

Multiscale mechanical performance of plant-based and hybrid yarns for biodegradable fishing Net

Shaghayegh Nazari

Hong Kong University of Science and Technology

Li Li

lillyli@ust.hk

Hong Kong University of Science and Technology

Article

Keywords: Pineapple leaf fiber (PALF), hybrid yarn, knot mechanics, biodegradable fishing net

Posted Date: October 9th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11058187/v1>

License:  This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Multiscale mechanical performance of plant-based and hybrid yarns for biodegradable fishing Net

Shaghayegh Nazari ¹, Li Li ^{1,*}

¹ Division of Integrative Systems and Design, The Hong Kong University of Science and Technology, Hong Kong, 999077, PR China

* Corresponding author

E-mail addresses: lillyli@ust.hk

Abstract

Marine plastic pollution from abandoned fishing gear has intensified the search for lower-persistence netting materials that retain adequate mechanical performance. This study investigated how yarn composition and twisting influence plant-based and polyester-containing two-ply yarns across three structural scales: yarns, double-weaver knots, and nets. Six yarn systems were produced at 200–500 TPM. Two-way ANOVA confirmed significant effects of composition, twist, and their interaction, whereas Grey Relational Analysis identified 400 TPM as the most suitable common twist condition. At the yarn scale, PALF/PALF showed the highest breaking force, whereas PES/PES exhibited the greatest extensibility. At the knot scale, PALF/PALF achieved the highest knot load and substantial geometric rearrangement, while PES/HF showed the greatest proportional strength retention. At the net scale, PALF/PALF maintained the strongest overall load-bearing response and was mechanically competitive with the PES/PES reference, although the polyester retained advantage. The numerical comparison favored the 10 cm over the 5 cm mesh-bar configuration under the adopted conditions. Seawater exposure caused greater surface deterioration in PALF and hemp than polyester. Overall, the results demonstrate that material ranking changes across structural scales and identify PALF-containing systems as promising candidates for further lower-persistence fishing-net development

Keywords: Pineapple leaf fiber (PALF); hybrid yarn; knot mechanics; biodegradable fishing net.

1. Introduction

Marine plastic pollution is a persistent global environmental challenge, with approximately 11 million metric tons of plastic waste entering the ocean annually and substantially higher inputs projected in the absence of additional intervention ^{1,2}. Although most marine plastic originates from land-based sources, lost, abandoned, or otherwise discarded fishing gear represents a particularly damaging marine-derived component because it can continue capturing organisms after being lost, a phenomenon known as ghost fishing ^{3,4}. Global estimates indicate annual loss rates of approximately 5.7% for fishing nets, 8.6% for traps, and 29% for fishing lines ⁵. In addition to contributing persistent polymeric debris to marine ecosystems, abandoned fishing gear can damage coral reefs and benthic habitats, entangle marine organisms, and generate ecological and economic losses ^{6,7}.

Early fishing nets were manufactured from natural fibers such as flax, hemp, cotton, and sisal, but these materials were progressively replaced by synthetic polymers because of their susceptibility to biological deterioration, variable mechanical performance, and maintenance requirements ⁸. Polyamide, polyethylene, and polypropylene subsequently became widely used in fishing-net construction owing to their favorable combination of mechanical strength, abrasion resistance, water resistance, and service durability. However, the same environmental persistence that supports their long service life becomes disadvantageous when fishing gear is lost or abandoned, because synthetic netting may remain in marine environments for extended periods and continue contributing to ghost fishing and plastic pollution ⁹.

Recent advances in sustainable fishing gear have explored several material strategies, including biodegradable polymers, recycled synthetic fibers, semi-biodegradable blends, bio-based composites, and natural plant fibers. Biodegradable polymers such as polybutylene succinate (PBS), polybutylene succinate adipate terephthalate (PBSAT), polybutylene adipate terephthalate (PBAT), and polylactic acid (PLA) have been investigated as alternatives to conventional nylon and polyethylene fishing gear because they can offer improved environmental performance while maintaining acceptable mechanical properties under controlled service conditions ^{6,9-11}. However, biodegradable fishing gear is still under development, and its environmental benefits must be carefully balanced with mechanical performance, net durability, fishing efficiency, and long-term stability in marine environments. In some cases, biodegradable gillnets have shown lower catch efficiency or reduced tensile properties compared with conventional nylon nets, indicating that

material replacement alone is not sufficient for practical application⁶. Importantly, material degradation should not be regarded automatically as environmental safety, because fragmentation, degradation rate, degradation products, and the persistence of residual material must also be considered when evaluating alternative fishing gear¹².

Meanwhile, natural fibers including hemp and pineapple leaf fiber (PALF) have attracted increasing attention because of their renewable origin, biodegradability, and relatively high specific mechanical strength. Pineapple leaf fiber (PALF) has attracted considerable attention as a sustainable lignocellulosic material because of its high cellulose content, relatively low cost, renewable origin, and favorable mechanical properties, particularly its comparatively high tensile strength and specific strength¹³. PALF has been reported to exhibit a broad range of tensile strength, approximately from 413 to 6127 MPa, together with a tensile modulus of about 60–82 GPa¹⁴. Its comparatively high mechanical performance is generally attributed to its high α -cellulose content, low microfibrillar angle, and the resulting efficient load transfer along the fiber axis, which collectively contribute to its high stiffness and strength¹⁵. Hemp fiber represents another established lignocellulosic material with relatively high specific strength, low density, renewable origin, and inherent biodegradability^{16,17}. Reported mechanical properties vary substantially with cultivar, extraction method, fiber morphology, testing conditions, and moisture content, as is typical of natural fibers. Although these characteristics make hemp attractive for sustainable textile structures, its relatively limited extensibility and sensitivity to moisture may influence yarn deformation, knot tightening, and stress redistribution within net structures. These materials generally exhibit lower moisture resistance, greater variability in mechanical performance, and reduced long-term durability compared with conventional synthetic polymers, making further structural optimization necessary for practical fishing-net applications¹⁸.

The successful implementation of sustainable materials in fishing nets depends not only on their environmental advantages but also on their ability to satisfy the demanding mechanical requirements of fishing operations. The load-bearing capacity of netting fabrics is an important factor governing their ability to maintain structural integrity under operational loads. While material strength is important, the overall performance of fishing nets is also strongly influenced by net architecture, knot behavior, mesh geometry, and deformation mechanisms. Therefore, understanding the mechanical response of netting materials before fracture is essential. Although

tensile breaking strength has traditionally been the main parameter considered for netting and ropes in aquaculture and fishing applications, limited attention has been given to stiffness, deformation behavior, and mechanical response prior to failure ¹⁹⁻²¹.

Previous studies have provided important information on the tensile behavior of conventional netting materials, the performance of biodegradable polymer-based fishing gear, knot-induced reductions in mechanical performance, and the influence of net geometry on structural and hydrodynamic behavior ^{22,23}. However, these aspects have largely been investigated independently. In particular, limited information is available on how the mechanical characteristics of plant derived yarns translate across successive structural scales from twist-dependent yarn behavior to knot tightening and load retention, and subsequently to strain redistribution and load-bearing capacity within a complete net panel. This gap is particularly important for natural fibers because differences in fiber stiffness, extensibility, surface morphology, and friction may produce responses at the knot and net scales that cannot be inferred directly from straight-yarn tensile properties.

The aim of this study was to investigate the early stage mechanical behavior of plant-derived and polyester containing yarn systems as potential materials for sustainable fishing net development. Specifically, the effects of yarn composition and twist level were examined across three structural scales: straight yarn, double weaver's knot, and complete net panel. Unlike previous studies that have generally evaluated yarn tensile behavior, knot performance, or net mechanics separately, the present work establishes a multiscale experimental framework linking twist dependent yarn properties to knot load retention and deformation, and subsequently to load distribution and mechanical response at the net scale. Preliminary seawater-induced surface changes in the plant based fibers were also compared with those observed in polyester as a synthetic reference. Rather than validating direct commercial application, this study was intended to provide a mechanistic understanding of how material composition and structural scale influence the performance of alternative fishing net materials and to support further development of biodegradable or lower-persistence fishing net system

2. Results and Discussion

2.1. Yarn scale

Twisting

The effect of the twist level on the breaking force and breaking extension of the different yarn combinations are presented in Table 1. The tested yarns included three hybrid systems, namely PES/HF, PES/PALF, and PALF/HF, and three homogeneous reference systems, namely PES/PES, PALF/PALF, and HF/HF. The twist level was varied from 200 to 500 turns per meter (TPM) to evaluate its influence on yarn-scale mechanical behavior.

Table 1. Breaking force and breaking extension of the six two-ply yarn compositions at different twist levels. The values are presented as mean $\pm$ standard deviation (n=3).

Yarn specimen No.	Yarn Type	Twist level (TPM)	Mechanical Property	
			breaking force (N)	Breaking extension %
1.	PES/HF	200	12.66 $\pm$ 1.49	4.16 $\pm$ 0.83
2.	PES/HF	300	12.85 $\pm$ 2.27	5.51 $\pm$ 1.52
3.	PES/HF	400	11.12 $\pm$ 1.93	9.71 $\pm$ 3.28
4.	PES/HF	500	9.48 $\pm$ 1.27	7.21 $\pm$ 4.40
5.	PES/PALF	200	18.48 $\pm$ 0.79	14.04 $\pm$ 3.28
6.	PES/PALF	300	18.84 $\pm$ 0.84	16.55 $\pm$ 4.78
7.	PES/PALF	400	19.41 $\pm$ 0.58	16.88 $\pm$ 2.83
8.	PES/PALF	500	18.95 $\pm$ 1.87	17.66 $\pm$ 2.71
9.	PALF/HF	200	16.48 $\pm$ 2.63	7.77 $\pm$ 2.09
10.	PALF/HF	300	13.71 $\pm$ 2.31	8.46 $\pm$ 5.42
11.	PALF/HF	400	12.96 $\pm$ 4.71	9.71 $\pm$ 3.27
12.	PALF/HF	500	13.85 $\pm$ 3.84	9.27 $\pm$ 3.12
13.	PALF/PALF	200	11.92 $\pm$ 0.78	9.96 $\pm$ 1.83
14.	PALF/PALF	300	12.00 $\pm$ 2.20	10.44 $\pm$ 2.03
15.	PALF/PALF	400	22.38 $\pm$ 1.61	20.44 $\pm$ 1.27

16.	PALF/PALF	500	10.20 ± 2.33	9.26 ± 2.20
17.	HF/HF	200	15.20 ± 0.98	5.66 ± 0.98
18.	HF/HF	300	16.16 ± 0.44	5.12 ± 0.55
19.	HF/HF	400	15.15 ± 1.27	5.98 ± 1.91
20.	HF/HF	500	14.74 ± 0.44	5.18 ± 0.82
21.	PES/PES	200	16.30 ± 1.20	15.88 ± 9.73
22.	PES/PES	300	18.65 ± 0.76	17.82 ± 3.08
23.	PES/PES	400	19.10 ± 1.23	20.76 ± 5.93
24.	PES/PES	500	18.85 ± 1.80	33.31 ± 5.08

The tensile response varied substantially among the yarn compositions and twist levels. The highest breaking force was recorded for PALF/PALF at 400 TPM, with a value of 22.38 ± 1.61 N and a breaking extension of $20.44 \pm 1.27\%$. This result indicates that PALF/PALF achieved particularly favorable yarn strength and deformation capacity at this intermediate twist level. In contrast, PES/PES exhibited the greatest breaking extension, reaching $33.31 \pm 5.08\%$ at 500 TPM, while maintaining a breaking force of 18.85 ± 1.80 N.

The effect of twisting was strongly dependent on the yarn composition. PES/PALF maintained a relatively stable breaking force of approximately 18.48–19.41 N across the investigated twist range, with a gradual increase in breaking extension. HF/HF also exhibited limited variation in breaking force, ranging from 14.74 to 16.16 N, but maintained comparatively low breaking extension values of 5.12–5.98%. Conversely, PALF/PALF exhibited a pronounced increase in both breaking force and breaking extension at 400 TPM, followed by a substantial reduction at 500 TPM. PES/PES showed a progressive increase in breaking extension with increasing twist, whereas the breaking force of PES/HF decreased at the highest twist level. These composition dependent trends indicate that a single general relationship between twist level and mechanical performance cannot be applied to all yarn systems.

The effects of yarn type and twist level on the breaking force and breaking extension are evaluated using two-way ANOVA which are summarized in Table 2.

Table 2. Two-way ANOVA results for the effects of yarn composition and twist level on breaking force and breaking extension.

Response Variable	Source	df	Mean Square	F-value	P-value
breaking force (N)	Twisting level	3	16.924	4.500	0.007
	Yarn composition	5	91.975	24.457	<0.001
	Twisting level $\times$ Yarn composition	15	19.410	5.161	<0.001
	Error	48	3.761	-	-
Breaking extension (%)	Twisting level	3	84.323	6.307	0.001
	Yarn composition	5	477.050	35.680	<0.001
	Twisting level $\times$ Yarn composition	15	42.308	3.164	0.001
	Error	48	13.370	-	-

Two-way ANOVA showed that both yarn composition and twist level significantly influenced yarn-scale mechanical performance. Yarn composition had a significant effect on breaking force ($F=24.457$, $p<0.001$) and breaking extension ($F=35.680$, $p<0.001$). Twist level also significantly affected breaking force ($F=4.500$, $p=0.007$) and breaking extension ($F=6.307$, $p=0.001$). These results confirm that both the constituent fiber system and the applied twist contributed to the mechanical response of the yarns. The observed differences may be related to variations in fiber stiffness, extensibility, morphology, alignment, and inter-fiber friction. Overall, polyester-containing yarns tended to exhibit greater breaking extension, whereas PALF-containing systems achieved comparatively high breaking force and favorable strength-related performance under selected twist conditions.

A significant interaction between yarn composition and twist level was also observed for breaking force ($F=5.161$, $p<0.001$) and breaking extension ($F=3.164$, $p=0.001$). This interaction indicates that the influence of twist depended on yarn composition and was therefore not uniform across the six yarn systems. For example, PALF/PALF exhibited a pronounced increase in both breaking force and breaking extension at 400 TPM, followed by a substantial reduction at 500 TPM, whereas HF/HF showed comparatively limited variation over the investigated twist range. PES/PES exhibited a progressive increase in breaking extension with increasing twist, while PES/HF showed a reduction in breaking force at 500 TPM. These composition-dependent trends indicate that no single twist–strength relationship can adequately describe all yarn systems. Accordingly, the effects of yarn composition and twist level should be interpreted in conjunction with their significant interaction rather than independently.

Although both yarn composition and twist level significantly affected the mechanical properties, breaking force and breaking extension did not necessarily reach their highest values under the same conditions. Grey Relational Analysis was therefore applied as a multi-response decision-making method to integrate both properties into a single performance index. This approach enabled selection of a common twist level that provided the optimal overall balance between breaking force and breaking extension across the six yarn compositions for the subsequent knot- and net-scale evaluations.

Grey Relational Analysis was applied to identify the twist level that provided the optimal combined performance in breaking force and breaking extension (Table 3). Both responses were treated as “larger-the-better” criteria and assigned equal weighting. The highest mean Grey Relational Grade was obtained at 400 TPM (0.520), followed by 500 TPM (0.484), 300 TPM (0.450), and 200 TPM (0.435). These results indicate that 400 TPM provided the optimal between the two mechanical responses across the six yarn compositions.

Table 3. Mean tensile properties and average Grey Relational Grades for the investigated twist levels.

Twisting level (TPM)	Mean breaking force (N)	Mean breaking extension (%)	Grey Relational Grade (GRG)
200	15.17	9.58	0.435
300	15.37	10.65	0.450
400	16.69	13.91	0.520
500	14.35	13.65	0.484

The results showed that 400 TPM had the highest GRG, indicating the most balanced mechanical performance among the tested twist levels. Although twist level significantly affected both breaking force and breaking extension in the two-way ANOVA, the significant interaction with yarn composition showed that its effect was not uniform among the yarn systems. Therefore, the GRA result should be interpreted as identifying the most suitable common twist level rather than the individual optimum for every composition. Based on its highest mean GRG, 400 TPM was selected for the subsequent knot- and net-scale evaluations.

At lower twist levels (200–300 TPM), insufficient fiber consolidation reduces mechanical efficiency, while at higher twist levels (500 TPM), excessive twisting introduces internal stress and potential fiber damage, reducing the overall performance. The intermediate twist level (400 TPM) achieves a balanced structure, optimizing interfiber cohesion while maintaining adequate flexibility.

Surface morphological changes after seawater immersion

Figure 1 shows the surface morphology of the yarns after immersion in natural seawater for one and two months, as part of a preliminary seawater biodegradability assessment based on SEM-observed surface degradation. As shown in Figure 1a, the polyester yarns exhibited limited visible surface changes after seawater exposure. Their surfaces remained generally similar to those of the unexposed specimens, although some deposited debris was observed. There is some surface debris, probably residues from seawater ²⁶. For the hemp yarn samples (Figure 1b) degradation of the

fibers is clearly apparent, including areas where the primary cell wall has been degraded exposing the cellulose microfibrils of the secondary cell layer. Cracks were visible after one month of immersion and became wider and deeper after two months.

For the pineapple yarns (Figure 1c) degradation of the fibers is clearly apparent with severe surface damage. After two months in sea water, large cracks are visible on the surface of the yarn and a strip looks as if it has been peeled off. There are also areas where the fibers are completely separated. In addition, Particles were also observed on some fiber surfaces and may represent microbial deposits, detached fiber fragments, or residues from the seawater ²⁷. Irregular cracks were observed on the surfaces. Some intact fibers are still visible even after two months of seawater exposure, indicating that degradation of pineapple fibers is non-uniform. Overall, these results support the biodegradation findings for both hemp and pineapple yarns, with the observed level of degradation corresponding well to the extent of biodegradation.

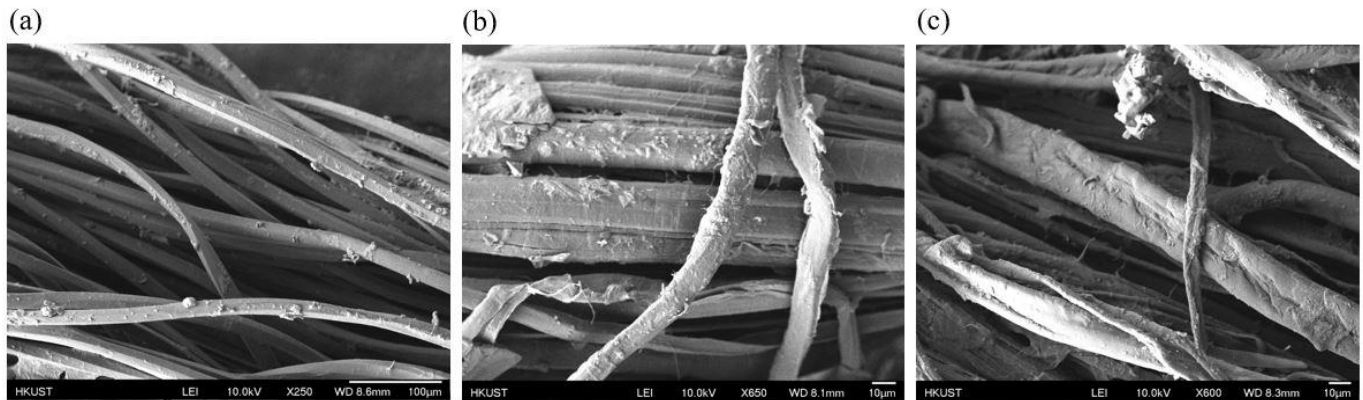


Figure 1. Surface degradation of fibers a) polyester fibers, b) hemp fibers, and c) pineapple fibers.

2.2.Knot Scale

Morphological observations of the knot structure

The morphology of the double weaver's knots prepared from the twisted yarns was examined using scanning electron microscopy, as shown in Figure 2. The knot-scale results are reported with standard deviation based on n=3 independent specimens for each composition. The SEM images were colored to distinguish the constituent fibers: yellow represents PALF, blue represents HF,

and purple represents PES. The double weaver's knot functions as a mechanical interlocking region between adjacent mesh bars; therefore, knot compactness, yarn arrangement, surface roughness, and fiber protrusion are important factors affecting load transfer during tensile loading.

Yarn hairiness and surface irregularity can be related to fiber alignment, folded or hooked fibers, and fiber migration within the yarn body. These structural features may influence yarn-to-yarn contact, friction, slippage, and stress concentration within the knot ²⁸. As shown in Figure 2, clear morphological differences were observed among the different yarn combinations. The PES/PES knot exhibited the most compact and uniform structure, with tightly packed filaments and limited surface hairiness. This morphology suggests stable yarn alignment and efficient load transfer, which may explain its relatively stable deformation behavior during tensile loading.

In contrast, the PALF/PALF knot showed a less compact structure with more visible fiber protrusions and surface irregularities. However, these irregularities should not be interpreted only as defects, because the rough surface of pineapple leaf fibers may increase inter-fiber friction and promote progressive knot tightening under load. These observations align with Rungruangkitkrai et al. (2026), who reported that the coarse, stiff and irregular morphology of PALF resulted in heterogeneous fiber distribution, surface migration, increased hairiness and non-uniform packing in PALF-containing blended yarns ²⁹. The HF/HF knot displayed an intermediate morphology, characterized by a rougher surface and moderate fiber protrusion. The hybrid yarns showed mixed structural features: the polyester component contributed to a more compact filament bundle, while the plant-based component introduced surface roughness and irregular packing around the knot.

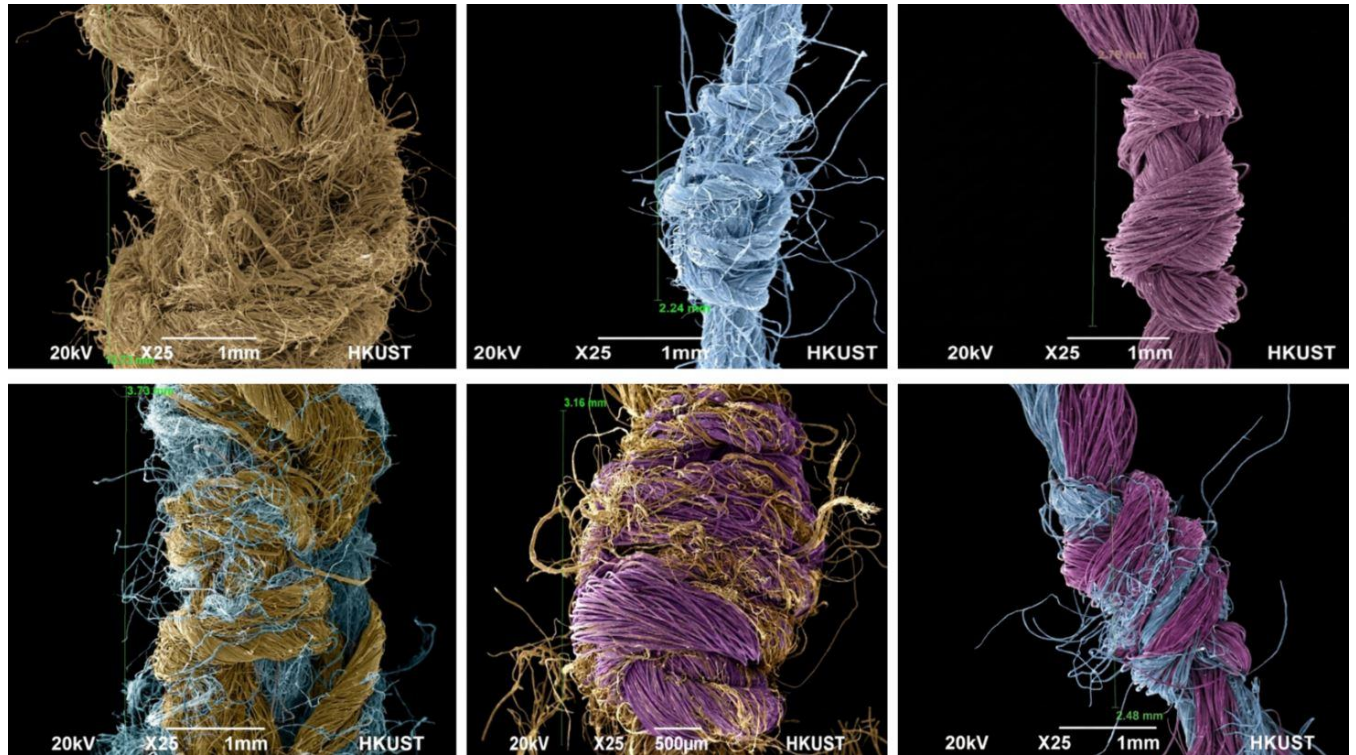


Figure 2. SEM morphology of double weaver's knots produced from PALF, HF, PES, and their hybrid yarn combinations. Yellow, blue, and purple indicate PALF, HF, and PES, respectively. Colors were digitally assigned after SEM acquisition solely to facilitate visual differentiation of the constituent yarn components.

Strength

The knot-scale mechanical response differed markedly among the six yarn compositions at 400 TPM. Maximum knot load, knot strength efficiency, and absolute knot area change are summarized in Table 4 and Figure 3. The knot strength efficiency was calculated as described in Section 2.3.2 and represents the proportion of the straight-yarn load-bearing capacity retained after knot formation. Because only three independent knot specimens were tested for each composition, the knot-scale results are interpreted primarily as comparative mechanical indicators rather than through inferential statistical analysis.

Table 4. Maximum knot load, knot strength efficiency, and absolute knot area change of the double weaver's knot specimens at 400 TPM. The values are presented as mean $\pm$ standard deviations (n=3).

Knot	Maximum knot load (N)	Knot strength efficiency (%)	knot-area change, ΔA (mm ²)
PALF/PALF	17.01 ± 2.87	76.0	19.50 ± 3.00
PES/PES	15.09 ± 1.02	79.0	17.99 ± 1.01
PES/HF	9.12 ± 1.34	82.0	11.1 ± 1.96
PALF/HF	9.26 ± 0.73	71.5	6.21 ± 1.53
HF/HF	6.79 ± 1.12	44.8	2.08 ± 0.83
PES/PALF	13.78 ± 1.04	71.0	4.77 ± 0.01

The PALF/PALF exhibited the highest absolute maximum knot load, reaching 17.01 ± 2.87 N, followed by PES/PES at 15.09 ± 1.02 N and PES/PALF at 13.78 ± 1.04 N. PALF/PALF also showed the largest absolute knot-area change, 19.50 ± 3.00 mm², indicating substantial geometric rearrangement and progressive tightening of the knot region before failure. Its knot strength efficiency was approximately 76.0%, showing that a considerable proportion of the straight-yarn load-bearing capacity was retained after knot formation. The relatively high knot load together with the large area change suggests that PALF/PALF combined favorable knot strength with a substantial capacity for structural rearrangement during loading.

PES/PES also exhibited comparatively high knot-scale performance, with a maximum knot load of 15.09 ± 1.02 N, a knot strength efficiency of approximately 79.0%, and an absolute knot-area change of 17.99 ± 1.01 mm². The combination of high load retention and substantial deformation indicates that the polyester yarn was able to accommodate knot tightening while maintaining a relatively large proportion of its straight-yarn strength. This behavior may be associated with the flexibility and uniform filament arrangement of the polyester yarn, which can facilitate redistribution of load within the knot.

Interestingly, PES/HF exhibited the highest knot strength efficiency, approximately 82.0%, despite having a lower absolute maximum knot load of 9.12 ± 1.34 N. This distinction demonstrates that absolute knot strength and knot strength efficiency represent different aspects of mechanical performance. The high efficiency of PES/HF indicates that the knot retained a relatively large

fraction of the breaking force of the corresponding straight yarn, although its absolute load-bearing capacity remained lower than those of PALF/PALF, PES/PES, and PES/PALF.

Among the remaining hybrid systems, PES/PALF reached a maximum knot load of 13.78 ± 1.04 N and retained approximately 71.0% of its straight-yarn load-bearing capacity. However, its absolute knot area change was only 4.77 ± 0.01 mm², substantially lower than those of PALF/PALF and PES/PES. PALF/HF exhibited a similar knot strength efficiency of approximately 71.5%, but its lower maximum knot load of 9.26 ± 0.73 N and knot-area change of 6.21 ± 1.53 mm² indicate a lower overall knot-scale mechanical response.

HF/HF exhibited the lowest maximum knot load, 6.79 ± 1.12 N, and the smallest absolute knot-area change, 2.08 ± 0.83 mm². Its knot strength efficiency was also the lowest among the six compositions, at approximately 44.8%. Thus, although the straight HF/HF yarn exhibited a breaking force of 15.15 N at 400 TPM, less than half of this load-bearing capacity was retained after knot formation. The combination of low load retention and limited knot deformation suggests that knot formation imposes a comparatively large mechanical penalty on the HF/HF system. Its relatively low extensibility may result in limited progressive tightening and stress redistribution within the knot, leading to earlier localized failure.

Overall, the knot scale results demonstrate that the mechanical ranking of the yarns based solely on straight-yarn breaking force was not completely preserved after knot formation. PALF/PALF showed the highest absolute knot strength, whereas PES/HF exhibited the highest proportional strength retention. In contrast, HF/HF showed both the lowest maximum knot load and the lowest knot strength efficiency. These findings indicate that the maximum knot load, strength retention, and knot deformation describe complementary aspects of knot performance and should therefore be considered together when evaluating yarn systems for knotted fishing-net structures.

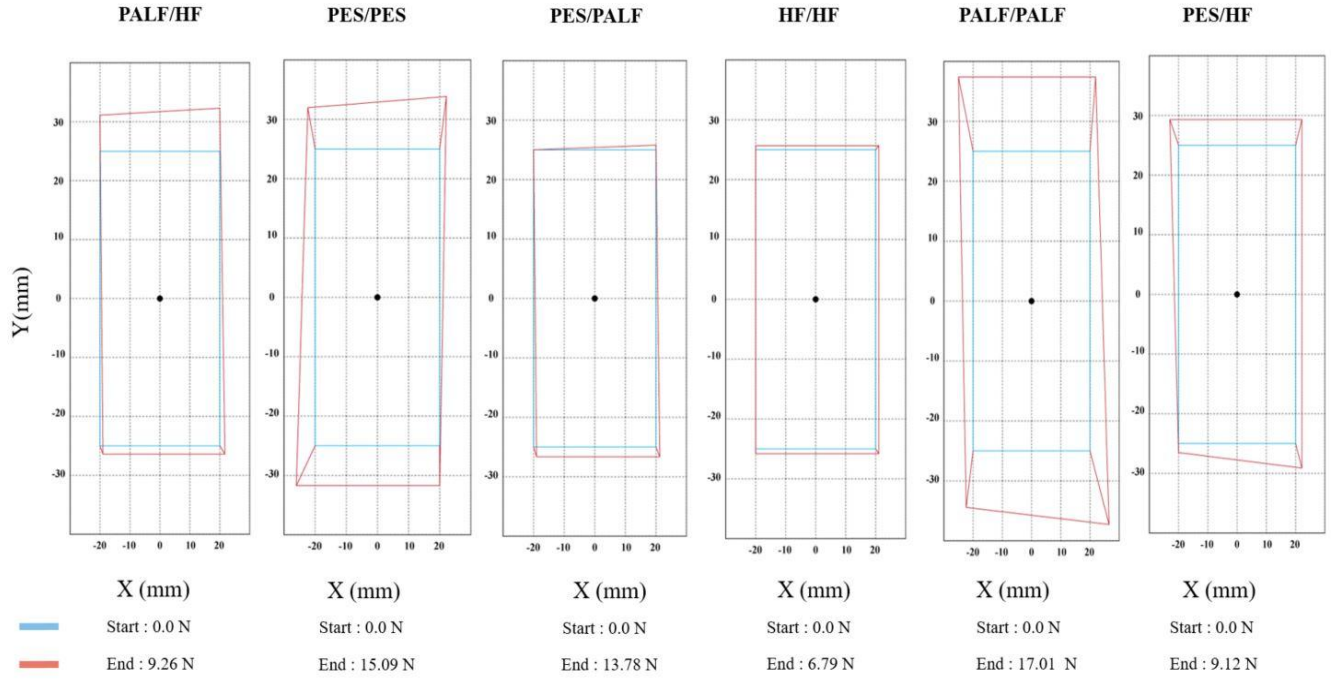


Figure 3. Initial and final configurations of double weaver's knot specimens produced from the six yarn compositions during tensile loading at 400 TPM. Blue dashed lines indicate the initial knot configuration at 0 N, while red dashed lines indicate the configuration immediately before failure. The displacement of the four tracked markers was used to calculate the absolute knot area change, ΔA .

2.3. Net scale

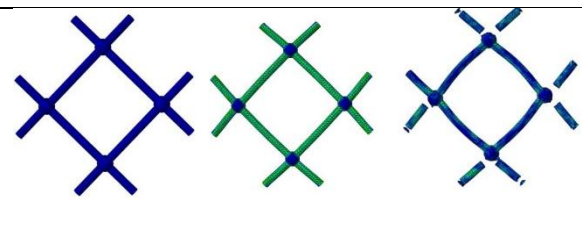
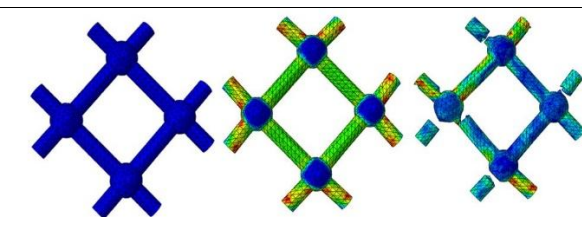
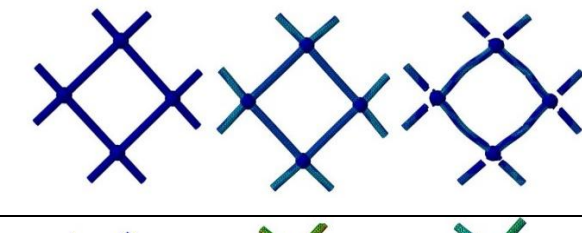
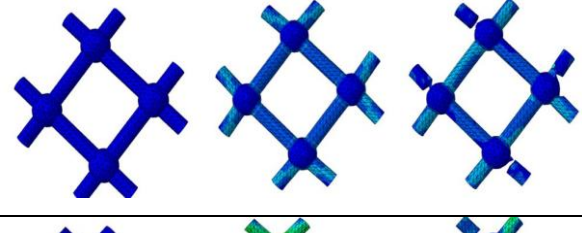
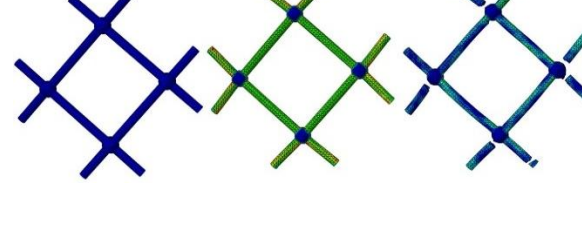
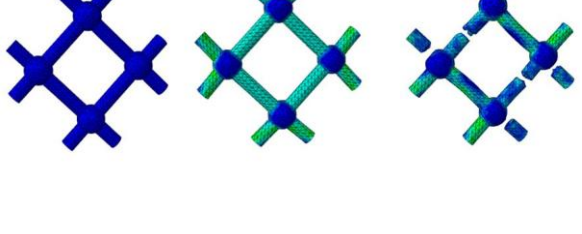
Optimizing the mesh size

Fishing nets can also be described on the basis of their mesh size, which refers to the spacing between adjacent knots or the length of the yarn segment connecting two knots, as illustrated in Figure 8c. In addition to material composition, mesh geometry strongly influences the mechanical response of netting structures because it affects the knot density, load distribution, deformation behavior, hydrodynamic resistance, and stress concentration during loading. Other researchers demonstrated that modifications in mesh size altered the spatial geometry, and sinking speed. Similarly, experimental studies have shown that the net material, mesh shape, solidity ratio, current velocity, and current direction significantly influence the hydrodynamic and dynamic loads acting on net structures^{23,30}.

Table 5 compares the stress distributions of the numerical net models with mesh-bar lengths of 5 and 10 cm. In the simulation contours, in the equivalent von Mises stress contours, blue represents lower stress and red represents higher stress. The 5 cm mesh structures generally showed more localized high-stress regions around the knots and short mesh bars. This behavior can be attributed to the higher knot density in the smaller mesh structure. Since knots act as stress-concentration points, increasing the number of knots per unit area can limit mesh deformation and increase local stress accumulation.

In contrast, the 10 cm mesh structures showed improved load distributions along the mesh bars and lower restrictions on mesh deformation. This improvement can be attributed to the reduction in the stress concentration around the knot regions and the more uniform distribution of the applied load throughout the net structure. This finding agrees with previous research investigating the relationship between mesh sizes and breaking strength. Sala et al. (2004) reported that increasing the mesh size could improve the breaking strength of netting structures, which was attributed to reduced knot interactions and improved load distribution within the net¹⁹.

Table 5. Comparative numerical results for net structures with mesh bar lengths of 5 and 10 cm.

Yarn composition	10 cm	5cm
PES/HF		
PES/PALF		
PALF/HF		

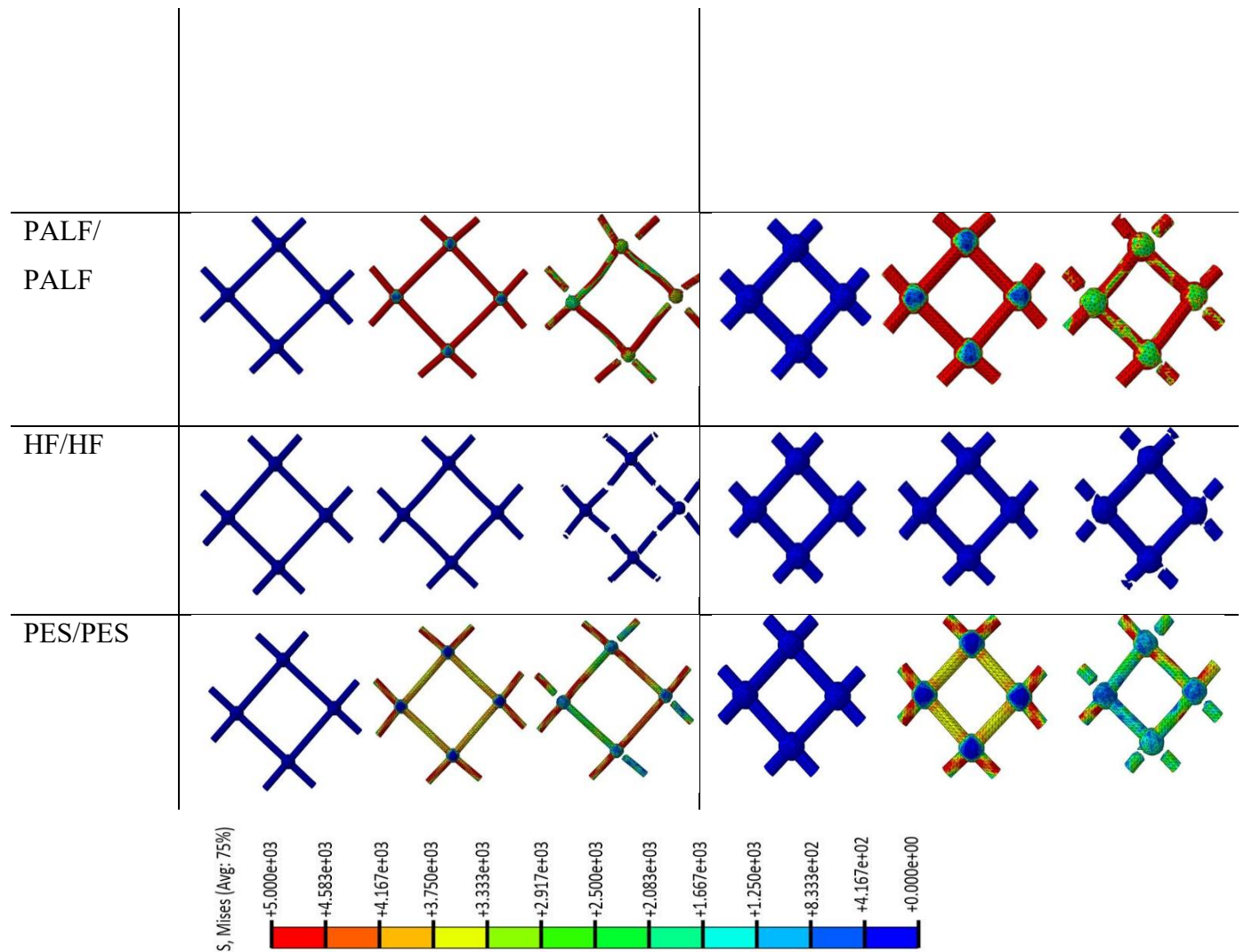


Figure 4 compares the simulated maximum reaction force reached before failure for the 5 and 10 cm mesh-bar configurations observed between all the monitored nets. Bar charts of the samples represent the maximum force of each net before failure. For PALF/PALF, the maximum load increased from 29.64 N at 5 cm to 34.98 N at 10 cm. PES/PES increased from 25.50 N to 26.01 N, while PES/PALF increased from 24.61 N to 25.32 N. Similarly, HF/HF, PALF/HF, and PES/HF increased slightly. Therefore, within the adopted numerical conditions, all six yarn systems exhibited higher simulated maximum reaction forces for the 10 cm mesh-bar configuration than for the corresponding 5 cm configuration. The numerical analysis therefore indicates a consistent relative advantage of the 10 cm configuration within the comparative modelling framework.

Among all samples, the PALF/PALF net showed the highest load-bearing capacity, reaching 34.98 N at the 10 cm mesh length. This result agrees with the high yarn and knot strength of the PALF/PALF system at 400 TPM. The superior performance of this net can be explained by the strong microfibrils structure of pineapple leaf fiber, its high cellulose content, and its rough surface morphology. The rougher PALF surface can increase frictional locking at the knot regions, reducing yarn slippage and improving load transfer between adjacent mesh bars. As a result, the PALF/PALF net was able to tolerate the highest load before failure.

The PES/PES and PES/PALF nets also showed relatively high maximum loads. PES/PES reached 26.01 N at 10 cm, while PES/PALF reached 25.32 N. The good performance of PES/PES is related to the uniform, flexible, and compact structure of polyester filaments, which supports stable strain distribution and efficient load transfer. PES/PALF also performed well because the polyester component provides flexibility and dimensional stability, while the PALF component contributes surface roughness and frictional resistance at the knots.

In contrast, the HF/HF and PES/HF nets showed the lowest load-bearing capacities. Although their strength also improved when the mesh length increased from 5 cm to 10 cm, their final load values remained lower than those of PALF/PALF, PES/PES, and PES/PALF. This may be related to the lower extensibility and higher stiffness of hemp fibers, which can increase local stress concentration around knots. In the PES/HF hybrid structure, the difference in stiffness and elongation between polyester and hemp may also cause uneven load sharing during deformation, leading to earlier failure.

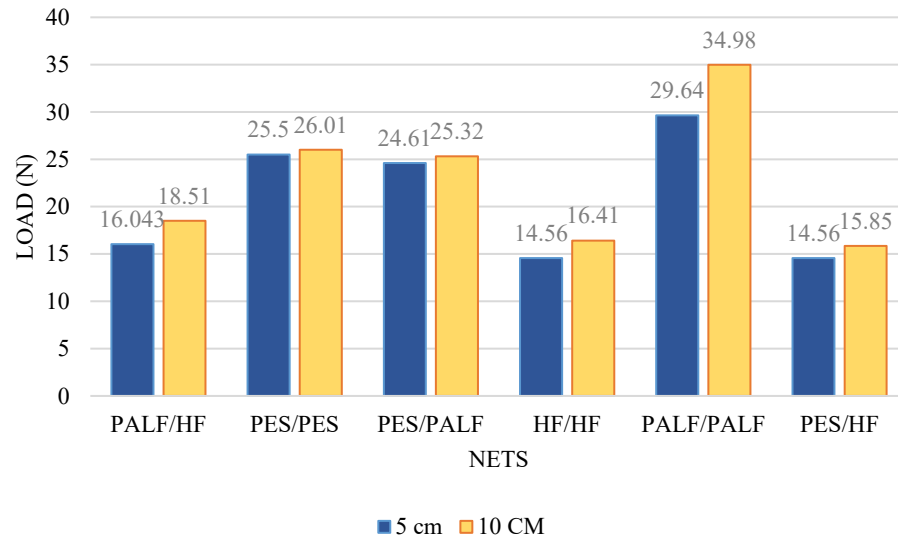


Figure 4. Simulated maximum reaction forces of the six yarn systems for the 5 and 10 cm mesh-bar configurations.

Strength

The net scale represents the final structural level investigated in this study, following the yarn and knot scales. At this level, the mechanical response is governed not only by the tensile behavior of the constituent yarns and the local resistance of the knots, but also by the interaction among mesh geometry, knot arrangement, and load transfer throughout the entire net structure. Fishing nets are inherently complex assemblies in which knots connect adjacent yarn segments to form a repeated mesh network. In a knotted net, each mesh bar is linked to neighboring bars through successive rows of knots. To ensure structural stability and a balanced net architecture, the orientation of the knots is alternated from one row to the next. As a result, the yarn segments maintain a consistent positional relationship as they pass through successive knots, which contributes to the overall geometric integrity of the net during loading.

Based on the previous simulation results, the 10 cm mesh length was selected for the experimental net-scale test. The distribution of the strain of the 10 cm net specimens was recorded using a high-speed camera and analyzed by tracking characteristic points during tensile loading, as shown in Figure 5.

As shown in Figure 5, a distinct difference was observed between nets manufactured from homogeneous yarn combinations and those manufactured from hybrid yarn combinations. The PES/PES, PALF/PALF, and HF/HF nets generally exhibited more continuous and spatially uniform strain distributions than the PES/PALF, PES/HF, and PALF/HF nets. The mechanical compatibility of identical yarn components, including comparable stiffness, extensibility, surface characteristics, and knot response, promoted more uniform load sharing among adjacent mesh bars. By contrast, differences in the mechanical and interfacial properties of the constituent fibers in hybrid yarns resulted in non-uniform strain, and localized strain concentrations.

The PES/PES net exhibited a relatively balanced strain distribution pattern, suggesting stable load transfer and structural regularity during extension. The PES/PALF and PALF/PALF nets showed more pronounced strain in selected vertical mesh bars, indicating that these structures underwent greater local extension before failure. In particular, the PALF/PALF net displayed a wider distribution of highly deformed mesh bars, which is consistent with its superior load-bearing capacity and suggests that the structure was able redistribute more mechanical energy before rupture. This behavior may be attributed to the relatively high yarn strength of PALF/PALF and the frictional resistance provided by the rougher pineapple-fiber surface, which can improve load transfer through the knot and mesh system.

In contrast, The PES/HF and PALF/HF nets exhibited pronounced strain localization. In both structures, high strain was confined to a limited number of mesh bars, while large portions of the net remained at relatively low strain. The lower extensibility of the hemp-containing yarns, combined with the mechanical mismatch between hemp and the second fiber component, reduced the uniformity of load redistribution. Consequently, strain was concentrated along specific mesh paths and around selected knots. The PES/HF net demonstrated particularly severe localization, whereas the PALF/HF net exhibited a slightly broader distribution of intermediate strain around the principal high-strain regions.

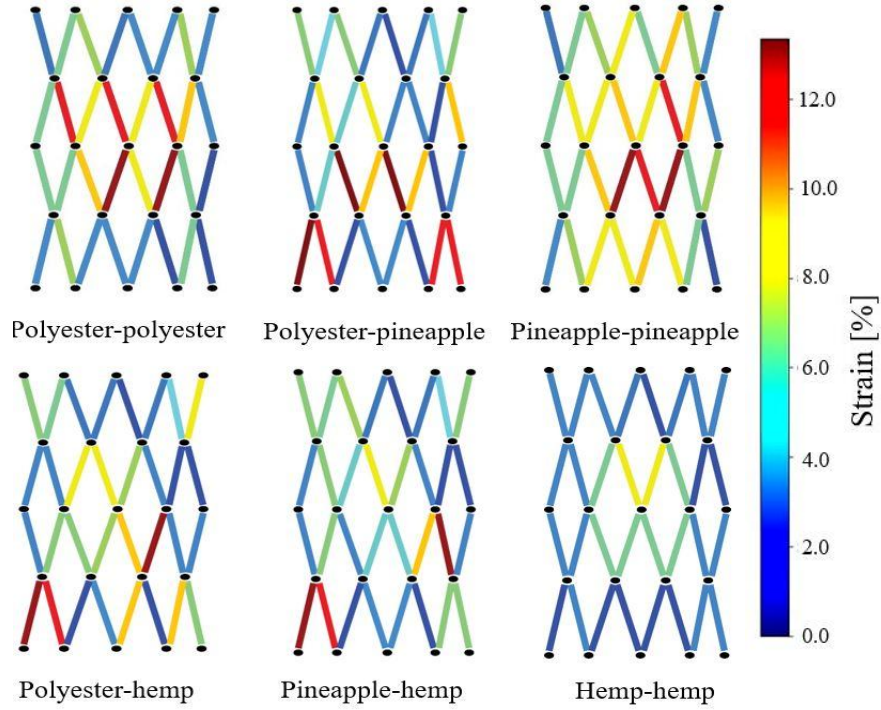


Figure 5. Spatial strain distributions of the six 10 cm mesh net structures immediately before failure during tensile loading.

The HF/HF net showed the most regular and symmetric strain distribution, with strain increasing gradually from the lateral regions toward the center. However, the overall strain magnitude remained comparatively low, consistent with the limited breaking extension of the HF/HF yarn. The mechanical similarity of the two hemp components promoted relatively uniform load transfer, whereas their limited extensibility restricted the total deformation sustained before failure. Therefore, a uniform strain field does not necessarily correspond to high strain capacity or high load-bearing performance.

Figure 6 presents the mean force–time responses obtained from three independent net-panel tests for each yarn composition. Among the homogeneous net structures, PALF/PALF exhibited the highest maximum force, reaching approximately 115 N after nearly 295 s of loading, which was consistent with its broad distribution of elevated strain and substantial deformation before failure. PES/PES reached a comparable maximum force of approximately 110–112 N at a shorter loading

time of about 155 s, corresponding to its relatively balanced strain distribution but more rapid development of tensile resistance. In contrast, HF/HF exhibited the lowest maximum force, approximately 27–30 N, despite its regular strain field.

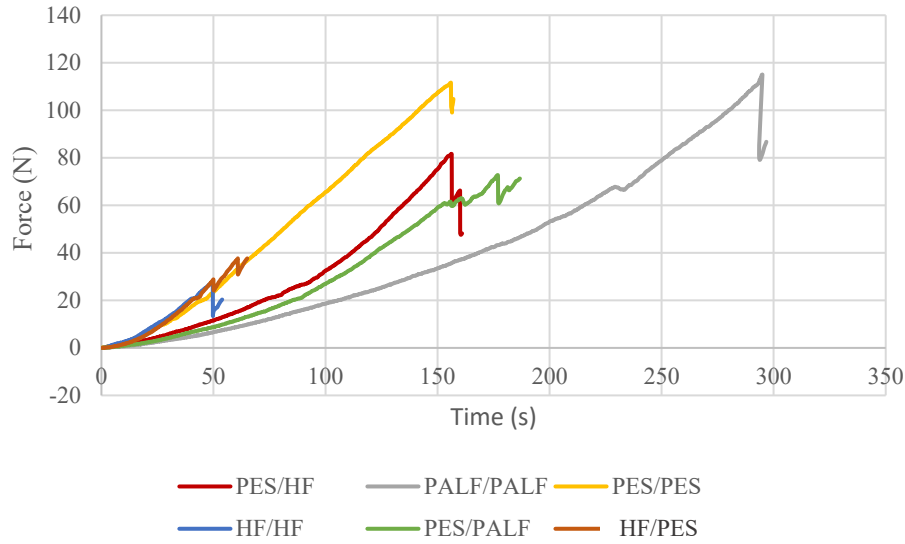


Figure 6. Mean force–time responses of 10 cm mesh net specimens produced from the six yarn compositions during tensile loading to failure (n = 3).

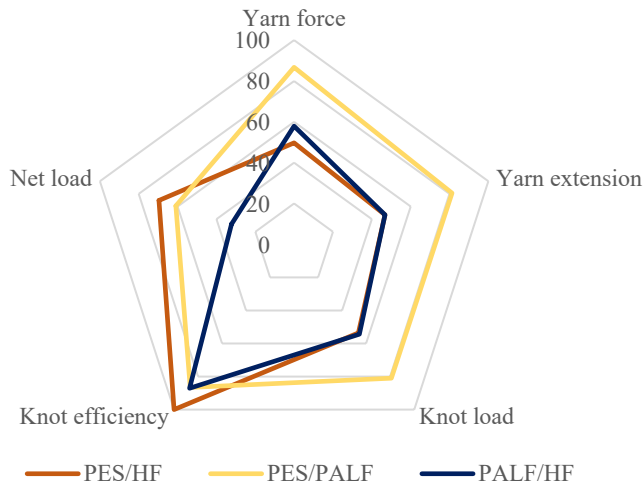
2.4. Multiscale comparison of mechanical performance

To provide an integrated comparison of mechanical performance across structural scales, the yarn, knot, and net scale results were normalized and summarized using radar plots (Figure 7). Five parameters were considered: yarn breaking force, yarn breaking extension, maximum knot load, knot strength efficiency, and maximum experimental net-panel load. For each parameter, the highest value observed among all six yarn compositions was assigned a normalized value of 100%, and the remaining values were expressed relative to this maximum. The radar plots therefore provide a comparative visualization of the mechanical performance profiles of the different yarn systems despite differences in the units and magnitudes of the measured parameters.

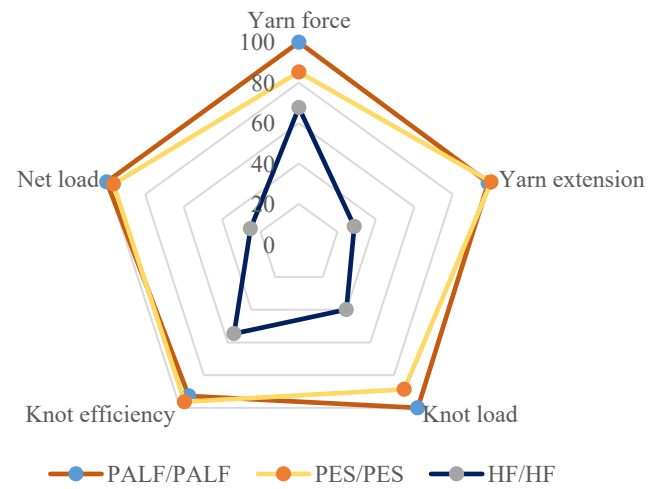
Among the homogeneous systems, PALF/PALF showed consistently high normalized values for yarn breaking force, maximum knot load, and experimental net panel load. PES/PES also maintained comparatively high performance across the investigated scales, particularly in yarn extensibility, knot strength retention, and net panel load. In contrast, HF/HF exhibited a moderate

yarn scale breaking force but markedly lower maximum knot load, knot strength efficiency, and net panel load. These differences indicate that the relative ranking of the materials at the yarn scale was not fully preserved after knot formation and integration into the net structure.

Among the hybrid systems, PES/PALF exhibited comparatively high yarn breaking force, breaking extension, and maximum knot load, giving it the most balanced mechanical behavior among the three hybrid combinations. PES/HF exhibited the highest knot strength efficiency, indicating that a relatively large proportion of its yarn load bearing capacity was retained after knot formation, although its absolute yarn and knot scale loads remained lower than those of PES/PALF. PALF/HF showed lower overall values across several of the evaluated parameters. These results show that absolute load bearing capacity and proportional strength retention represent different and complementary aspects of knot and net performance.



(a)



(b)

Figure 7. Normalized multiscale mechanical performance of the investigated yarn systems at 400 TPM. Radar plots compare yarn breaking force, yarn breaking extension, maximum knot load, knot strength efficiency, and maximum experimental net-panel load. For each parameter, values were normalized to the highest value observed among the six yarn compositions, which was assigned a value of 100%. (a) Hybrid yarns and (b) Homogeneous yarns.

3. Discussion

The present study examined how composition yarn and twist influence mechanical behavior as the material is progressively transformed from straight yarns into double weaver's knots and complete net structures. The results demonstrate that this transition between structural scales substantially alters the relative performance of the investigated yarn systems. In particular, the ranking observed from straight-yarn properties was not consistently maintained after knot formation and integration into the net structure, indicating that yarn scale mechanical properties alone cannot adequately describe the performance of knotted fishing net materials.

At the yarn scale, yarn composition, twist level, and their interaction significantly influenced both breaking force and breaking extension, demonstrating that the effect of twist was composition dependent. PALF/PALF exhibited the most pronounced response to twist. Its breaking force increased from approximately 12 N at 300 TPM to 22.38 N at 400 TPM, corresponding to an increase of about 1.9-fold, before decreasing to 10.20 N at 500 TPM. A similar response was observed for extension, which approximately doubled at 400 TPM relative to the neighboring twist conditions. By contrast, PES/PES responded primarily through increased extensibility, with breaking extension rising from 20.76% at 400 TPM to 33.31% at 500 TPM, representing an increase of approximately 60%. These contrasting trends confirm that no universal relationship between twist and mechanical performance can be applied across all fiber systems.

The Grey Relational Analysis nevertheless identified 400 TPM as the most suitable common twist level for subsequent knot and net scale evaluation. This result should not be interpreted as the individual optimum for every composition, particularly because the significant yarn composition $\times$ twist interaction demonstrated that the response to twisting differed among the six systems. Instead, 400 TPM represented the condition that provided the most balanced combination of breaking force and extension across the investigated yarns.

At the knot scale, the differences among the materials became more pronounced. PALF/PALF exhibited the highest maximum knot load, 17.01 N, approximately 2.5 times that of HF/HF. Its absolute knot area change was also approximately 9.4 times greater than that of HF/HF, indicating a much greater capacity for geometric rearrangement and knot tightening before failure. PES/PES

also maintained comparatively high knot scale resistance and substantial deformation. These observations suggest that maintaining load-bearing capacity after knot formation requires not only high straight yarn performance but also sufficient structural rearrangement within the knot.

An important distinction was observed between absolute knot load and knot strength efficiency. PES/HF exhibited the highest knot strength efficiency, approximately 82%, despite having a substantially lower absolute knot load than PALF/PALF and PES/PES. In contrast, HF/HF retained less than half of its straight yarn load bearing capacity after knot formation. This demonstrates that absolute knot resistance and proportional strength retention represent complementary aspects of mechanical behavior and should therefore be considered together when evaluating yarns for knotted structures.

The observed differences in knot behavior may also be associated with yarn morphology. SEM images showed greater surface irregularity and fiber protrusion in PALF containing yarns, whereas PES/PES exhibited a more compact filament arrangement. Such differences may influence yarn to yarn contact, local slippage, and progressive tightening. However, because inter-yarn friction was not quantified directly, the SEM observations should be interpreted as supporting morphological evidence rather than as proof of the mechanisms governing knot performance.

At the net scale, the numerical comparison showed that all six yarn systems developed higher maximum reaction forces in the 10 cm configuration than in the corresponding 5 cm configuration. For PALF/PALF, the simulated maximum reaction force increased from 29.64 to 34.98 N, corresponding to an increase of approximately 18%. In comparison, PES/PES and PES/PALF exhibited only modest increases. These results indicate that the mechanical response to changes in mesh bar length was also material dependent. However, because changing the mesh-bar length simultaneously changed the overall dimensions of the numerical panel, the results should be interpreted as a comparative assessment of two geometrically different configurations rather than as evidence of an isolated mesh size effect.

The experimental net scale results further emphasized the importance of structural scale. PALF/PALF sustained approximately four times the maximum force of HF/HF, while PES/PES also retained a high net scale load bearing capacity. Nevertheless, HF/HF exhibited the most

regular and symmetric strain pattern despite its comparatively low maximum force. This contrast demonstrates that spatial regularity of strain does not necessarily indicate superior load bearing capacity. Rather, the final response of the net reflects the combined influence of yarn extensibility, knot deformation, load retention, mesh geometry, and redistribution of forces throughout the structure.

The difference between homogeneous and hybrid systems was also evident from the strain maps. Homogeneous nets generally exhibited more spatially continuous strain distributions, whereas hybrid structures showed greater localization along selected mesh paths. This response may arise from differences in stiffness and extensibility between dissimilar constituent fibers. Nevertheless, hybridization did not produce a single consistent mechanical response. PES/PALF exhibited the most balanced profile among the hybrid systems, whereas PES/HF was distinguished by its high proportional knot strength retention. These findings indicate that the influence of hybridization depends on how the mechanical characteristics of the constituent fibers interact at different structural scales.

The preliminary seawater exposure results provided an environmental complement to the mechanical analysis. Hemp and PALF developed substantially greater visible surface alteration than polyester, including cracking, peeling, and fiber separation, whereas polyester remained comparatively unchanged. These observations indicate greater susceptibility of the plant derived fibers to seawater induced surface deterioration. However, SEM observations alone cannot quantify degradation rate, mass loss, mineralization, or complete biodegradation. Consequently, further quantitative and long-term investigations are required before the environmental persistence of the investigated systems can be established.

Overall, the multiscale analysis demonstrates that material performance evolves as structural complexity increases from yarn to knot and net. PALF/PALF maintained comparatively high performance across all three levels, whereas HF/HF showed a pronounced loss of load bearing capacity after knot formation and integration into the net. The results therefore support the use of multiscale evaluation rather than yarn testing alone when screening plant based and hybrid materials for fishing nets.

Several limitations should be considered when interpreting the present findings. The knot and net scale experiments were based on a limited number of independent specimens, and all mechanical tests were conducted under dry laboratory conditions. In addition, only two mesh-bar configurations were evaluated numerically, and the numerical model was intended primarily for comparative rather than predictive analysis. The seawater exposure assessment was based on SEM observed surface morphology and therefore does not provide quantitative evidence of biodegradation rate, mass loss, or mineralization. Although the fully plant based PALF/PALF system showed mechanical performance comparable to, and in several load-bearing measures greater than, the PES/PES reference during the initial laboratory evaluation, polyester remained superior in extensibility and represents a more established benchmark for fishing net applications. Future studies should focus on three main directions: (i) evaluating long term mechanical durability under realistic marine conditions, (ii) quantitatively assessing biodegradation and environmental persistence, and (iii) validating net performance through hydrodynamic and field-scale testing. Larger sample sizes and further calibration of the numerical model would also improve the statistical reliability and predictive capability of the multiscale framework.

4. Conclusions

This study demonstrated that the mechanical performance of plant-based and polyester-containing fishing-net yarns is strongly dependent on both material composition and structural scale. Polyester remained an important reference material because of its high extensibility and comparatively stable mechanical behavior. However, the initial dry-state tests showed that the fully plant-based PALF/PALF system was comparable to, and in several load-bearing measures exceeded, the PES/PES reference at the yarn, knot, and net scales. This suggests that plant-based systems may provide mechanically competitive alternatives for future lower-persistence fishing-net structures, although their suitability cannot yet be considered equivalent to that of established synthetic netting materials. The numerical analysis further indicated a relative advantage of the larger investigated mesh-bar configuration under the adopted modelling conditions, while seawater exposure produced greater surface deterioration in PALF and hemp than in polyester.

5. Materials and methods

5.1. Materials and preparation of two-ply yarns

In this investigation, three types of yarns were used: polyester multifilament yarn, pineapple leaf fiber yarn, and hemp yarn. The polyester multifilament yarn, with a linear density of 33 tex, was purchased from Zhejiang Guxiandao Polyester Dope Dyed Yarn Co., Ltd., China. The pineapple leaf fiber yarn, with a linear density of 33 tex, was supplied by CTA High-tech Fiber Co., Ltd., China. The hemp yarn, with a count of 30 Nm, equivalent to approximately 33.3 tex, was purchased from Tianjin Glory Tang New Material Co., Ltd., China. The hemp yarn count was selected to provide a linear density comparable to the polyester and pineapple yarns, allowing the comparison to focus mainly on the effect of fiber composition rather than large differences in yarn fineness.

To evaluate the effects of yarn composition and twist level on mechanical performance, the yarns were combined to produce two-ply yarn structures. The plying process was carried out using a ring twisting machine (Amsler, 12 spindles) operated at a constant spindle speed of 11,000 rpm. Six yarn combinations were prepared: polyester/hemp (PES/HF), polyester/pineapple (PES/PALF), pineapple/hemp (PALF/HF), pineapple/pineapple (PALF/PALF), polyester/polyester (PES/PES), and hemp/hemp (HF/HF). The homogeneous yarns (PALF/PALF, PES/PES, and HF/HF) were used as reference systems for comparison with the hybrid yarns.

For each yarn combination, nominal plying twist levels of 200, 300, 400 and 500 turns per meter (TPM) were applied. A total of 24 experimental conditions were investigated, comprising six yarn compositions and four twist levels. Three specimens were tested for each yarn composition–twist condition, resulting in a total of 72 yarn specimens.

Because the component yarns had an S-twist, the final plying twist was applied in the Z-direction to produce a balanced yarn structure and minimize snarling during net fabrication (Figure 8a). Before testing, all specimens were conditioned for at least 24 h at $20\pm 2^{\circ}\text{C}$ and $65\pm 2\%$ relative humidity. Mechanical testing was subsequently performed at 21°C and approximately 50% relative humidity.

5.2. Net fabrication and specimen preparation

Following yarn scale optimization, yarns prepared at 400 TPM were used to fabricate the knot and net specimens. Net panels were produced using double weaver's knots with a nominal mesh-bar length of 10 cm. Successive knot rows were arranged in alternating orientations to maintain the

repeated diamond-mesh geometry. Net panel specimens consisted of five staggered rows containing 5–4–5–4–5 knots, corresponding to 23 knots per specimen. Three net panel specimens were prepared for each yarn composition. The double weaver's knot specimens used for the knot scale testing were obtained from the corresponding fabricated panels.

5.3.Mechanical characterization

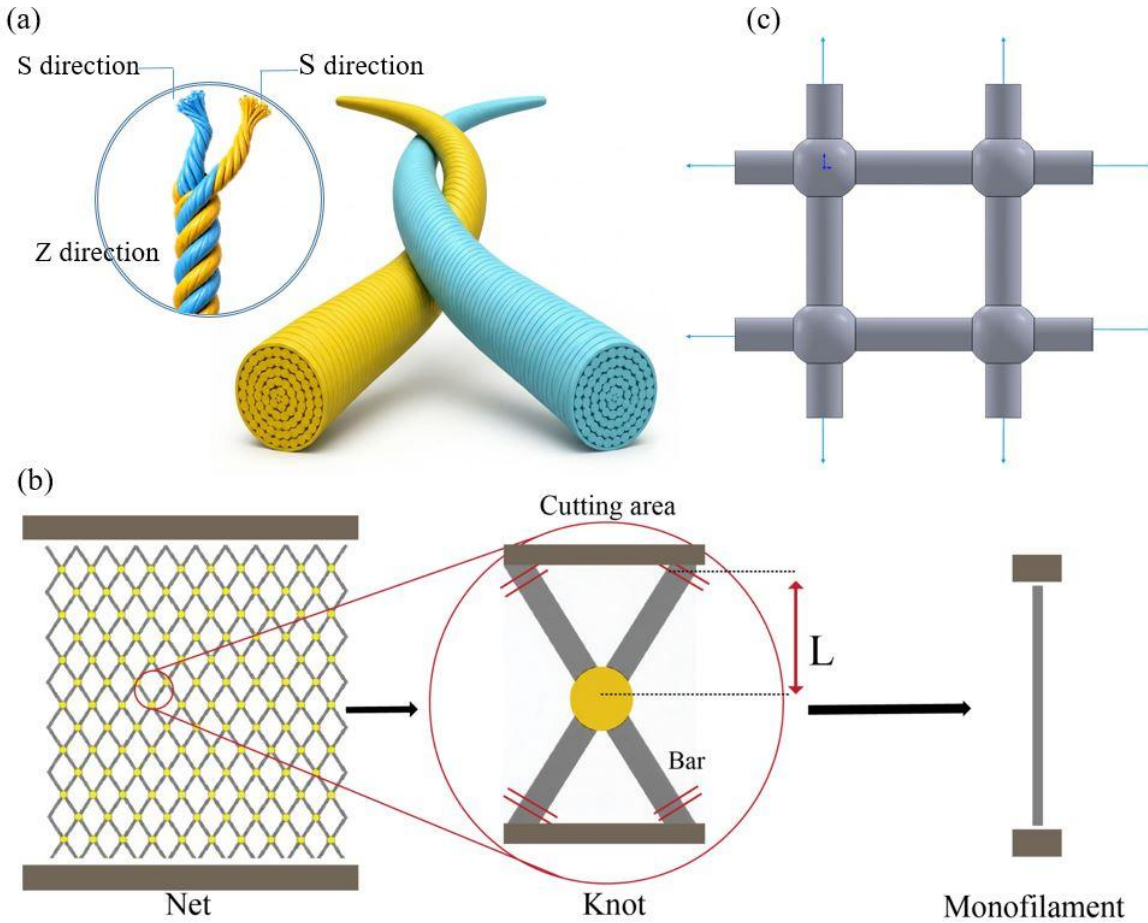


Figure 8. (a) S-twist direction of the component yarns and Z-direction of the plying twist; (b) schematic representation of the yarn-, knot-, and net-scale specimens; and (c) boundary conditions applied in the numerical net model.

5.3.1. Yarn-scale tensile testing

Yarn-scale tensile tests were performed using an Instron Universal Testing Machine (Model 5969, Instron Corporation) equipped with a 5 kN load cell. The initial gauge length was 100 mm. Each

yarn specimen was clamped at both ends and extended at a displacement rate of 10 mm min⁻¹ until rupture. The load at break (N) and breaking extension (%) were obtained from the tensile test. Three specimens were tested for each yarn composition–twist condition. The breaking extension was calculated as Equation (1):

$$\varepsilon_b = \frac{L_b - L_0}{L_0} \times 100 \quad (1)$$

Where ε_b is the breaking extension (%), L_0 is the initial gauge length (mm), and L_b is the specimen length at break (mm).

2.3.2. Knot-scale mechanical testing

Following the yarn-scale evaluation, yarns prepared at 400 TPM were selected for the knot-scale tests. Double weaver's knot specimens were obtained from the fabricated net panels, with each specimen consisting of a central knot region and four free yarn ends. The free ends were attached to the loading beams to preserve the knot configuration and enable controlled tensile loading.

Tensile loading was applied at a displacement rate of 10 mm min⁻¹ until failure. The highest load recorded during the test was defined as the maximum knot load (N). Three independent knot specimens were tested for each yarn composition.

To assess the extent to which yarn-scale load-bearing capacity was retained after knot formation, knot strength efficiency was calculated by normalizing the mean maximum knot load to the mean breaking force of the corresponding straight yarn tested at 400 TPM:

$$\eta_k = \frac{F_k}{F_y} \times 100$$

Where η_k is the knot strength efficiency (%), F_k is the maximum knot load (N), and F_y is the breaking force (N) of the corresponding straight yarn at 400 TPM. Higher values of η_k indicate greater retention of the yarn-scale strength after knot formation.

During tensile loading, knot deformation was recorded using a high-speed camera (Fastec, HiSpec Series Cameras) positioned normal to the specimen plane. Four characteristic markers surrounding

the knot region were tracked throughout the loading process. The coordinates of these markers were subsequently used to quantify changes in knot geometry, as described in Section 2.4.

2.3.3. Net-panel mechanical testing

Net-panel specimens fabricated from yarns prepared at 400 TPM were used for the net-scale evaluation. Each panel consisted of five staggered rows containing 5–4–5–4–5 knots, corresponding to a total of 23 knots. The upper and lower edges of each specimen were attached to 10 cm mounting beams to distribute the applied load across the net width.

Net deformation was simultaneously recorded using the same high-speed camera system employed for the knot-scale tests. The displacement of selected knot positions and the strain developed along the mesh bars were subsequently determined through image processing, as described in Section 2.4.

2.3.4. Testing conditions

All yarn, knot, and net specimens were tested in the dry state. Before mechanical testing, the yarn specimens were conditioned for at least 24 h at 20 °C and 65±2% relative humidity. Mechanical testing was performed under laboratory conditions of approximately 21 °C and 50% relative humidity. Figure 8b summarizes the experimental setup used for the yarn scale, knot scale, and net scale tensile tests, with the yellow crosses indicating the knot positions used for deformation tracking.

5.4. Image processing

The deformation of the knot specimens and the strain distribution of the net-panel specimens were recorded using a high-speed camera (Figure 9). A total of 36 videos were analyzed, comprising three replicates for each of the six yarn compositions at both the knot and net scales. From each video, image frames were extracted at a rate of 60 frames per second to track the deformation process during loading.

For the knot specimens, four markers surrounding the knot region were tracked throughout loading. The change in the enclosed quadrilateral area was used as a geometric indicator of knot

deformation, because tightening, rearrangement, and movement of the yarn segments altered the spatial positions of the four tracked markers. Knot deformation was quantified as the absolute knot-area change, defined as Equation (2):

$$\Delta A = |A_f - A_0| \quad (2)$$

Where A_0 is the initial area enclosed by the four markers, A_f is the area at the selected final frame before failure, and ΔA is the absolute knot-area change (mm^2). The extracted images were then processed using Python to identify and record the coordinates of selected characteristic points on the knot and net structures within a two-dimensional coordinate system. These coordinates were used to calculate the displacement, deformation, and strain evolution during tensile loading. This image-processing approach was adapted from the procedure reported by Le Gué et al. ²⁴.

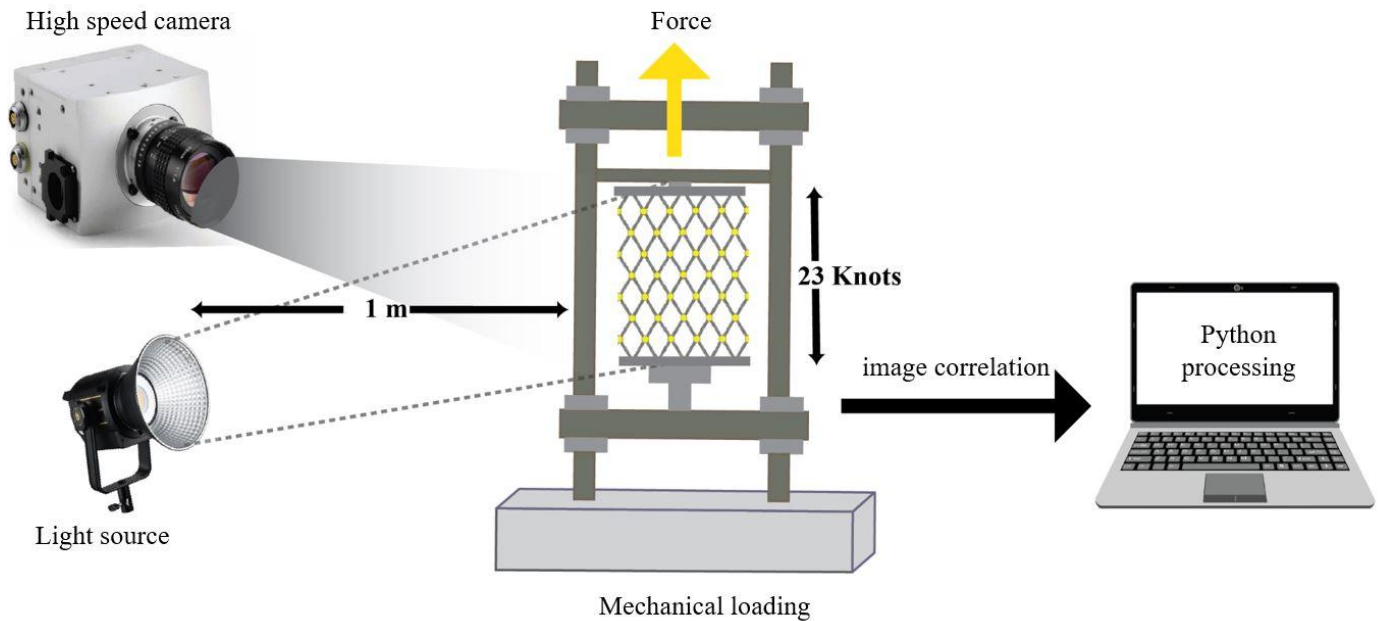


Figure 9. Experimental setup and image-processing workflow for deformation and strain analysis of the fishing-net specimen.

5.5. Grey Relational Analysis (GRA)

Grey Relational Analysis (GRA) was applied as a multi-response optimization method to identify the twist level that provided the best balance between load at break and breaking extension. Since both strength and elongation are important for fishing-net yarn performance, GRA was used to convert these two responses into a single performance index, known as the Grey Relational Grade (GRG) ²⁵.

Normalization of Data

The first step in GRA is data normalization, which converts the experimental values into dimensionless values between 0 and 1. In this study, both load at break and breaking extension were considered as “larger-the-better” responses. Therefore, the normalized value was calculated using Equation (3):

$$x(k) = \frac{x_i(k) - \min x_i(k)}{\max x_i(k) - \min x_i(k)} \quad (3)$$

Where $x(k)$ is the normalized value of the k -th response for the i -th experimental condition, $x_i(k)$ is the original experimental value, and $\max x_i(k)$ and $\min x_i(k)$ are the maximum and minimum values of the k -th response, respectively. The index i represents the experimental trial, while k represents the response variable.

In the present study, $k=1$, and corresponded to load at break, whereas $k=2$, corresponded to breaking extension.

Deviation of Data

After normalization, the deviation sequence, which measures the absolute difference between the normalized values and the reference sequence (ideal value), is calculated. The deviation sequence $\Delta 0_i(k)$ is defined by Equation (4):

$$\Delta 0_i(k) = |x_0(k) - x_i(k)| \quad (4)$$

Here, $\Delta 0_i(k)$ is the deviation sequence for the i -th trial at the k -th response variable, $x_0(k)$ is the ideal reference value for the k -th response, and $x_i(k)$ is the normalized value for the k -th trial and k -th response variable.

The minimum and maximum deviations among all experimental conditions and responses were subsequently determined as Equation (5):

$$\Delta_{\min} = \min_{i, k} \Delta_{0i}(k) \quad (5)$$

And

$$\Delta_{\max} = \max_{i, k} \Delta_{0i}(k)$$

Grey Relational Coefficient

The Grey Relational Coefficient (GRC) quantifies the relationship between the reference and comparability sequences. The GRC is calculated using Equation (6):

$$\xi_i(k) = \frac{\Delta_{\min} + \zeta \Delta_{\max}}{\Delta_{0i}(k) + \zeta \Delta_{\max}} \quad (6)$$

In this equation, $\xi_i(k)$ is the GRC for the i -th response at the k -th condition, $\Delta_{\min}$ and $\Delta_{\max}$ are the minimum and maximum deviation sequences, and ζ is the distinguishing coefficient, typically set to 0.5.

Grey Relational Grade

The Grey Relational Grade (GRG) provides a single value representing the overall performance of each experimental condition. The GRG is calculated using Equation (7):

$$\gamma_i = 1/n \sum_k \xi_i(k) \quad (7)$$

Where γ_i is the GRG for the i -th experiment and n is the number of responses. In the present study, normalization and Grey Relational Coefficient calculations were first performed separately for each of the 24 yarn composition–twist conditions. The Grey Relational Grade for each condition was obtained by averaging the coefficients corresponding to load at break and breaking extension, with both responses assigned equal weighting. The resulting condition-level GRGs were subsequently averaged across the six yarn compositions at each twist level to obtain the twist-level GRGs reported in Table 3. The twist level with the highest mean GRG was considered to provide the optimal overall balance between the load at break and breaking extension.

5.6. Simulation

The numerical model was developed as a comparative framework rather than as a predictive model for reproducing the absolute experimental failure loads. Its purpose was to evaluate the relative influence of mesh-bar length on the mechanical response of the net structures under identical modelling assumptions and boundary conditions. Therefore, the simulated reaction forces were used to compare the 5 and 10 cm mesh configurations within each yarn system and should not be interpreted as direct predictions of the experimentally measured net-panel loads.

5.6.1. Governing equations

Finite element simulation was used to evaluate the break at load response and failure behavior of the net panels at break. The model considers large deformation, contact interactions between yarns, surface friction, elastic–plastic deformation, and progressive failure. An explicit dynamic solver was selected because it is suitable for nonlinear problems involving large deformation, contact, material damage, and fracture.

The mechanical response of the model was governed by the dynamic equilibrium Equation (8):

$$M \cdot \ddot{U} = P - I \quad (8)$$

Where, M is the mass matrix of the structure, $\ddot{u}$ is the acceleration vector of the structure, P is the external force vector applied, I is the internal force of the structure (determined jointly by the deformation and motion of the structure).

The strain during tensile deformation was calculated from the change in length. Since large deformation may occur during stretching, logarithmic strain was used Equation (9):

$$\mathcal{E} \log = \ln \left(\frac{L}{L_0} \right) \quad (9)$$

Here, L represents the deformed length, and L_0 represents the initial length.

In the elastic region, the stress–strain relationship was described using Hooke’s law (Equation 10):

$$\sigma = C: \varepsilon \quad (10)$$

Where σ is stress, C is the Young’s modulus, and ε is strain. Plastic yielding was described using the von Mises yield criterion (Equation 11):

$$f(\sigma) = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_4)^2}{2}} - \sigma_y \leq 0 \quad (11)$$

Among them, $\sigma_1 \geq \sigma_2 \geq \sigma_3$ are the principal stresses, and σ_y represents the yield strength of the material.

Yielding occurs when the equivalent stress reaches the yield stress of the material (Equation 12):

$$\sigma_{eq} \geq \sigma_y \quad (12)$$

Contact between yarn surfaces was represented using Coulomb's friction model (Equation 13):

$$f = \mu N \quad (13)$$

Where, f is the friction force, μ is the friction coefficient, N is the normal pressure between the contact surfaces

Progressive failure was described using a ductile damage approach. The damage variable was defined as Equation (14):

$$D = \frac{\varepsilon_p}{\varepsilon_{p \text{ crit}}} \quad (14)$$

Where D is the damage variable, ε_p is the equivalent plastic strain, and $\varepsilon_{p \text{ crit}}$ is the critical equivalent plastic strain. The damage variable ranges from 0 to 1, where $D=0$ represents the undamaged state and $D=1$ indicates complete failure. Element removal was applied when the following condition was reached (Equation 15):

$$D = 1 \quad (15)$$

5.6.2. Mesh geometry and boundary conditions

Two net configurations with nominal mesh-bar lengths of 5 and 10 cm were developed for the comparative numerical analysis. Both models had the same network topology, including the same number and arrangement of knots and mesh bars. The principal geometric difference between the two configurations was therefore the length of the individual mesh bars. Consequently, the overall

dimensions of the net panels differed between the two models, with the 10 cm mesh bar configuration occupying a larger overall area than the corresponding 5 cm configuration.

The 5 cm mesh-bar model was discretized using 8,923 tetrahedral elements, whereas the 10 cm model was discretized using 14,261 tetrahedral elements. The difference in element number resulted from the different geometric dimensions of the two configurations. The same material definitions, contact formulation, and numerical modeling approach were applied to both configurations to provide a consistent basis for comparison.

The numerical models were developed primarily for comparative rather than predictive purposes. Specifically, the analysis was used to examine differences in stress distribution, deformation behavior, and maximum reaction force between the 5 and 10 cm mesh bar configurations under a consistent modeling framework. Because changing the mesh bar length also changed the overall dimensions of the net panel, the numerical results should be interpreted as a comparison between two geometrically different net configurations rather than as an isolated quantitative assessment of mesh bar length alone. Accordingly, the simulated force values were used to identify relative differences between the two configurations and were not intended to reproduce the absolute failure loads measured in the experimental net-panel tests.

5.7. Scanning electron microscopy observations

Scanning electron microscopy (SEM) was used to examine the surface morphology of the yarns before and after seawater immersion and to characterize the morphology of the double weaver's knot structures. The observations were performed at accelerating voltages of 10–20 kV and at magnifications appropriate for the feature scale. The exact accelerating voltage, magnification, and scale bar are provided in each micrograph. The samples were sputter-coated with gold to improve the electrical conductivity and image quality. For the knot micrographs, the SEM images were digitally false-colored after acquisition solely to facilitate visual differentiation of the constituent yarn components. The colors therefore represent the assigned fiber types and do not correspond to elemental, chemical, or spectroscopic mapping. SEM images were used to evaluate fiber surface morphology, structural arrangement within the knots, and surface changes following seawater exposure.

5.8. Statistical analysis and visualization.

The results were analyzed using two-way analysis of variance at a significance level of $\alpha=0.05$. The statistical analyses were performed using SPSS 27, while Minitab 22 was used for supplementary calculations. Image processing and image-correlation analysis were carried out using Python 3.9.18. Matplotlib was used for data visualization and graphical presentation of the results.

Funding Declaration

This work was supported by the Hong Kong General Research Fund (Project No. 15608124).

Data Availability

The datasets generated and/or analysed during the current study are available from the corresponding author upon reasonable request.

References

- 1 Lau, W. W. *et al.* Evaluating scenarios toward zero plastic pollution. *Science* **369**, 1455-1461 (2020).
- 2 Juan, R. *et al.* Challenges and opportunities for recycled polyethylene fishing nets: Towards a circular economy. *Polymers* **13**, 3155 (2021).
- 3 An, H.-C., Kim, S.-H., Lim, J.-H. & Bae, J.-H. Catching efficiency of the biodegradable gill net for Pacific herring (*Clupea pallasii*). *Journal of the Korean Society of Fisheries and Ocean Technology* **49**, 341-351 (2013).
- 4 Matsuoka, T., Nakashima, T. & Nagasawa, N. A review of ghost fishing: scientific approaches to evaluation and solutions. *Fisheries Science* **71**, 691-702 (2005).
- 5 Richardson, K., Hardesty, B. D. & Wilcox, C. Estimates of fishing gear loss rates at a global scale: A literature review and meta-analysis. *Fish and Fisheries* **20**, 1218-1231 (2019).
- 6 Grimaldo, E. *et al.* Fishing efficiency of biodegradable PBSAT gillnets and conventional nylon gillnets used in Norwegian cod (*Gadus morhua*) and saithe (*Pollachius virens*) fisheries. *ICES Journal of Marine Science* **75**, 2245-2256 (2018).
- 7 Do, H.-L. & Armstrong, C. W. Ghost fishing gear and their effect on ecosystem services—Identification and knowledge gaps. *Marine Policy* **150**, 105528 (2023).
- 8 Bekker-Nielsen, T. Ancient nets and fishing gear. (2010).
- 9 Kim, J. *et al.* Biodegradation behavior of polybutylene succinate (PBS) fishing gear in marine sedimentary environments for ghost fishing prevention. *Polymer Degradation and Stability* **216**, 110490 (2023).
- 10 Wataniyakun, W., Le Gall, M., El Rakwe, M., Karl, C. W. & Larsen, R. B. Biodegradable fishing gears: A potential solution to ghost fishing and marine plastic pollution. *Marine Pollution Bulletin* **212**, 117607 (2025).
- 11 Le Gué, L. *et al.* Degradation mechanisms in PBSAT nets immersed in seawater. *Polymer Degradation and Stability* **225**, 110788 (2024).

- 12 Wright, L. S., Napper, I. E. & Thompson, R. C. Potential microplastic release from beached fishing gear in Great Britain's region of highest fishing litter density. *Marine Pollution Bulletin* **173**, 113115 (2021).
- 13 Uddin, N., Miah, S., Jalil, M., Islam, M. & Siddika, A. A review on extraction, characterization and application of pineapple leaf fiber (PALF) in textiles and other fields. *International Journal of Advanced Research* **5**, 112-116 (2017).
- 14 Bakhori, S. N. M. *et al.* Mechanical properties of PALF/Kevlar-reinforced unsaturated polyester hybrid composite laminates. *Polymers* **14**, 2468 (2022).
- 15 Gadzama, S. W., Sunmonu, O., Isiaku, U. & Danladi, A. Effects of surface modifications on the mechanical properties of reinforced pineapple leaf fibre polypropylene composites. *Adv. Chem. Eng. Sci* **10**, 24-39 (2020).
- 16 Bismarck, A., Baltazar-Y-Jimenez, A. & Sarikakis, K. Green composites as panacea? Socio-economic aspects of green materials. *Environment, development and sustainability* **8**, 445-463 (2006).
- 17 Arockiasamy, F. S. *et al.* Exploring the strength and durability of hemp fiber reinforced moringa bioresin composites for skateboard applications. *AIP Advances* **14** (2024).
- 18 Todkar, S. S. & Patil, S. A. Review on mechanical properties evaluation of pineapple leaf fibre (PALF) reinforced polymer composites. *Composites Part B: Engineering* **174**, 106927 (2019).
- 19 Sala, A., Lucchetti, A. & Buglioni, G. The change in physical properties of some nylon (PA) netting samples before and after use. *Fisheries research* **69**, 181-188 (2004).
- 20 Moe, H., Olsen, A., Hopperstad, O. S., Jensen, Ø. & Fredheim, A. Tensile properties for netting materials used in aquaculture net cages. *Aquacultural engineering* **37**, 252-265 (2007).
- 21 Nazari, S. & Li, L. A review of the relationships of structure with mechanical performance in fishing nets. *Journal of Industrial Textiles* **56**, 15280837261463061 (2026).
- 22 Xu, L., Miao, Y., Wu, X., Li, P. & Qin, H. Experimental investigation on loads of nets with different types under current. *Scientific Reports* **15**, 16891 (2025).
- 23 Tang, H. *et al.* Effect of mesh size modifications on the sinking performance, geometry and forces acting on model purse seine nets. *Fisheries Research* **211**, 158-168 (2019).
- 24 Le Gué, L. *et al.* Influence of knot strength on the mechanical performance of a biodegradable gillnet. *Scientific Reports* **14**, 15450 (2024).
- 25 Shakeri, Z., Benfriha, K., Zirak, N. & Shirinbayan, M. Mechanical strength and shape accuracy optimization of polyamide FFF parts using grey relational analysis. *Scientific Reports* **12**, 13142 (2022).
- 26 Royer, S.-J., Wiggin, K., Kogler, M. & Deheyn, D. D. Degradation of synthetic and wood-based cellulose fabrics in the marine environment: Comparative assessment of field, aquarium, and bioreactor experiments. *Science of The Total Environment* **791**, 148060 (2021).
- 27 Hassan, M. M., Collie, S., Brorens, P. & Fowler, I. Marine Biodegradation Behavior of Wool and Other Textile Fibers. *Water, Air, & Soil Pollution* **235** (2024).
- 28 Soltani, P. & Johari, M. A study on siro-, solo-, compact-, and conventional ring-spun yarns. Part II: yarn strength with relation to physical and structural properties of yarns. *Journal of The Textile Institute* **103**, 921-930 (2012).
- 29 Rungruangkitkrai, N. *et al.* Valorization of Pineapple Leaf Agro-Residues into Bio-Based Ring-Spun Yarns: Microstructural Mapping and Mechanical Behavior of PALF–Cotton Blends. *Journal of Sustainability Research* **8** (2026).
- 30 Shan, C. *et al.* Sinking behavior of netting panels made with various twine materials, solidity ratios, knot types, and leadline weights in flume tank. *Journal of Marine Science and Engineering* **11**, 1972 (2023).