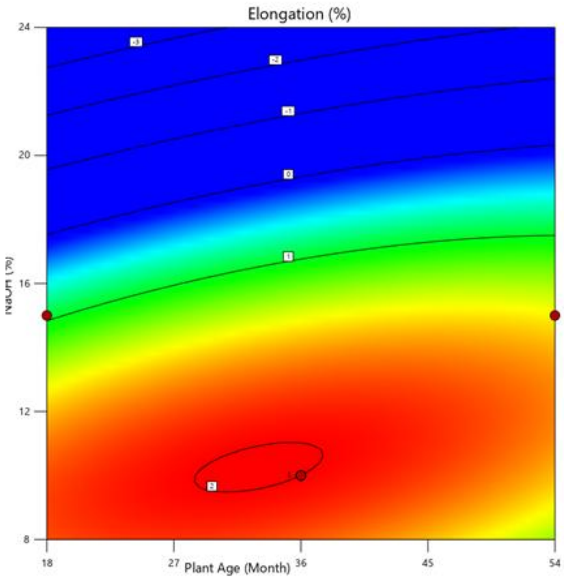


b)

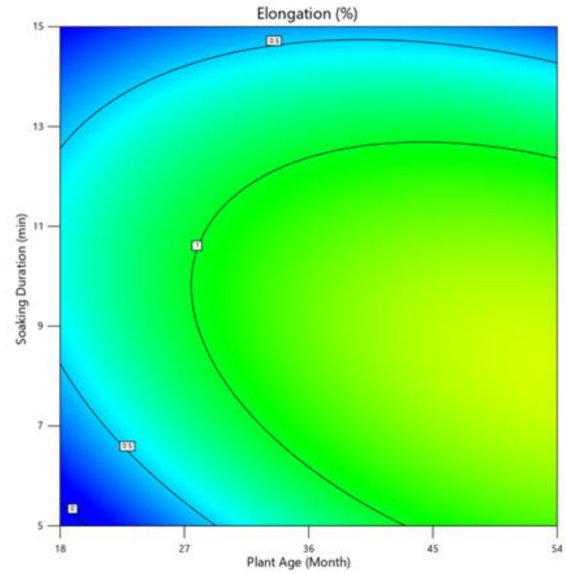
Figure 16 3D- Plot of two-factor interaction effect on Tenacity, a) Plant age vs Concentration, b) Soaking duration vs Plant age , c) Concentration vs soaking duration



c)

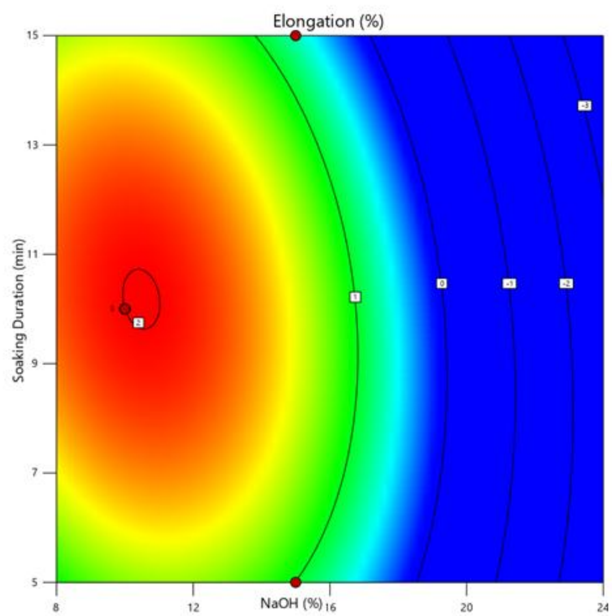


a)

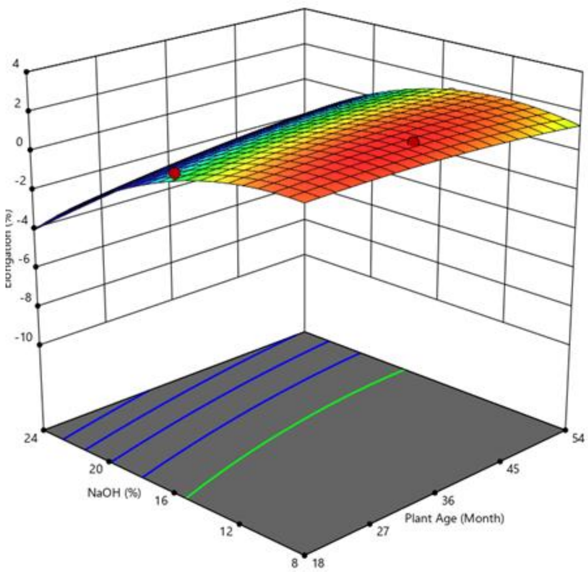


b)

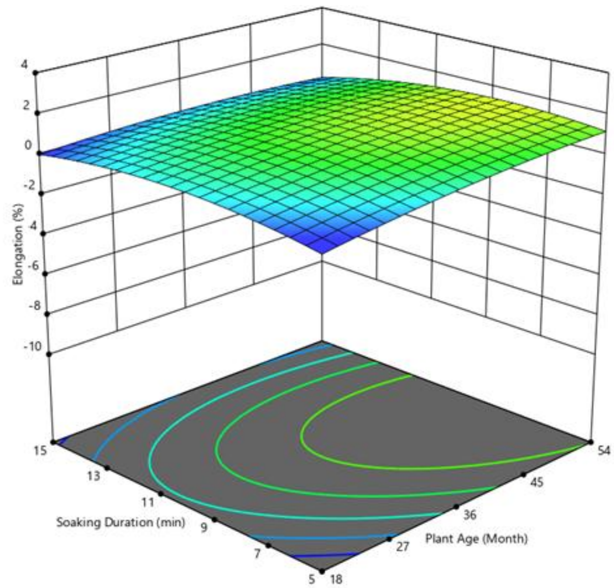
Figure 17 2D- Plot of two-factor interaction effect on elongation, a) Plant age vs Concentration, b) Soaking duration vs Plant age , c) Concentration vs soaking duration



c)

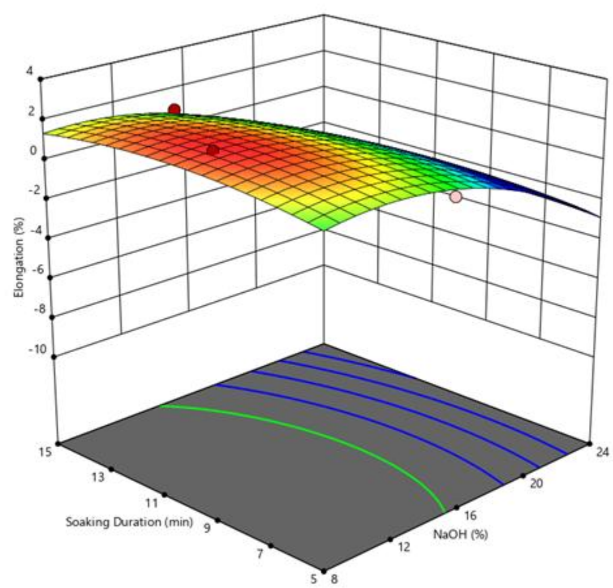


a)

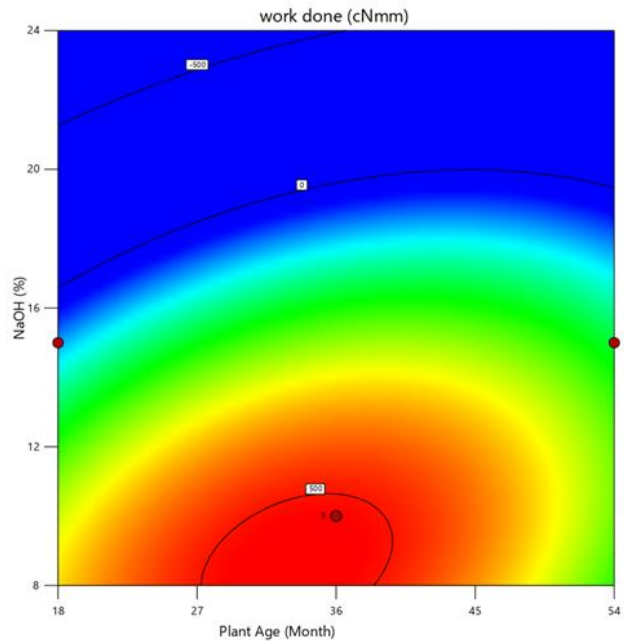


b)

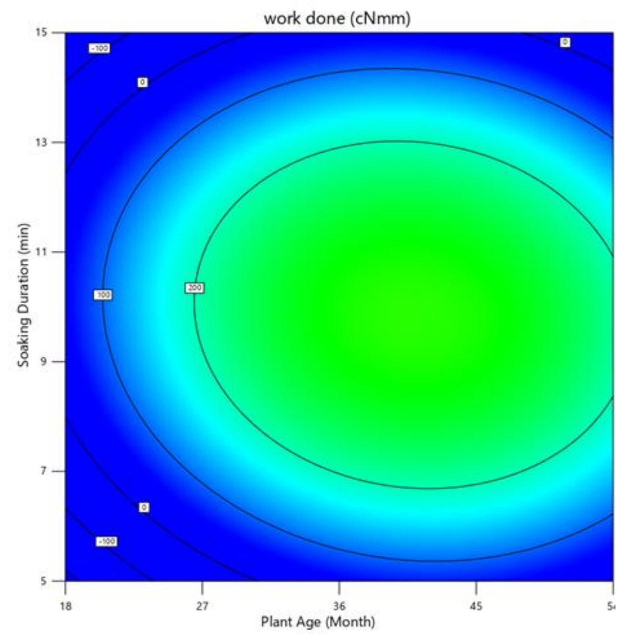
igure 18 3D- Plot of two-factor interaction effect on longation, a) Plant age vs Concentration, b) Soaking luration vs Plant age , c) Concentration vs soaking duration



c)

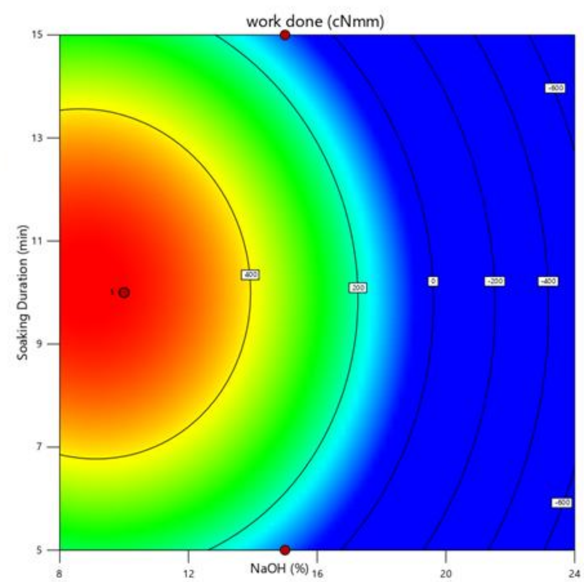


a)

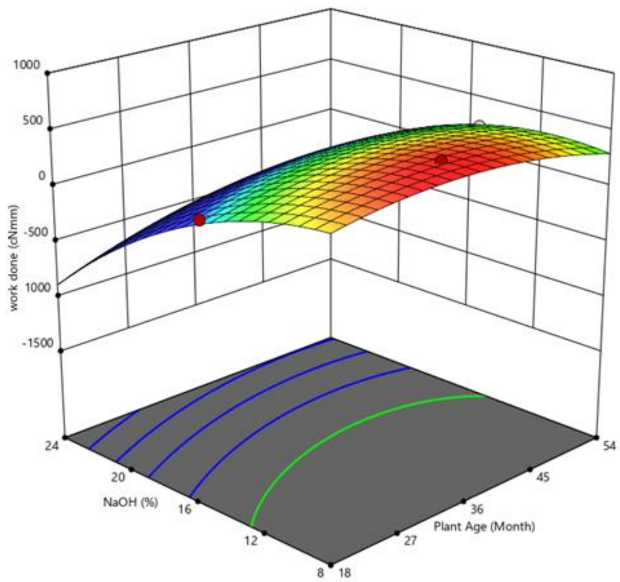


b)

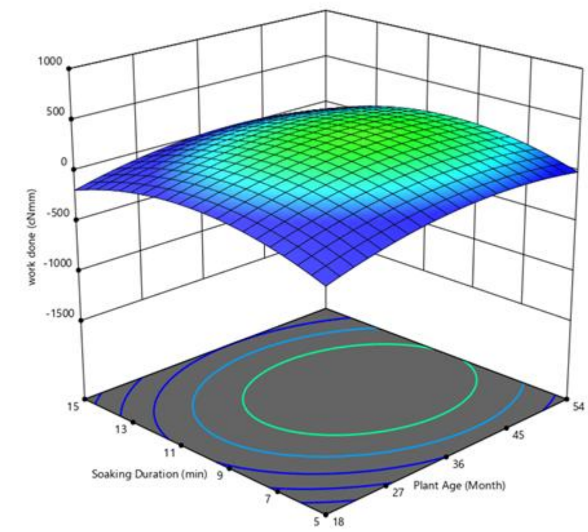
Figure 19 2D- Plot of two-factor interaction effect on Work Done, a) Plant age vs Concentration, b) Soaking duration vs Plant age , c) Concentration vs soaking duration



c)

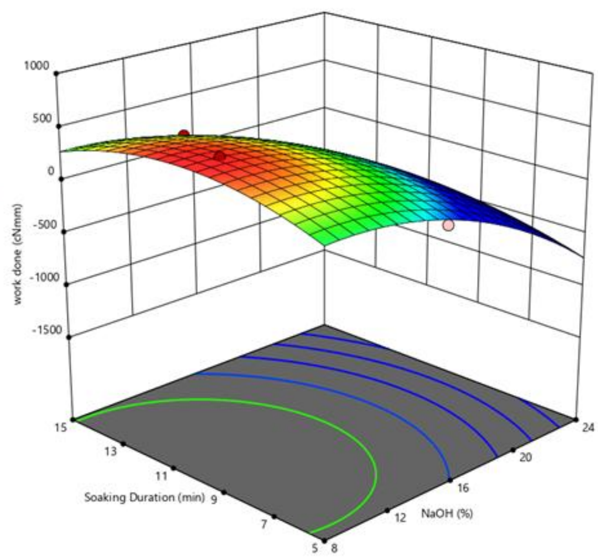


a)



b)

Figure 20 3D- Plot of two-factor interaction effect on Work Done, a) Plant age vs Concentration, b) Soaking duration vs Plant age , c) Concentration vs soaking duration



c)

4. Conclusions

This study explores how alkali treatment plant age and alkali soaking time affect the mechanical properties of single fibers from the indigenous lowland Ethiopian bamboo species, a material that has garnered attention for its sustainability and versatility in various applications. Key factors such as breaking force, elongation, tenacity, work done, and modulus were meticulously analyzed to provide a comprehensive understanding of the fiber's performance under different treatment conditions. The researchers employed a sophisticated Box–Behnken design of response surface methodology, a statistical approach that allows for the investigation of how three critical variables, plant age, soaking duration, and sodium hydroxide (NaOH) concentration, interact and influence these mechanical properties.

The findings discovered that increasing alkali concentration significantly aids in reducing the fiber's weight by enhancing the removal of lignin and hemicellulose, which are components that typically contribute to the fiber's heaviness and limit its mechanical capabilities. As a result, the mechanical properties of the bamboo fibers generally improved with both the alkali concentration and plant age, suggesting that these factors play a crucial role in the optimization of fiber quality. However, it is important to note that this positive trend began to plateau or even decline after reaching certain thresholds, indicating a possible point of diminishing returns. Interestingly, the modulus exhibited a unique behavior, remaining consistent in its improvement even as the other properties began to level off. Overall, the study not only underscores the potential to optimize treatment conditions to enhance bamboo fiber performance but also emphasizes the importance of balancing chemical treatment with the natural properties of the fibers to achieve the desired outcomes. The implications of these findings could extend beyond academic interest, offering valuable insights for industries seeking to leverage bamboo fiber for various applications, including sustainable textiles and composite materials.

Future work will focus on validating these results through further experimental trials and pinpointing the most effective combination of variables to maximize fiber performance for practical applications. By examining the intricate relationships between treatment conditions, this research aims to contribute to a broader understanding of bamboo fiber characteristics and promote the sustainable use of this renewable resource.

Declarations

Conflict of interest: The author declares no conflict of interest exists with the publication of this manuscript or its data.

Funding declaration (Financial interest): The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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