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Research article

Fiber Yield and Characterization of Locally Grown Abaca (*Musa textilis* Née) Cultivars in Aklan, Philippines

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Abstract: Abaca (*Musa textilis* Née) is a natural fiber-producing plant that is endemic to the Philippines. It is primarily grown for its fibers in textile and industrial applications. Currently, five locally described Abaca cultivars are grown in Aklan: *Tabukanon*, *Bisaya*, *Agbayanon*, *Negro*, and *Totoo*. Limited information exists, and no in-depth research has been conducted on the yield of these Abaca cultivars. The study investigated the fiber yield performance of Abaca cultivars in Aklan using a linear mixed-effects model (LMM) and Tukey's HSD method at a 5% level to determine differences between cultivars. Findings highlighted highly significant differences among cultivars in terms of tuxy weight, extracted fiber weight, dry weight, moisture content, fiber length, and fiber count. Findings revealed that significant differences were observed in the inner layers of tuxy, extracted fibers, moisture content, and fiber length, while in the outer layers, significant differences were observed only in dry weight and fiber count. Moreover, no significant differences were observed in the tuxy weight, extracted fiber, moisture content, and fiber length for the outer layers, whereas extracted fiber and dry weight were significantly different for the inner layers. The study highlighted that *Bisaya* and *Tabukanon* exhibited high inner fiber yield and tuxy weight but have shorter fiber lengths and potential for commercial production. In contrast, the *Totoo* cultivar produced a high fiber count; however, it had lower tensile strength, shorter length, and lower dry weight. Among all cultivars, *Negro* exhibited significantly longer fibers (both layers), and *Agbayanon* had moderate fiber characteristics, which are desirable for industrial applications.

Keywords: Abaca; fiber; manila hemp; textile

1. Introduction

Abaca (*Musa textilis* Née) is a native plant thriving in the Philippines. It is mainly cultivated for its fibers for textile and industrial applications. Due to its export value, the Philippines is the top exporter of Abaca fibers, supplying 85% of global demand and ranking as a top crop dollar earner. Its fiber is considered the strongest among natural fibers due to its high durability and tensile strength, and is primarily used for ropes, cords, marine cordage, and reinforcing materials [1, 2]. Additionally, Abaca is widely used in specialty papers, non-woven products, pulp production, and other specialized products, both locally and internationally [3]. Despite its economic significance, this fiber crop faces several challenges, including poor fiber yield, limited varietal information, limited research on fiber yield, and limited adoption of other technologies, resulting in an overall decline in production. The demand for Abaca fiber is expected to grow due to global demand in the pulp, paper, and fiber industries [4, 5].

Fiber characterization of locally described Abaca fiber yield is vital for optimizing and increasing production to meet the global demand for Abaca fiber. According to Research and Markets [6], the global Abaca fiber market is expected to grow at a CAGR of 15.2% from 2025 to 2030, driven by the government's push for the adoption of natural fibers as substitutes for hazardous synthetic fibers. The Abaca plant has emerged as an important material to address environmental concerns, such as forest conservation, and to attract other industries because of its potential properties and increasing demand locally and internationally. There is a need for Abaca cultivars with desirable agronomic traits and quality attributes to meet the increasing demand for high-quality fiber in the international market [5]. However, there is limited information on the fiber yield of Abaca cultivars, which is rarely discussed in research and literature, especially for unregistered cultivars.

Several varieties and hybrids exist in the Philippines, and as many as 200 Abaca cultivars thrive in the Philippines, which has not yet been fully explored. Studies have shown that these varieties exhibit different morphological and fiber yield performance [7], and there are only three registered varieties under the National Seed Industry Council (NSIC), including Inosa, Abuab, and Tangongon. Aklan is the top abaca-producing province in the Western Visayas Region and one of the leading Abaca-producing provinces in the Philippines. There are five locally described Abaca cultivars identified in Aklan: *Bisaya*, *Agbayanon*, *Tabukanon*, *Negro*, and *Totoo*. However, no in-depth research has been conducted on fiber yield performance. Exploring the fiber yield of these unregistered cultivars can provide valuable insights and reveal superior fiber traits that can be introduced to the market, contributing to fiber productivity, boosting the Abaca industry, and advancing scientific research.

Evaluating the fiber yield of these Abaca cultivars and comparing them with other varieties will provide new insights into the fiber yield in the Abaca industry. Hence, this study aimed to provide comprehensive information to assess the fiber yield characteristics of Abaca cultivars, which are crucial for improving production, enhancing economic viability, and optimizing their use. This study aimed to evaluate and identify specific fiber yield traits, including tuxy weight, extracted fibers, fiber yield, dry weight, moisture content, fiber length, and fiber number, for the five cultivars used in the Province of Aklan. The generated information will be valuable to all farmers, breeders, stakeholders, and industries to optimize the yield performance of this Abaca to meet the high demand for high-quality fiber in the global market.

2. Materials and Methods

The study employed an observational comparative study with inferential analysis to determine, assess, and evaluate the fiber yield traits of Abaca fibers extracted from different cultivars in the province of Aklan. It was carried out in the municipality of Libacao, where fibers from the *Bisaya*, *Agbayanon*, *Tabukanon*, and *Negro* (Figure 1a – d) cultivars were collected and extracted, as these cultivars were grown in the Eastern Aklan (1st District) of the Province of Aklan. Meanwhile, the *Totoo* (Figure 1e) cultivar was exclusively grown in the municipality of Makato in Western Aklan (2nd District). Figure 2 shows the site of the study.

2.1 Harvesting and Sample Collection

Fibers were gathered from ten (10) samples of each cultivar at every sampling location to obtain a representative yield per cultivar–location combination. The fiber yields of the Abaca cultivars from the ten samples were averaged to represent each cultivar in that location. Tuxying was conducted in separating several layers of the leaf sheaths (outer layer and inner layer) by inserting a tuxy-knife between the layers. This was followed by manual hand stripping to extract all the fibers from the tuxies [8-10]. Moreover, PhilFIDA provided all the modified Abaca stripping knives (MASK) used in the study to the farmers. All extracted fibers were separately sun-dried per plant/cultivar to remove moisture and prevent fungal growth.

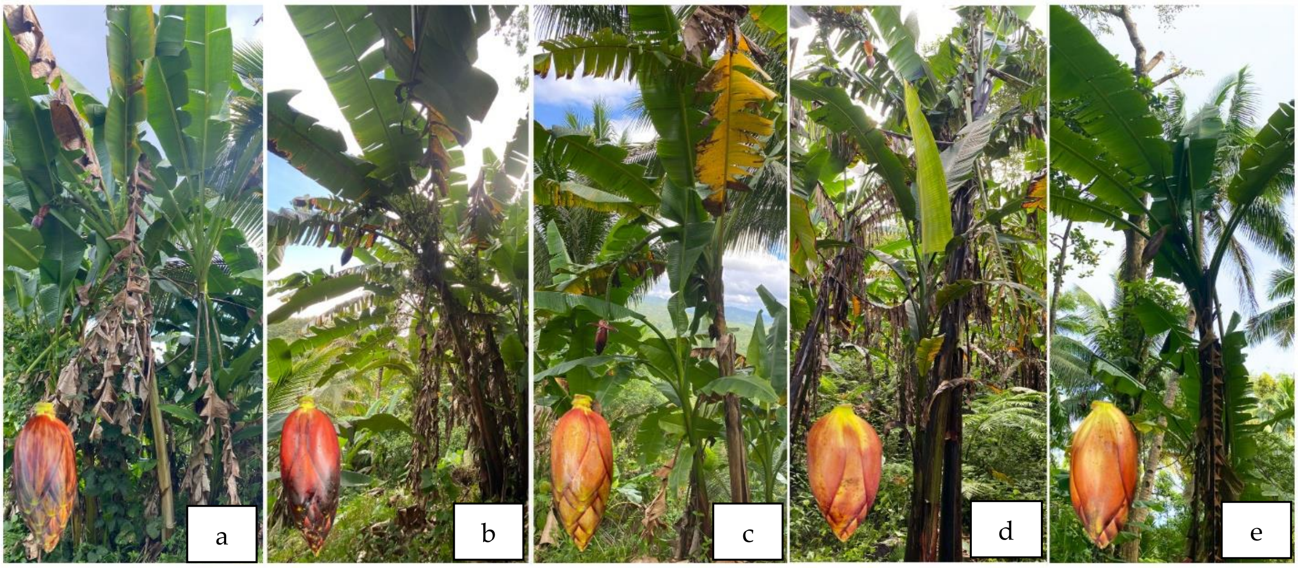

Figure 1. Aklan Abaca cultivars: (a) *Bisaya*, (b) *Agbayanon*, (c) *Tabukanon*, (d) *Negro*, and (e) *Totoo*.

2.2 Agroclimatic Conditions

Data on agroclimatic conditions in Makato and Libacao, Aklan, including soil, climate, and topography, were gathered from various government agencies and legitimate sources. Climate data, including rainfall, humidity, and temperature, were sourced from the Philippine Atmospheric, Geophysical, and Astronomical Services Administration (PAGASA), Global Historical Weather and Climate Data to determine annual rainfall, humidity, and average temperature during data collection. Soil data, including soil type, were obtained from the Bureau of Soil and Water Management. Furthermore, the National Mapping and Resource Information Authority (NAMRIA) obtained the land cover and topography.

2.3 Tuxy and Fresh Weight

The outer and inner layers of the leaf sheath were immediately separated to gather the weight using a digital weighing scale (kg). The tuxy (inner and outer) was weighed three times, and the average was used to ensure data accuracy. In terms of fiber weight, after stripping the fibers and removing non-fibrous material, the freshly extracted fibers were immediately weighed using a digital weighing scale, recorded three times, and the average was calculated to ensure uniformity and minimize human error and variation.

2.4 Dry Weight

This was measured and weighed using a digital weighing scale in grams (g). It was calibrated before the measurement session with a precision of at least 0.01 g. The fibers were measured and labeled separately, and the procedure was repeated three times by the same observer to ensure data accuracy and minimize inter-observer variability. The average dry weight of the repeated readings was used in the analysis.

2.5 Moisture content

This was measured after the fresh weight and dry weight of the sample plants were recorded using the digital weighing scale in grams (g). To compute the moisture content percentage, the formula below was used:

$$\text{Moisture Content (\%)} = \frac{(Fresh\ Weight - Dry\ Weight)}{Fresh\ Weight} \times 100\% \quad (1)$$

2.6 Fiber Length

Ten (10) representatives with the longest air-dried fibers in each cultivar were measured using a meter roll in centimeters. Visual inspections were carefully conducted to ensure that the fibers were not stretched or tangled. Upon measuring, the fibers were carefully straightened to avoid curling. At least two people conducted the process to ensure data accuracy by holding and carefully aligning the fiber. Data on fiber length were carefully tabulated for each cultivar.

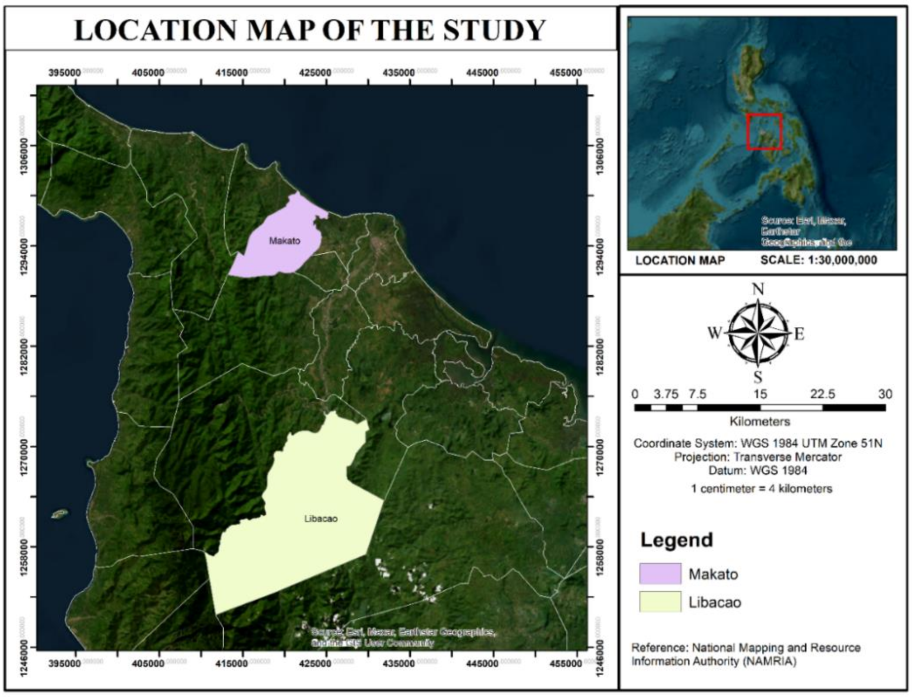

Figure 2. Study site.

2.7 Number of Fibers

The fibers extracted were manually counted to determine the fiber count or total number of fibers produced per cultivar. The fibers were carefully separated to ensure their accuracy. This process was repeated three times for each batch, and the average fiber count was recorded to reduce human error.

2.8 Statistical Tool Analysis

The data were analyzed using R statistical software (version 4.4.3, R Core Team, 2023), and the study employed a linear mixed-effects model (LMM) to handle the variability in data and unbalanced designs, where some cultivars are absent in specific locations. In the model, location was included as a random effect to account for variability across sampling sites, while cultivars were treated as fixed effects to assess differences in fiber characteristics. This modeling choice reflects the study's focus on the fixed effects of Abaca cultivars rather than on comparing specific locations. Although some cultivars were limited to fewer locations, recent literature supports the inclusion of random effects with fewer than five levels when the grouping variables serve as a nuisance factor rather than a primary target of inference [11]. Tests of fixed effects were performed using Satterthwaite's approximation for denominator degrees of freedom. For models with very small degrees of freedom (DenDF ≤ 3), a parametric bootstrap test with 1000 simulations was conducted to validate the significance of the fixed effect. In cases where the bootstrap test disagreed with the F-test result, inference was based on the bootstrap p-value.

3. Results and Discussion

3.1 Agroclimatic Conditions

According to the Global Historical Weather and Climate Data and the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA), the municipality of Libacao has an average monthly rainfall of 243.85 mm, a temperature of 28.35°C, and a humidity of 79.54%. Meanwhile, the Municipality of Makato has an average monthly rainfall of 166.77 mm, a temperature of 29.98°C, and a humidity of 84.09% [12]. Studies show that Abaca ideally thrives in areas with temperatures of 22 °C to 28 °C [13], high relative humidity (78-85%) and evenly distributed rainfall [9]. In terms of soil, Makato and Libacao have clay loam soils according to the BSWM, with Libacao having alimodian clay and san manuel clay loam. On the other hand, Makato has alimodian clay loam, makato clay, and buang clay. Abaca thrives in loamy soils, as they provide proper drainage and ideal moisture retention, which are vital for the roots and growth and development of the Abaca plant [14]. Meanwhile, the vegetative cover data provided by NAMRIA shows that the majority of the land area of Makato is classified as perennial crops (62.18%), whereas the majority of the vegetative cover of Libacao has 41.88% brush/shrub land. Abaca is a shade-loving plant that thrives well under shady conditions. Several studies have shown that it is widely intercropped with other perennial crops, such as fruit trees and timber, but still produces a high fiber yield [15-17]. Additionally, topography shows that both municipalities have gentle to moderate terrain (8-8%). According to PhilFIDA, Abaca is grown in areas with sloping, rolling, hilly, or mountainous terrain, as it provides proper drainage and reduces the risk of waterlogging. Overall, the municipality of Makato has a suitable climate and vegetative cover favorable to Abaca fiber production. Meanwhile, Libacao's climate and vegetative cover are slightly lower than Makato's, but they still have good potential for Abaca cultivation.

3.2 Fiber Characteristics of Abaca Cultivars in Aklan

The study presents the fiber yield characteristics of the five Abaca cultivars. Findings revealed significant variation in fiber characteristics across all cultivars. There were significant differences in tuxy weight, extracted fiber weight, moisture content, fiber length, and fiber count on the inner layer of all cultivars. In the outer layer, only fiber dry weight and fiber number differed significantly, but not tuxy weight, extracted fiber weight, moisture content, or fiber length. No significant differences across the outer layer of cultivars were observed for any fiber morphology measured (fiber weight, moisture content, and fiber length). The results of the linear mixed-effects model (LMM) ANOVA for the fiber characteristics of Abaca cultivars are presented in Table 1. The estimated marginal means (EMMs), which account for random effects, are shown in Table 2. Pairwise comparisons of fiber characteristics among Abaca cultivars are summarized in Table 3.

3.3 Tuxy Weight

The results indicate significant differences in tuxy weight for the inner layer, $F(4, 6) = 104.97$, $p < 0.001$, whereas the outer layer showed no significant differences, $F(4, 6) = 1.70$, $p = 0.267$ (Table 1). Tuxy weight varied across cultivars, ranging from 1.44 to 3.54 in the outer layer and 1.53 to 6.28 in the inner layer (Figure 3a). Among the cultivars, *Totoo* exhibited the heaviest tuxy weight in the outer layer (M = 3.54, 95% CI [2.55, 4.71]) but had the lightest tuxy weight in the inner layer (M = 1.53, 95% CI [1.24, 1.88]) as presented in Table 2. For the inner layer tuxy weight, *Agbayanon* exhibited significantly lighter values than *Tabukanon* (MD = −2.86, SE = 0.28) and *Negro* (MD = −2.22, SE = 0.44), but was heavier than *Totoo* (MD = 1.88, SE = 0.27). *Tabukanon* demonstrated significantly heavier weights than *Totoo* (MD = 4.74, SE = 0.27), *Agbayanon* (MD = 2.86, SE = 0.28), and *Bisaya* (MD = 2.06, SE = 0.27). Additionally, *Negro* was significantly heavier than *Totoo* (MD = 4.11, SE = 0.27), as shown in Table 3.

Totoo exhibited lighter tuxy weight in the inner layer, which may be due to genetic differences and could indicate lower fiber yield. The inner layer of all cultivars weighs more than the outer layer, except for the *Totoo* cultivar, contributing to the significant variation in tuxy weight across all cultivars. The inner layer consists of secondary fibers and pulpy material, resulting in a heavier weight, while the outer layers contain primary fibers, resulting in a lower, finer density[18, 8]. Moreover, cultivars (*Tabukanon*, *Negro*, and *Bisaya*) have higher inner tuxy weight, which can be optimized for pulp production and used for paper, bank notes, tea bags, and other applications [19-21]. There is an increasing demand for pulp production, underscoring the urgent need to increase fiber yield. There is an urgent need to increase fiber production [22]. The demand for Abaca pulp across several industries is rapidly increasing and expanding, and it contributes 70 to 80% of the total income in these industries, highlighting its importance to economic growth [23]. Furthermore, Abaca pulp has a substantial addressable market, as the global Abaca pulp market is anticipated to expand at a compound annual growth rate of 13.9% between 2024 and 2030, amounting to USD 1.0 billion by 2030, according to Grandview Research [24]. In comparison, other NSIC varieties also produce more pulp, such as Inosa, and were recommended for pulp and paper production [22].

Table 1. ANOVA Results for Fiber Characteristics of Abaca Cultivars Using Linear Mixed-Effects Model (LMM).

Characteristics	Fixed Effects	Sum Square	Mean Square	NumDF	DenDF	F-value	p-value	p-value (PB)
Tuxy Weight								
Outer Layer	Cultivars	6.00	1.50	4	6	1.70	0.267	
Inner Layer	Cultivars	31.86	7.96	4	6	104.97	p<0.001 **	
Extracted Fiber Weight								
Outer Layer	Cultivars	1.71	0.43	4	4.94	3.81	0.088	
Inner Layer	Cultivars	8.99	2.25	4	5.33	15.56	0.004 **	
Fiber Yield Recovery								
Outer Layer	Cultivars	0.25	0.06	4	6	9.06	0.010 *	
Inner Layer	Cultivars	0.17	0.04	4	4.84	5.16	0.053	
Fiber Dry Weight								
Outer Layer	Cultivars	0.11	0.03	4	2	53.83	0.018 *	0.051
Inner Layer	Cultivars	0.07	0.02	4	6	0.66	0.640	
Moisture Content								
Outer Layer	Cultivars	0.06	0.01	4	2	1.58	0.423	0.572
Inner Layer	Cultivars	0.10	0.03	4	6	6.40	0.023 *	
Length of Fiber								
Outer Layer	Cultivars	6270	1567.50	4	6	3.05	0.108	0.027*
Inner Layer	Cultivars	11145	2786.20	4	2	27.05	0.036 *	
Number of Fiber								
Outer Layer	Cultivars	5939908	1484977	4	6	36.12	p<0.001 **	
Inner Layer	Cultivars	14112901	3528225	4	6	65.75	p<0.001 **	

*Significant at 5% level. **Significant at 1% level. NumDf= Numerator Degrees of freedom; DenDf = Denominator Degrees of freedom. F-tests were performed using Satterthwaite's method to approximate Dendf. For models with DenDF≤3, parametric bootstrap (PB) tests with 1000 simulations were additionally performed to validate fixed-effect significance. Random effect (Location) was included as a random intercept in all models; variance estimates were small but retained for model validity.

3.4 Extracted Fiber

Findings revealed that the extracted fiber weight in the outer layer was similar across Abaca cultivars ($F(4, 4.94) = 3.81$, $p = 0.088$). However, significant differences were observed in the inner layer $F(4, 5.33) = 15.56$, $p = 0.004$, as shown in Table 1. Moreover, Table 2 presents that extracted fiber weight ranged from 0.21 to 1.35 in the outer layer and the inner layer, with *Tabukanon* garnering the highest extracted fiber (2.63 kg), followed by *Bisaya* (2.11 kg), *Negro* (2.01 kg), *Agbayanon* (0.75 kg), and *Totoo* (0.26 kg) having least weight (Figure 3b). The pairwise comparisons in Table 3 confirm that *Totoo* weighed significantly less than *Tabukanon* (MD = 2.37, SE = 0.39) and *Bisaya* (MD = 1.84, SE = 0.32). The study highlighted that the outer layer is relatively uniform across all cultivars, whereas the inner layer shows significant differences. Generally, cultivars such as *Tabukanon* and *Bisaya* contain heavier fibers, which attract farmers and industries to commercial fiber production due to a per-kilo payment structure, in addition to grading and classification, which influence the profitability of Abaca farmers [25]. In a previous study, most of the cultivars used in the Province of Aklan were *Tabukanon* and *Bisaya,* as these cultivars produce more suckers and fiber [26]. It has an economic and industrial impact that is key to profitability in fiber-processing industries. Meanwhile, *Totoo* exhibited relatively low extracted fiber yields, which may contain a high density of non-fibrous materials and result in biomass loss [15].

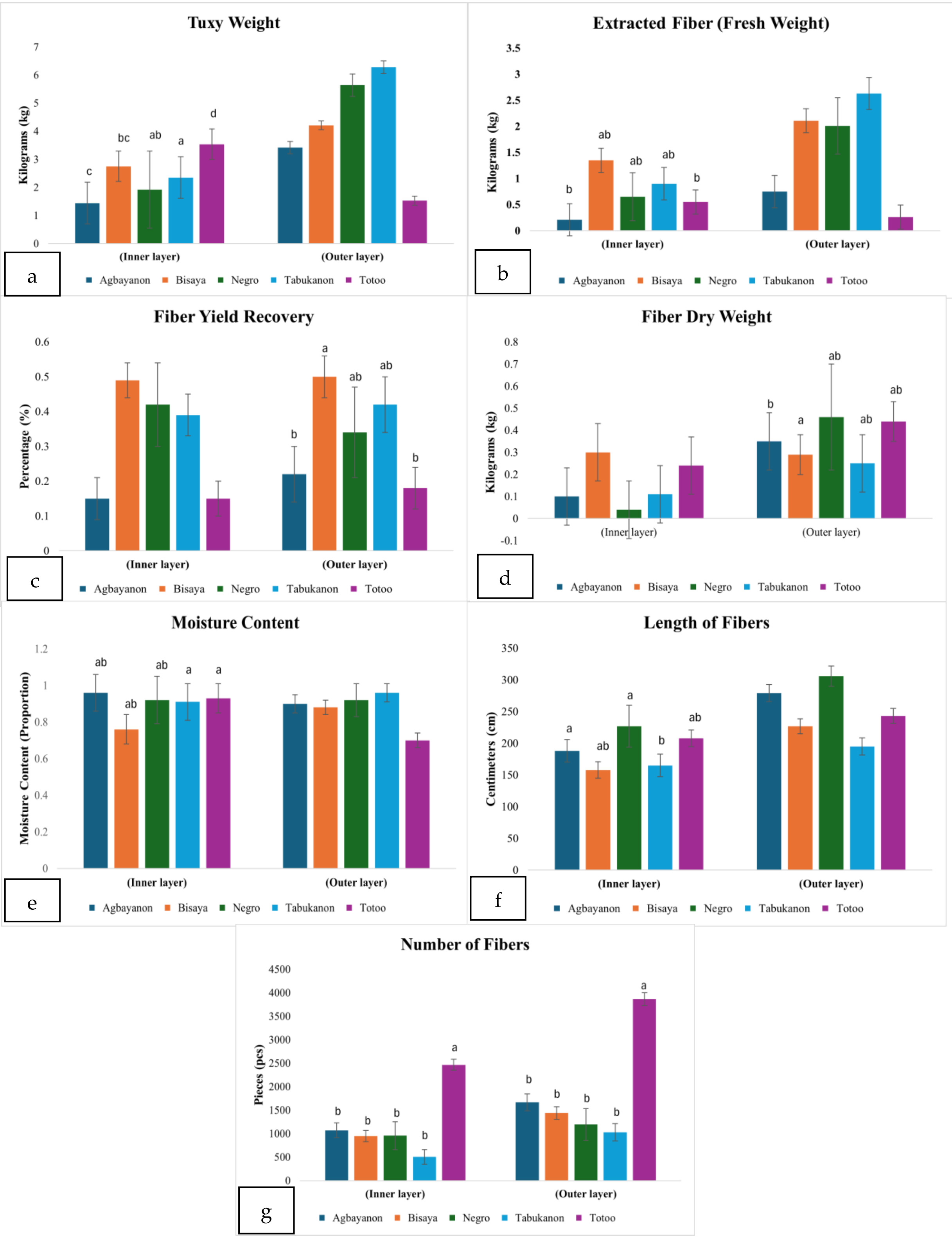

Figure 3. Fiber yield characteristics of the five Abaca cultivars: (a) tuxy weight, (b) extracted fiber, (c) fiber yield recovery, (d) fiber dry weight, (e) moisture content, (f) length of fibers, and (g) number of fibers. Statistical analysis was conducted with a Linear Mixed-Effects Model (LMM) with F-tests being performed using method of Satterthwaite for approximating the denominator degrees of freedom. Different superscript letters indicate significant difference among cultivars

3.5 Fiber Yield Recovery

Significant differences were observed among cultivars for the outer layer ($p = 0.010^*$, F -value = 9.06) as shown in Table 1. This study result implies that different Abaca cultivars can produce different percentages of fiber from the outer layer, which is relevant in identifying Abaca cultivars that produce a high yield. In contrast, the inner layer did not yield significant differences in fiber at the 5% level ($F(4, 4.84) = 5.16$, $p = 0.053$). The estimated marginal means (Table 2) reveal that fiber yield varied from 0.15 to 0.49 in the outer layer and 0.18 to 0.50 in the inner layer, with *Totoo* consistently showing the lowest yield (M = 0.15, 95% CI [0.08, 0.29]) in the outer layer and (M = 0.18, 95% CI [0.07, 0.26]) in the inner layer. In contrast, *Bisaya* had the highest fiber yield (M = 0.49, 95% CI [0.40, 0.58] in the outer layer and (M = 0.50, 95% CI [0.39, 0.60]) in the inner layer (Figure 3c). Table 3's pairwise comparison further confirms that *Bisaya* exhibited significantly higher fiber than *Agbayanon* (MD = -0.34, SE = 0.08), and *Totoo* exhibited significantly lower outer fiber yield than *Bisaya* (MD = 0.34, SE = 0.07) and other cultivars. Hence, the study indicates that cultivars *Bisaya* and *Tabukanon* are the best choices for fiber production due to their higher fiber yield potential, which encourages farmers to cultivate them and optimize yields, thereby increasing their profitability. Several factors affect fiber yield, including environmental factors (wind, drought, location, temperature, and rainfall), nutrient availability, and water availability [16]. Studies have shown that the Abaca thrives in high humidity, less sunlight, and wind [9], thus producing more fiber yield. Some studies reported that the location of the Abaca greatly impacts the fiber yield. For instance, Abaca planted in hilly areas produced lower fiber yields and lower fiber quality [27]. Moreover, intercropping (coconut, coffee, mango, cacao, and bamboo) greatly benefits Abaca plants and farmers by providing shading and protection from the sun and strong winds, thereby enhancing fiber yield and farmers' income [8; 14]. Most Abaca plantations were also intercropped with leguminous trees (nitrogen-fixing plants), which enhanced fiber yield. Studies have shown that planting legumes significantly affects the overall vigor of the Abaca plant by producing longer, wider pseudostems with wider leaves, thus increasing fiber yield [1].

3.6 Fiber Dry Weight

LMM ANOVA (Table 1) revealed that, in terms of dry weight, fiber significantly differs in the outer layer across Abaca cultivars ($F(4, 2) = 53.83$, $p = 0.018$), while the inner layer displayed similar dry weight ($F(4, 6) = 0.66$, $p = 0.640$). The outer layer demonstrated a significant difference ($p = 0.018^*$), and the corresponding F-value (53.83) indicated significant differences between the cultivars in outer layer fiber dry weight. This could be important for fiber processing as dry weight affects handling and quality. In contrast, the inner layer of all cultivars did not have significance at all ($p = 0.640$); likewise, the F-value (0.66) is very low. *Agbayanon* was the lightest cultivar in the outer layer (M = -0.01, 95% CI [0.3, 0.27]), while *Bisaya* was the heaviest (M = 0.30, 95% CI [0.40, 0.58]). In the inner layer, *Tabukanon* was the lightest (M = 0.25, 95% CI [-0.27, 0.51]), and *Negro* was the heaviest (M = 0.46, 95% CI [0.26, 0.59]) as presented in Table 2. A pairwise comparison of outer-layer fiber dry weight revealed that *Agbayanon* had significantly lower values than *Bisaya* (MD = −0.31, SE = 0.02). According to the data, *Totoo* obtained the maximum value of inner layer fiber dry weight (0.44g), while *Agbayanon* obtained the minimum value (0.35g). In the outer layer, the highest fiber dry weight was found in *Bisaya* (0.30g), and the lowest in *Agbayanon* (0.10g) (Figure 3d). Abaca fibers contain polymers such as hemicelluloses, cellulose, and lignin, which contribute to a high crystalline index (≥65%) [28] and also affect the total weight of the Abaca fiber. Moreover, Abaca cultivars can yield highly extracted fiber but also experience significant biomass loss during sun drying, which greatly affects dry weight. A study found that 15% to 30% shrinkage was observed after drying [15]. Other studies showed that 48 tons of biomass waste were produced for every ton of dry fiber [15;29]. Proper drying is vital for removing moisture from fibers and greatly affects fiber quality [30]. Moreover, dried fibers have an economic impact on farmers, as traders prefer properly dried Abaca fibers for several reasons. The high moisture content of the fibers can easily deteriorate and grow mold and mildew, thereby degrading fiber quality [4]. Likewise, the payment scheme for Abaca fibers is per kilo; thus, traders avoid paying the water weight rather than the actual fiber weight [25].

3.7 Moisture Content

Moisture content across Abaca cultivars was similar in the outer layer, F (4, 2) = 1.58, p = 0.423, but significantly differed in the inner layer, F (4, 6) = 6.40, p = 0.023 (Table 1). Regarding the outer layer, the study found no significant effect of cultivar (p = 0.423), indicating that moisture content in the outer fiber layer is relatively similar across cultivars. However, in the inner layer, the difference is significant (p = 0.023), demonstrating that the moisture content is different between cultivars. The F-value (6.40) indicates that genetic determinants might be involved in moisture retention of the inner fibers and may have implications on drying and storage properties. Table 2 shows the estimated marginal means (EMMs) for moisture content, which ranged from 0.76 to 0.96 in the outer layer and from 0.70 to 0.96 in the inner layer (Figure 3e). These cultivars have almost identical moisture content in the outer and inner layers, except for *Totoo,* which has the lowest inner-layer moisture content (0.70%). Moreover, further testing (Table 3) indicates that *Tabukanon* had significantly higher inner-layer moisture content than *Totoo* (MD = 0.26, SE = 0.06). High moisture content in Abaca fibers significantly affects the mechanical performance of composite materials due to their hydrophilic nature, which allows them to absorb more moisture from the environment and thereby affects the overall performance of Abaca fiber composites [31]. Abaca is highly saturated with water and has high initial moisture uptake [9]. According to other studies [32,33], Abaca's pseudostems comprise 93% - 96% water and 1.3-5% fiber. Hence, the present findings aligned with other studies showing that extracted fibers from different cultivars exhibited varying levels of moisture. Additionally, a study shows that the moisture content of newly harvested Abaca fibers can be reduced to 8% after 2-3 hours of sun exposure under summer heat conditions [34]. The present study indicates that the inner layer of *Totoo* (70%) may dry faster than *Tabukanon* (96%) and is less prone to microbial damage and fiber deterioration, such as mold. In contrast, *Tabukanon* may take longer to dry to the recommended 8% moisture content for safe storage and processing.

3.8 Fiber Length

Fiber length was significantly different in the inner layer, F (4, 2) = 27.05, p = 0.036, but not in the outer layer, F (4, 6) = 3.05, p = 0.108, as shown in Table 1. The only other variable for which a significant difference was detected (p = 0.036*) was the inner layer, indicating differences in inner fiber lengths between cultivars. A high F-value (27.05) indicates that cultivar selection may be essential for obtaining longer inner-layer fibers , which might be preferred in some industrial applications (Milosevic *et al*., 2022). Fiber length also varied significantly, ranging from 158 cm to 227 cm in the outer layer and 195 cm to 306 cm in the inner layer (Figure 3f). *Negro* had the longest fibers among cultivars, both in the outer layer (M = 227 cm, 95% CI [182, 274]) and the inner layer (M = 306 cm, 95% CI [285, 327]), followed by *Agbayanon* (M = 279 cm, 95% CI [263, 293]), *Totoo* (M = 243 cm, 95% CI [233, 256]), *Bisaya* (M = 227 cm, 95% CI [216, 238]) and *Tabukanon* (M = 195 cm, 95% CI [179, 256]) has the shortest as shown in Table 2. The fibers in the inner layer are generally longer, and the longest fibers are produced by *Negro* in both layers, while *Bisaya* (outer) and *Tabukanon* (inner) have the shortest. Moreover, the pairwise comparison further confirmed that *Tabukanon* consistently produced shorter fibers in the inner layer compared to *Negro* (MD = −111.0, SE = 13.3) and *Agbayanon* (MD = −83.8, SE = 10.1), as presented in Table 3. As a result, *Negro* fibers are considerably longer than those of *Bisaya* and *Tabukanon*. On the other hand, *Agbayanon* fibers are much longer than *Tabukanon* fibers. Abaca can reach up to 7.5 meters in height, with an average monthly increment of 14 cm [9; 16]. Hence, plant height may also directly influence fiber length and can be attributed to some factors (physiological and genetic). Generally, as the height of the Abaca plant increases, the leaf sheath elongates, thereby increasing fiber length. Several studies concluded that plant height significantly influences fiber elongation [35]. A previous study reported that among cultivars, *Negro* is the tallest plant (5 – 6 m), while *Tabukanon* (3 -3.5 m) and *Bisaya* are the shortest (4 m)[26]. Typical fiber length ranges from 1.5 to 3.5 meters, depending on the cultivar. In comparison, the fiber length of Abaca cultivars in Aklan was shorter than in other studies [2; 36]. The length of Abaca fibers is pivotal in grading and classifying fiber grades. As mentioned, Abaca fibers are not homogeneous and vary according to cultivars, growth , and development. The minimum requirements for normal grades are no less than 60 cm, while the residual grade is less than 60 cm according to the Philippine National Standards for grading and classifying Abaca fibers. However, some studies reported that fiber strength and abrasion resistance decline at the initial feet of the fiber top portion, although longer fiber length can be beneficial for other industrial applications [37].

Table 2. Estimated Marginal Means (EMMs) for Fiber Characteristics of Abaca Cultivars.

Characteristics	Outer Layer				Inner Layer			
	EMM	SE	95% CI Lower Bound	95% CI Upper Bound	EMM	SE	95% CI Lower Bound	95% CI Upper Bound
Tuxy Weight								
Agbayanon	1.44	0.74	0.11	2.81	3.42	0.22	3.03	3.82
Bisaya	2.75	0.54	1.68	3.74	4.21	0.16	3.90	4.51
Negro	1.92	1.37	0.09	3.89	5.64	0.40	5.10	6.22
Tabukanon	2.35	0.74	1.03	3.73	6.28	0.22	5.89	6.68
Totoo	3.54	0.54	2.55	4.71	1.53	0.16	1.24	1.88
Extracted Fiber weight								
Agbayanon	0.21	0.31	-0.27	0.71	0.75	0.31	0.21	1.30
Bisaya	1.35	0.23	0.97	1.71	2.11	0.23	1.67	2.51
Negro	0.65	0.46	-0.02	1.39	2.01	0.54	1.27	2.81
Tabukanon	0.90	0.31	0.42	1.39	2.63	0.31	2.09	3.18
Totoo	0.55	0.23	0.196	0.96	0.26	0.23	-0.14	0.74
Fiber Yield								
Agbayanon	0.15	0.06	0.03	0.27	0.22	0.08	0.09	0.35
Bisaya	0.49	0.05	0.40	0.58	0.50	0.06	0.39	0.60
Negro	0.42	0.12	0.26	0.59	0.34	0.13	0.16	0.54
Tabukanon	0.39	0.06	0.27	0.51	0.42	0.08	0.29	0.55
Totoo	0.15	0.05	0.07	0.26	0.18	0.06	0.08	0.29
Fiber Dry Weight								
Agbayanon	0.01	0.13	-0.04	0.03	0.35	0.13	0.11	0.58
Bisaya	0.30	0.13	0.28	0.33	0.29	0.09	0.10	0.46
Negro	0.04	0.13	-0.01	0.08	0.46	0.24	0.14	0.80
Tabukanon	0.11	0.13	0.08	0.15	0.25	0.13	0.02	0.48
Totoo	0.24	0.13	0.22	0.27	0.44	0.09	0.27	0.65
Moisture Content								
Agbayanon	0.96	0.10	0.80	1.08	0.90	0.05	0.81	0.99
Bisaya	0.76	0.08	0.65	0.86	0.88	0.04	0.80	0.94
Negro	0.92	0.13	0.71	1.10	0.92	0.09	0.80	1.05
Tabukanon	0.91	0.10	0.73	1.03	0.96	0.05	0.87	1.05
Totoo	0.93	0.08	0.83	1.05	0.70	0.04	0.64	0.78
Length of Fiber								
Agbayanon	188	17.7	156	221	279	13.5	263	293
Bisaya	158	13.1	133	182	227	11.8	216	238
Negro	227	32.9	182	274	306	16.0	285	327
Tabukanon	165	17.7	133	198	195	13.5	179	210
Totoo	208	13.1	184	236	243	11.8	233	256
Number of Fiber								
Agbayanon	1072	158	786	1369	1667	181	1340	2007
Bisaya	948	117	719	1163	1440	134	1177	1685
Negro	958	295	561	1382	1195	337	742	1679
Tabukanon	504	158	219	800	1029	181	704	1367
Totoo	2466	117	2254	2719	3865	134	3622	4154

SE= standard error; CI= confidence interval. EMM confidence intervals were computed using parametric bootstraps with 1000 simulations to improve the reliability of the estimates.

Table 3. Pairwise Comparisons of Fiber Characteristics of Abaca Cultivars.

Cultivars		Inner Layer Tuxy Weight (kg)		Inner Layer Extracted Fiber Weight (kg)		Outer Layer Fiber Yield (%)	
i	**j.**	**Estimate (MD)**	**SE**	**Estimate (MD)**	**SE**	**Estimate (MD)**	**SE**
Agbayanon	*Bisaya*	-0.80	0.27	-1.35	0.38	-0.34	0.08
	Negro	-2.22 *	0.44	-1.26	0.58	-0.27	0.13
	Tabukanon	-2.86 **	0.28	-1.88	0.38	-0.24	0.08
	Totoo	1.88 **	0.27	0.49	0.39	-0.01	0.08
Bisaya	*Negro*	-1.43	0.43	0.09	0.58	0.07	0.13
	Tabukanon	-2.06 **	0.27	-0.53	0.38	0.10	0.08
	Totoo	2.68 **	0.23	1.84 **	0.32	0.34 **	0.07
Negro	*Tabukanon*	-0.63	0.44	-0.62	0.58	0.03	0.13
	Totoo	4.11 **	0.43	1.75	0.59	0.27	0.13
Tabukanon	*Totoo*	4.74 **	0.27	2.37 **	0.39	0.24	0.08

Cultivars		Inner Layer Moisture Content (%)		Inner Layer Length of Fiber (cm)		Outer Layer Number of Fiber		Inner Layer Number of Fiber	
i	**j.**	**Estimate (MD)**	**SE**	**Estimate (MD)**	**SE**	**Estimate (MD)**	**SE**	**Estimate (MD)**	**SE**
Agbayanon	*Bisaya*	0.02	0.06	51.3	10.5	123.67	197	227	225
	Negro	-0.02	0.10	-27.2	13.3	114.00	321	472	366
	Tabukanon	-0.06	0.06	83.8 *	10.1	568.00	203	638	232
	Totoo	0.20	0.06	35.3	17.9	-1394.33*	197	-2198 **	225
Bisaya	*Negro*	-0.04	0.10	-78.5	13.5	-9.67	317	245	362
	Tabukanon	-0.09	0.06	32.5	10.5	444.33	197	411	225
	Totoo	0.17	0.05	-16.0	16.7	-1518.00*	166	-2426 **	189
Negro	*Tabukanon*	-0.04	0.10	111.0 *	13.3	454.00	321	166	366
	Totoo	0.21	0.10	62.5	19.9	-1508.33 *	317	-2670 **	362
Tabukanon	*Totoo*	0.26 *	0.06	-48.5	17.9	-1962.33*	197	-2836 **	225

Cultivars i and j denote the two Abaca cultivars being compared. MD=Mean difference; SE=standard error. *Significant at 5% level. **Significant at 1%. The Tukey's HSD method was used for post-hoc pairwise comparisons to control for family-wise error rates.

3.9 Number of Fibers

Fiber count differed significantly among Abaca cultivars both in the outer layer, $F(4, 6) = 36.12$, $p < 0.001$, and inner layer, $F(4, 6) = 65.75$, $p < 0.001$ (Table 1). There was a highly significant difference ($p < 0.001$) among cultivars in the outer layer. The F-value was very high (36.12). The high sum of squares (5,939,908) indicates that cultivar choice significantly influenced fiber production potential. The inner layer was also observed to have a highly significant difference ($p < 0.001$), with a higher F-value (65.75). That means genetic variation influences the inner layer's fiber count even more heavily than the outer layers. The exceptionally large sum square (14,112,901) supports the idea that choosing a cultivar makes a huge contribution to fiber content.

Findings revealed that the number of fibers varied widely across cultivars. *Tabukanon* produced the fewest fibers, with an average of 504 fibers (95% CI [219, 800]) in the outer layer and 1029 fibers (95% CI [704, 1367]) in the inner layer. In contrast, *Totoo* had the largest fiber count, averaging 2466 fibers (95% CI [3622, 4154]) in the outer layer and 3865 fibers (95% CI [2254, 2719]) in the inner layer (Table 2 and Figure 3g). Thus, *Totoo* has the highest number of fibers in both layers, while *Tabakanon* has the lowest. This result contrasts with the findings on fiber yield, where *Tabukanon* shows the highest extracted fiber yield while *Totoo* shows the lowest, this is primarily due to the diameter of the *Totoo* fiber extracted, which ranged from 0.10 – 0.20 (EF fiber grade), whereas *Tabukanon* fibers ranged from 0.20-0.50 (S2), resulting in a greater number of fibers extracted from *Totoo*.

Fiber grades, quality, and fiber counts sometimes vary depending on the extraction process, leaf sheaths, and stripping knives used. Other studies confirmed that knife serrations greatly influenced the Abaca fiber [38]. The Philippine National Standard for fiber grading and classification indicates that thinner fibers (smaller strand sizes) produce excellent fiber grades (excellent soft) compared to other fibers with larger strands [18]. Cultivars producing smaller fiber sizes yield higher fiber counts and excellent fiber grade, which will generate more income for the farmer [9]. Hence, the study indicates that *Tabukanon* may produce a higher fiber yield; however, *Totoo* produces excellent-quality fiber, generating higher prices and income for the farmers. Further tests confirmed that *Totoo* displayed a significantly lower number of fibers in the outer layer compared to *Tabukanon* (MD = −1962.33, SE = 197), *Bisaya* (MD = −1518.00, SE = 166), *Totoo* (MD = −1508.33, SE = 317), and *Agbayanon* (MD = −1394.33, SE = 197). Similarly, the inner layer fiber count of *Totoo* significantly differed from the other Abaca cultivars, with mean differences as follows: *Tabukanon* (MD = −2836, SE = 197), *Negro* (MD = −2670, SE = 362), *Bisaya* (MD = −2426, SE = 189), and *Agbayanon* (MD = −2198, SE = 225) as presented in Table 3. In addition, *Totoo* has many more fibers than other cultivars. *Tabukanon*, on the other hand, has much less fiber than most cultivars.

Statistical Considerations and Limitations

The study acknowledged that certain tests had low degrees of freedom due to the limited number of replicates, which could affect the validity of the F-statistics. Linear Mixed-Effects Models (LMM) with Satterthwaite's approximation were used to address this issue and supplemented with parametric bootstrap validation for models with low DenDF. Moreover, results demonstrate consistent trends in fiber yield traits among cultivars and are cautiously interpreted. Future studies with larger sample sizes are recommended to replicate the findings in multiple locations, thereby enhancing statistical power and strengthening and confirming the results and trends.

4. Conclusions

The study investigated the fiber characteristics of Abaca cultivars in Aklan. Findings highlighted highly significant differences among cultivars in terms of tuxy weight, extracted fiber weight, dry weight, moisture content, fiber length, and fiber count. In terms of the fiber yield traits, findings revealed that significant differences were observed in the inner layers of tuxy, extracted fibers, moisture content, and fiber length, while, for the outer layers, significant differences were observed only in dry weight and fiber count. Moreover, no significant differences were observed in the tuxy weight, extracted fiber, moisture content, and fiber length for the outer layers, whereas extracted fiber and dry weight were significantly different for the inner layers. The study highlighted that *Bisaya* and *Tabukanon* exhibited high inner fiber yield and tuxy weight but have shorter fiber lengths and potential for commercial production. While *Totoo* produced a high fiber count, it showed the lowest performance among all fiber characteristics. Among all cultivars, *Negro* exhibited significantly longer fibers (both layers), and *Agbayanon* had moderate fiber characteristics, which are desirable for industrial applications. The results of the study provide valuable information for stakeholders, farmers, breeders, and researchers, and are used in industrial applications, breeding programs, further research, policy development, and to optimize fiber production.

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