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# Physical and engineering characterization of linseed (*Linum usitatissimum* L.) straw for mechanized handling and industrial utilization

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**Abstract**
The efficient utilization of agricultural residues as sustainable industrial raw materials requires a thorough understanding of their physical and engineering characteristics. In this study, the physical and engineering properties of linseed (*Linum usitatissimum* L.) straw obtained from five selected varieties (RFC-2019, RLC-92, Shekhar, Neelam, and Sheela) were systematically evaluated to assess their suitability for mechanized handling and fiber extraction. Key properties including moisture content, straw length, diameter, fiber thickness, mass, bulk density, stem length, and angle of repose were determined using standard experimental procedures. The moisture content of linseed straw ranged from 28.18% to 38.65% (wet basis). Straw length varied between 318 and 483 mm, with a maximum value observed for the RFC-2019 variety, while fiber thickness reached up to 2.19 mm in the Sheela variety. The mean bulk density of linseed straw was found to be 7.92 kg $m^{-3}$, indicating its lightweight and voluminous nature. The angle of repose averaged approximately 40°, reflecting limited flowability typical of fibrous agricultural materials. The results highlight significant varietal variability in physical and engineering behavior, emphasizing the need for adaptable design parameters in handling, storage, and fiber extraction machinery. Overall, the study establishes linseed straw as a promising underutilized biomass resource and provides essential baseline data for the development of efficient, variety-specific processing and valorization technologies for textile, composite, and other bio-based industrial applications.

**Keywords:** Linseed, linseed fiber, straw, physical property, stem fiber

## Introduction

The growing concern over environmental sustainability and the adverse impacts of synthetic materials has intensified global efforts to promote renewable, biodegradable, and eco-friendly alternatives. Natural plant fibers have emerged as viable substitutes due to their low density, biodegradability, renewability, and favourable mechanical properties. In recent years, agricultural residues have attracted increasing attention as potential sources of natural fibers, offering both environmental and economic benefits through waste valorization and enhanced utilization of biomass resources.

Linseed (*Linum usitatissimum* L.), commonly referred to as flax, is a multipurpose crop cultivated extensively across temperate and subtropical regions of the world. It is primarily valued for its seeds, which contain approximately 35-45% oil and are widely used for nutritional, pharmaceutical, and industrial purposes. Linseed oil finds applications in food products, paints, varnishes, linoleum, printing inks, and coatings, while the residual oil cake serves as a protein-rich feed material (Cunnane & Thompson, 1995; Oomah, 2001) [3, 8]. In addition to its oilseed importance, linseed is one of the oldest known fiber crops, with historical records indicating its use in textile production as early as 3000 BC (Hamilton, 1986; Barber, 1991) [6, 2].

The fibers extracted from linseed stems belong to the category of bast fibers and are recognized for their high tensile strength, fineness, durability, and excellent moisture absorption characteristics. Compared to many conventional natural fibers, linseed fibers exhibit superior strength-to-weight ratios and dimensional stability, making them suitable for applications such as linen fabrics, canvas, ropes, industrial textiles, and reinforcement materials in bio-composites (Sharma & Van Sumere, 1992; Singhal & Samuel, 2003;

Assanova *et al.*, 2024) [12, 13, 1]. Moreover, linseed fibers are biodegradable and recyclable, and their production requires considerably less energy than synthetic fibers, reinforcing their relevance in sustainable material systems.

Despite the significant industrial potential of linseed fibers, a large proportion of linseed straw generated after seed harvesting remains underutilized, particularly in developing countries such as India. In many cases, linseed straw is either left in the field, burned, or disposed of inefficiently, leading to resource wastage and environmental concerns. Efficient utilization of linseed straw for fiber extraction and industrial processing requires a thorough understanding of its physical and engineering properties, which govern its behaviour during handling, storage, and mechanical processing.

Physical properties such as length, diameter, thickness, mass, and moisture content are critical parameters influencing the performance of agricultural materials during cutting, crushing, conveying, and fiber extraction operations. Similarly, engineering properties including bulk density and angle of repose play a vital role in the design of storage structures, feeding mechanisms, conveyors, and fiber extraction machinery (Gupta & Das, 1997; Sahay & Singh, 2009) [4, 10]. Variations in these properties across different linseed varieties further necessitate systematic evaluation to support the development of efficient and variety-specific processing equipment.

Although several studies have reported on the chemical composition and mechanical behaviour of flax fibers, comprehensive information on the physical and engineering properties of linseed straw particularly under Indian agro-climatic conditions remains limited. The lack of such data poses constraints in the design and optimization of post-harvest handling systems and mechanized fiber extraction technologies. Therefore, detailed characterization of linseed straw is essential to bridge this knowledge gap and facilitate its effective utilization as a sustainable raw material.

In view of these considerations, the present study was undertaken to evaluate the key physical and engineering properties of linseed straw obtained from selected linseed varieties. The findings of this research are expected to provide essential baseline data for the design and development of linseed straw handling, storage and fiber extraction machinery, thereby promoting the efficient utilization of linseed biomass in textile, composite and allied industrial applications.

## Materials and Methods

### Selection of Linseed Varieties

The present investigation was conducted using five linseed (*Linum usitatissimum* L.) varieties, namely RFC-2019, RLC-92, Shekhar, Neelam, and Sheela. These varieties were selected to represent commonly cultivated linseed genotypes with varying morphological characteristics. Mature linseed plants were harvested at physiological maturity, and the straw obtained after seed removal was used for subsequent analysis. All samples were collected from the same agro-climatic region to minimize environmental variability.

### Sample Preparation

Linseed straw samples were cleaned manually to remove foreign matter, leaves, and broken fragments. The straw was air-dried under ambient laboratory conditions to achieve uniform moisture distribution prior to experimentation. For physical measurements, randomly selected straw samples were used to ensure representative sampling. Unless otherwise stated, a total of 30 straw samples were considered for dimensional and mass-related measurements.

### Determination of Physical Properties of Linseed Straw

### Length, Diameter, and Fiber Thickness

A total of 30 linseed straw samples were randomly selected for the measurement of physical dimensions, including length, thickness of fiber, and diameter. The average length (L), thickness of fiber (T), and diameter (D) of the linseed straw. The length of individual straw samples was measured using a measuring tape with an accuracy of ± 1 mm. Straw diameter and fiber thickness were determined at the mid-point of the straw using a digital vernier calliper with a least count of 0.01 mm, as shown in Figure 1. The calculations were performed using the following formulae as suggested by Singhal and Samuel (2003) [13]:

$$L = \frac{\sum_{i=1}^{n} l}{N}$$

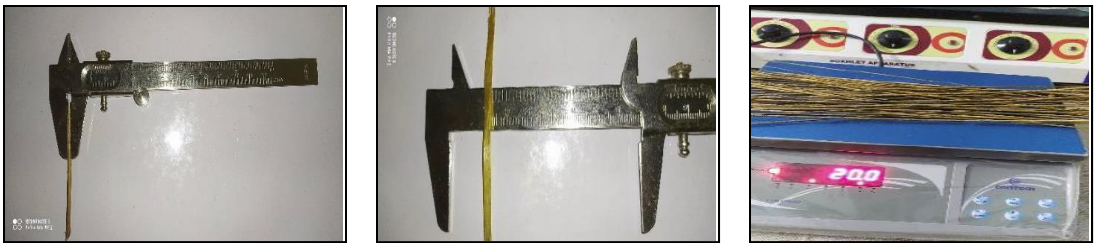
$$T = \frac{\sum_{i=1}^{n} t}{N}$$

$$D = \frac{\sum_{i=1}^{n} d}{N}$$

where *L*, *T*, and *D* represent the measured length, thickness, and diameter in millimetres, respectively; $n = 1, 2, 3, \ldots, N$, where *N* is the total number of linseed straw samples. Standard deviation (SD) and coefficient of variation (CV) were also computed to assess the variability of the measured properties.

### Determination of Test Weight

To determine the mass characteristics of linseed straw, individual straws were cut into uniform lengths of 300 mm. Bundles containing 20 straws each were prepared and weighed using an electronic balance with a least count of 0.001 g. A total of 30 samples (six samples per variety) were evaluated. The average mass, standard deviation, and coefficient of variation were calculated for comparative analysis among varieties.



(a) (b) (c)

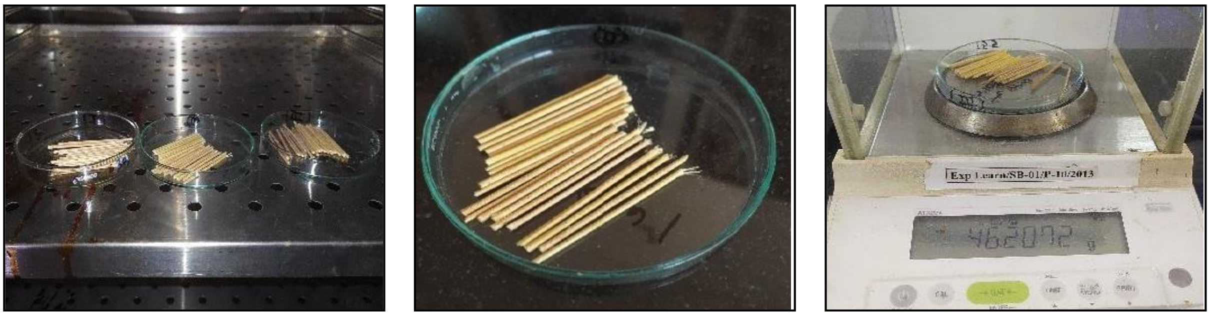
**Fig 1:** Measurement of physical dimensions and mass of linseed straw

**Determination of Moisture Content**

The moisture content of linseed straw on a wet basis was determined using the hot air oven (gravimetric) method shown in Figure 2. The samples were dried at 105 ± 1 °C for 24 h in a laboratory oven, following the procedure described by Gupta and Das (1997) [4].

$$M_C = \frac{W_2 - W_3}{W_3 - W_1} \times 100$$

where, $M_C$ is moisture content, %; $W_1$ is the weight of the container and its cover, (g);
$W_2$ is the weight of the container, its cover, and its contained sample before drying, (g);
$W_3$ is the weight of the container, its cover and its contained sample after drying, (g);
$W_2 - W_3$ is moisture loss, (g); $W_3 - W_1$ is the fresh weight of the sample, (g).



(a) (b) (c)

Fig. 2. Determination of moisture content of linseed straw using the hot air oven method: (a) weighing of fresh sample before drying, (b) oven drying of samples at 105 ± 1 °C, and (c) weighing of oven-dried samples after attaining constant weight.

**Determination of Bulk Density**

Bulk density of linseed straw was determined using the cylindrical container method described by Madamba *et al.* (1993) [7]. A cylindrical container with a known diameter (7 cm) and height (9.6 cm) was used for the experiment. Linseed straw samples were chopped to a length equal to the height of the cylinder and placed vertically inside the container without applying external compaction.

The filled container was weighed using an electronic balance with a least count of 0.001 g. Bulk density was calculated using the following equation:

$$b_d = \frac{W_t}{L \times (\frac{\pi d^2}{4})}$$

$$\frac{2.85}{0.369} = 7.72\ kg\ m^{-3}$$

where, $b_d$ is bulk density, $kg\ m^{-3}$; $W_t$ is the weight of the sample, 2.85 kg; L is the length of the cylinder, m; d is the diameter of the cylinder, m; Three replications were conducted, and the mean bulk density value was reported.

**Determination of Engineering Properties of Linseed Stem**

**Length of Linseed Stem**

The length of extracted linseed stems was measured to determine its relevance in the design of crushing rollers and fiber extraction mechanisms. Randomly selected stems were measured using a measuring scale, and the observed range was recorded. Stem length is a crucial parameter that influences roller clearance and rotational speed in fibre extraction machinery.

**Angle of Repose**

The angle of repose of linseed stem material was determined using the fixed-base tilting box method, as described by Sahay and Singh (2009) [10]. A rectangular box with one transparent side was filled with linseed stem material and gradually tilted until the material began to slide in bulk. The angle at which sliding initiated was measured using a graduated scale attached to the apparatus. The angle of repose was calculated using the following relation:

$$\emptyset = \tan^{-1} \frac{2\,(H_a - H_b)}{D}$$

where, $\emptyset$ is the angle of repose, in degree; $H_a$ is the height of the cone, in cm; $H_b$ is the height of the platform, in cm; $D$ is the diameter of the platform, in cm.

Five replications were performed, and the mean value was reported.

**Results and Discussion**

**Moisture Content of Linseed Straw**

Moisture content is a critical parameter influencing the mechanical behaviour, storability, and processing efficiency of lignocellulosic materials. In the present study, the moisture content of linseed straw samples, determined using the hot air oven method, varied from 28.18% to 38.65% (wet basis). This variation reflects differences in field drying conditions, varietal characteristics, and internal straw structure.

Higher moisture content generally enhances flexibility and reduces brittleness, which may improve fiber separation during mechanical processing but can adversely affect storage stability and increase susceptibility to microbial degradation. Conversely, lower moisture content improves storability but may increase straw breakage during crushing and decortication. Similar moisture ranges have been reported for linseed and flax straw by Assanova *et al.* (2024) [1], highlighting the necessity of moisture regulation prior to mechanized processing. Table 1 summarizes the moisture content determination of linseed straw samples used in the study.

**Table 1:** Moisture content of linseed straw samples

| Sample No. | Container weight, (g) | Container weight with sample, (g) | Weight after oven dried, (g) | Moisture content, (%) |
|---|---|---|---|---|
| 1 | 46.22 | 52.36 | 51.01 | 28.18 |
| 2 | 47.33 | 53.62 | 52.09 | 32.14 |
| 3 | 43.86 | 53.69 | 50.95 | 38.65 |
| | | | | |

### Dimensional Characteristics of Linseed Straw

### Straw Length

Straw length is an essential physical property influencing fiber length, feeding uniformity, and roller clearance in fiber extraction machinery. The measured straw length ranged from 318 mm to 483 mm, with an average value of 393.8 mm. Among the varieties studied, RFC-2019 exhibited the maximum straw length, whereas Sheela and Neelam recorded comparatively shorter lengths. Longer straw lengths are generally advantageous for producing continuous fibres with better mechanical integrity; however, excessively long lengths may cause feeding difficulties in mechanised systems. The observed length range is consistent with recent findings on flax straw morphology reported by Assanova *et al.* (2024) [1], confirming the strong varietal influence on straw geometry.

### Straw Diameter and Fiber Thickness

Straw diameter and fiber thickness directly affect crushing resistance, decortication efficiency, and power requirement during fiber extraction. In the present investigation, straw diameter varied from 4.13 mm to 5.62 mm, while fiber thickness ranged from 1.16 mm to 2.40 mm, with average values of 5.00 mm and 1.73 mm, respectively. Variety Sheela exhibited the highest fiber thickness, indicating potentially stronger fibers but higher resistance during mechanical separation. In contrast, Shekhar recorded the highest straw diameter, which may influence material stiffness and feeding behaviour. Comparable dimensional trends have been reported for flax straw in pulp and fiber studies (Hailemariam & Woldeyes, 2024) [5].

### Mass Characteristics of Linseed Straw

The mass of linseed straw bundles (20 straws per bundle, each 300 mm long) ranged from 20.0 g to 27.8 g, with an average value of 23.28 g. The higher bundle mass observed for Sheela can be attributed to its greater fiber thickness and compact structure. Bundle mass is a vital parameter for estimating material throughput, energy consumption, and load distribution in fiber extraction and handling equipment. Variability in mass across varieties highlights the importance of adaptable feeding mechanisms in processing machinery (Selge *et al.*, 2024) [11]. The detailed varietal comparison of physical properties is presented in Table 2.

**Table 2:** Physical properties of linseed straw for selected varieties

| S. N. | Name of varieties | Length (mm) | Diameter (mm) | Thickness of fiber (mm) | Weight of a bundle of 20 linseed straws (g) |
|---|---|---|---|---|---|
| 1 | RLC-92 | 453.83 | 4.87 | 1.52 | 20.0 |
| 2 | RFC-2019 | 477.67 | 4.78 | 1.65 | 20.2 |
| 3 | Shekhar | 348.83 | 5.35 | 1.72 | 22.5 |
| 4 | Neelam | 345.83 | 4.91 | 1.58 | 25.9 |
| 5 | Sheela | 342.83 | 5.11 | 2.19 | 27.8 |
| | | Avg. | 393.8 | 5.00 | 1.73 |
| | | SD | 186.49 | 0.228 | 0.267 |
| | | CV % | 0.168 | 0.046 | 0.154 |

### Bulk Density of Linseed Straw

Bulk density is a key engineering property influencing storage volume, transportation efficiency, and material flow behaviour. The bulk density of linseed straw ranged from 7.72 to 8.08 kg m$^{-3}$, with a mean value of 7.92 kg m$^{-3}$.

The low bulk density indicates that linseed straw is a lightweight and voluminous material, requiring large storage space and efficient compaction or baling strategies. Similar low bulk density values have been reported for flax straw and other bast fiber crops, emphasizing challenges associated with storage and transport (Madamba *et al.*, 1993; Assanova *et al.*, 2024) [7, 1]. The bulk density values obtained from replicated trials are presented in Table 3.

**Table 3:** Bulk density of linseed straw

| Samples | Weight of the samples | Bulk density, kg m$^{-3}$ |
|---|---|---|
| $S_1$ | 2.85 kg | 7.70 |
| $S_2$ | 2.93 kg | 7.94 |
| $S_3$ | 2.98 kg | 8.08 |
| Mean | 2.92 kg | 7.92 |

### Length of Linseed Stem

The length of extracted linseed stems ranged from 8 mm to 25 mm. Stem length significantly affects fiber continuity and separation efficiency during mechanical processing. Excessively short stems may lead to fiber breakage, while longer stems are favourable for producing continuous fibers. Stem length is influenced by operational factors such as straw moisture content, feeding rate, roller speed, and clearance between crushing elements. The observed stem length range aligns well with values reported for mechanized flax straw processing systems (Selge *et al.*, 2024) [11].

### Angle of Repose of Linseed Stem

The angle of repose of linseed stem material varied from 39.35° to 40.98°, with a mean value of 40.08°. This relatively high angle of repose indicates greater inter-particle friction and reduced flowability, which is characteristic of fibrous agricultural materials. From an engineering design perspective, hopper walls, chutes, and sieve inclinations should be designed at angles exceeding

41° to ensure uninterrupted material flow. Comparable angles of repose have been reported for fibrous biomass materials used in agricultural processing (Sahay & Singh, 2009; Ramachandran *et al.*, 2022) [10, 9]. The statistical summary of angle of repose measurements is presented in Table 4.

**Table 4:** Angle of repose (°) of linseed stem

| Observation | Angle |
|---|---|
| Mean (x) | 40.08 |
| Range | 39.35-40.98 |
| SD | 0.621 |
| CV% | 0.155 |

**Engineering Significance of Findings**

The physical and engineering properties evaluated in this study provide essential baseline data for the design of linseed straw handling, storage, and fiber extraction systems. The observed variability among varieties highlights the necessity for adjustable machine parameters, particularly roller clearance, feeding rate, and hopper inclination. These findings strongly support the potential of linseed straw as a sustainable raw material for textile, composite, and bio-based industrial applications, consistent with recent research on flax straw valorization (Assanova *et al.*, 2024; Hailemariam & Woldeyes, 2024) [1, 5].

**Discussion**

The present investigation provides valuable insight into the physical and engineering characteristics of linseed straw, highlighting its suitability for mechanized handling and industrial utilization. The observed variability in moisture content, dimensional properties, bulk density, and flow behaviour reflects the heterogeneous nature of linseed straw, which is typical of lignocellulosic agricultural residues. Such variability underscores the necessity of incorporating material-specific parameters into the design and operation of post-harvest processing systems. Moisture content emerged as a critical factor influencing the mechanical response of linseed straw during processing. Elevated moisture levels enhance flexibility and reduce brittleness, which can facilitate fiber separation; however, excessive moisture may negatively affect storage stability and promote biological degradation. This indicates the importance of maintaining optimal moisture conditions prior to mechanical processing, consistent with recent findings on flax straw utilization (Assanova *et al.*, 2024) [1].

Dimensional characteristics, including straw length, diameter, and fiber thickness, varied notably among the studied varieties, emphasizing the influence of genetic and morphological factors. Longer straw length is advantageous for obtaining continuous fibers, while increased fiber thickness may improve fiber strength but require higher mechanical energy during separation. These results suggest that fiber extraction equipment should be designed with adjustable operating parameters to accommodate varietal differences and minimize fiber damage. The low bulk density of linseed straw indicates challenges related to storage and transportation efficiency, as larger volumes are required to handle relatively small masses. This characteristic necessitates appropriate engineering solutions such as compaction or baling to reduce handling costs. Furthermore, the relatively high angle of repose observed in this study reflects the poor flowability of fibrous materials, necessitating the design of hoppers and chutes with adequate inclination angles to prevent material blockage during handling operations (Sahay & Singh, 2009) [10]. Overall, the findings confirm that linseed straw possesses favourable physical and engineering properties for industrial applications. However, efficient utilization requires careful consideration of its variable behaviour during processing, reinforcing the need for tailored engineering solutions rather than generalized approaches.

**Future Scope**

The findings of this study provide a foundation for further research aimed at enhancing the utilization of linseed straw as a sustainable industrial resource. Future work may focus on detailed mechanical characterization of extracted fibers to establish relationships between straw properties and fiber performance. Investigations into the influence of controlled moisture conditioning on fiber extraction efficiency and energy consumption would further support process optimization. The property data generated in this study can be extended to the design and simulation of advanced linseed straw handling and fiber extraction machinery, incorporating adjustable parameters to accommodate varietal differences. Additionally, exploration of value-added applications such as bio-composites, geotextiles, and nanocellulose could significantly enhance the economic viability of linseed straw utilization. Comprehensive life cycle and techno-economic assessments would also be beneficial to evaluate the sustainability and commercial potential of large-scale linseed straw processing systems.

**Conclusion**

The present study systematically evaluated the physical and engineering properties of linseed straw to assess its suitability for mechanized handling and industrial utilization. The results demonstrated that linseed straw exhibits considerable variability in moisture content, dimensional characteristics, bulk density, and flow behaviour across different varieties. Straw length ranged up to 477.67 mm, fiber thickness reached 2.19 mm in certain varieties, and the mean bulk density was found to be 7.92 kg $m^{-3}$, confirming the lightweight and voluminous nature of the material. The angle of repose, averaging approximately 40°, indicated limited flowability, which has direct implications for the design of storage bins, hoppers, and conveying systems. These findings highlight the importance of accounting for varietal differences and material-specific behaviour in the design of linseed straw processing and fiber extraction equipment. The low bulk density and relatively high angle of repose necessitate appropriate engineering interventions, such as adjustable machine components and optimized handling systems, to ensure efficient material flow and processing performance. Overall, the study establishes linseed straw as a promising and underutilized agricultural resource with significant potential for applications in textiles, composites, and other bio-based industries. The physical and engineering property data generated provide essential baseline information to support the development of efficient, variety-adaptable processing technologies, thereby contributing to the sustainable valorization of linseed biomass.

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