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Multivariate Morphological Analysis of Indigenous and Hybrid Poplar Strands for Oriented Strand Board and Laminated Strand Lumber Production

Ahmed Altaher Omer Ahmed, Tibor Alpar and László Bejó *

Institute of Applied Sciences, Faculty of Wood Engineering and Creative Industry, University of Sopron, 9400 Sopron, Hungary; altaher.omer.ahmed.ahmed@phd.uni-sopron.hu (A.A.O.A.); alpar.tibor@uni-sopron.hu (T.A.)
* Correspondence: bejo.laszlo@uni-sopron.hu

Abstract

Geometric uniformity in lignocellulosic furnish plays a central role in determining the mechanical reliability and density stratification of engineered wood products. This study presents a comprehensive morphological assessment of wood strands produced from indigenous poplar (*Populus nigra* L.) and hybrid poplar (*Populus* × *euramericana* (Dode) Guinier) strands under full industrial flaking conditions. A total of 600 strands were characterized for weight, length, width, and thickness and analyzed using a multivariate statistical framework integrating Principal Component Analysis (PCA) and bivariate correlation modeling. Despite being processed to the same nominal target length (120 mm), the two provenances exhibited markedly different dimensional behaviors. Hybrid poplar strands were substantially heavier (mean 0.536 g vs. 0.291 g) and slightly thicker on average, while indigenous strands were marginally wider; strand length did not differ significantly between provenances (p = 0.354). PCA applied to four variables (weight, length, width, and mean thickness) revealed that weight and width were the dominant contributors to PC1 (57.0% of total variance), enabling clear separation of the two provenances into distinct multivariate clusters. These findings indicate that hybrid furnish, due to its coarser and more variable geometry, may require enhanced mat densification during hot pressing to minimize internal voids and achieve a stable vertical density profile (VDP). The dataset and analytical approach presented here provide actionable insights for optimizing flaker calibration, strand classification, and resin dosing strategies in the production of Oriented Strand Board (OSB) and Laminated Strand Lumber (LSL), particularly when integrating fast-growing hybrid poplar resources into industrial manufacturing lines.

Keywords: poplar strands; strand morphology; geometric variability; thickness distribution; principal component analysis (PCA); morphological fingerprinting; industrial flaking; oriented strand board (OSB); laminated strand lumber (LSL)

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1. Introduction

The global forest products sector is undergoing a structural transition toward sustainable, fast-growing hardwood resources to alleviate pressure on traditional softwood supplies and meet the rising demand for high-performance engineered wood products (EWPs) [1,2]. Within this bio-economic context, the genus *Populus* (poplar) has emerged as a strategically important raw material for strand-based composites such as Oriented Strand Board (OSB) and Laminated Strand Lumber (LSL). Recent studies confirm that indigenous poplar and European hybrid clones represent an increasingly vital resource for OSB and LSL manufacturing, particularly in Central and Eastern Europe, where these species combine rapid growth with favorable fiber characteristics [1,3].

The mechanical performance and reliability of strand-based composites are fundamentally governed by the geometric and gravimetric attributes of the constituent strands. Unlike veneer-based products, OSB and LSL rely on discrete wood flakes whose length (L), width (W), thickness (t), weight, and derived ratios—such as slenderness (L/t) and aspect ratio (L/W)—control stress transfer, mechanical interlocking, mat porosity, and resin distribution within the mat [2,4,5]. Strand weight in particular governs horizontal density variation within the pressed mat, yet it has received comparatively little attention relative to length and thickness in the existing literature [6]. Comparative studies between poplar and other hardwoods, such as beech, demonstrate that variability in strand dimensions directly influences key mechanical properties, including the Modulus of Rupture (MOR) and Modulus of Elasticity (MOE) [7,8]. Shaler [5] demonstrated that slenderness ratios above 150 are associated with improved bending stiffness through enhanced fiber-alignment efficiency, while Nishimura et al. [6] showed that strand thickness is among the most influential geometric variables controlling horizontal density variation in OSB mats.

Despite these advantages, poplar—particularly hybrid varieties—may present specific manufacturing challenges. Reported issues include density fluctuations, drying difficulties, and a high proportion of tension wood, all of which can compromise strand quality [9]. Industrial flaking processes introduce additional "geometric noise," causing strands to deviate from nominal targets due to knife wear, log moisture variability, and anatomical heterogeneity [10]. Research on fast-growing species such as poplar and willow indicates that, although they can yield acceptable OSB properties, industrial-scale processing often results in significant dimensional variance [11]. Recent findings further suggest that juvenile wood and new hybrid clones may produce strands with greater variability in thickness and width, necessitating more precise calibration of flaker knife settings [12].

Provenance-related differences become particularly pronounced when comparing indigenous poplar (*Populus nigra*) with hybrid clones, which often differ in basic density, growth rate, fiber anatomy, and surface chemistry [13,14]. Indigenous *P. nigra* typically produces denser, narrower stems with lower moisture content at harvest, whereas hybrid cultivars achieve higher above-ground biomass at the cost of lower basic density and broader stem cross-sections [14]. These macro-anatomical differences are expected to propagate into the geometry of strands produced by industrial flakers; however, whether this propagation differs systematically between anatomical zones within the stem—and not merely between provenances—has rarely been rigorously quantified in a factorial experimental design [14]. Studies have also shown that indigenous poplar frequently exhibits superior wettability relative to certain hybrid varieties, directly influencing adhesive penetration and cross-linking efficiency [15,16].

To address these complexities, this study combines a large descriptive and multivariate dataset with a balanced factorial sub-sample that explicitly disentangles species and anatomical wood-zone effects. Principal Component Analysis (PCA) is used to develop "morphological fingerprints" that map dimensional stability and clustering behavior across the industrially relevant furnish [1,17], while independent-samples *t*-tests and a two-way factorial ANOVA (Species $\times$ Wood Zone) provide formal hypothesis tests and effect-size estimates that were not available in earlier, purely descriptive characterizations of this furnish. The specific objectives are to: (i) quantify the dimensional and gravimetric distributions of strand weight, length, width, thickness, and slenderness ratio; (ii) statistically test for between-species differences using independent-samples *t*-tests with effect sizes; (iii) determine, via a balanced two-way ANOVA, whether species differences persist once anatomical wood zone (lower-stem versus upper-stem) is accounted for and whether species and zone interact; (iv) identify the principal morphological variables contributing to multivariate variance using PCA and bivariate correlation modeling; and (v) evaluate the implications of these differences for mat compaction, pressing schedules, and process optimization in structural composite manufacturing.

2. Materials and Methods

2.1. Plantation Sourcing and Industrial Logistics

Round logs of indigenous poplar (*Populus nigra*) and hybrid poplar (*Populus* × *euramericana*) were harvested from certified plantation stands in western Hungary (Győr-Moson-Sopron County, 47°41′ N, 17°13′ E) supplying the SwissKrono production facility in Vásárosnamény, Hungary, ensuring industrial relevance and traceability of the raw material [18]. To capture within-stem anatomical heterogeneity, logs were sampled from two stem positions: a lower zone (Zone L: 0.5–1.5 m above ground), representing juvenile and reaction wood, and an upper zone (Zone U: 4.0–5.0 m above ground), representing more mature wood. Four log batches were processed: indigenous lower (Ind-L), indigenous upper (Ind-U), hybrid lower (Hyb-L), and hybrid upper (Hyb-U). Logs were stored in a conditioned chamber at 20 °C and 65% relative humidity for four weeks prior to processing to equilibrate moisture content (Figure 1).

(**a**) (**b**)

Figure 1. Hybrid (**a**) and indigenous (**b**) poplar strands used in morphological measurements.

2.2. Strand Production

The strands used in this study were manufactured at the Vásárosnamény plant of SWISS KRONO Kft. (Vásárosnamény, Hungary), where they are produced for structural oriented strand board (OSB/3) manufacturing in accordance with EN 300 [19]. Before delivery, the company sorted the incoming log shipments into indigenous (domestic) and hybrid categories on the basis of their visual appearance and supplied the strands in a dry state, at an approximate moisture content of 4%. The strands were produced with a conventional (traditional) ring flaker. In total, 600 strands—300 hybrid poplar and 300 indigenous poplar (Figure 1)—were used and taken at random for measurement, without any systematic selection.

2.3. Sampling Design

A total of 600 strands—300 hybrid poplar and 300 indigenous poplar—were taken at random from the material supplied by the company and measured, after sieving to remove fines (<10 mm). This sample (n = 300 per species) provides a rich distributional dataset for the descriptive statistics and Principal Component Analysis (PCA). For the balanced two-way analysis of variance (ANOVA), a subset of 400 strands was used, comprising 100 strands for each Species × Wood Zone combination (indigenous and hybrid, each sampled from a lower and an upper stem zone), so that species and wood-zone effects could be tested within a fully balanced factorial design. This nested sampling approach follows industry benchmarking practice for strand-based panels, ensuring that the measured distributions of length, width, thickness, and weight are representative of the production furnish while retaining sufficient statistical power for factorial hypothesis testing [4,20]. For context, a standard OSB/3 panel (2440 mm × 1220 mm × 18 mm, nominal density 620 kg/m^3) contains approximately 15,000–20,000 strands; the present 600-strand sample is therefore intended to characterise the furnish-level morphological distribution rather than to estimate full product-scale variability, following the strand-benchmarking approaches recommended in the literature [4,20].

2.4. Conditioning and Moisture Control

All strands were oven-dried at 103 ± 2 °C for 24 h prior to weighing and dimensional measurement, equilibrating each strand to a consistent oven-dry moisture reference state. Conditioned subsamples were sealed in polyethylene bags and stored in a climate-controlled room until testing to minimize variability between the drying and measurement steps [21,22].

2.5. Morphological and Gravimetric Measurements

Strand dimensions were recorded using high-precision digital calipers (Mitutoyo CD-15CPX, Mitutoyo Corporation, Kawasaki, Japan, resolution 0.01 mm). Each strand was measured for: (a) overall length (L) from tip to tip; (b) overall width (W) at the widest point; and (c) thickness (t) at five equidistant points along the centerline (Figure 2), with the mean of the five readings (S1–S5) reported as mean thickness, mitigating the influence of local anatomical variability. Slenderness ratio was computed as S = L/t. Individual strand weight was recorded on a precision analytical balance (Mettler Toledo ME204, Mettler-Toledo GmbH, Greifensee, Switzerland, resolution 0.1 mg). All measurements were conducted by the same operator to minimize inter-observer variability [23].

Figure 2. Digital micrometer used to determine strand thickness at five points (S1–S5) along the centerline.

2.6. Statistical Analysis

Descriptive statistics (mean, standard deviation, minimum, maximum, skewness) were computed for weight, length, thickness, and slenderness across both species (n = 300 per species). Normality was assessed using the Shapiro–Wilk test; all six distributions (weight, length, and mean thickness for each species) were non-normal ($p < 0.05$), consistent with the right-skewed profiles visible in Figures 3 and 4. Independent-samples *t*-tests are nevertheless robust to non-normality at $n = 300$ per group by the Central Limit Theorem. Between-species differences were tested using independent-samples *t*-tests; Levene's test assessed equality of variances, with Welch's correction applied where heteroscedasticity was confirmed (Levene $p < 0.05$). Effect sizes were quantified as Cohen's d [24]. A two-way factorial ANOVA (Type II sums of squares) was conducted on the balanced sub-sample ($n = 400$) for weight, length, and mean thickness, with Species and Wood Zone as fixed factors; partial eta-squared (η^2) was reported as the effect-size index. Principal Component Analysis (PCA) was applied to standardized values of weight, length, width, and mean thickness ($n = 600$); components with eigenvalues > 1 were retained (Kaiser criterion [25]). Pearson correlations among length, width, and mean thickness were also computed for the combined sample. All analyses were performed in IBM SPSS Statistics v29 [26]. Significance was set at $\alpha = 0.05$ throughout; values $0.05 < p < 0.10$ are described as marginal.

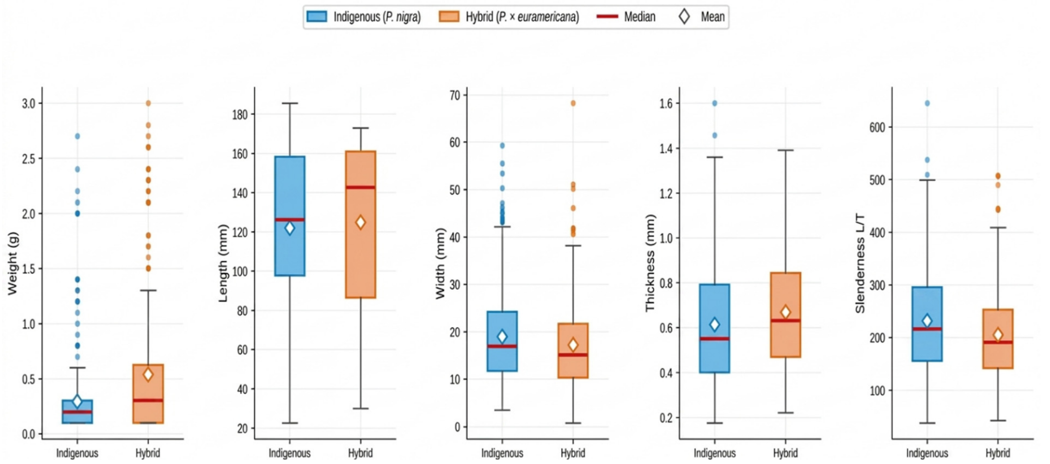

Figure 3. Box plots of the four strand morphological traits by species ($n = 300$ per species). Red line = median; white diamond = mean; circles = outliers.

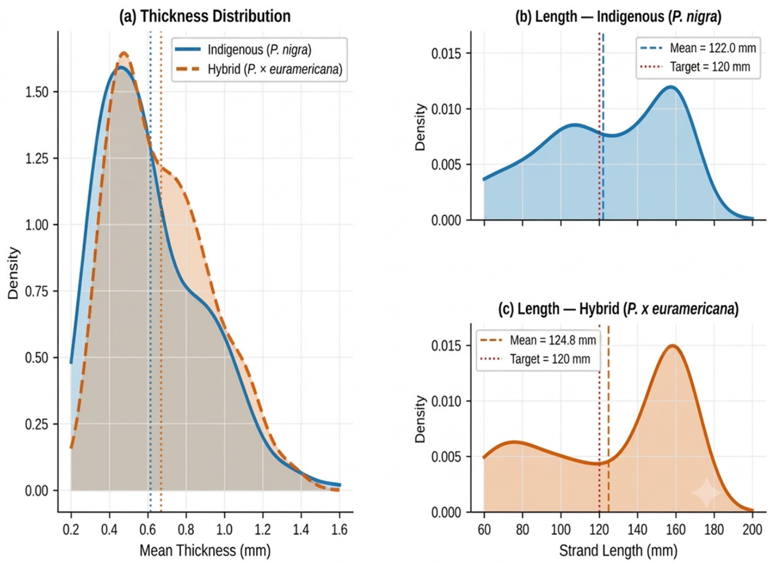

Figure 4. Kernel density estimates of strand mean thickness (**a**) and length for indigenous (**b**) and hybrid (**c**) by species ($n = 300$ per species). Dashed lines = species means; dotted red line in (**b**,**c**) = nominal target length of 120 mm.

3. Results

The morphological analysis of 600 industrially representative strands (300 indigenous and 300 hybrid), including a balanced n = 400 sub-sample stratified by anatomical wood zone, confirmed pronounced geometric and gravimetric heterogeneity in the furnish. The results below quantify this variability and link it to dimensional distributions, formal hypothesis tests, bivariate relationships, and multivariate structure, in line with the statistical framework described in Section 2.6.

3.1. Descriptive Statistics and Dimensional Distributions

Table 1 summarizes the morphological properties of strands from both species (n = 300 per species). Hybrid strands were substantially heavier (mean 0.536 g vs. 0.291 g; +84.2%), reflecting greater cross-sectional dimensions; weight distributions were strongly right-skewed (indigenous: 3.73; hybrid: 2.08). Length was similar between species (mean 121.97 mm indigenous vs. 124.80 mm hybrid), approximating the 120 mm nominal target, with slight negative skewness for both. Indigenous strands were on average slightly wider (18.97 mm vs. 17.19 mm). Thickness was positively skewed for both species (indigenous: 0.81; hybrid: 0.61) Figure 5. Notably, indigenous strands showed higher mean slenderness (231.34 vs. 204.70), both well above the recommended minimum of 150 [5].

Table 1. Descriptive statistics for strand morphological traits (n = 300 per species). SD = standard deviation.

Trait	Species	Min	Max	Mean	SD	Skewness
Weight (g)	Ind. (*P. nigra*)	0.10	2.70	0.291	0.376	3.73
	Hyb. (*P.* × *euramericana*)	0.10	3.00	0.536	0.589	0.73
Length (mm)	Ind. (*P. nigra*)	22.66	185.66	121.97	35.41	−0.45
	Hyb. (*P.* × *euramericana*)	30.03	173.09	124.80	39.30	−0.57
Width (mm)	Ind. (*P. nigra*)	3.52	59.26	18.97	9.65	1.30
	Hyb. (*P.* × *euramericana*)	0.79	68.24	17.19	9.62	1.41
Thickness (mm)	Ind. (*P. nigra*)	0.177	1.600	0.614	0.270	0.81
	Hyb. (*P.* × *euramericana*)	0.222	1.390	0.669	0.250	0.61
Slenderness (L/t)	Ind. (*P. nigra*)	38.20	645.22	231.34	103.65	0.69
	Hyb. (*P.* × *euramericana*)	43.14	507.89	204.70	83.72	2.08

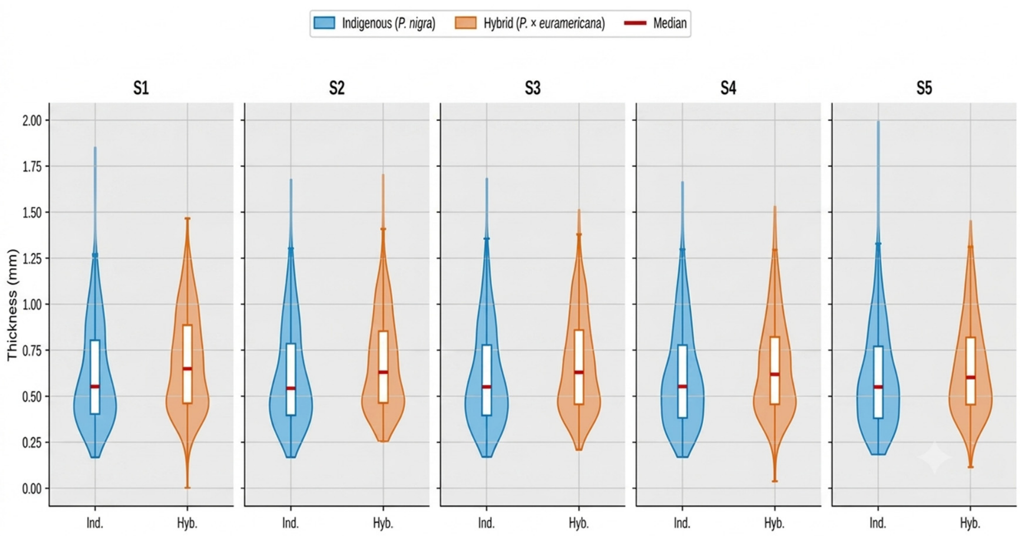

Figure 5. Intra-strand thickness variation across the five measurement points (S1–S5) for indigenous and hybrid poplar (split violin plots), illustrating consistent within-strand thickness but a broader interquartile range for hybrid strands.

Histograms and kernel density estimates (Figure 4) show that indigenous poplar strands exhibit a near-Gaussian length distribution centered close to the nominal target, whereas hybrid strands display a more skewed distribution with a higher frequency of shorter fragments. Width distributions showed comparable spread between species (SD $\approx$ 9.6 mm for both), with indigenous strands slightly wider on average. Thickness density estimates show both species peaking near 0.45–0.50 mm, with hybrid strands displaying a heavier upper tail consistent with their higher mean thickness (0.669 mm vs. 0.614 mm). Intra-strand thickness variation across the five measurement points (S1–S5) is illustrated in Figure 5.

3.2. Between-Species Differences: Independent-Samples t-Tests

Table 2 presents independent-samples *t*-test results for all five strand traits (n = 300 per species; Welch correction applied where Levene's test indicated unequal variances). Weight showed the largest between-species difference (t = 6.063, $p < 0.001$, Cohen's d = 0.495, medium effect). Width also differed significantly (t = 2.257, $p = 0.024$, d = 0.184, small effect), with indigenous strands slightly wider on average. Thickness differed significantly (t = 2.607, $p = 0.009$, d = 0.213; mean Δ = 0.055 mm), with hybrid strands systematically thicker—practically relevant for mat density uniformity [27]. Slenderness differed significantly (t = 3.405, $p = 0.001$, d = 0.278), with indigenous strands showing higher slenderness (231.34 vs. 204.70); both provenances remain above the recommended minimum of 150 [5]. Importantly, strand length did not differ significantly between species (t = 0.927, $p = 0.354$, d = 0.076, negligible effect).

Table 2. Independent-samples *t*-test results (n = 300 per species). Welch correction applied where Levene's test indicated unequal variances (Weight, Slenderness). ns = not significant; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Trait	t	*p*-Value	Cohen's d	Effect Size	Sig.
Weight (g)	6.063	<0.001	0.495	Medium	***
Length (mm)	0.927	0.354	0.076	Negligible	ns
Width (mm)	2.257	0.024	0.184	Small	*
Thickness (mm)	2.607	0.009	0.213	Small	**
Slenderness (L/t)	3.405	0.001	0.278	Small	***

3.3. Two-Way ANOVA: Species × Wood Zone Effects

Table 3 reports the two-way factorial ANOVA (Type II sums of squares, n = 400). Only weight showed a significant main effect of species ($F(1, 396) = 24.784$, $p < 0.001$, $\eta^2 = 0.059$). The main effect of species was non-significant for both length ($F(1, 396) = 1.605$, $p = 0.206$) and thickness ($F(1, 396) = 2.295$, $p = 0.131$). Wood zone was non-significant for all three traits (all $p > 0.48$). The Species × Zone interactions for length ($p = 0.096$) and thickness ($p = 0.094$) were marginal but did not reach $\alpha = 0.05$. Figure 6 presents the ANOVA interaction plots, illustrating the pattern of means across zones for both species. These results indicate that, once anatomical position is controlled for in a full factorial model, species identity reliably predicts strand weight but not strand length or thickness; the *t*-test differences observed for length and thickness in Section 3.2, while statistically significant at n = 600, do not represent robust factorial effects once zone is accounted for. The absence of zone effects is consistent with the disk flaker integrating across the full cross-section of each disk, which averages local anatomical variation and may mask finer-scale within-stem patterns.

3.4. Bivariate Correlations and Dimensional Coupling

The relationship between length and width was examined using scatterplots with linear regression (Figure 7). Both provenances show a mild positive correlation between length and width (indigenous: r = 0.29; hybrid: r = 0.38; both $p < 0.001$). When the two datasets are combined ($n = 600$), the Pearson correlation structure among length, width, and mean thickness is summarized in Table 4.

Table 3. Two-way factorial ANOVA (Type II sums of squares) for strand weight, length, and mean thickness ($n = 400$; 100 per Species × Wood Zone cell). NS = not significant; † marginal ($0.05 < p < 0.10$); ** $p < 0.001$.

Trait	Source	df (eff.)	df (err.)	F	*p*	η^2	Sig.
Weight (g)	Species	1	396	24.784	<0.001	0.059	**
	Wood Zone	1	396	0.497	0.481	<0.001	NS
	Species × Zone	1	396	1.033	0.310	0.003	NS
Length (mm)	Species	1	396	1.605	0.206	0.004	NS
	Wood Zone	1	396	0.008	0.929	<0.001	NS
	Species × Zone	1	396	2.789	0.096	0.007	†
Thickness (mm)	Species	1	396	2.295	0.131	0.006	NS
	Wood Zone	1	396	0.063	0.803	<0.001	NS
	Species × Zone	1	396	2.820	0.094	0.007	†

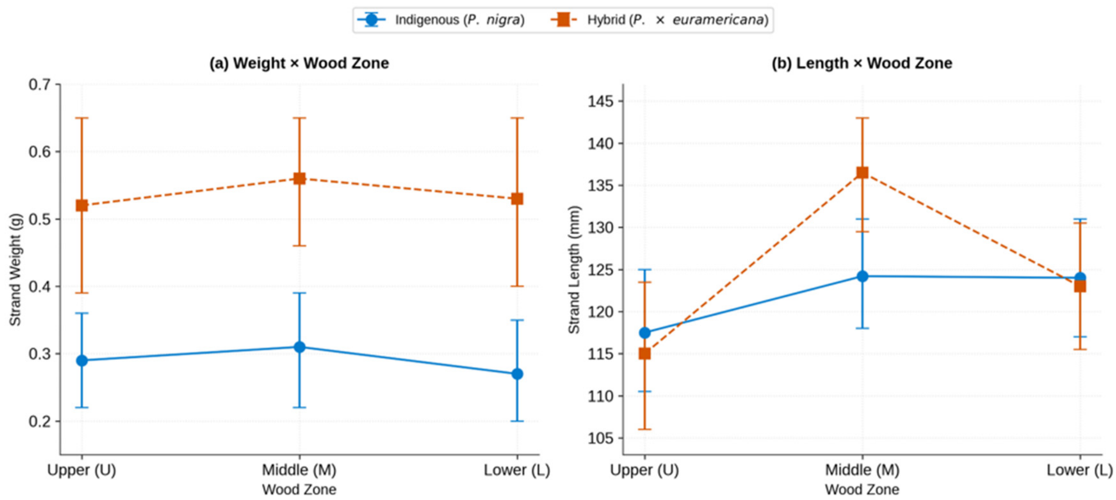

Figure 6. ANOVA interaction plots (mean ± SEM, $n = 100$ per cell) for strand weight (**a**) and length (**b**) by Species × Wood Zone. The crossing pattern for length ($p = 0.096$, marginal) suggests a trend toward interaction warranting investigation with larger samples.

Table 4. Pearson correlation matrix for length, width, and mean thickness (combined dataset, $n = 600$). All correlations significant at $p < 0.001$.

Variable	Length	Width	Mean Thickness
Length	1.00	0.34	0.28
Width	0.34	1.00	0.28
Mean Thickness	0.28	0.28	1.00

Strand weight was also examined jointly with slenderness ratio (Figure 8), since both traits independently differentiated the species (Table 2) and weight is the only trait with a robust factorial species effect (Table 3). A weak negative association was observed for indigenous strands (r = −0.18, $p = 0.002$), whereas the relationship was non-significant for hybrid strands (r = −0.10, $p = 0.077$). Despite this tendency, the great majority of strands for both species remained above the recommended minimum slenderness of 150 [5], so the practical alignment performance of the furnish is not expected to be compromised.

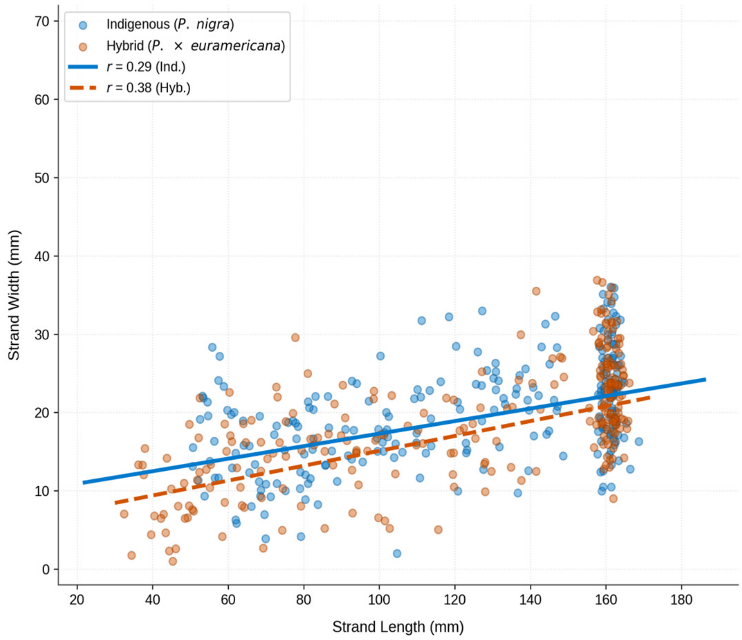

Figure 7. Dimensional correlation between strand length and width, with regression lines, for both provenances.

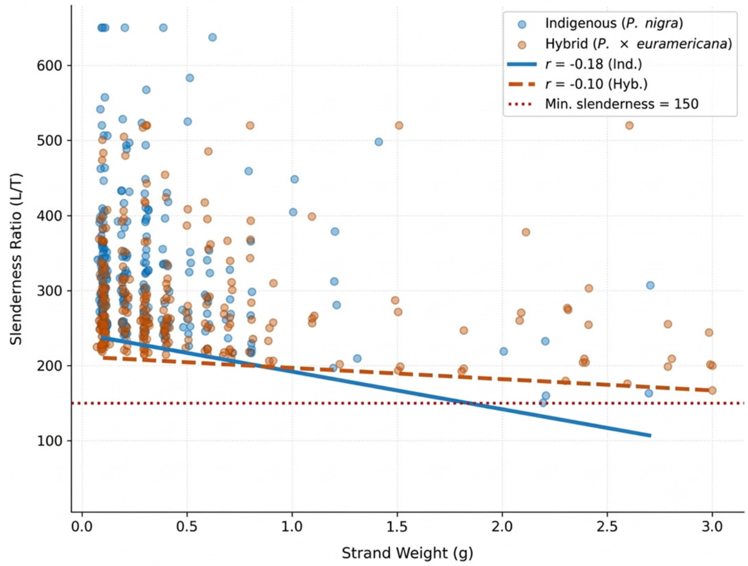

Figure 8. Slenderness ratio vs. strand weight by species (n = 300 per species). Dashed lines = species regression fits with Pearson r values; dotted red line = recommended minimum slenderness of 150.

The moderate positive correlation between width and mean thickness suggests that coarser strands tend to be both wider and thicker, particularly in the hybrid furnish. The relatively low correlation between length and thickness indicates that fragmentation processes affect length more strongly than thickness, which is largely governed by flaker settings and wood anatomy rather than breakage.

3.5. Multivariate Differentiation: Principal Component Analysis

To synthesize the multidimensional variability, a combined PCA was performed on all 600 strands using four standardised input variables: weight, length, width, and mean thickness. The first two principal components together explained 75.6% of total variance (PC1 = 57.0%, PC2 = 18.6%; Table 5).

Table 5. PCA loadings for the first two principal components (n = 600; variables: weight, length, width, mean thickness). h^2 = communality (PC1 + PC2 combined).

Variable	PC1 (57.0% Variance)	PC2 (18.6% Variance)	Communality (h^2)
Weight (g)	0.59	−0.09	0.36
Length (mm)	0.43	−0.16	0.21
Width (mm)	0.52	−0.47	0.50
Mean Thickness (mm)	0.43	0.86	0.93

PC1 is dominated by weight and width (loadings ≥ 0.52), capturing the overall size and coarseness of the furnish. PC2 is driven by mean thickness (loading = 0.86), reflecting strand cross-sectional profile. The PCA scores clearly separate the two provenances: hybrid strands shift toward positive PC1 values (heavier, wider; mean PC1 = +0.16), while indigenous strands cluster in the negative PC1 region (mean PC1 = −0.16; Table 6, Figure 9). PC2 centroids were ±0.11 for both groups, consistent with the non-significant length difference between species.

Table 6. Mean PCA scores (PC1 and PC2) for indigenous and hybrid poplar strands.

Provenance	Mean PC1 Score	Mean PC2 Score
Indigenous	−0.16	−0.11
Hybrid	0.16	0.11

Figure 9. PCA biplot showing multivariate clustering of indigenous and hybrid poplar strands (n = 600), including loading vectors for weight, length, width, and mean thickness (PC1 = 57.0%, PC2 = 18.6%).

These results confirm that PCA provides a robust "morphological fingerprint" of the furnish, with hybrids occupying a distinct region of the PC1–PC2 space characterized by coarser geometry and higher dimensional variability—consistent with, and statistically corroborated by, the factorial ANOVA results in Section 3.3.

4. Discussion

The morphological characterization of strands from indigenous *P. nigra* and hybrid *P.* × *euramericana* reveals that the two provenances produce measurably distinct strand populations, but the nature and magnitude of these differences depend critically on the statistical framework applied. The two-way ANOVA, which partitions species and zone effects simultaneously, identifies strand weight as the primary axis of inter-species differentiation. This is biologically expected: hybrid poplars typically exhibit 10–20% lower basic wood density than indigenous black poplar [13,14], yet faster radial growth produces broader annual rings that translate into heavier strands per unit knife pass. The medium effect size ($\eta^2 = 0.059$) confirms that species identity is a reliable predictor of strand weight and, by extension, mat mass distribution.

4.1. Fragmentation Mechanics and Structural Reliability

In contrast, the non-significant ANOVA effects for length ($p = 0.206$) and thickness ($p = 0.131$) indicate that the t-test differences for these traits—though statistically significant at $n = 600$ (Section 3.2)—do not represent robust factorial effects once anatomical wood zone is accounted for. This distinction is practically important: from an OSB manufacturing perspective, species blending primarily introduces strand weight heterogeneity into the mat rather than dimensional heterogeneity, and alignment-system settings or strand-length screening thresholds need not differ substantially between the two provenances [28]. This conclusion is supported by the PCA, where PC1—dominated by weight and width—drove the between-species separation, while length's modest loading (0.43 on PC1, −0.16 on PC2) is consistent with its non-significant ANOVA result. The skewed length distribution and higher frequency of short fragments in hybrid strands (Table 1, Figure 4) nonetheless suggest a modest tendency toward fragmentation during flaking, plausibly linked to lower basic density and more heterogeneous anatomy [3,10,12]; slenderness ratios L/t remained well above 150 for both provenances, indicating that the furnish remains within the range considered adequate for efficient load transfer in structural composites [5,7,29].

4.2. Thickness Variance, VDP Formation, and Pressing Strategy

Thickness emerged as a practically relevant, if not factorially dominant, source of variability between provenances. The higher mean thickness observed in hybrids (Table 1), together with the broader intra-strand variability revealed by the violin plots (Figure 5), indicate that hybrid furnish is more likely to form a heterogeneous mat. Thicker strands act as thermal insulators during hot pressing, slowing heat transfer to the core and delaying resin cure [29]. Consequently, hybrid-based panels, and particularly mats blending both provenances, may require adjusted pressing schedules—longer press times or higher platen temperatures—to achieve comparable core densification and internal bond (IB) strength relative to panels made predominantly from indigenous poplar [12,13]. The combination of significantly higher weight and a small but significant thickness difference reinforces the need to account for both gravimetric and dimensional distributions, not just mean values, when optimizing press parameters for mixed-provenance furnish.

4.3. Dimensional Coupling, Resin Efficiency, and Outlier Screening

The correlation matrix (Table 4) and PCA loadings (Table 5) show that width and mean thickness are moderately correlated and jointly dominate PC1, which separates the two provenances. This coarseness axis has direct implications for resin efficiency: coarser strands have a lower specific surface area per unit mass, meaning that a fixed resin dosage will result in more resin per unit area for hybrids than for indigenous strands [15]. The box plots (Figure 3) further reveal pronounced outliers in weight and slenderness for both species—strands far exceeding the median that likely arise from local density gradients, knot proximity, and grain deviation. Such outliers can cause local density spikes in OSB mats, degrading surface quality and bending-stiffness uniformity; a production screening step removing strands above the 95th percentile in weight, or below the 10th percentile in slenderness, could substantially reduce mat heterogeneity for both provenances.

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4.4. Anatomical Zone Effects and Implications for Industrial Optimization

Wood zone had no significant main effect on any trait (all $p > 0.48$), and the marginal Species × Zone interactions observed for length and thickness ($p = 0.094$–0.096) did not reach conventional significance, although the crossing pattern visible in the interaction plots (Figure 6)—hybrid strands from Zone L tending to be longer than Zone U strands, with the opposite trend in indigenous strands—warrants investigation with larger within-cell sample sizes (e.g., $n = 200$) in future work. The absence of strong zone effects is consistent with the disk flaker integrating across the full radial cross-section of each log disk, which averages local anatomical variation and may mask finer-scale within-stem patterns. Taken together, the dimensional statistics, formal hypothesis tests, correlation structure, and PCA results demonstrate that indigenous and hybrid poplar furnish behave as distinct morphological populations primarily through strand weight and cross-sectional coarseness rather than through systematic anatomical-zone effects. For mills aiming to integrate hybrids into existing OSB or LSL lines, this implies that resin dosing and pressing-schedule adjustments should be calibrated chiefly to provenance-specific weight and thickness distributions, while flaker knife settings and zone-specific harvesting protocols may be standardized across stem height with comparatively little loss of furnish uniformity. Future work should couple the present dataset with full mechanical testing (MOR, MOE, IB, thickness swelling) to quantify the direct performance consequences of the observed gravimetric and dimensional differences.

5. Conclusions

This study provides a statistically validated morphological characterization of 600 industrially representative poplar strands, combining descriptive analysis, independent-samples *t*-tests, a balanced two-way factorial ANOVA (Species × Wood Zone), and multivariate PCA. Hybrid poplar (*Populus × euramericana*) strands were significantly heavier than indigenous (*Populus nigra*) strands (0.536 g vs. 0.291 g; +84.2%; Cohen's d = 0.495, medium effect), and this weight difference remained the dominant, statistically robust inter-species effect across all analyses, confirmed by the two-way ANOVA ($F(1, 396) = 24.784$, $p < 0.001$, $\eta^2 = 0.059$). Independent-samples *t*-tests detected significant between-species differences for four of the five strand traits examined (weight, width, thickness, and slenderness; $p < 0.05$), with strand length not differing significantly between provenances ($p = 0.354$), but once anatomical wood zone was accounted for in the factorial model, species differences in length ($p = 0.206$) and thickness ($p = 0.131$) were no longer significant, indicating that these smaller dimensional effects are less robust than the weight effect. Wood zone (lower-stem versus upper-stem) had no significant effect on any trait, and Species × Zone interactions for length and thickness were only marginal ($p = 0.094$–0.096), suggesting a possible zone-dependent species effect that merits further investigation with larger samples.

Principal Component Analysis extracted a weight-and-width axis (PC1, 57.0% of variance) that clearly separated the two provenances, and a thickness-profile axis (PC2, 18.6% of variance) showing more modest species differentiation, corroborating the ANOVA results. Box plots revealed substantial outlier populations in weight and slenderness for both species, highlighting the value of production screening to reduce mat density heterogeneity. Both species produced strands with slenderness ratios well above the recommended minimum of 150 (indigenous: 231.34; hybrid: 204.70), confirming suitability for structural OSB and LSL manufacturing. Overall, these findings indicate that blending indigenous and hybrid poplar provenances in industrial furnish primarily introduces strand-weight heterogeneity—rather than dimensional heterogeneity—into the mat, with direct implications for resin dosing, mat density uniformity, and pressing-schedule calibration. This study demonstrates that combining detailed morphological and gravimetric measurements with formal statistical testing and multivariate analytics provides a scientifically rigorous and practically actionable pathway for understanding furnish behavior and optimizing industrial composite manufacturing.

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