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Mechanical Performance of Hemp-Containing Denim Fabrics with Core-Engineered Weft Yarns

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Highlights

What are the main findings?

- Denim mechanical performance depends jointly on warp composition, weft yarn architecture and fabric compactness—not on hemp content alone; core-engineered dual-core weft yarns shift the tensile/tear balance independently of warp fibre type.

What are the implications of these findings?

- Adding hemp to denim warp is not a stand-alone design choice: warp and weft must be engineered together, giving manufacturers a practical route to more sustainable denim without sacrificing durability.

Abstract

The mechanical performance of hemp-containing denim fabrics depends not only on fibre selection but also on how fibre composition is translated into yarn and fabric structure. Substituting part of the cotton warp with hemp is one possible step toward more sustainable denim production, but this study makes no independent sustainability claim (i.e., no life-cycle assessment was performed) and instead focuses solely on mechanical behaviour. This study comparatively evaluated eleven denim fabrics produced with 100% cotton or cotton/hemp-blended (69/31) warp yarns and different rigid, elastane-core and PET/PTT+elastane dual-core weft yarns. Grab tensile strength and tear strength were assessed in warp and weft directions and interpreted together with structural parameters. The results showed that mechanical response was governed by the combined effect of warp composition, weft architecture and structural compactness rather than by fibre substitution alone. Fabrics containing hemp in the warp did not show a uniform mechanical gain or loss across the sample set; instead, their tensile and tear behaviour depended on the associated weft design and fabric construction. Core-engineered weft yarns, particularly dual-core structures, altered the balance between tensile and tear response, indicating that yarn architecture played an important role in load distribution and deformation behaviour. Overall, the findings show that the mechanical design of hemp-containing denim fabrics should be approached through an integrated fibre–yarn–fabric perspective.

Keywords: hemp-containing denim; hemp warp; dual-core weft; grab tensile; tear strength; mechanical performance

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1. Introduction

Denim development increasingly seeks material solutions that can help reduce environmental burden without compromising fabric performance. Among alternative fibres, hemp has attracted considerable attention because of its lower agricultural input requirement, rapid renewability, and growing industrial relevance in textile value chains [1,2]. At the same time, the successful integration of hemp into denim cannot be evaluated only through sustainability-related arguments, because denim fabrics are also expected to maintain adequate mechanical durability during garment manufacture and wear [3,4].

From an end-use perspective, the mechanical performance of denim fabrics remains one of the key determinants of product quality. Tensile and tear resistance are particularly important because they influence sewing performance, local damage tolerance and service-life behaviour. In woven fabrics, these properties are governed not only by fibre composition but also by yarn count, fabric sett (thread density, i.e., ends/cm and picks/cm), yarn architecture and load transfer between warp and weft systems. This makes structure–property interpretation essential in hemp-containing denim design [5,6].

Hemp incorporation adds further complexity to this relationship. Although hemp-containing yarns and fabrics are attractive from a sustainability standpoint, the mechanical response of the final fabric does not necessarily improve or deteriorate in a uniform manner. Instead, the outcome depends on how hemp is introduced into the yarn and fabric system and how this interacts with structural variables such as yarn architecture, fineness and compactness. More recent studies have also shown that both textile-grade hemp preparation and spinning route can substantially influence the performance of hemp-blended yarns [4,7,8].

In parallel with the increasing use of hemp and other sustainable fibres, core-engineered yarn systems have become an important part of denim fabric design. Elastane-core and dual-core yarns incorporating a supportive filament such as PET/PTT (T400®) are widely used to improve dimensional stability, recovery and broader performance characteristics. Recent studies have further demonstrated that optimised elastane/T400 systems, alternative filament selections, and modified feeding routes can substantially alter yarn and fabric behaviour [9–13].

However, much of the recent literature has either concentrated on fabric comfort behaviour or focused on yarn-level quality indicators rather than on fabric-level mechanical performance within a comparable hemp-containing denim sample set. Comparable fabric-level studies of rigid, core-spun and dual-core weft architectures have so far been reported mainly for cotton/polyester warp–weft systems rather than for hemp-containing warps [14], underlining the gap that the present study addresses. In this context, the present study focuses specifically on the mechanical behaviour of denim fabrics and comparatively evaluates eleven denim variants produced with 100% cotton or cotton/hemp-blended warp yarns and different rigid, elastane-core, and PET/PTT+elastane dual-core weft yarns. The fabrics were examined in terms of grab tensile strength and tear strength in warp and weft directions, and the results were interpreted together with structural parameters. The study therefore aims to clarify how hemp-containing warp systems and core-engineered weft yarns jointly influence the mechanical performance of hemp-containing denim fabrics.

Unlike previous studies focusing on transport comfort or yarn-level quality indicators, the present work exclusively addresses fabric-level mechanical response by jointly evaluating grab tensile and tear behaviour in warp and weft directions within the same denim sample set. The novelty of the study lies in its structure-sensitive interpretation of mechanical performance, in which warp hemp content, weft architecture and weft count are considered together rather than as isolated variables.

2. Materials and Methods

2.1. Fabric Materials and Sample Design

Eleven denim fabrics representing industrially relevant 3/1 twill constructions were selected for comparative evaluation. The sample set comprised two warp families and several weft architectures. The warp yarns were either 100% cotton or a cotton/hemp blend (69/31). The weft yarns included rigid yarns, elastane-core yarns and PET/PTT (T400®)+elastane dual-core yarns differing in count and sheath composition. Across the sample set, the fabrics therefore varied in warp composition, weft architecture, yarn count and structural compactness while remaining within a comparable denim construction range. The eleven constructions were not generated from an a priori full-factorial design; rather, each combination corresponds to a construction produced at industrial scale, so the sample size reflects the range of commercially available warp–weft combinations rather than a controlled statistical matrix, as also noted in Section 4.

The principal aim of the sample design was to examine how hemp-containing warp systems and core-engineered weft yarns jointly influence fabric mechanical response. Structural parameters including ends/cm, picks/cm, dry mass, and thickness were also used to support fabric-level interpretation. The detailed structural specifications of all samples are presented in Table 1.

Table 1. Structural design and selected physical parameters of the denim fabrics, measured in the grey (as-woven, pre-wash) state.

Fabric	Warp Family	Warp Composition	Weft Architecture	Weft Count (Ne)	Ends/cm	Picks/cm	Mass g/m^2
TYPE 1	Cotton warp	100% cotton	Rigid	8.6/1	26.0	16.8	325
TYPE 2	Cotton warp	100% cotton	Rigid	8.6/1	26.0	18.0	345
TYPE 3	Cotton warp	100% cotton	Dual-core	10/1	27.2	16.8	330
TYPE 4	Cotton warp	100% cotton	Dual-core	14/1	28.0	17.2	312
TYPE 5	Cotton warp	100% cotton	Dual-core	18/1	27.6	16.8	285
TYPE 6	Hemp warp	cotton/hemp (69/31)	Rigid	8.6/1	24.0	18.8	330
TYPE 7	Hemp warp	cotton/hemp (69/31)	Elastane-core	8/1	24.8	18.0	341
TYPE 8	Hemp warp	cotton/hemp (69/31)	Dual-core	10/1	24.8	18.0	301
TYPE 9	Hemp warp	cotton/hemp (69/31)	Dual-core	14/1	26.0	18.0	285
TYPE 10	Hemp warp	cotton/hemp (69/31)	Dual-core	18/1	26.4	16.8	265
TYPE 11	Hemp warp	cotton/hemp (69/31)	Rigid	8.6/1	24.4	18.4	321

The ends/cm, picks/cm, mass, and thickness reported in Table 1 were measured on the fabrics in their grey (as-woven, pre-wash) state; each mass value is the mean of five specimens per ASTM D3776/D3776M-20. By contrast, the mechanical properties reported in Section 3 (grab tensile strength and tear strength, Table 3) were measured after the fabrics had undergone the mill's standard industrial finishing wash (desizing, followed by rinse and enzyme wash steps), consistent with denim end-use testing practice; each mechanical value in Table 3 is the mean of five specimens per direction.

To provide additional yarn-level context for the two warp yarns used in this study (100% cotton and 69/31 cotton/hemp, both Ne 8.6/1), Table 2 summarises their evenness (U%, CVm%), imperfection indices (thin places, thick places, neps), hairiness, elongation, and specific tenacity, as recorded in the mill's routine yarn quality-control testing. Twist level (turns/cm) was not recorded in the available quality-control records and could not be included.

Table 2. Selected quality characteristics of the two warp yarns (source: in-house yarn quality-control testing of the collaborating mill).

Warp Yarn	U (%)	CVm (%)	Thin Places (−50%/km)	Thick Places (+50%/km)	Neps (+200%/km)	Hairiness (H)	Elongation (%)	Tenacity (cN/tex)
100% cotton, Ne 8.6/1	18.3	21.5	4700	15	180	8.0	6.8	14.8
69/31 cotton/hemp, Ne 8.6/1	16.0	23.0	8000	200	1800	10.0	5.5	12.5

The hemp-blended warp yarn shows higher irregularity (U%, CVm%), more imperfections, and lower specific tenacity than the 100% cotton warp yarn, consistent with the greater processing difficulty of hemp fibre reported in the literature [4,7,8].

2.2. Mechanical and Structural Testing

Grab tensile strength was determined in warp and weft directions according to ASTM D5034-21 [15]. Tear strength was measured in both directions using the Elmendorf method according to ASTM D1424-21 [16]. Fabric mass per unit area was determined according to ASTM D3776/D3776M-20 [17], and thickness was evaluated according to ISO 5084:1996 [18]. All measurements were carried out under standard textile testing conditions.

These variables were selected because grab tensile and tear strength are among the most informative indicators of denim mechanical behaviour in processing and end use. Tensile performance reflects resistance to directional loading and structural failure, whereas tear resistance represents resistance to local damage propagation. When interpreted together with mass and thickness, these parameters provide a practical framework for understanding the mechanical design of hemp-containing denim fabrics.

2.3. Data Evaluation

The data were evaluated comparatively at the fabric level, with emphasis on directional differences in grab tensile and tear strength in relation to warp composition and weft architecture. The interpretation focused on three levels: (i) comparison between the two warp families, (ii) comparison among rigid, elastane-core and dual-core weft systems, and (iii) within-group interpretation of weft count effect where relevant.

In addition to descriptive comparison, exploratory Pearson correlation analysis was used to examine the relationships between grab tensile strength and tear strength in warp and weft directions. Correlation coefficients were calculated, while the broader comparison of fabric types and subgroup means was retained as descriptive. Each reported value is itself the mean of five specimens per direction (Section 2.1); however, the individual specimen-level measurements and their standard deviations were not retained in the dataset available for this analysis, so the statistical interpretation was limited to comparative and exploratory analysis of the mean values rather than a fully factorial confirmatory design with error propagation.

3. Results

The results are presented to comparatively examine how warp hemp content and weft architecture influenced the mechanical performance of the denim fabrics. The interpretation focuses on grab tensile strength and tear strength in warp and weft directions, supported by selected structural parameters. Table 3 summarises the principal mechanical results for the eleven fabric types.

Table 3. Grab tensile and tear strength results of the denim fabrics. Each value is the mean of five specimens per direction, tested after the standard industrial finishing wash described in Section 2.1.

Fabric	Tensile Warp (N)	Tensile Weft (N)	Tear Warp (N)	Tear Weft (N)
TYPE 1	706.1	519.8	64.0	54.4
TYPE 2	804.1	402.1	50.5	33.9
TYPE 3	892.4	490.3	64.0	64.0
TYPE 4	931.6	333.4	64.0	54.4
TYPE 5	941.4	274.6	63.3	45.4
TYPE 6	598.2	421.7	62.7	51.2
TYPE 7	814.0	519.8	57.6	53.7
TYPE 8	657.0	460.9	60.1	64.0
TYPE 9	706.1	353.0	61.4	59.5
TYPE 10	647.2	245.2	61.4	54.4
TYPE 11	608.0	480.5	60.8	55.0

3.1. Grab Tensile Strength

The grab tensile results indicate that the mechanical response of the denim fabrics did not depend on warp composition alone; rather, the response was jointly governed by warp fibre content, weft architecture and structural compactness. In the warp direction, the highest tensile strength was observed for TYPE 5 (941.4 N), followed by TYPE 4 (931.6 N) and TYPE 3 (892.4 N), whereas the lowest values were recorded for TYPE 6 (598.2 N) and TYPE 11 (607.8 N). In the weft direction, the highest tensile values were found for TYPE 1 and TYPE 7 (519.8 N), whereas the lowest value was recorded for TYPE 10 (245.2 N). The directional differences in grab tensile strength are shown in Figure 1.

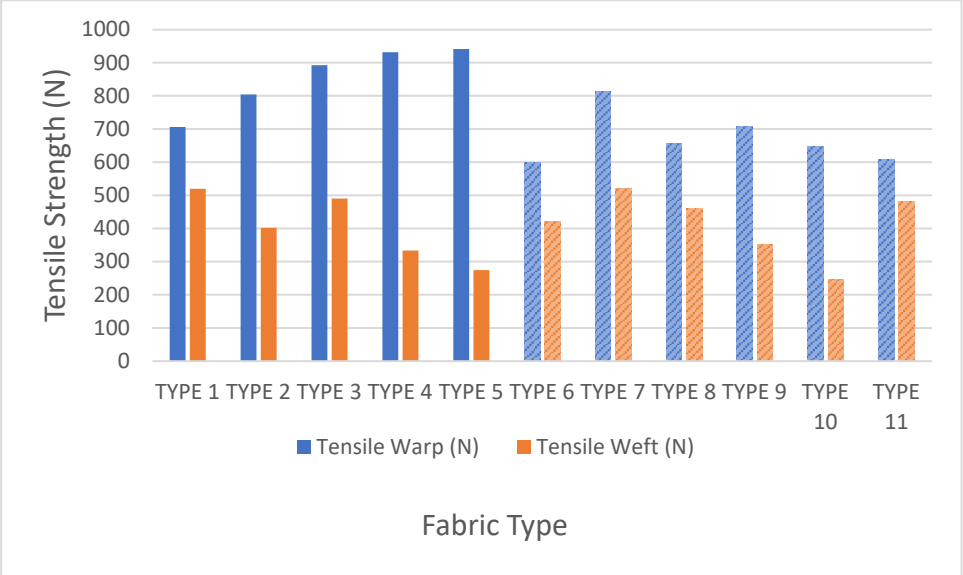


Figure 1. Grab tensile strength (N) of the eleven denim fabrics in warp and weft directions. Hatched bars denote hemp-warp fabrics (TYPE 6–11); solid bars denote 100% cotton-warp fabrics (TYPE 1–5).

When grouped by warp family, cotton-warp fabrics showed a markedly higher mean warp tensile strength than hemp-warp fabrics (855.1 vs. 671.7 N), whereas the mean weft tensile values of the two warp groups were much closer (404.0 vs. 413.4 N). This indicates that warp composition had a stronger effect on warp-direction load bearing than on weft-direction strength. Figure 1 also shows that warp and weft directions did not respond identically to changes in warp composition and weft architecture, suggesting that yarn structure and fabric direction interacted in a non-uniform manner [19–21].

3.2. Tear Strength

Tear strength showed a related but not identical pattern to grab tensile behaviour. In the warp direction, the highest tear values were observed for TYPE 1, TYPE 3 and TYPE 4 (64.0 N), whereas the lowest value was recorded for TYPE 2 (50.5 N). In the weft direction, the highest tear strength was found for TYPE 3 and TYPE 8 (64.0 N), while TYPE 2 again showed the lowest value (33.9 N). The corresponding tear strength trends are presented in Figure 2.

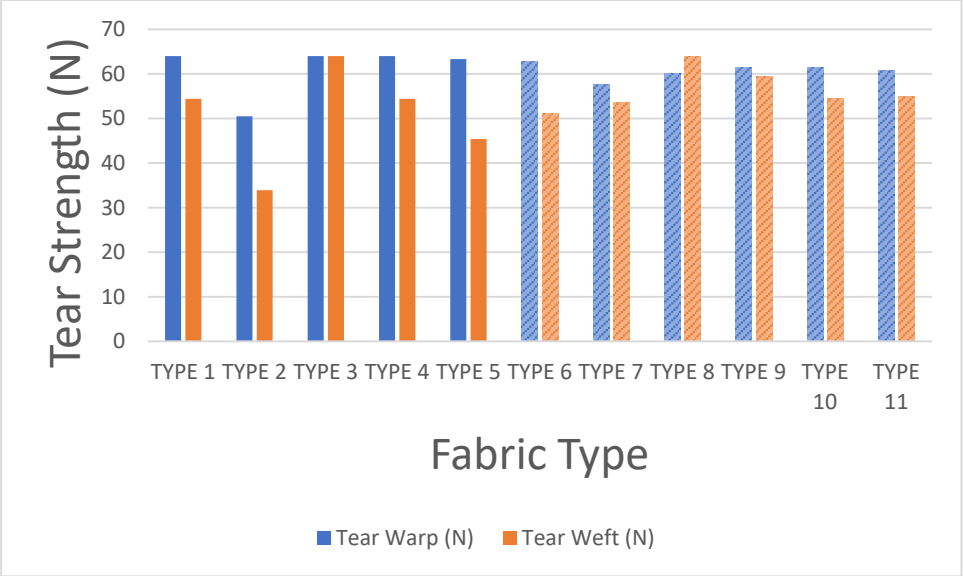


Figure 2. Tear strength (N) of the eleven denim fabrics in warp and weft directions. Hatched bars denote hemp-warp fabrics (TYPE 6–11); solid bars denote 100% cotton-warp fabrics (TYPE 1–5).

Figure 2 indicates that tear strength followed a related but not identical pattern to grab tensile strength. Fabrics showing stronger directional load-bearing behaviour did not always display the highest resistance to tear propagation, indicating that tensile and tear properties should not be treated as interchangeable descriptors of denim mechanics. The effect of core-engineered wefts was again evident in the tear results, suggesting that yarn structure and hybrid construction route influenced local damage propagation within the fabric [9–11].

3.3. Structural Interpretation of Mechanical Response

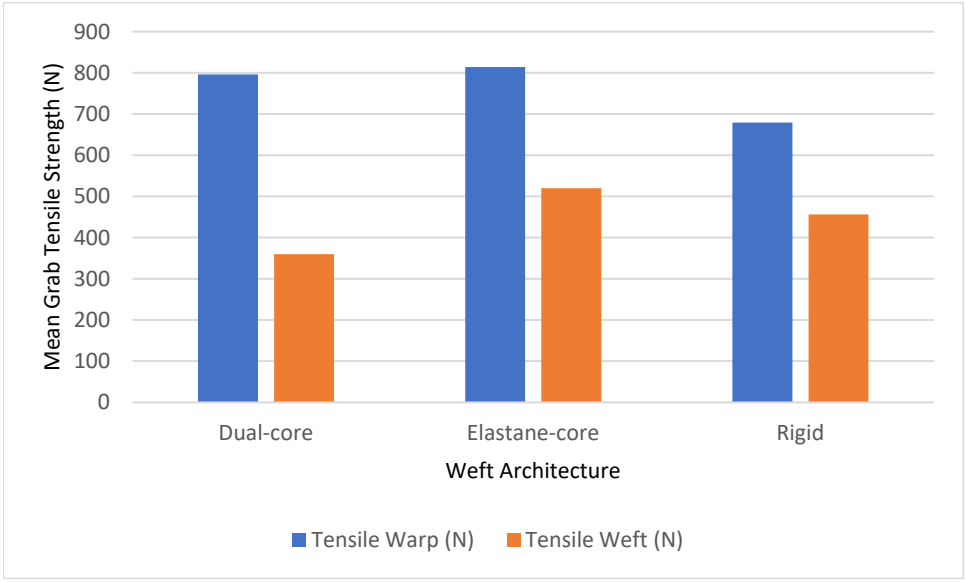
To support comparative interpretation, subgroup means according to weft architecture and warp family are summarised in Table 4. The grouped data show that rigid fabrics had the lowest average warp tensile strength (679.2 N), whereas dual-core fabrics exhibited the highest average tear resistance in both warp (62.4 N) and weft (56.9 N) directions. The elastane-core category showed the highest mean weft tensile value (519.8 N), but this group was represented by only one fabric and should therefore be interpreted descriptively.

The warp-family comparison in Table 4 further indicates that cotton-warp fabrics were mechanically stronger in the warp direction, while hemp-warp fabrics tended to show higher mean tear resistance in the weft direction. This suggests that the contribution of hemp-containing warp systems to mechanical behaviour was structure-dependent rather than uniformly positive or negative.

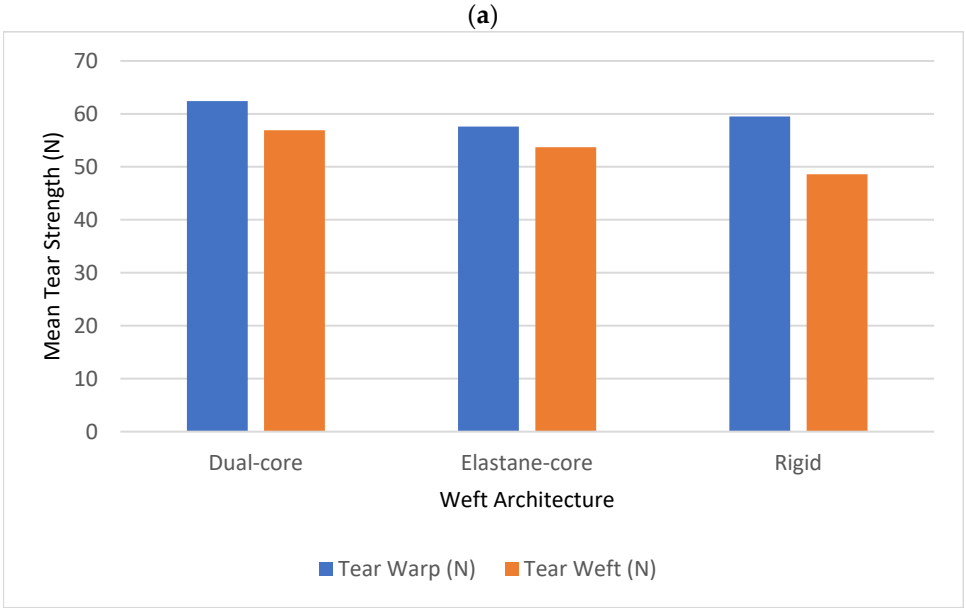
The grouped means in Table 4 indicate that weft architecture altered the mechanical profile of the denim fabrics relative to rigid references. Because the elastane-core category was represented by only one fabric, these subgroup comparisons should be interpreted descriptively rather than inferentially (Figure 3).

Table 4. Comparative subgroup summary of mechanical performance.

A. Grouped by weft architecture					
Weft structure	Fabric type(s)	Mean tensile warp (N)	Mean tensile weft (N)	Mean tear warp (N)	Mean tear weft (N)
Rigid	TYPE 1, 2, 6, 11	679.2	456.0	59.5	48.6
Elastane-core	TYPE 7	813.9	519.8	57.6	53.7
Dual-core	TYPE 3, 4, 5, 8, 9, 10	795.9	359.6	62.4	56.9
B. Grouped by warp family					
Warp family	Fabric type(s)	Mean tensile warp (N)	Mean tensile weft (N)	Mean tear warp (N)	Mean tear weft (N)
Cotton warp	TYPE 1, 2, 3, 4, 5	855.1	404.0	61.2	50.4
Hemp warp	TYPE 6, 7, 8, 9, 10, 11	671.7	413.4	60.7	56.3



(**a**)



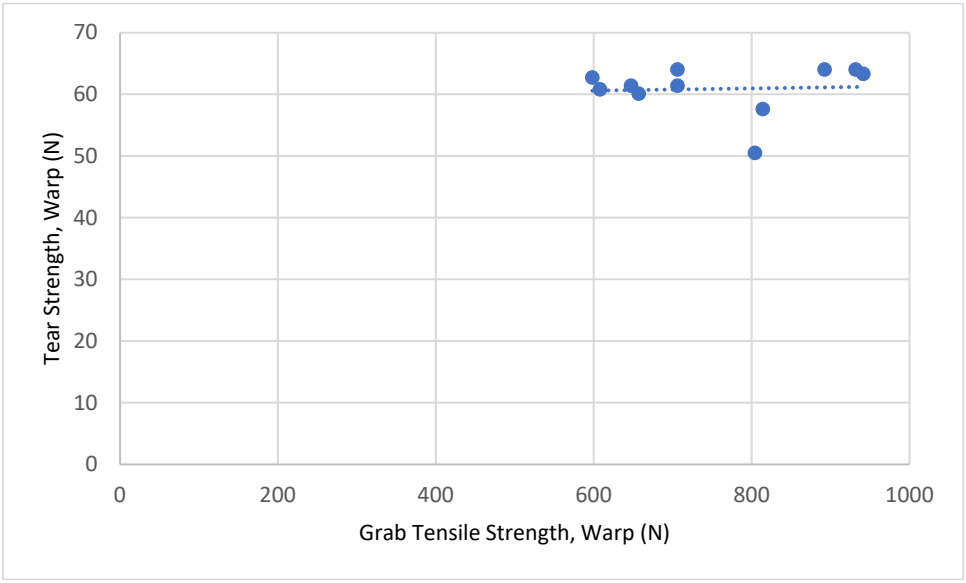
(**b**)

Figure 3. Comparative mechanical response grouped by weft architecture (rigid, elastane-core and dual-core): (**a**) mean grab tensile strength (N); (**b**) mean tear strength (N). Fabric types included in each subgroup are listed in Table 4.

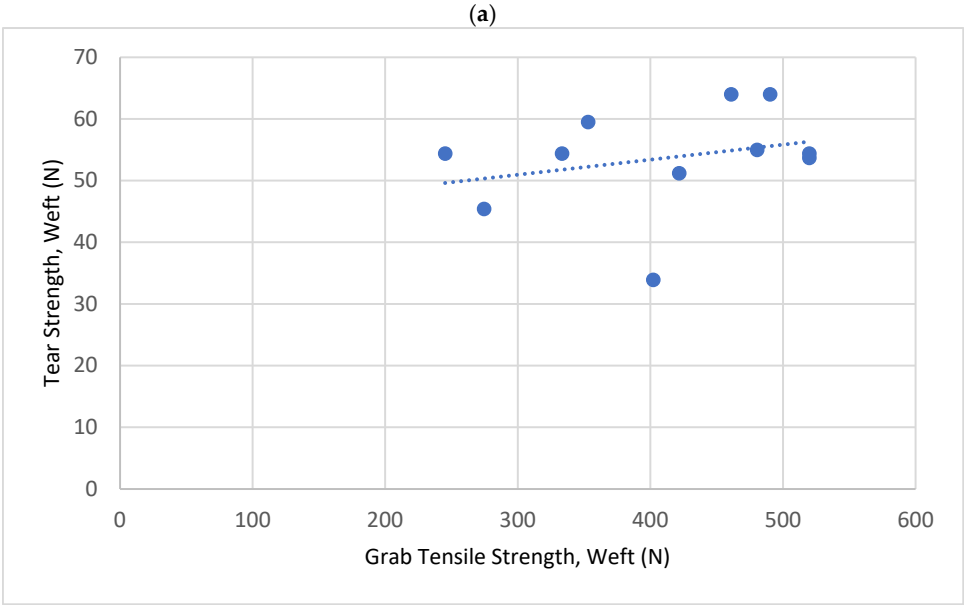
Within the dual-core subgroup, the fabrics shared the same general concept but still differed in tensile and tear performance. This indicates that count-related differences and constructional compactness played an additional role in determining the final mechanical behaviour. Similar structure-dependent trends have been reported in comparative studies on dual-core and hybrid yarn systems used in denim-oriented applications [10,12,13].

3.4. Relationship Between Tensile and Tear Behaviour

The relationship between tensile and tear responses is further visualised in Figure 4. The scatter distributions indicate that tensile and tear properties were associated but not fully parallel across the sample set. Pearson analysis confirmed that the association was weak in both directions (warp: r = 0.058, p = 0.864; weft: r = 0.279, p = 0.406). Accordingly, fabrics with higher tensile strength did not necessarily exhibit proportionally higher tear resistance.



(**a**)



(**b**)

Figure 4. Relationship between grab tensile strength (N) and tear strength (N) in the denim fabrics: (**a**) warp direction; (**b**) weft direction.

Figure 4 illustrates that tensile and tear responses were associated but not fully parallel across the sample set. The weak correlation observed in both directions supports the view that denim mechanical behaviour should not be interpreted through a single performance indicator.

From an application perspective, these results suggest that tensile strength, tear resistance and structural configuration should be evaluated together within an integrated fibre–yarn–fabric framework.

4. Discussion

The present results show that the mechanical response of hemp-containing denim fabrics cannot be interpreted through fibre substitution alone. Although hemp is attractive from a sustainability perspective, the use of a hemp-containing warp did not lead to a uniform mechanical gain or loss across the sample set. Instead, grab tensile and tear performance depended on how warp composition interacted with weft architecture and basic structural compactness. This interpretation is consistent with studies indicating that textile-grade hemp behaviour is highly sensitive to fibre preparation, structural integration and the route through which hemp is incorporated into the textile system [4,7,8].

A second important outcome is that weft architecture exerted a clear influence on the balance between tensile and tear behaviour. Compared with rigid-reference structures, core-engineered wefts altered the way in which load was carried and damage was propagated through the fabric. This suggests that elastane-core and especially PET/PTT+elastane dual-core systems should not be viewed only as stretch-related yarn solutions, but also as structural modifiers of fabric mechanics. Similar behaviour has been reported in studies showing that optimised elastane/T400 dual-core systems, modified feeding routes and advanced core-supported designs can improve the balance between strength, extensibility and dimensional response in denim-oriented structures [9–13].

The comparison between tensile and tear response further indicates that these two properties should not be treated as interchangeable indicators of denim durability. Fabrics showing stronger directional load-bearing behaviour did not necessarily exhibit the highest resistance to tear propagation. This distinction is mechanically meaningful because tensile strength reflects resistance to general loading, whereas tear strength is more sensitive to local yarn mobility, structural release and damage progression. Previous studies on engineered yarn systems have likewise shown that the final mechanical outcome depends on a combination of filament type, yarn geometry, and the way in which core elements are positioned and stabilised within the structure [10,11,22].

Within the dual-core subgroup, fabrics based on the same general concept still differed in mechanical response. This suggests that yarn count and constructional compactness also contributed to the final behaviour. In other words, the results support a fibre–yarn–fabric interpretation in which hemp content, core architecture, and count act together rather than independently. Comparable conclusions have been reported in studies on dual-core, siro dual-core, and multi-core yarn configurations, where small changes in filament combination or yarn-building route produced clear differences in performance response [11–13,20].

This directional asymmetry may be attributed to the different roles of warp and weft systems in load-bearing and tear propagation. While grab tensile strength is more strongly linked to directional yarn continuity and structural compactness, tear strength is more sensitive to local yarn mobility and the ease with which the structure can redistribute stress after crack initiation.

Overall, the findings indicate that hemp-containing denim design should not rely on hemp substitution alone as a mechanical (or sustainability) guarantee. Instead, the successful use of hemp-containing warp systems depends on whether the accompanying

weft architecture and structural design can maintain a favourable balance between strength and damage tolerance. All eleven fabrics were processed through the same standard industrial finishing wash recipe (desizing, rinse and enzyme wash steps at fixed liquor ratio, temperature, time and pH; Section 2.1), so finishing variation is unlikely to explain the difference between closely related constructions such as TYPE 1 and TYPE 2; their differing mechanical response is therefore more plausibly attributable to the structural difference between them (picks/cm and the resulting fabric weight, Table 1) than to finishing. A limitation of the present work is that the available dataset represents an industrial sample set with simultaneous variation in several constructional variables. Accordingly, the discussion should be interpreted as a comparative structure–property analysis rather than a fully factorial statistical model. Even so, the results are sufficiently clear to show that core-engineered weft systems provide an effective route for balancing mechanical performance in hemp-containing denim fabrics.

5. Conclusions

This study comparatively evaluated the mechanical performance of hemp-containing denim fabrics produced with hemp-containing warp systems and different weft architectures. The results showed that mechanical response was governed by the combined effect of warp composition, weft architecture and structural compactness rather than by fibre substitution alone. Fabrics containing hemp in the warp did not exhibit a uniform mechanical gain or loss across the sample set; instead, their grab tensile and tear behaviour depended on the associated weft design and fabric structure.

Core-engineered weft yarns, particularly dual-core constructions, altered the balance between tensile and tear response and therefore influenced the overall mechanical profile of the fabrics. These findings indicate that the successful mechanical design of hemp-containing denim fabrics requires an integrated fibre–yarn–fabric perspective rather than a composition-only approach.

A limitation of the present work is that the available dataset represents an industrial sample set with simultaneous variation in several constructional variables. Each mechanical value is the mean of five replicate specimens per direction (Section 2.1), but the individual specimen-level measurements and their standard deviations were not retained in the dataset available to us, precluding the calculation of error bars for Table 3 and Figures 1–3. Future work should therefore include retention of specimen-level replicate data and more tightly controlled experimental designs, together with characterisation of warp yarn twist level, to enable stronger statistical comparison across hemp levels, yarn counts and core architectures, and to support more robust mechanical optimisation of hemp-containing denim fabrics.

Author Contributions: Y.E.: Conceptualisation; methodology; validation; formal analysis; resources; writing—review and editing; supervision; project administration; funding acquisition. S.K.: Conceptualization; methodology; validation; formal analysis; investigation; data curation; writing—original draft preparation; visualisation. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: Author Semira Koçak was employed by the company Arseteks Tekstil Tarım Kimya. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ASTM	American Society for Testing and Materials
ISO	International Organization for Standardization
PET/PTT	Poly(ethylene terephthalate)/poly(trimethylene terephthalate)
Ne	English cotton count
N	Newton (SI unit of force)

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