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Mechanical Performance of Single and Double English Knots in 210D/21 Multifilament Polyamide Netting

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ABSTRACT

This study evaluates the mechanical performance of Single English Knot (SEK) and Double English Knot (DEK) configurations in 210D/21 multifilament polyamide (PA) netting. Monotonic tensile testing was conducted in strict accordance with the ISO 1805 standard using a universal testing machine (UTM) under standardized environmental conditioning. The statistical analysis, executed via Welch's t-test and supplemented by Hedges' g effect size estimation, revealed that the DEK configuration exhibited a significantly higher mean breaking strength of 290.1 N compared to 263.5 N for the SEK ($p < 0.001$; Hedges' $g = 2.45$). Conversely, the SEK demonstrated greater extensibility, yielding an average elongation at break of 34.71%, whereas the DEK reached 32.25% ($p < 0.001$; Hedges' $g = -2.10$). Notably, structural failure consistently occurred within the mesh legs rather than at the knot junctions; no knot rupture or slippage was observed under the experimental conditions. The superior tensile resistance of the DEK is attributed to its complex interlocking geometry, which extends the fiber-to-fiber contact area, increases cumulative friction, and optimizes intra-twine stress distribution, albeit at the expense of longitudinal extensibility. These structural insights suggest that the DEK configuration is highly advantageous for capture fisheries applications requiring tight dimensional mesh stability. However, further investigations addressing dynamic cyclic fatigue and long-term environmental weathering remain imperative to definitively determine its operational field durability.

1. INTRODUCTION

In the Indonesian archipelago, capture fisheries are overwhelmingly dominated by small-scale fisheries (SSF), which serve as the socio-economic backbone for coastal communities [1, 2]. However, traditional fishers often construct their fishing gear without standardized engineering designs, frequently relying on empirical habits rather than mechanical principles when selecting knot configurations, such as the Single English Knot (SEK) or Double English Knot (DEK). Multifilament polyamide (PA) netting remains the fundamental material in these global and local capture fisheries due to its superior mechanical stability, high tensile strength, and flexibility. While recent studies have heavily explored biodegradable alternatives to mitigate environmental impacts [3], conventional PA twines consistently exhibit higher catch efficiency and operational durability [4], making them indispensable for high-load commercial applications [5]. Consequently, maximizing the mechanical efficiency and longevity of PA nets through structural optimization is critical. Enhancing the mechanical retention of these nets not only sustains consistent fishing performance under variable field conditions, but also serves as a pragmatic engineering approach to reducing the frequency of gear failure, thereby mitigating the ecological ramifications associated with discarded nets and ghost fishing.

Within these net structures, the knot configuration serves as a critical design variable that governs the overall mechanical integrity of the mesh [6, 7]. From a structural engineering perspective, knots act as geometric discontinuities that alter stress distribution and influence load transfer mechanisms [8]. In fibrous systems subjected to tensile loading, the internal architecture of a knot determines the degree of inter-fiber friction and strain accommodation [9]. For instance, analogous to biomechanical findings in PA multifilament structures [10], incorporating more complex topologies, such as DEK, theoretically provides a larger contact area and higher frictional resistance compared to the simpler SEK. However, an increase in knot complexity may restrict the extensibility of the mesh bars, highlighting a necessary mechanical trade-off between absolute breaking strength and elongation capacity that requires precise quantification.

Despite the widespread application of PA netting, the specific mechanical performance differences between SEK and DEK topologies in high-density multifilament twines (e.g., 210D/21) remain empirically unquantified. Previous literature has primarily focused on the chemical degradation or general tensile properties of unknotted twines, leaving a substantial research gap regarding how specific knot topologies regulate mesh failure modes under monotonic loading. Therefore, this study aims to comparatively evaluate the mechanical performance of SEK and DEK configurations in 210D/21 multifilament PA netting. The explicit contributions of this study are:

(1) quantifying the absolute breaking strength and elongation differences between SEK and DEK structures under standardized ISO tensile loading conditions;

(2) elucidating the topological influence of knot geometry on stress distribution and failure mode localization (i.e., whether failure occurs at the knot junction or the mesh legs;

(3) providing empirical, engineering-based guidelines for net manufacturers and small-scale fishers in selecting knot configurations that optimally balance tensile resistance and mesh stability for long-term operational sustainability.

2. MATERIALS AND METHODS

2.1 Material specifications and sampling design

The experimental evaluations were performed using commercially manufactured multifilament PA netting. To eliminate potential material heterogeneity and confounding biases across experimental groups, all net specimens were systematically harvested from a single, identical industrial production batch manufactured at PT Arteria Daya Mulia, Indonesia. The primary material under evaluation was high-density PA netting with a nominal commercial specification of 210D/21.

To ensure complete empirical replicability and transparency, the structural and geometric architecture of the twine was rigorously quantified and standardized. The multifilament twine exhibited an actual measured diameter of 1.9 mm and a calculated linear density of 532.2 tex. The 210D/21 designation indicates a nominal structure of 21 single yarns, each with a linear density of 210 denier (yielding a theoretical total of 4410 denier). However, due to structural contraction (twist take-up) caused by the primary (309 TPM) and secondary (180 TPM) twisting processes, the actual assembled total linear density increases to the measured 4789.9 denier (equivalent to 532.2 tex). The internal structural integrity of the fibrous assembly was maintained via a precise twisting configuration, characterized by a primary twist level of 309 turns per meter (TPM) and a secondary twist level of 180 TPM. The nominal mesh size was specified at 4.0 inches, with the actual knot-to-knot geometry tightly regulated within an operational range of 99.6–103.6 mm (±2% tolerance limit). Two distinct knot topologies were evaluated: SEK and DEK. A total of 20 complete mesh specimens were prepared and evaluated (n = 10 independent replicates per knot configuration). Crucially, to eliminate human error, non-uniform hand-tightening, and subjective variations in pretension, all knot topologies evaluated in this study were machine-tied under standardized automated mechanical tension using industrial net-making looms.

2.2 Mechanical testing protocol

Quasi-static monotonic tensile tests were conducted utilizing a Shimadzu AGS-J 1 kN universal testing machine (UTM) [11], integrated with Trapezium II software for real-time high-resolution data acquisition. Prior to mechanical characterization, all netting specimens were conditioned in a climate-controlled laboratory environment maintained at a standardized temperature of 20 ± 2 °C and a relative humidity of 65 ± 4% for 48 hours, strictly adhering to standard textile testing atmospheres [12, 13]. All destructive tensile tests were executed under dry laboratory conditions.

The mechanical testing protocol adhered strictly to the ISO 1805 standard for the determination of breaking force and elongation of netting yarns [14]. The testing apparatus was configured with specialized anti-slip bollard grips designed specifically to prevent localized stress concentrations at the fixtures and to eliminate clamp slippage. Extensive validation confirmed that grip slip was negligible under the maximum load regimes encountered; consequently, material elongation and strain accommodation were validly and directly derived from the crosshead displacement data. The UTM was configured with a nominal gauge length of 250 mm, and the crosshead pulling speed was maintained at a constant velocity of 500 mm/min. This specific kinematic profile ensured that progressive, monotonic failure occurred within the standard-mandated temporal window of 17–23 seconds.

During testing, each specimen was meticulously aligned parallel to the principal loading axis to minimize parasitic bending or torsional stresses. To preserve data validity, any specimen that exhibited catastrophic failure within the gripping zone or demonstrated visible structural damage induced by the clamp fixtures was rejected from the analysis and replaced with a fresh replicate.

2.3 Statistical analysis

To strictly align the manuscript with international scientific reporting standards, the primary metric of mechanical force utilized throughout this study is the Newton (N). Raw breaking strength values initially recorded in kilogram-force (kgf) were converted using the standard acceleration of gravity (1 kgf = 9.80665 N), and all subsequent datasets were formatted utilizing dot decimals [15].

Statistical analyses were carefully tailored to evaluate the absolute mechanical differences between the SEK and DEK topologies. Given the specific constraints of the small sample size (n = 10 replicates per group), and following established methodological frameworks for small datasets [16], the central tendencies and structural differences between the two configurations were evaluated using Welch's independent-samples t-test. This approach avoids the restrictive assumption of equal population variances. The experimental results are expressed as the mean ± standard deviation (SD). To provide robust parameter estimation, 95% confidence intervals (CI) for the mean differences were explicitly computed and reported [17].

To evaluate the magnitude and practical significance of the topological effect independently of the sample size, the standard effect size was quantified using Hedges' g, which incorporates a correction factor specifically optimized for small samples (n < 20) to prevent the overestimation of effect magnitudes [16]. The assumption of normality was evaluated via the Shapiro-Wilk test. The relative percentage change in mechanical parameters of the DEK relative to the SEK configuration was computed via the following equation:

$$Percentage\ change = (\frac{\mu\, DEK - \mu\, SEK}{\mu\, SEK}) \times 100\%$$

All inferential statistical calculations were performed using SPSS v26 software, with the a priori level of statistical significance established at $\alpha = 0.05$.

3. RESULTS AND DISCUSSION

3.1 Breaking strength and mechanical failure modes

Quasi-static monotonic tensile characterization of the 210D/21 multifilament PA netting revealed clear, systematic variations in mechanical performance dictated by knot topology. As illustrated by the empirical distribution in Figure 1, the DEK configuration exhibited a distinct upward shift in ultimate tensile capacity compared to the SEK. The DEK group achieved a mean breaking strength of 290.1 ± 11.3 N (spanning a tight, homogeneous range of 277.5–302.6 N), whereas the SEK group demonstrated a lower mean breaking strength of 263.5 ± 9.4 N (ranging between 254.1 and 276.6 N). The absolute mean difference of 26.6 N represents a +10.10% increase in peak tensile capacity directly attributable to the double-wrap topological architecture.

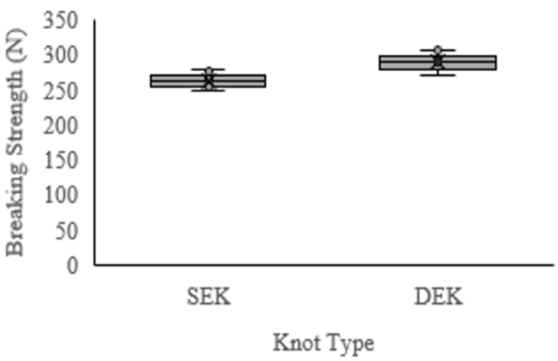

Figure 1. Empirical distribution of ultimate breaking strength (N) for Single English Knot (SEK) and Double English Knot (DEK) configurations (n = 10 per group)

Note: Box plots define the interquartile range (IQR), internal horizontal lines signify medians, diamonds indicate group means, and individual data points reflect actual replicate values.

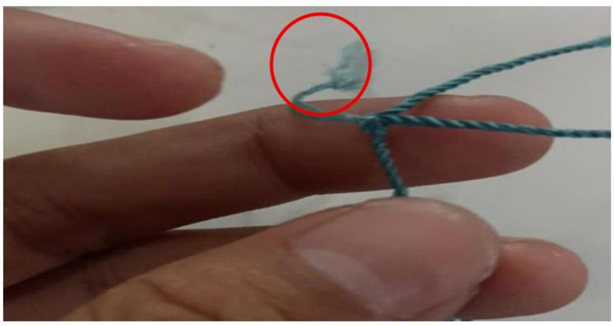

Figure 2. Representative post-failure netting specimen showing catastrophic tensile rupture localized within the mesh legs (red circle), while the knot junction remains intact

The assumptions of normality and homoscedasticity were assessed prior to hypothesis testing using Shapiro–Wilk and Levene's tests, respectively, with all p-values exceeding 0.05. Welch's independent-samples t-test confirmed that the observed increase in peak load for the DEK configuration was statistically highly significant ($t(17.43) = 5.71$, $p < 0.001$). The magnitude of this experimental variance was substantial, as demonstrated by an exceptionally large standardized effect size (Hedges' g = 2.45), confirming that the topological advantage is robust and practically meaningful.

Despite the significant variance in peak breaking force, the macroscopic failure localization was perfectly uniform across all experimental groups. In 100% of the destructive trials (n = 20/20), catastrophic structural rupture occurred exclusively within the linear mesh legs. No incidences of knot structural failure, macroscopic slippage, or localized unraveling were detected at the junction cores under the single-pull monotonic loading protocol (Figure 2).

3.2 Mesh elongation at break

In stark contrast to the ultimate breaking strength trends, the simpler topological architecture of the SEK configuration offered superior global extensibility prior to failure. The empirical data distribution indicates that the structural transition from SEK to DEK significantly limits the material's capacity for strain accommodation (Figure 3). The SEK specimens achieved a mean elongation at break of 34.71 ± 0.96% (ranging from 33.40% to 36.10%), whereas the DEK specimens exhibited a reduced mean elongation of 32.25 ± 1.45% (ranging from 30.10% to 34.20%). This absolute reduction of 2.46 percentage points (95% CI: 1.29–3.63%) equates to a −7.09% reduction in deformability for the double-knotted net system.

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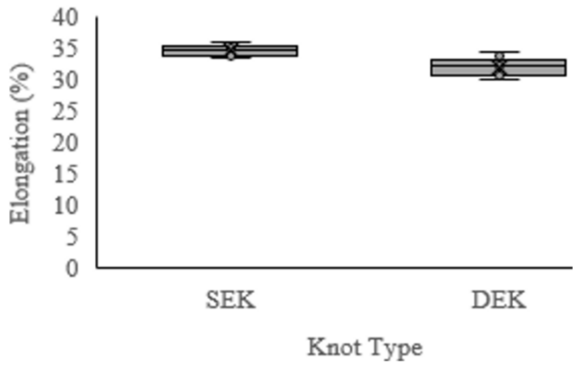

Figure 3. Empirical distribution of elongation at break (%) for Single English Knot (SEK) and Double English Knot (DEK) netting configurations (n = 10 per group)

Note: Diamonds represent group means, demonstrating a significant reduction in deformability for the DEK group.

Welch's independent-samples t-test confirmed that the lower extensibility observed in the DEK group was statistically significant ($t(15.60) = 4.47$, $p < 0.001$), accompanied by a very large standardized effect size (Hedges' g = 1.92).

3.3 Mechanical mechanisms and topological trade-offs

The empirical absence of overlap between the breaking strength ranges of the SEK (254.1–276.6 N) and DEK (277.5–302.6 N) establishes that the mechanical superiority of the double-wrap topology is a systematic structural phenomenon rather than an artifact of outlier distribution. From a structural mechanics perspective, the elevated breaking strength of the DEK is governed by its complex interlocking pathway. The additional yarn wrap inherent to the DEK amplifies both the effective contact length and the cumulative normal contact pressure acting at the internal yarn-to-yarn interfaces within the knot core [18]. When subjected to axial tension, this dense geometrical configuration enhances frictional load transfer, restricting internal yarn slippage and thereby delaying structural failure.

The uniform localization of catastrophic failure within the mesh legs, rather than at the knot junctions, challenges the conventional assumption that knots invariably represent the absolute weakest structural link in netting systems. This exclusive mesh-bar failure observed under quasi-static conditions indicates that the machine-controlled automated tightening and standardization of pretension on industrial looms successfully brought both the SEK and DEK to a stable, highly locked state. In this state, internal clamping friction effectively suppresses relative slipping within the knot core, redistributing the peak tensile stresses away from the junction and directly into the uncurved mesh legs. This stable anchoring behavior demonstrates that when high-grade synthetic filaments are paired with precise machine fabrication, the knot junction can match or exceed the nominal tensile capacity of the parent yarn.

The structural trade-off observed between ultimate strength and elongation at break represents a fundamental mechanical phenomenon governed by topology-dependent strain accommodation. The SEK configuration features fewer interlocking loops and a less restricted physical pathway, making it more permissive to internal yarn rearrangement and micro-slippage prior to macro-rupture, which manifests as a higher global extensibility (34.71%) that facilitates strain-energy absorption. Conversely, the strict geometric constraint of the DEK forces an earlier and stiffer mechanical interlocking of the filaments under lower initial displacements [18]. This limitation prevents extraction of the multifilament twine's hidden length, resulting in significantly higher peak load resistance at the direct expense of reduced total deformation capacity.

From an engineering design perspective, the selection of the optimal knot topology must be strategically aligned with the specific environmental and operational demands of the target fishery. The DEK topology proves to be highly advantageous for gear applications that prioritize strict dimensional stability, low mesh distortion, and maximum peak load resistance under heavy hydrodynamic drag pressures. On the other hand, the SEK remains suitable for specific marine deployments where flexibility, elastic compliance, and high strain-energy dissipation are required to withstand transient dynamic impacts. Therefore, balancing these structural trade-offs allows gear technologists to optimize netting performance according to the unique load-bearing requirements of different small-scale capture operations.

To provide a comprehensive and accessible overview for fishery applications, the quantitative mechanical parameters of both knot configurations and their qualitative engineering implications are synthesized in Table 1.

Table 1. Summary of mechanical parameters, statistical comparisons, and operational implications of SEK and DEK configurations

Mechanical Parameter	SEK (μ ± SD)	DEK (μ ± SD)	95% CI of Diff.	*p*-value	Hedges' g
Breaking strength (N)	263.5 ± 9.4	290.1 ± 11.3	[16.8, 36.4]	<0.001	2.45
Elongation at break (%)	34.71 ± 0.96	32.25 ± 1.45	[1.25, 3.67]	<0.001	−2.1

Note: SEK = Single English Knot, DEK = Double English Knot, SD = standard deviation, CI = confidence intervals.

3.4 Applicability, limitations, and field durability

Although the DEK configuration demonstrates a clear mechanical advantage under quasi-static monotonic tensile loading in a laboratory setting, extrapolating this initial strength to long-term field durability requires extreme caution. Netting systems operated in marine environments are exposed to various degrading factors that were not evaluated in the present study. For instance, prolonged exposure to natural sunlight triggers photo-oxidative degradation, which progressively reduces the breaking strength of PA fishing net materials over time [19]. Furthermore, the mesh breaking strength of PA nets is significantly altered by exposure to varying temperatures and aquatic environmental concentrations [13]. Multi-season marine operations and long-term use also lead to continuous structural degradation of the netting systems [20].

Because the current study did not evaluate these environmental and dynamic variables, the unweathered strength of the DEK documented here must be viewed strictly as a baseline mechanical capability. Consequently, actual field durability is not claimed as an absolute conclusion in this study; rather, it represents a critical parameter that necessitates future empirical testing under controlled marine weathering conditions.

From a practical standpoint, the applicability of these mechanical findings is inherently limited to the specific parameters tested, namely machine-fabricated 210D/21 multifilament PA twine. Nevertheless, within these explicit limitations, the findings provide a relevant mechanical baseline for small-scale fisheries, which dominate coastal capture operations and rely heavily on gear efficiency to sustain their livelihood strategies [1, 2]. Transitioning to the DEK configuration offers a strictly mechanical strategy to maximize the initial load-bearing capacity of the gear before inevitable environmental degradation occurs.

4. CONCLUSIONS

This study evaluated the mechanical trade-offs between SEK and DEK configurations in multifilament PA netting. The results conclusively demonstrate that knot topology fundamentally governs the balance between tensile resistance and deformability. The DEK provides a systematically higher breaking strength due to increased frictional interlocking, whereas the SEK yields superior elongation, allowing for greater structural compliance. Crucially, the exclusive occurrence of mesh-bar failures across all specimens challenges the conventional assumption that knots invariably act as the weakest point in netting systems. Under the tested quasi-static conditions, both knot configurations functioned as robust anchoring elements rather than preferential failure initiators.

These findings contribute to the existing body of knowledge by providing empirical evidence that strategic knot selection can be used to optimize net performance for specific operational regimes. When dimensional stability and peak load resistance are prioritized, the DEK is highly advantageous. Conversely, the SEK remains preferable for applications demanding high energy absorption and flexibility. By demonstrating that high-quality material paired with consistent knot construction can shift the failure locus away from the junction, this study offers a functional baseline to enhance overall gear integrity.

These mechanical improvements also have environmental implications: enhancing net structural integrity is a critical strategy for extending gear service life and subsequently mitigating gear loss, ghost fishing, and marine plastic pollution. However, while the DEK exhibits superior initial quasi-static strength, long-term durability in marine environments is governed by a complex interplay of mechanical fatigue and environmental degradation. Therefore, future research must prioritize cyclic and dynamic loading tests integrated with controlled environmental weathering, such as prolonged UV exposure, saltwater immersion, and abrasion, to translate these laboratory-based rankings into reliable predictions of operational lifetime.

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NOMENCLATURE

SEK	Single English Knot
DEK	Double English Knot
PA	Polyamide
N	Newton (unit of mechanical force)
kgf	Kilogram-force
SD	Standard Deviation
CI	Confidence Interval