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COMPARISON OF FIBER EXTRACTION METHODS IN LEAVES FROM DIFFERENT STRATA IN PINEAPPLE MD2 PLANTS

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ABSTRACT

Pineapple (*Ananas comosus*) crop generates a high volume of harvest residues, resulting in significant environmental impact, primarily due to the large quantity of biomass left after fruit harvesting. This study aimed to evaluate fiber production and quality using two defibration methods, manual and mechanical, on leaves from three strata of MD2 pineapple plants subjected to different pre-conditioning techniques: soaking in water for 8 and 15 days, and NaOH solution for 1 hour. Results of this study demonstrated that 70 % of the leaves were suitable for defibration. The highest fiber yields were obtained from leaves in the middle and upper strata of the plants, with values of 8.98 and 12.4 g, respectively. The extraction time was shorter in the mechanical method, being 22 times more efficient than the manual method. The mechanical method favored fiber production when no prior conditioning of the leaves was performed, extracting an average of 50.5 g per plant. The manual method performed better when leaves were subjected to soaking in water or NaOH, extracting between 14.5 and 16.3 g per plant. Additionally, changes in the mechanical properties of the fiber were found to depend on the stratum of the plants and leaf pre-conditioning techniques. Our results contribute to explore the potential uses of fiber extracted by strata and highlight the possibilities of implementing pre-conditioning techniques.
Additional keywords: Elongation, mechanical extraction, plant residues, strength, sustainability

RESUMEN

Comparación de métodos de extracción de fibra en hojas de diferentes estratos en plantas de piña MD2
El cultivo de piña (*Ananas comosus*) produce un alto volumen de residuos de cosecha que genera un impacto ambiental significativo, debido a la gran cantidad de biomasa que queda después de la recolección del fruto. Este estudio tuvo como objetivo evaluar la producción y calidad de fibra mediante dos métodos de desfibrado, manual y mecánico, en hojas de tres estratos de plantas de piña MD2 sometidas a diferentes técnicas de pre-acondicionamiento: remojo en agua durante 8 y 15 días, y solución de NaOH durante 1 hora. Los resultados demostraron que el 70 % de las hojas eran aptas para el desfibrado. Los mayores rendimientos de fibra fueron obtenidos de las hojas de los estratos medio y superior de las plantas, con valores de 8,98 y 12,4 g, respectivamente. El tiempo de extracción fue menor en el método mecánico, siendo 22 veces más eficiente que el método manual. El método mecánico favoreció la producción de fibra cuando no se realizó ningún acondicionamiento previo de las hojas, extrayendo un promedio de 50,5 g por planta. El método manual tuvo mejor desempeño cuando las hojas fueron sometidas a remojo en agua o NaOH, extrayendo entre 14,5 y 16,3 g por planta. Además, se encontró que los cambios en las propiedades mecánicas de la fibra dependen del estrato de las plantas y de las técnicas de pre-acondicionamiento. Nuestros resultados contribuyen a explorar los usos potenciales de la fibra extraída por estratos y resaltar las posibilidades de implementar técnicas de pre-acondicionamiento.
Palabras clave adicionales: Elongación, extracción mecánica, residuos vegetales, resistencia, sostenibilidad

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INTRODUCTION

Pineapple crop generates a large amount of plant residues or biomass, as each plant produces approximately 40-50 leaves or 2.3 kg of plant residue, equivalent to 250 metric tons per hectare of fresh biomass (Chen et al., 2020). After fruit harvesting, plant residues are generally considered waste material by farmers. Common management practices include leaving the leaves on the ground

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until decomposition, soil incorporation, composting for organic fertilizer production, or disposal through burning (Apipatpapha et al., 2022). The latter is the most common practice, and it generates environmental impact through greenhouse gas emissions and ecological imbalance in the soil by eliminating living organisms with high temperatures (Zhu et al., 2021). The ongoing challenge for pineapple-producing regions worldwide is to seek alternatives for the utilization of harvest residues through a business model that contributes to their sustainable management (Sarangi et al., 2023; Eixenberger et al., 2024).

In recent years, the use of natural fibers has gained worldwide interest as a potential substitute for synthetic materials due to their mechanical properties, as well as their abundant availability (Jain and Sinha, 2022; Lalhruaitluangi and Mandal, 2024). Components of plant fibers such as lignocellulosics have low densities, are relatively inexpensive, biodegradable, consume less energy during production, allow to produce high-strength composite materials, pose good acoustic properties, do not cause machine abrasion, and present minimal health risks when inhale (Gaba et al., 2021; Sethupathi et al., 2024). Therefore, they have been utilized as raw materials in various industries including textiles, agri-food, packaging, among others (Padzil et al., 2020; Sarangi et al., 2023; Eixenberger et al., 2024). In recent years, pineapple leaf fibers (PALF) have been demonstrated to be a viable substitute for synthetic fibers due to their economic and renewable nature. Furthermore, some of their mechanical characteristics have been highlighted, such as the fineness and intrinsic mass, the elongation and the strength. The fiber content ranges between 2.5% to 7% of its total biomass, and extraction can be carried out using manual or mechanical techniques (Chaves et al., 2024; Sethupathi et al., 2024). The manual method is the simplest and most rudimentary, using diverse blunt objects such as ceramic plates, metal elements, or coconut shells to scrape the leaf surface, removing the fleshy components until the fibers are fully exposed. The disadvantage of this method is its slow and tedious nature (Rafiqah et al., 2020). The mechanical method can be conducted using a scraping machine consisting of multiple blades mounted on a rotating drum, which removes the leaf pulp, leaving behind the fibers (Radoor et al., 2020; Sethupathi et al., 2024). To promote fiber extraction, different pre-conditioning techniques have been used, with the most efficient being the soaking of leaves in water or chemical solutions. It has been proposed that the presence of microorganisms in the water helps degrade the organic matrix, which simplifies the separation of the fiber (Pandit et al., 2020; Peng et al., 2023; Chaves et al., 2024). In addition, alkaline treatments, such as sodium hydroxide, are common chemical methods used to solubilize hemicellulose, lignin, oils, waxy components, and pectin, thereby removing them from the natural fiber surface (Gnanasekaran et al., 2021; Mustafa et al., 2024). At the same time, it has been reported that this treatment is an easier and cost-effective method of pre-treatment which improves the surface of fiber (Gnanasekaran et al., 2021; Bernardes et al., 2023). Another important factor to consider is that a pineapple plant has leaves at various stages of maturation, which may differ in width, length, and fiber production (Vásquez et al., 2023). This variation is attributed to the phyllotaxy of the pineapple plant; as its leaves are arranged spirally along the stem. The youngest leaves are closest to the apical meristem, while the older leaves are found at the bottom of the plant. The growing demand for agronomic practices with low environmental impact is an accelerating factor for the utilization of natural fibers in the coming years. This context has led researchers to focus their efforts on studying the characteristics of plant fibers and their potential uses under different production and handling conditions. The hypothesis is proposed that the combination of factors such as plant stratum, conditioning technique, and extraction method could affect the production and quality of the fiber. Thus, this study aimed to evaluate the time, production, and quality of fiber extracted using two methods, manual and mechanical, on leaves from different strata of MD2 pineapple plants subjected to various pre-conditioning techniques.

MATERIALS AND METHODS

Location. The experiment was conducted in the second semester of 2022, using pineapple leaves from an experimental MD2 plot established in 2021 at the Palmira Research Center of

Agrosavia in Valle del Cauca, Colombia. The fiber extraction from pineapple leaves was performed at a farmer's field in the municipality of Totoró, Cauca department, Colombia, while the evaluation of mechanical properties of the fibers was conducted at a textile quality laboratory in Medellín, Antioquia department, Colombia.

Morpho-agronomic characterization of plant leaf strata. Plants of the MD2 cultivar were randomly selected after fruit harvesting. Initially, the pseudostem of each plant was cut into three equally sized fragments to separate the leaves from the three strata (U: Upper, M: Middle, L: Lower) and morpho-agronomically characterized through the measurement of the following variables: Total number of leaves (TNL), number of useful leaves (NUL) - those that did not present any type of damage or injury-, number of useless leaves (NNL) -corresponding to leaves that showed visible physical damage-, leaf thickness (LT) (mm), width of leaf in the middle zone (LW) (cm), leaf length (LL) (cm), fresh leaf weight (LWf) (g), fiber length (FL), fiber production per leaf (FPL) (g) -calculated by dividing the fiber production per stratum (FPS) (g) by the number of useful leaves (NUL)-. Additionally, the percentage of fiber (Fp) (%) was estimated by dividing the fiber production per leaf (FPL) (g) by the fresh leaf weight (LWf) (g), and fiber production per stratum (FPS) (g). For each stratum, 32 plants were evaluated, for a total of 96 experimental units (n=96). Dimension variables were measured using a Mitutoyo digital caliper (±0.01 mm), and weight variables were measured using a Mettler Toledo precision balance (±0.01 g).

Fiber extraction. The fiber extraction was carried out in the municipality of Totoró, Cauca, Colombia, with an annual average temperature and relative humidity of 10.3°C and 79%, respectively. A 2x3x4 factorial experimental design was employed, evaluating fiber production per plant (PP) (g) for two defibration methods, MA: manual and ME: mechanical, on leaves from three plant strata, U: upper, M: middle, and L: lower, and four pre-conditioning techniques: soaking in water for 8 days and 15 days, and in 10% NaOH solution for 60 minutes in tanks with a capacity of 100L, and an absolute control without any pre-conditioning technique. These techniques were selected to evaluate differences in fiber yield and their potential effect on the mechanical characteristics of PALF.

For manual fiber extraction, the pineapple leaf was placed on a wooden surface, and both the upper and lower sides of the leaf were scraped with a 40 cm long blunt knife, removing the fleshy components until the fibers were fully exposed. For mechanical extraction, a machine with a 15 HP, four-stroke engine was used, typically employed for leaf fiber extraction from fique (*Furcraea* spp.) (Asparagaceae). This scraping machine consists of several metal blades attached to a rotating drum. As the leaves are fed into the machine, friction against a fixed blade removes the pulp, separating it from the fiber. To adapt the machine to the size of pineapple leaves, the distance between the rotating and fixed blades was set to 0.9 mm using a spark plug gauge, based on results from previous tests with different blade openings. This adjustment aimed to produce long fibers with the least possible amount of residue. Once the fiber was obtained using both mechanical and manual methods, it was washed with water to remove impurities and then air-dried under solar exposure for 48 hours. To determine the efficiency of fiber extraction in each method, the defibration time (DT) (s) was measured.

Mechanical variables of fiber. Three variables related to mechanical properties were considered since most natural fibers have an irregular diameter along their length. The Titer (T) is the linear density (tex) of the fiber and represented the mass (g) of a 1000 m long fiber, as it is the most useful and reliable way to describe the fiber in terms of its fineness or coarseness. The determination of the variables Strength (S) and Elongation (E) was conducted at the Textile Quality Laboratory of SENA in Medellín, Antioquia, Colombia. The experimental unit consisted of a set of 10 threads selected from: 5 leaves x 3 strata x 4 pre-conditioning techniques x 2 extraction methods (n=120).

Tensile tests were carried out according to the standards NTC-386:2011 and ASTM D-2256:2015, using a Lloyd Instruments EZ20 universal testing machine with a tensile capacity of 250 N. Pneumatic grip jaws with neoprene pads were used. The tensile test was conducted at a constant displacement rate of 20 $mm.min^{-1}$, with a relative humidity of 65 % and a temperature of 21.9 °C. Tensile tests for each sample were performed using a gauge length of 25 mm. The NEXYGEN Plus software was used for equipment handling and data recording.

Statistical analyses. To determine the effect of plant strata (U, M, L) on morpho-agronomic variables, a one-way analysis of variance (ANOVA) was performed. The efficiency of extraction was analyzed using defibration time by comparing the two methods with ANOVA. Fiber production per plant and fiber mechanical variables were analyzed using factorial ANOVA ($p \leq 0.05$). In all cases, Fisher's LSD multiple comparison test was used with a 95% confidence level for comparing means. To analyze the interdependence of variables and determine those contributing most to the variability of the experiment, a principal component analysis (PCA) was conducted, separately for each of the two fiber extraction methods. Statistical analyses were performed using the Statgraphics Centurion XVI statistical software (Royal Technologies S.A., Hudsonville, MI, USA).

RESULTS

The pineapple MD2 plants evaluated in this study produced 30.4 leaves across the three strata, of which 70 %, or 21.2 leaves, were useful for the defibration process due to their physical condition, while 8.9 leaves were discarded due to damage that hindered defibration, representing a 30 % leaf loss. The total fiber production per plant (PP) was 24.24 g (Table 1). At the leaf level, they exhibited an average thickness of 1.97 mm, width of 3.58 cm, and length of 49.1 cm. The three strata showed significant differences ($p \leq 0.001$) in all morphological variables except for LW, which ranged from 3.46 to 3.64 cm; and Fp, which ranged from 2.15 to 3.38 %. The upper stratum showed significantly higher values in the variables TNL, NUL, and LL, with values of 14.6, 11.2, and 63.3, respectively. The upper and middle strata exhibited the highest values without significant differences between them in the variables LW, LWf, FPL, Fp, and FPS, with values above 2.08, 31.1, 1.0, 3.53, and 8.98, respectively. Meanwhile, the lower stratum presented the highest value of NNL with 6.0.

Table 1. Morpho-agronomic characteristics of leaves in the strata of MD2 pineapple plants.

Strata	TNL	NUL	NNL	LT	LW	LL	LWf	FPL	Fp	FPS
Upper (U)	14.6a	11.2a	3.3b	2.12a	3.64a	63.3a	32.2a	1.05a	3.28a	12.42a
Middle (M)	8.8b	8.3b	0.5c	2.08a	3.64a	53.9b	31.1a	1.00a	3.38a	8.98b
Lower (I)	7.8b	1.8c	6.0a	1.7b	3.46a	30c	17.5b	0.55b	2.15a	2.84c
Average	10.1	7.1	3	1.97	3.58	49.1	20.8	0.87	3.45	4.89
p-valor	<0.001	<0.001	<0.001	<0.001	0.323	<0.001	<0.001	<0.001	0.266	<0.001
CV (%)	23.7	31.5	46.4	20.28	15.99	21.5	17.6	9.34	11.45	2.9
Total	30.4	21.2	8.9							24.24

TNL: Total number of leaves, NUL: number of useful leaves, NNL: number of useless leaves, LT: leaf thickness (mm), LW: width of leaf in the middle zone (cm), LL: leaf length (cm), LWf: fresh leaf weight (g), FPL: fiber production per leaf (g), Fp: the percentage of fiber (%) and FPS: fiber production per stratum (g). Means with distinct letters are statistically different according to LSD test ($p \leq 0.05$).

For the analysis by stratum, the variables included: Total number of leaves (TNL), number of useful leaves (NUL), number of non-usable leaves (NNL). For leaf and fiber study: leaf thickness (LT) (mm), leaf width (LW) (cm), leaf length (LL) (cm), fresh leaf weight (LWf) (g), fiber production per leaf (FPL) (g), fiber percentage (Fp) (%), and fiber production per stratum (FPS) (g). Mean values followed by different letters in the same column indicate statistically significant differences according to the LSD test ($p \leq 0.05$). The variables related to fiber production per leaf (FPL), fiber percentage (Fp), and fiber production per stratum (FPS) had a coefficient of variation of less than 15 % (Table 1), indicating adequate leaf selection for fiber extraction in each stratum. Conversely, the variable number of useless leaves (NNL) exhibited coefficients of variation greater than 30%, with higher leaf discards in the lower stratum, as mentioned earlier. This may be related to agronomic management during the field phase. The variables leaf thickness (LT), leaf width (LW), and leaf length (LL) had coefficients of variation between 15 and 20 %, indicating differences among plant strata, which could be influenced by plant age or stage of development. These results are acceptable for statistical analysis as they are conditioned by the randomization factors of the plants used for this study. The average defibration time showed highly significant statistical differences ($p \leq 0.001$) between the two extraction methods. With the mechanical method, the defibration time was 6 s per leaf, making it 22 times more efficient compared to the manual defibration method, which yielded a value of 134 s per leaf (Figure 1)

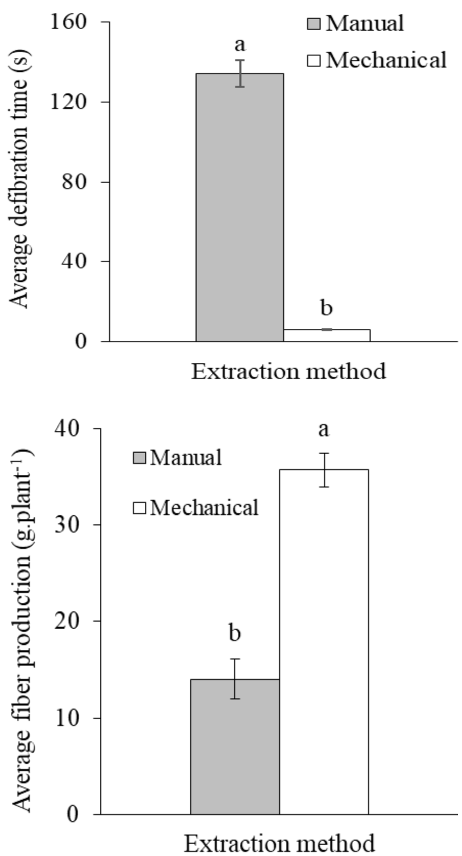

Figure 1. Average defibration time and fiber production with manual and mechanical methods. Columns with distinct letters are statistically different according to LSD test ($p \leq 0.001$).

The fiber production per plant (PP) showed highly significant statistical differences ($p \leq 0.001$) between the defibration methods. With the mechanical method, an average of 35.7 g of fiber per plant was produced, whereas with the manual method, only 14 g was produced. Therefore, the mechanical method extracted 154 % more fiber (Figure 1).

The fiber production per plant (PP) showed highly significant differences in the interaction between the extraction method and pre-conditioning technique ($p \leq 0.001$) (Figure 2). In the mechanical extraction method, the highest fiber production was achieved without any pre-conditioning technique, with a corresponding value of 50.5 $g.plant^{-1}$ which was 41.8 % higher than the other treatments. In contrast, 34.0 $g.plant^{-1}$, 35.6 $g.plant^{-1}$, and 22.6 $g.plant^{-1}$ were manually extracted with the pre-conditioning techniques of 8 days, 15 days in water, and 1 hour in NaOH, respectively. On the other hand, fiber production in the manual extraction method was significantly lower in the control, where 9.6 $g.plant^{-1}$ was produced, compared to 14.5 $g.plant^{-1}$, 15.8 $g.plant^{-1}$, and 16.3 $g.plant^{-1}$ with the pre-conditioning techniques of 8 days, 15 days in water, and 1 hour in NaOH, respectively, which were more of 51 % higher than the Control.

In terms of the mechanical quality of the fiber, significant differences were found in all three variables for the main effect of plant stratum and pre-conditioning techniques ($p \leq 0.05$) (Figures 3 and 4). The highest values of fiber titer and elongation were found in the upper stratum of the plant, with values of 1.2 tex and 2.26 %, respectively, which were 46 % and 21 % higher than those in the middle stratum, respectively (Figure 4). Regarding fiber strength, the highest value was observed in the middle stratum, followed by the upper and then the lower stratum, with values of 1.63 N, 1.34 N, and 0.87 N, respectively.

The highest Titer and Elongation values were found when the leaves were soaked in 10% NaOH, with values of 1.45 and 2.08%, respectively (Figure 4). In contrast, the highest Strength value was found without any pre-conditioning technique, with a value of 1.93N. These values decreased to 1.78N, 1.71N, and 1.57N when the leaves were pre-treated with water for 8 days, 15 days, and NaOH, respectively.

Based on the PCA for the manual defibration method, components 1 and 2 represented 90.2 % of the total variability of the experiment (Figure 5). The multivariate analysis allowed grouping sets of treatments by similarity. The first group consisted of treatments corresponding to pre-conditioning techniques in the upper and middle strata: MA-15-U, MA-15-M, MA-8-U, MA-8-M, MA-OH-U, MA-OH-M, which were related to the variables TNL, FPS, F and Fp that explained 48.8 % of the variation. The second group consisted of treatments corresponding to pre-conditioning techniques in the lower stratum and treatments without pre-conditioning technique in all three strata: MA-15-L, MA-OH-L, MA-8-L, MA-0-L, MA-0-M, and MA-0-U, explaining 42.1 % of the variation. This analysis showed that the treatments did not influence the variables DT, E, T, and S.

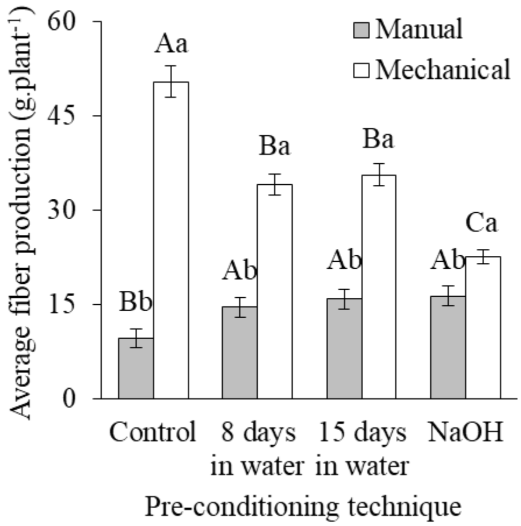

Figure 2. Average fiber production in the interaction of extraction method and pre-conditioning technique. Columns with distinct letters are statistically different according to LSD test (p≤0.05). Uppercase letters indicate differences between pre-conditioning techniques within each extraction method. Lowercase letters indicate differences in pre-conditioning techniques between both extraction methods.

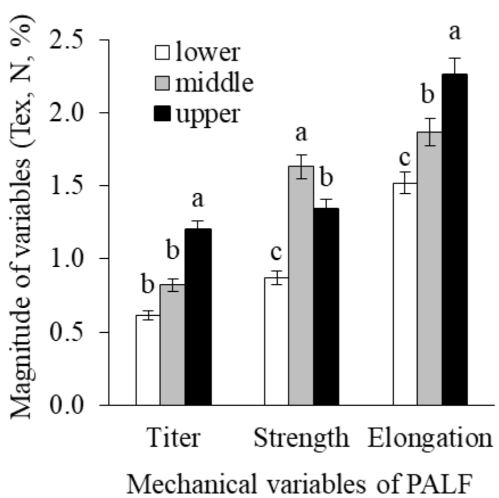

Figure 3. Mechanical variables of pineapple leaf fiber: titer (tex), strength (N), and elongation (%) in the three strata of the plant: lower, middle, and upper, extracted using the two methods. Columns with distinct letters are statistically different according to LSD test (p≤0.05).

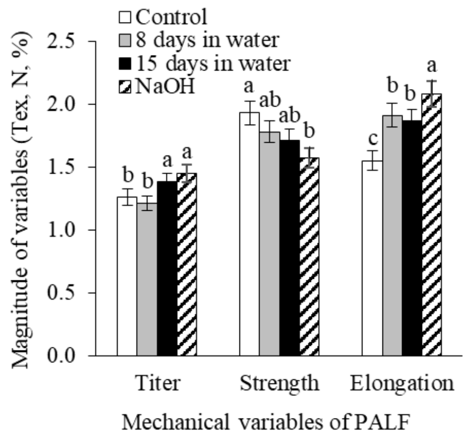

Figure 4. Mechanical variables of pineapple leaf fiber: titer (tex), strength (N), and elongation (%) subjected to treatments control; soaking in water for 8 days; soaking in water for 15 days, and OH: soaking in a 10% NaOH solution for 60 minutes, of fiber extracted with the two methods. Columns with distinct letters are statistically different according to LSD test ($p \leq 0.05$). PALF: pineapple leaf fiber.

In Figure 6, the result of the PCA for the mechanical method is presented; the first two components explain the majority (70.2 %) of the total variability of the observations. Multivariate analysis allowed grouping two sets of treatments by similarity. The first group consisted of treatments corresponding to pre-conditioning techniques in the middle and upper strata, and in treatments without pre-conditioning: ME-8-M, ME-8-S, ME-15-M, ME-15-U, ME-OH-U, ME-0-M, and ME-0-U, which were related to fiber production variables FL, FPS, and TNL and fiber quality variables S and T, explaining 44.7 % of the variation. The second group consisted of treatments corresponding to pre-conditioning techniques in the lower stratum, with only one treatment including the middle stratum: ME-8-L, ME-15-L, ME-OH-L, ME-0-L, and ME-OH-M, which were associated with fiber production variables Fp and DT, explaining 25.5 % of the variation. The method did not show a direct effect on variable E.

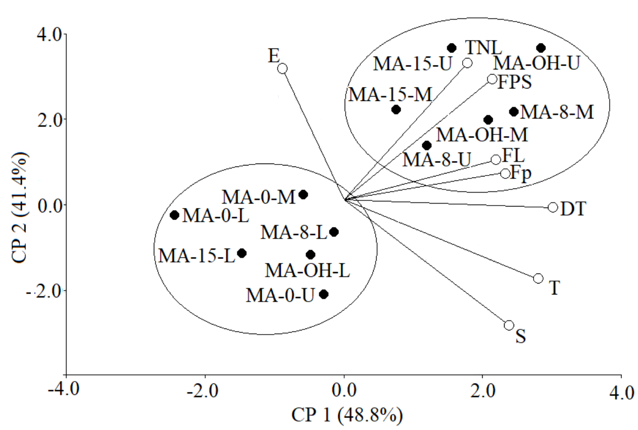

Figure 5. Biplot from the principal component analysis (PCA) grouped by similarities in the variables (unfilled points) of the twelve treatments (black points) for the manual extraction. MA: manual; 0: control; 8: eight days and 15: fifteen days of soaking in water; OH: soaking for 1 hour in NaOH; L: lower stratum; M: middle stratum; U: upper stratum of the plant. The studied variables were FPS: fiber production (g); TNL: Total number of leaves; FL: Fiber length (cm); DT: defibration time ($s.leaf^{-1}$); Fp: fiber percentage (%); T: titer (tex); S: Strength (N) and E: elongation (%).

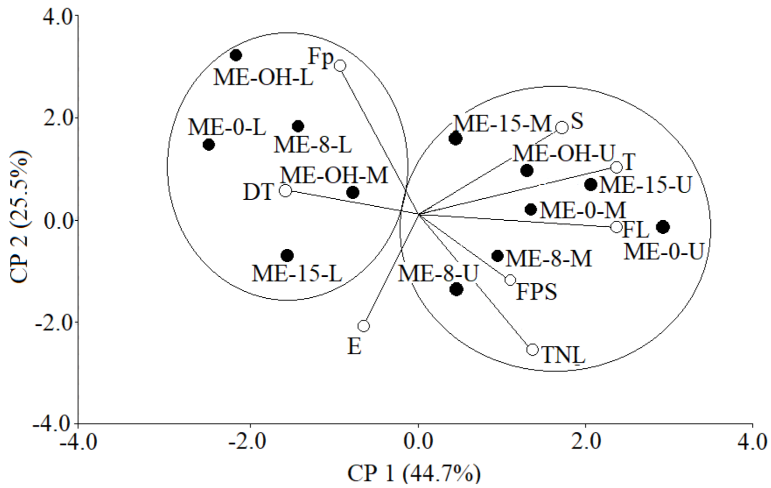

Figure 6. Biplot from the principal component analysis (PCA) grouping the twelve treatments (black dots) based on similarities in the variables (unfilled dots) for the mechanical extraction. ME: mechanical; 0: control; 8: eight days soaking in water; 15: fifteen days soaking in water; OH: one hour soaking in NaOH; I: lower stratum of the plant; M: middle stratum of the plant; U: upper stratum of the plant. The studied variables were FPS: fiber production (g); TNL: Total number of leaves; FL: Fiber length (cm); DT: defibration time ($s{\cdot}leaf^{-1}$); Fp: fiber percentage (%); T: titer (tex); S: Strength (N); E: elongation (%).

DISCUSSION

The results in this study allowed us to conduct a comparative analysis of the production and quality of fiber obtained with two defibration methods, using leaves from three strata of MD2 commercial cultivar plants. Overall, fiber production per plant (PP) with the manual method was lower compared to the mechanical method (Figure 1) because the force applied with the debarking tool is not uniform along the leaf and is concentrated at some points, causing fiber breakage and loss, which affects total yield (Lalhruaitluangi and Mandal, 2024). In contrast, with the mechanical method, by calibrating the distance between the fixed and the rotating blades of the drum, friction applied to the leaf was homogenized, reducing losses. These results are consistent with those reported by (Lalhruaitluangi and Mandal, 2024) who found that waste with mechanical defibration is very low, close to 2-8 %, compared to that obtained by the manual method, which can reach 50-88 %. Furthermore, the defibration process of the machine, through drum rotation at 4500 revolutions per minute, significantly accelerated the process (Figure 1). Thus, the efficiency of the mechanical defibration method was significantly higher than that of the manual method in both time and amount of extracted fiber. In the present study, the efficiency of the mechanical method was approximately 22 times greater than manual method; similar results were reported by Mondal et al., (2023), who determined a greater performance with mechanical defibration. Regarding the advantages of implementing each method, the accessibility and cost-benefit of the two methods must be analyzed. Many people are needed to defibrate one ton of pineapple leaves, consequently the manual method could increase fiber production costs (Nayak et al., 2024). On the other hand, although the mechanical method is more efficient in the extraction process, its implementation requires an initial investment due to the cost of machinery and supplies for its operation and maintenance, which requires an effort of association by the producers. Additionally, the results showed differential characteristics of the fiber extracted from the leaves of the three strata under study, which could be influenced by the effect of leaf morphology and quantity in these strata. Particularly, the upper and middle strata generated the highest fiber yield correlated to the highest quantity of leaves and presented leaves with larger dimensions in terms of length, thickness, and width (Table 1). On the other hand, the lower stratum was the plant section where less fiber was generated, as it had the lowest quantity of leaves and smaller size at the time of collection. Another characteristic of these leaves is that, being the oldest, they presented physical damage caused by phytosanitary problems, dehydration, and senescence, exhibiting the highest quantity of leaves unsuitable for defibration. Additionally, it has been reported that there is high morphological variability in pineapple leaves; therefore, the quality of fiber obtained from mature leaves must be considered, generally very mature leaves produce short, thick, and fragile fibers (Chaves et al., 2024; Nayak et al., 2024).

The analysis of the variables also showed an effect of pre-conditioning techniques on the two fiber extraction methods. In the manual extraction method, pre-conditioning techniques were observed to enhance fiber production (Figure 2). These findings are consistent with those reported by Mat et al. (2024), who suggested that soaking in water or NaOH improves fiber production, possibly due to the affinity of these solutions with plant tissues. When immersed, plant cells can swell, facilitating cell detachment and fiber release. Similarly, Peng et al. (2023) reported that the presence of microorganisms in water solutions, as was observed in our experiments (8 and 15 days), may contribute to the degradation of the non-fibrous organic matrix of the leaf, which contains pectins, hemicellulose, fats, waxes, minerals, and other compounds, thereby easing fiber separation. Additionally, Radoor et al. (2020) demonstrated that treating PALF with NaOH removes impurities and promotes defibrillation by breaking down lignin and hemicellulose. In contrast, for mechanical defibration, unlike the manual method, greater fiber yields were obtained when no treatment was applied to the leaves (Figure 2). Under these conditions, soaking in water or chemical solutions weakens the fibers, and when subjected to mechanical blades, they lose mechanical resistance, causing them to break and be lost, as also observed by Mondal et al. (2023).

In this study, changes in the fineness and elasticity of the fibers were also found among the leaves from different strata of the plant (Figure 3). The highest titer values were found in the upper stratum of the plant where the leaves are younger, likely because the fiber has not fully developed, resulting in lower lignin and cellulose accumulation, which are components of its cell matrix, resulting in finer fiber (Karim et al., 2022). However, descending through the plant strata, the fiber becomes coarser and less elastic because it is more mature and structurally better consolidated. These findings suggest a directly proportional relationship between the titer and elongation variables of the fibers (Chaves et al., 2024). A different behavior was found in the fiber strength variable, where the highest value was found in the middle stratum of the plant but was lost in the younger and older leaves. Possibly, the decrease in resistance may be due to this variable in plant fibers being largely dependent on the content of cellulose, hemicellulose, length of its polymeric chain, and the presence of lignin, which vary according to the age of the leaf (Karim et al., 2022; Chaves et al., 2024). Additionally, the effect of the plant stratum on variables related to fiber production and mechanical properties in each extraction method was also evident in the PCA analysis. In the manual extraction method, a positive correlation was observed between production variables and the middle and upper strata of the plant, indicating the direct influence of pre-conditioning treatments on the leaves of these strata (Figure 6). In the mechanical extraction method, correlations between the middle and upper strata, pre-conditioning treatments, fiber production, and mechanical characteristics were also positive. In contrast, leaves from the lower stratum showed a negative correlation with production variables and extraction times, suggesting that these leaves are less suitable for fiber extraction (Figure 7). This variability in results across plant strata is a common characteristic of natural fibers, including PALF. It can also be attributed to additional factors such as soil composition, temperature, and moisture conditions where the plants are grown, which create unique characteristics within fiber groups that can vary between plants, or even within the same leaf (Jawaid et al., 2020; Chaves et al., 2024). Considering the above, for the extraction of high-quality fiber with specific characteristics, the morphological characteristics, and mechanical properties of pineapple leaves in each stratum of the plant and the potential uses of the extracted fiber could be considered. These results may be related to fiber diameter, which has been documented to be greater in the apical part of the leaves, independent of plant age (Chaves et al., 2024). Variation in the strength of PALF has been reported in the same variety grown in the same region (Gaba et al., 2021; Mat et al., 2024). Similar findings were observed in several studies regarding the tensile strength of fibers extracted from different parts of pineapple leaves and crops of different regions (Bernardes et al., 2023; Chaves et al., 2024). The inherent variability in the properties of pineapple leaf fiber exposes significant challenges to ensuring the uniformity and quality of the product; however, these variations also suggest different possibilities for use.

Finally, the mechanical properties of the fibers were influenced by pre-conditioning techniques, with higher titer and elongation values observed when leaves were treated with sodium hydroxide compared to water-only treatments or the control (Figure 5). Gaba et al. (2021) found a similar behavior in elongation when the fiber was chemically treated with 9 % NaOH concentration, increasing this variable by 18%. The highest strength values were found when the leaves were not pretreated, followed by those immersed in water, and the lowest values when treated with NaOH. Similarly, previous research has indicated that fiber treatment with different chemicals modifies its structural properties, reducing strength (Gaba et al., 2021). These results contradict those reported by Mustafa et al. (2024) who found an increase in fiber strength when treated with an alkaline substance. On the other hand, Karim et al. (2022), have studied the mechanics of pineapple fibers and assert that pineapple fibers are of good quality as they contain type I cellulose structure, which has good elastic properties and can withstand high tensions comparable to other similar fibers. Thus, chemical agents could reduce the fiber´s diameter, due to the removal of extracellular materials such as lignin, hemicellulose, and cellulose present on the surface, resulting in finer and elongated fiber, as well as a strength reduction (Gaba et al., 2021; Karim et al., 2022; Mat et al., 2024). Therefore, the mechanics and mechanical properties of byproducts made from plant fibers depend not only on the properties and characteristics of the fibers themselves but also on the handling they receive before, during and after extraction (Mondal et al., 2023). These properties are particularly useful in the cottonization process as an example of the changes in fibers when pre-treatment is provided. Similarly, during the spinning process, they can improve string cohesion, withstand greater tension and improve the natural fibre-polymer matrix adhesion in industrial processes (Gnanasekaran et al., 2021; Bernardes et al., 2023; Sethupathi et al., 2024). The results of this study provide a starting point for classifying PALF based on its innate characteristics or those improved with pre- or post-treatments, as these properties could represent a selection criterion for its use as raw material for industries with a wide market in the production of yarns, industry, leather composites, or in products for the aerospace or automotive industries, and in engineering.

CONCLUSIONS

Considering that fiber extraction is a labor-intensive task, this study provides recommendations to optimize the use of plant material for obtaining fiber from MD2 pineapple, as a contribution to the substitution process of synthetic fibers. Fiber production and quality were found to be superior in the upper and middle strata of the plant, with yields of 12.42 g and 8.98 g, respectively. Additionally, the mechanical properties—titer (tex), strength (N), and elongation (%)—were also higher in these strata, which correspond to younger leaves, making them suitable for use even before the fruit is harvested. Among the common pineapple leaf fiber extraction methods, our study showed that the mechanical method is 22 times faster and 154% more efficient than the manual method in terms of defibration time and fiber production, respectively. This method, without pre-conditioning treatments, produced the highest fiber yield, with 50.5 g per plant, which was 41.8 % higher than other treatments. In contrast, the manual method yielded better results when pre-conditioning techniques, such as soaking in water or NaOH, were applied, resulting in a fiber yield of 14.5 g per plant, which was 51% higher than the control.

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