

# Mechanical quality of hemp fiber as influenced by tillage, cover crop, and nitrogen management in regenerative organic systems

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## ABSTRACT

Industrial hemp (*Cannabis sativa* L.) is an emerging crop for renewable fiber materials. For farmers, finding a balance between agronomic performance and economic return is crucial, especially when targeting specific markets like the textile industry, which values not just fiber quantity, but overall quality. This field study, conducted at the Rodale Institute in Kutztown, Pennsylvania, assessed the effects of tillage (till vs. no till), cover crop (with cover vs. no cover), and nitrogen (N) rate (0, 50, 100, 150 kg ha<sup>-1</sup>) on hemp fiber yield, N concentrations in leaf and stalk, and mechanical performance under regenerative organic conditions. Fiber mechanical properties, including maximum load, tenacity, work of rupture, and modulus of elasticity were analyzed at Thomas Jefferson University. Results showed that biomass yield increased with N input, peaking at 9.2 Mg ha<sup>-1</sup> under till systems with cover crop at 150 kg N ha<sup>-1</sup>. However, fiber quality declined at higher N rates. The highest fiber quality metrics, including tenacity (610.5 MPa), modulus of elasticity (3.5 GPa), and work of rupture (31.4 newton mm<sup>-2</sup>) was achieved in no till system with cover crops and no N addition. A clear trade-off emerged: high N increased biomass yield but compromised fiber quality, while moderate input levels (e.g., till system with cover crop at 50 kg N ha<sup>-1</sup>) offered a balanced outcome. This suggests that regenerative practices not only support soil health but also improve fiber strength and flexibility. Farmers can tailor input strategies to match end-use goals: low-input systems for premium textile fibers and moderate inputs for bio-composite applications, supporting both ecologically sound and market demands.

## 1. Introduction

Industrial hemp (*Cannabis sativa* L.) offers immense potential as a versatile and valuable crop with diverse applications in textiles, construction materials, bio-composites, and other biobased products (Poniatowska et al., 2019; Vandepitte et al., 2020). Hemp fibers, with their unique properties such as high tensile strength, excellent fineness, and remarkable durability, are increasingly sought after for industrial uses (Manaia et al., 2019). These mechanical properties, such as maximum load, modulus, work of rupture, and modulus of elasticity are critical determinants of fiber quality and suitability for applications in products like bio-composites, textiles, and insulation (Ali et al., 2015; Amaducci et al., 2015). In 2023, U.S. production of field-grown hemp for

fiber was estimated at 22,272.7 metric tons, a 133 % increase from 2022, with a total value of \$11.6 million (USDA NASS, 2024). As industry continues to expand, enhancing both the yield and quality of hemp fiber remains a key priority for researchers and producers.

Hemp fiber properties are influenced by a range of environmental and agronomic factors, including soil quality, temperature, humidity, sunlight, sowing density, nitrogen (N) fertilization, and harvesting (timing and methods). These factors influence stem growth, fiber partitioning, and the mechanical characteristics of the fibers, thereby affecting both yield and quality (Leoni et al., 2022; Pappaert et al., 2025; Westerhuis et al., 2009). These variables notably affect both fiber yield and quality. In conventional hemp cultivation, maximizing biomass yield is often the primary goal, typically achieved through intensive

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management practices such as high N fertilization and conventional tillage. However, while such approaches may boost biomass production, they do not necessarily improve fiber quality (Landi et al., 2019).

The excessive N application can lead to overly vigorous vegetative growth, producing taller plants with thinner, weaker stems. This shift in plant morphology has been shown to reduce cellulose and lignin content, compromising stem strength and diminishing key fiber properties like tensile strength and elasticity (Cosentino et al., 2013; Manian et al., 2021). Moreover, high N levels can decrease the root-to-shoot dry-weight ratio, further weakening the plant's structural integrity (Ribeiro et al., 2023) and may delay harvest by keeping stems green for longer (Bouloc et al., 2013). Aubin et al. (2015) conducted multi-location trials in Canada using various N rates (0, 50, 100, 150, and 200 kg ha<sup>-1</sup>) and found that N fertilization influenced cellulose and hemicellulose concentrations in biomass, though the overall effect was minimal. In contrast, environmental factors, such as favorable weather patterns, improved soil fertility and enhanced plant growth conditions were more strongly associated with increased biomass carbon (C) accumulation, resulting in higher fiber and hurd yields than fertilizer treatments (Panday et al., 2025a).

Specific agronomic interactions also significantly influence fiber traits. For example, Visković et al. (2024) reported that the interactions between seeding date and row spacing, seeding date and cultivar, and row spacing and cultivar significantly affected plant height, while only the latter two interactions influenced plant thickness. Flowering behavior and developmental stage at harvest impact fiber quality, with earlier harvest stages yielding stronger and more elastic fibers. Moreover, differences between male and female plants also affect fiber structure (Salentijn et al., 2019; Duran, 2025). Furthermore, post-harvest factors such as timing and retting method (e.g., water vs. dew retting) play a crucial role in determining the mechanical properties of hemp fiber (Ribeiro et al., 2023). Therefore, optimizing both nutrient management and agronomic practices is essential for producing high quality hemp fiber suited for industrial applications.

Emerging research suggests that more sustainable practices, such as reducing N inputs and integrating cover crops, may provide a better balance between biomass production and fiber quality. For instance, Ribeiro et al. (2023) found that optimal tensile strength in hemp was achieved under a sowing density of 50 kg ha<sup>-1</sup>, no N fertilization, water retting, and cultivation in Bragança, Portugal. This study highlights the potential benefits of low-input systems, where reduced N use and appropriate retting methods contribute to stronger fiber qualities.

While direct studies on the impact of leguminous cover crops, such as hairy vetch (*Vicia villosa*) or clover (*Trifolium* spp.), on hemp fiber quality are limited, their known benefits to soil health and nutrient availability suggest potential advantages for hemp cultivation. These cover crops naturally fix atmospheric N, providing a sustainable nutrient source for subsequent crops and reducing the need for synthetic fertilizers (Fageria et al., 2005; Snapp et al., 2005). For instance, hairy vetch can fix between 43 and 190 kg N ha<sup>-1</sup>, while red and white clover can fix 84–224 kg N ha<sup>-1</sup> (Clark, 2008). Moreover, the use of cover crops in no till systems can reduce soil erosion, prevent compaction, and promote deeper root growth (Teasdale et al., 2004; Blanco-Canqui and Ruis, 2020; Parr et al., 2011), all of which are beneficial for hemp cultivation. These practices foster a healthier soil ecosystem, promoting better nutrient uptake and plant growth, which are essential for producing high-quality fibers.

In regenerative organic systems, where maintaining soil health is a central goal, cover cropping and reduced tillage contribute to enhanced soil organic matter and biological activity. These improvements are vital for achieving both sustainable biomass production and superior fiber quality (Panday et al., 2025a; 2025b). This research aims to evaluate how varying N application rates, and the inclusion of cover crops affect hemp fiber biomass yield and mechanical properties, including maximum load, tenacity, work of rupture, and modulus of elasticity. Specifically, this study explore to determine whether integrating cover

crops with reduced N inputs can enhance soil health, fiber quality, and yield in a manner that is both environmentally sustainable and economically viable. We hypothesize that cover crop integration and optimized N management will lead to high-yielding hemp with improved fiber strength and elasticity. By deepening our understanding of how N management and cover cropping affect hemp fiber properties, this research can help guide future production practices that meet both industrial standards and environmental sustainability goals.

## 2. Materials and methods

### 2.1. Site Description

Field studies were conducted from June to September in 2022 and 2023 at the Rodale Institute Organic Research Farm in Kutztown, Pennsylvania, U.S. The research site attributes Clarksburg silt loam soil (fine-loamy, mixed, superactive, mesic Oxyaquic Fragiudalf) with a 3–5 % slope.

To establish baseline soil conditions, chemical properties were assessed annually at a depth of 0–20 cm. Soil samples were collected from multiple points, and values were averaged across the site to account for natural variability. The experiment took place in a different field each year. In 2022, soil pH was 6.8, total N was 0.3 %, and active C at 734.5 mg kg<sup>-1</sup>. In 2023, soil pH was 7.0, total N increased to 0.4 %, and active C at 626.7 mg kg<sup>-1</sup>.

The region experiences a continental climate with significant annual temperature variations. Average daily minimum temperatures drop below freezing from December to March, while maximum temperatures exceed 35°C during July and August. Weather data for both years were obtained from the National Weather Service station at Reading Regional Airport, Reading, PA (Fig. 1).

### 2.2. Experimental layout

The experiment was designed using a split-split plot structure to evaluate: (i) the main effects of tillage (conventional tillage vs. no tillage), (ii) sub-plot effects of cover cropping (cover crop vs. no cover crop), and (iii) sub-sub plot effects of N application rates (no or 0, 50, 100, and 150 kg ha<sup>-1</sup>) on fiber and grain hemp production. Fiber and grain hemp were assigned to separate blocks during field research; however, grain hemp data is not included here. To avoid confusion, this manuscript refers to nitrogen as "N" in chemical/soil contexts and spells out "newton" when referring to the SI unit of force.

Each block measured 24.1 m and 36.6 m and was split evenly between conventional tillage (till) and no tillage (no till) treatments. For the cover crop treatments, each tillage section was divided into four

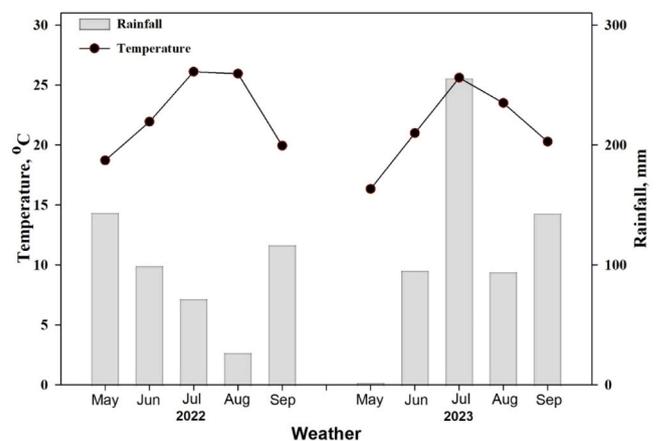


Fig. 1. Mean temperature and cumulative rainfall during the growing season at field site in 2022 and 2023.

strips (3.1 m × 36.6 m). Each cover crop strip was further divided into four sub-sub plots, each receiving one of four N fertilizer rates. Nitrogen was applied using blood meal, an OMRI-listed organic fertilizer derived from dried animal blood, containing 12 % N. Each treatment combination was replicated four times, resulting in 128 experimental units, each measuring 3.1 m by 9.1 m.

### 2.3. Field management

Each September before hemp planting, the entire experimental area was moldboard plowed, and seedbeds were prepared using either a Treffler plow or a disk and packer. In plots assigned with cover crops, hairy vetch was seeded at 22.4 kg ha<sup>-1</sup> and winter pea (*Pisum sativum* var. arvense) at 84.1 kg ha<sup>-1</sup>, denoted as ‘with cover’ throughout the manuscript. The cover crops overwintered and resumed growth the following season.

In conventional tillage plots, cover crops were mowed, incorporated with a chisel plow in mid-May, then disked and packed. The same steps were followed in plots without cover (or no cover) crops. In reduced-tillage plots, cover crops were roller-crimped on the day of hemp planting. Weed control in plots without cover crops relied primarily on mowing, with additional flame weeding and roller-crimping in 2022.

During the fertilizer application, bloodmeal was weighed for each sub-sub plot and spread by hand. In conventional tillage, it was applied post-plowing and incorporated with a disk. In reduced tillage, it was spread before roller-crimping. Fiber hemp (Santhica 27 cultivar) was seeded in early June at 72.8 kg ha<sup>-1</sup>, targeting 2.5 million plants ha<sup>-1</sup>. A grain drill was used for conventional tillage, while a no till drill was used for reduced tillage.

### 2.4. Sample collection

Hemp was sampled for experimental purposes in mid-August, allowing the plants to reach maximum vegetative growth before collection. By this time, the plants had also reached seed maturity, enabling evaluation as a potential dual-purpose crop. Whole-plant samples were hand-harvested from two 1-m transects per sub-sub plot, placed in cloth bags, and dried at 41°C. Leaf and seed material were stripped from the plants either manually while fresh or post-drying using a 2 mm sieve. Leaf and stem material from the dried whole-plant samples was analyzed for tissue N using the combustion method.

Separate samples were collected for retting. Thirty fiber hemp plants per sub-sub plot were field-retted for 21–27 days and flipped at least twice for even retting. Samples were monitored for graying, dark speckling, bark separation from the hurd, and bowing of smaller stems.

Once these indicators appeared, samples were removed and stored in a dry, enclosed environment.

Fiber separation involved re-wetting and soaking samples for several hours before hand-stripping the bast fiber from the hurd. Separated fiber and hurd material were re-dried at 41°C for at least a week before measuring dry weights. Fiber samples were then sealed in airtight plastic bags, stored in an indoor dry location without climate control, and sent to Thomas Jefferson University’s lab for further analysis in November 2023 (Fig. 2a). Hemp remained in the field for approximately 84 days. After sample collection, the remaining plants were removed using a sickle bar mower and baler.

### 2.5. Mechanical testing procedure

To evaluate the mechanical properties of hemp fibers, a series of tensile tests were conducted using an ADMET MicroTester (eXpert 4000, ADMET, Norwood, Massachusetts) equipped with a 10 lbf (~ 44.5 newton) load cell (Fig. 2b). A total of 2560 specimens (128 plots × 20 replicates) were tested following ASTM D2256, the standard test method for tensile properties of single-strand fibers.

Prior to testing, fibers were conditioned in a standard laboratory environment at 21 (±1) °C and 61 % relative humidity (RH) for at least 48 h to reach moisture equilibrium. Each fiber specimen was visually inspected by the naked eye to identify and exclude samples with noticeable defects such as kinks, twists, fibril misalignment, or irregular thickness variations. Any residual hurd or cortex particles were removed by lightly rubbing the fiber.

Each fiber specimen was cut to a standardized length of 250 mm before testing. To account for variations in fiber fineness, linear density (TEX) was measured for each sample prior to mechanical testing. TEX was determined using:

$$TEX = \frac{\text{Fiber mass}(g)}{\text{Fiber length}(km)}$$

where:

$$TEX = \text{linear density (commonly reported in } g \text{ km}^{-1}\text{)},$$

Tensile tests were conducted at 40 mm gauge length using GR-1T Filament Grips with 10 mm min<sup>-1</sup> crosshead speed. A 0.196 newton preload removed fiber slack before displacement zeroing. Force and extension were continuously recorded until failure. Tests showing grip slippage or abnormal load-displacement behavior were discarded and repeated. Maximum Load, Modulus of Elasticity, Tenacity, and Work of Rupture were determined for each specimen.

**Maximum Load:** The maximum force a fiber can withstand before breaking was recorded as the peak tensile load (newton).

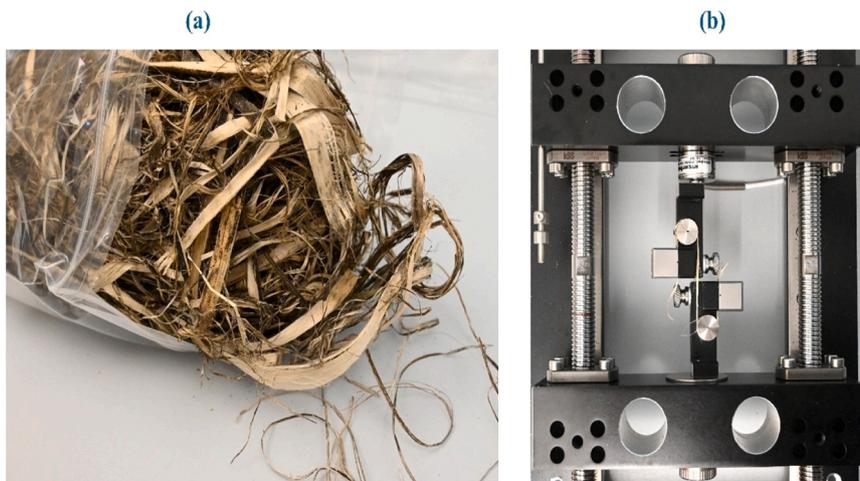


Fig. 2. (a) Collected hemp fiber bundle samples and (b) ADMET micro tensile setup with fiber grips.

**Modulus of Elasticity:** The modulus of elasticity, or Young's modulus, measures fiber stiffness and resistance to deformation. The modulus of elasticity ( $E$ ) is calculated as:

$$E = \frac{\sigma}{\epsilon}$$

where:

$E$  = Modulus of Elasticity in Newton  $\text{TEX}^{-1}$  initially,  $\sigma$  = Stress, and  $\epsilon$  = Strain.

**Tenacity:** In textile science, tenacity is reported in Newton  $\text{TEX}^{-1}$ , where  $\text{TEX}$  is a unit of linear density; however, in engineering and materials science, stress and modulus are measured in megapascals (MPa) or gigapascals (GPa). Therefore, unit conversion was necessary to make the values compatible with standard engineering stress equations.

$$\text{TEX} = \frac{1 \text{ g}}{1 \text{ km}} = \frac{10^{-3} \text{ kg}}{10^3 \text{ m}} = 10^{-6} \frac{\text{kg}}{\text{m}}$$

This means that when using Newton  $\text{TEX}^{-1}$ , the force is already normalized by a mass-per-length unit in  $\text{kg m}^{-1}$ , making it necessary to include the material's density ( $\rho$ ) to convert it into a true stress value.

Stress ( $\sigma$ ) is defined as force per unit area:

$$\sigma = \frac{\text{Force}}{\text{Area}} = \frac{\text{Newton}}{\text{m}^2} = \text{Pa}$$

Since tenacity is measured as force per linear mass unit, we multiply by the density ( $\rho$ ) of the material to convert it into MPa:

$$T_{\text{MPa}} = T \times \rho \times 10^3$$

where:

$T$  = tenacity in Newton  $\text{Tex}^{-1}$  and  $\rho$  = density of the material in  $\text{kg m}^{-3}$ .

Since the modulus of elasticity is measured as force per linear mass unit, we multiply by the material's density to convert it into MPa:

$$E_{\text{GPa}} = E \times \rho$$

**Work of Rupture:** The Work of Rupture represents the energy absorbed by the fiber up to the point of failure. In this study, Work of Rupture is expressed in Newton  $\text{mm}^{-2}$  (force per unit area), a common unit for tensile testing, indicating energy per unit area under the stress-strain curve.

The Work of Rupture (WoR) Newton  $\text{mm}^{-2}$  is calculated as:

$$\text{WOR} = \int_0^{\epsilon} \sigma(\epsilon) d\epsilon$$

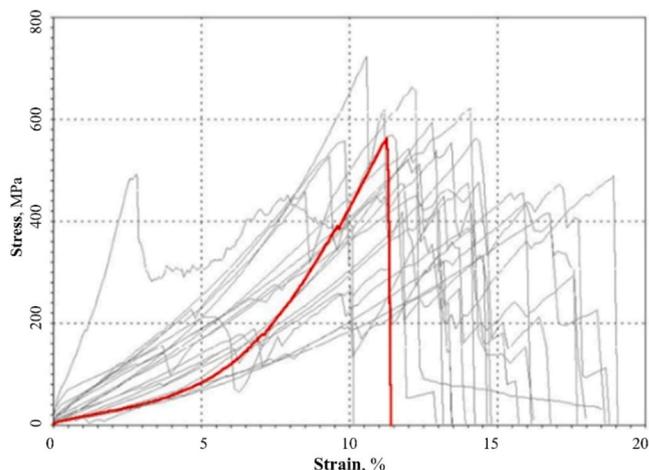
where:

$\sigma(\epsilon)$  = stress at a given strain, measured in Newton  $\text{mm}^{-2}$  (which is equivalent to MPa), and  $\epsilon$  = strain at failure (dimensionless).

A density of  $1500 \text{ kg m}^{-3}$  was selected as a representative value for laboratory-conditioned hemp fibers stored at  $21^\circ\text{C}$  and 61 % RH, conditions that maintain 6–9 % equilibrium moisture content. This results in moderate fiber expansion and a density lower than fully dried fibers ( $\sim 1.6 \text{ g cm}^{-3}$ ) but higher than moisture-rich fibers ( $\sim 0.9\text{--}1.2 \text{ g cm}^{-3}$ ). This selection ensures that stress calculations reflect the real-world mechanical properties of hemp fibers, aligning with reported density values in prior studies (Liu et al., 2017; Manaia et al., 2019; Ribeiro et al., 2023). To ensure robust results, 20 individual fiber samples were selected from each plot, and a single run was chosen based on the data that most closely matched the average performance of all fibers tested. A typical stress-strain analysis for one of these selected fibers is shown in Fig. 3.

## 2.6. Statistical Analysis

Statistical analysis was performed using R statistical software (version 4.4.2). Analysis of variance was conducted to assess the main



**Fig. 3.** Stress-strain curve for a selected hemp fiber sample from 20 forms in one experimental plot. The red curve represents the stress-strain relationship of the fiber that most closely matches the average performance of all tested fibers.

effects of tillage, cover crop, and N rates, as well as their interactions, on agronomic and mechanical variables using `sp.plot()` function. Tillage, cover crop, and N rates were treated as fixed factors, while replication and year were treated as random factors. Agronomic data were collected in 2022 and 2023; however, as no significant main effect or interaction of year was observed, the data were averaged across years (detailed yearly results are not presented here, as a separate article focusing on agronomic performance is under consideration). Mechanical variable values were reported from 2023 growing season only. Post hoc means separation was performed using the least significant difference test via the `LSD.test()` function at a significance level of  $\alpha = 0.05$ . Data visualization was conducted using the `ggplot2` package in R and Minitab® software.

## 3. Results

### 3.1. Fiber hemp yields and N concentrations

The hemp biomass yield ranged from  $1.1$  to  $1.3 \text{ Mg ha}^{-1}$  in 2022 and from  $1.0$  to  $1.5 \text{ Mg ha}^{-1}$  in 2023, with a slightly higher yield in 2023, though the difference was not statistically significant (data not shown). A significant interaction between tillage and cover crop was observed for biomass yield, with the highest yields recorded in the till and cover crop plots. Although the effect of N rate on biomass yield was not statistically significant, there was a clear trend of increasing biomass yield with higher N application rates. Biomass yield was highest ( $9.2 \text{ Mg ha}^{-1}$ ) in the till and cover crop plots and lowest under no till conditions, regardless of cover crop treatment. Tillage had a significant main effect on leaf yield, with till plots producing the highest yield ( $2.0 \text{ Mg ha}^{-1}$ ). A significant interaction between tillage and cover crop were noted for stem yield, showing a consistent trend with total biomass yield.

Leaf N concentrations were significantly influenced by both the interaction of tillage and cover crop and the main effect of N rate (data not shown). Leaf N concentration increased from 2.8 % at no N addition to 3.2 % at  $150 \text{ kg N ha}^{-1}$ . Under no till conditions, leaf N concentration was higher in those plots with cover crop treatment compared to no cover crops. Stalk N concentrations were significantly affected by the main effects of tillage and N rate, with noticeable increases at 50 and  $150 \text{ kg N ha}^{-1}$ . Overall, the results suggest that tillage combined with cover cropping enhances both biomass production and N uptake in fiber hemp, with the benefits of cover crops being more pronounced under till conditions.

### 3.2. Mechanical properties of hemp fiber bundles

#### 3.2.1. Maximum load

Maximum load ranged from 0.2 to 39.7 newton, with the highest medians in no till, with cover crop plots without N addition (Fig. 4). In contrast, till systems combined with higher N rates (100 and 150 kg ha<sup>-1</sup>) tended to show lower median values and more consistent distributions. Outliers were more prominent in till systems, indicating some degree of variability in response to N and cover crop conditions.

A significant three-way interaction among tillage, cover crop and N rate was observed for maximum load (Table 1), with detailed results provided in Table 2. The highest load (23.8 newton) was observed under no till with cover crop and no N addition, while the lowest values (<7.0 newton) were observed under till systems with cover crop at 100 and 150 kg N ha<sup>-1</sup> (Table 2). No till systems consistently outperformed till ones, for example, increasing N beyond 50 kg ha<sup>-1</sup> under till conditions substantially reduced fiber strength, while the no till system appeared to buffer some of these negative effects, as seen in no till, with cover crop at 150 kg N ha<sup>-1</sup> (15.9 newton) (Table 2). This pattern indicates that the three-way interaction occurred cover crops, especially under no till, buffered the negative effects of N on fiber traits. Maximum fiber load was achieved in regenerative systems (no till, with cover, and no N addition), while high N under till conditions reduced fiber quality.

#### 3.2.2. Modulus of elasticity

The modulus of elasticity ranged from 0 to 8.9 GPa (Fig. 5), with the highest medians observed in no till, with cover crop and N at 50 and 100 kg ha<sup>-1</sup>. Likewise in maximum load, outliers were more prominent in till systems with no cover crop and increasing N rates. A significant three-way interaction among tillage, cover crop, and N rate was observed for modulus of elasticity (Table 1), with detailed interactions presented in Table 2. The highest value (3.5 GPa) occurred under till systems with cover crop and 50 kg N ha<sup>-1</sup>, while the lowest value (0.5 GPa) was observed in no till, no cover crop and 150 kg N ha<sup>-1</sup>, indicating the negative effect of high N under no cover crop systems. These results suggest that integrating cover crops with moderate N inputs improves fiber elasticity, particularly under no till systems, while high N under no cover conditions reduce it.

#### 3.2.3. Tenacity

Tenacity values ranged from 21.0 to 1032.0 MPa across all plots (Fig. 6). A significant three-way interaction among tillage, cover crop, and N rate was observed for tenacity (Table 1), with detailed interactions shown in Table 2. The highest tenacity (610.5 MPa) occurred under no till, with cover crop, and no N addition, while the lowest tenacity (91.1 MPa) was recorded under till system with cover crop, and

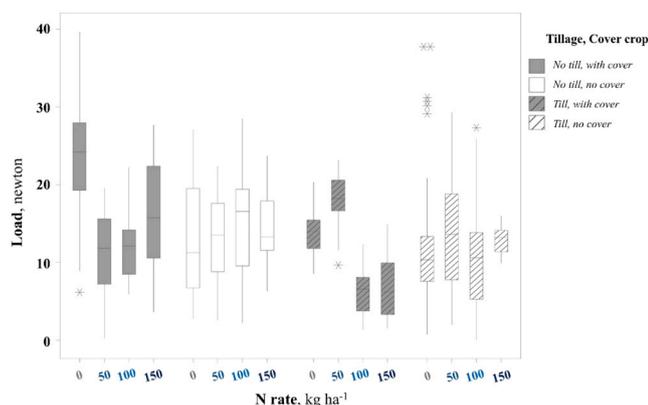


Fig. 4. Boxplot of hemp fiber load as affected by tillage (till vs. no till), cover crop (with cover vs. no cover), and N rate (0, 50, 100, and 150 kg kg<sup>-1</sup>). Boxes show the interquartile range (IQR), the center line represents the median, whiskers extend to 1.5 × IQR, and asterisks denote outliers.

Table 1

Effects of tillage, cover crop and nitrogen rate on mechanical properties of hemp fiber.

Source of Variation	Maximum Load (Newton)	Modulus of Elasticity (GPa)	Tenacity (MPa)	Work of Rupture (Newton mm <sup>-2</sup> )
<b>Treatment</b>				
<b>Tillage (T)</b>				
Till	11.9	2.0	272.5	17.8
No till	14.9	2.1	273.7	20.7
Significance	***	NS	NS	***
<b>Cover crop (C)</b>				
With cover	13.8	2.3	317.5	18.4
No cover	12.8	1.7	223.5	20.1
Significance	**	***	***	**
<b>Nitrogen rate (N), kg ha<sup>-1</sup></b>				
0	15.5	1.9	344.9	23.4
50	13.9	2.6	326.4	19.8
100	11.2	1.8	180.4	14.3
150	12.5	1.7	222.5	19.1
Significance	***	***	***	***
<b>Interaction</b>				
T x C	***	***	***	NS
T x N	***	***	***	***
C x N	***	***	***	***
T x C x N	***	***	***	*

Note: Means within a column followed by the same lowercase letter are not significantly different. \*P < 0.05, \*\*P < 0.01, \*\*\*P < 0.001. NS, not significant.

Table 2

The three-way interaction effects of tillage, cover crop, and nitrogen rate on mechanical properties of hemp fiber.

Treatment	Maximum Load (Newton)	Modulus of Elasticity (GPa)	Tenacity (MPa)	Work of Rupture (Newton mm <sup>-2</sup> )
Ti x Co x N0	13.8 de	1.5 ef	354.9c	22.3 cd
Ti x Co x N1	18.3 b	3.5 a	415.4 b	20.8 cde
Ti x Co x N2	6.3 h	1.2 fg	91.1 g	8.0 g
Ti x Co x N3	6.9 h	2.3 cd	323.6c	9.9 g
Ti x NC x N0	11.6 fg	2.4 bc	245.5 d	15.8 ef
Ti x NC x N1	13.7 de	2.2 cd	318.6c	24.0 bc
Ti x NC x N2	10.6 g	1.5 ef	192.5 ef	19.7 de
Ti x NC x N3	13.0 def	0.9 gh	186.8 ef	15.9 ef
NT x Co x N0	23.8 a	2.2 cd	610.5 a	31.4 a
NT x Co x N1	11.4 fg	2.6 b	316.4c	14.1 f
NT x Co x N2	11.8 efg	3.2 a	222.5 de	9.6 g
NT x Co x N3	15.9c	2.1 d	175.2 f	27.1 b
NT x NC x N0	12.6 ef	1.7 e	168.7 f	24.1 bc
NT x NC x N1	13.3 def	2.2 cd	232.0 de	19.3 dc
NT x NC x N2	14.7 cd	1.1 g	193.3 ef	18.2 e
NT x NC x N3	14.4 cde	0.5 h	179.4 ef	21.5 cde
Significance	***	***	***	*

Note: Means in a column followed by same lowercase letter are not significantly different. \*P < 0.05, \*\*\*P < 0.001. Treatments include (i) tillage: till (Ti) and no till (NT), (ii) cover crop: with cover (Co) and no cover (NC), and (iii) nitrogen rate: 0 (N0), 50 kg ha<sup>-1</sup> (N1), 100 kg ha<sup>-1</sup> (N2), and 150 kg ha<sup>-1</sup> (N3).

100 kg N ha<sup>-1</sup>. Nitrogen exhibited a non-linear effect, when the rate increased from 50 to 100 kg N ha<sup>-1</sup>, tenacity dropped from 270 MPa to 60 MPa (a 4.5-fold decrease) under till and from 210 MPa to 150 MPa (a

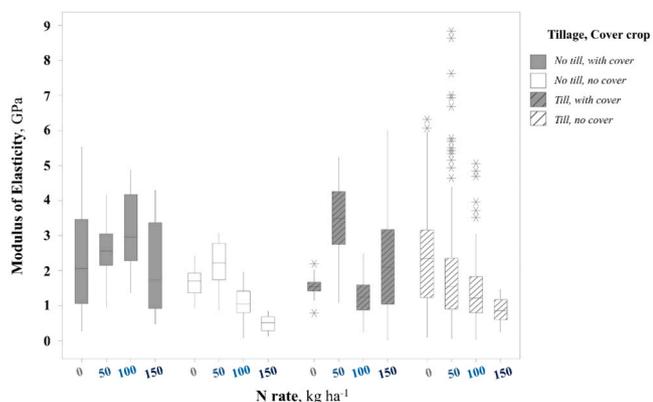


Fig. 5. Boxplot of hemp fiber modulus of elasticity as affected by tillage (till vs. no till), cover crop (with cover vs. no cover), and N rate (0, 50, 100, and 150 kg kg<sup>-1</sup>). Boxes show the interquartile range (IQR), the center line represents the median, whiskers extend to 1.5 × IQR, and asterisks denote outliers.

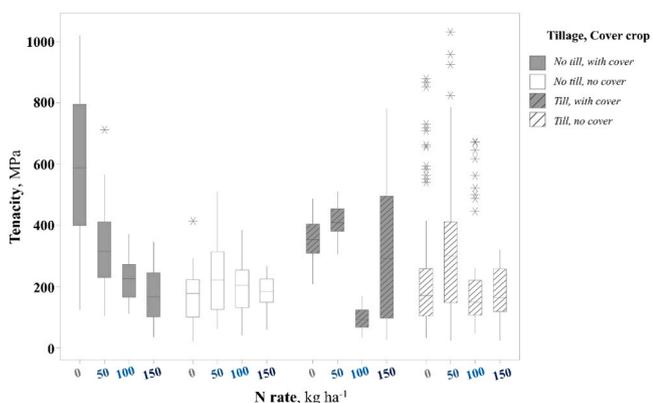


Fig. 6. Boxplot of hemp fiber tenacity as affected by tillage (till vs. no till), cover crop (with cover vs. no cover), and N rate (0, 50, 100, and 150 kg kg<sup>-1</sup>). Boxes show the interquartile range (IQR), the center line represents the median, whiskers extend to 1.5 × IQR, and asterisks denote outliers.

1.4-fold decrease) under no till conditions (Table 2). These results suggest that no till systems combined with cover cropping, especially without N addition, improve fiber tenacity, whereas higher N rates under till with cover crop conditions reduce it.

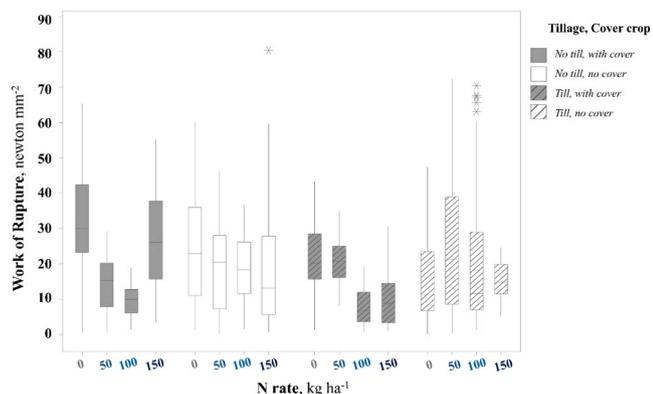


Fig. 7. Boxplot of hemp fiber work of rupture as affected by tillage (till vs. no till), cover crop (with cover vs. no cover), and N rate (0, 50, 100, and 150 kg kg<sup>-1</sup>). Boxes show the interquartile range (IQR), the center line represents the median, whiskers extend to 1.5 × IQR, and asterisks denote outliers.

### 3.2.4. Work of rupture

Work of rupture ranged from 0 to 80.5 newton mm<sup>-2</sup> (Fig. 7). A significant three-way interaction among tillage, cover crop, and N rate was observed for work of rupture (Table 1), with detailed interactions shown in Table 2. The highest work of rupture (31.4 newton mm<sup>-2</sup>) occurred under no till, with cover crop, and no N addition, while the lowest work of rupture (8.0 newton mm<sup>-2</sup>) was recorded under till system with cover crop, and 100 kg N ha<sup>-1</sup>. Nitrogen had a non-linear effect, peaking at no N fertilization, dropping to a minimum at 100 kg N ha<sup>-1</sup>, and partially rebounding at 150 kg N ha<sup>-1</sup>. These results highlight the effectiveness of no till systems with cover crop and low or no N in maintaining higher work of rupture values.

### 3.2.5. Relationship between strain and tenacity

The relationship between mean axial strain at break and mean tenacity of hemp fibers across different N rates and cover crop treatments is presented in Fig. 8. Under cover conditions, strain and tenacity were positively correlated ( $r^2 = 0.56$ ,  $P < 0.05$ ), indicating that fibers became both stronger and slightly more extensible as N decreased below 100 kg ha<sup>-1</sup>. In contrast, no significant correlation was observed in those plots which received no cover crops. These findings indicate that the cover crop supports concurrent improvement in tenacity and strain at break under low N conditions.

## 4. Discussion

Our study demonstrates that agronomic management practices have a significant impact on both the yield and mechanical properties of industrial hemp fiber, driven by complex interactions among tillage, cover crop, and N fertilization rate (Tables 1 and 2). Biomass yields exhibited a positive trend with increasing N rates but were highest under till system combined with cover crop. This highlights the critical role of tillage and cover cropping in enhancing nutrient availability and plant uptake. Elevated N concentrations in hemp leaves and stalks under these treatments further support this trend. These findings are consistent with previous research showing that inclusion of cover crop improves soil nutrient cycling, N use efficiency, and hemp productivity (Amaduucci et al., 2015; Fageria et al., 2005; Mecione et al., 2025).

Environmental factors also contributed to plant performance. Although temperatures fluctuated more in 2023 compared to 2022 (Fig. 1), no significant main effect or interaction of year (along with applied treatments) was detected for the measured agronomic variables. Favorable soil moisture availability throughout the 2023 growing season supported both growth and fiber development. These results are

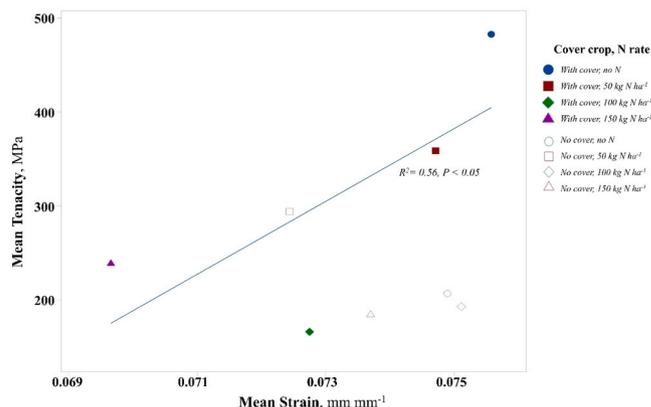


Fig. 8. Relationship between mean tenacity and mean strain of hemp fibers as affected by cover crop (with cover vs. no cover) and N rate (0, 50, 100, and 150 kg kg<sup>-1</sup>). Data points represent treatment combinations, with symbols and colors indicating cover crop presence and N rate, respectively. A linear regression line indicates a significant positive relationship between tenacity and strain under cover cropped conditions.

consistent with studies highlighting the importance of adequate water availability for biomass accumulation and fiber quality in hemp (Cosentino et al., 2013; Panday et al., 2025a).

However, these yield improvements were accompanied by trade-offs in fiber quality. Mechanical testing revealed that the magnitude of fiber property values observed in this study falls within the range reported in available hemp literature, though on the lower end for modulus. For instance, Amaducci et al. (2015) reported tensile strengths ranging from 300–800 MPa and moduli of 20–60 GPa for aligned fiber bundles, depending on genotype and retting method. Similarly, Ribeiro et al. (2023) found that hemp grown without N had higher tensile strength (~550 MPa) than that grown with high N (~300 MPa), and that water-retted fibers were stronger than dew-retted ones. In contrast, the values in our study were lower due to the use of technical fibers (which included portions of non-bast matrix material) as well as differences in fiber preparation methods. Our study used dew retting, which can be harsher on fiber strength. This explains why even our strongest fibers reached only about 500 MPa.

Despite this, the relative differences observed among treatments provide important agronomic insights. Notably, no till system combined with cover crop and reduced or no N input yielded the highest maximum load (23.8 newton) and tenacity (610.5 MPa), key indicators of fiber strength and quality. As shown in the results section, these combinations produced lower biomass yields, confirming that regenerative practices can yield stronger and high quality fibers. In contrast, high N rates under till systems with cover crop conditions negatively affected these mechanical properties, due to excessive vegetative growth resulting in less lignified fibers, as reported in fiber crops like hemp and flax (Kostic et al., 2008; Pervaiz and Sain, 2003; Vandepitte et al., 2020).

The modulus of elasticity also remained high across N levels combined with cover crop and no till management but declined sharply without them (Table 2). This highlights the role of cover crops in preserving fiber elasticity under variable fertility conditions. In this study, cover crops improved modulus of elasticity by 36 % and tenacity by 43 % in absence of N fertilization. These improvements are likely due to enhanced soil biological activity and micronutrient availability that support microfibril development in the fiber cell walls (Liu et al., 2017; Pylypchenko et al., 2023). These results are aligned with others who emphasized that hemp fiber quality is strongly influenced by both nutrient management and soil conservation practices (Adesina et al., 2020; Leoni et al., 2022; McLennon et al., 2024).

Strain and tenacity were positively correlated in cover crop systems (Fig. 8), indicating that regenerative practices not only improve strength but also enhance fiber extensibility. In contrast, no such relationship was found in no cover plots. Similarly, the work of rupture followed the same trend, with the highest strength under regenerative conditions and lowest in till system with high N rates, reinforcing the conclusion that regenerative systems produce structurally superior fiber. Importantly, our results reveal that maximum fiber load can be achieved in regenerative systems, while high N inputs under till systems can reduce it. This challenges conventional fertilization assumptions, showing non-linear responses of fiber properties to N rates, with optimal outcomes typically at 0–50 kg N ha<sup>-1</sup>. For instance, tenacity dropped 4.5-fold when N increased from 50–100 kg ha<sup>-1</sup> in till plots, supporting Ribeiro et al. (2023), who found that excess N reduces structural integrity by altering shoot-to-root ratios.

Fiber end-use applications also influence optimal management strategies. For textile use, where fiber quality is paramount, Vandepitte et al. (2020) emphasized that effective fiber yield (fiber quality × fiber quantity) is the key metric for textile applications. While some varieties may produce high long-fiber yield, but if fiber fineness and strength were low, their utility in textile will be limited. Textile uses favor high tenacity and fine bundles, which were achieved at most under no till systems with cover crop and low N fertilization (Table 2). Bio-composites benefit from coarser yet consistent fibers, supported by till systems under moderate N management (Ribeiro et al., 2023;

Amaducci et al., 2015).

An important practical insight from this research is the potential for an agronomically and economically optimal balance in dual-purpose hemp production. While fiber quality peaks with minimal N input in regenerative no till systems, higher N and tillage could boost seed (grain) yield, an economically valuable co-product. Therefore, maximizing high quality fiber yield may require an intermediate management approach. For instance, minimal inputs may result in excellent fiber quality but insufficient biomass, while high inputs increase biomass but compromise quality. While translating this concept here, multiplying fiber yield by tenacity offers a simple index of "quality-weighted yield." By this metric, the till system with cover crop and 50 kg N ha<sup>-1</sup> stands out, producing a moderate yield (~3.0 Mg ha<sup>-1</sup>) and high tenacity (~326 MPa), resulting in a quality-weighted yield of ~978 units. This compares favorably to till system without cover crop at 150 kg N ha<sup>-1</sup> (4.7 Mg ha<sup>-1</sup> × 184 MPa = 865 units) or no till system with cover crop and no N input (1.8 Mg ha<sup>-1</sup> × 483 MPa = 869 units). This suggests that growers can tailor input based on product priorities, whether maximizing fiber quality, seed yield, or both, offering a scenario that is both environmentally and economically attractive.

From a sustainability perspective, this work supports regenerative organic systems that reduce dependence on synthetic N inputs while enhancing soil health via cover crops and no till practices. Although fiber yield under no till system is lower, the premium fiber quality and long-term soil benefits may economically and environmentally justify this trade-off. Future research should explore optimal N replacement strategies via legumes, impacts on dual-purpose hemp economics, and refine management tailored to specific fiber applications. Overall, moderate or no N fertilization, when integrated with ecologically sound practices, can enhance hemp fiber properties without compromising economic viability or quality standards.

## 5. Conclusions

This study confirms that agronomic management practices, particularly tillage, cover crop, nitrogen input play a critical role in determining both the yield and fiber quality of industrial hemp. While till systems with higher nitrogen rates produced greater biomass, no till systems with cover crops and minimal or no nitrogen inputs consistently yielded superior fiber quality, including greater strength, tenacity, and elasticity. These findings highlight a trade-off between fiber quantity and quality that is essential when designing regenerative hemp systems. The results also offer a decision-making framework, for example, low N under no till systems are best suited for premium textile fiber production. Overall, the integration of ecological practices with targeted nutrient management presents a viable pathway for sustainable and product-specific hemp production.

## CRediT authorship contribution statement

**Dinesh Panday:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Parinaz Heydar:** Writing – review & editing, Writing – original draft, Software, Methodology, Data curation. **Alyssa Pierce:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Casey Lapham:** Writing – review & editing, Validation, Resources, Methodology, Data curation. **Arash Ghalehgholabbehbahani:** Writing – review & editing, Funding acquisition, Conceptualization. **Madhav Dhakal:** Writing – review & editing, Project administration, Investigation, Data curation, Conceptualization. **Gabriella Fioravanti:** Writing – review & editing, Methodology, Data curation. **Ronald Kander:** Writing – review & editing, Validation, Supervision, Conceptualization.

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## Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Dinesh Panday reports financial support was provided by US Department of Agriculture. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data availability

Data will be made available on request.

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