Indian Journal of Engineering & Materials Sciences
Vol. 31, October 2024, pp. 714-720
DOI: 10.56042/ijems.v31i5.10127

Development of a portable bundle strength tester for lignocellulosic fibres

Nageshkumar T*, Prateek Shrivastava, D B Shakyawar, Avijit Das, Manisha Jagadale & Gunasindhu Sardar
ICAR-NINFET, Kolkata 700 040, India

Received: 03 April 2024; accepted: 04 September 2024

The present study intended to develop a portable, low-cost, digital bundle strength tester for measuring strength of lignocellulosic fibres. The developed instrument comprises of mechanical fibre breaking unit and embedded system. The fibre breaking unit consists of base frame, jaws, clamping unit, feed screw and gear drive. Embedded system has been developed using Arduino Mega 2560, limit switch, load cell with HX711 interface, motor driver, buck converter and potentiometer. Fibres of jute, mesta, bimli and banana have been tested in this instrument and results have been compared with existing electronic bundle strength tester to justify the validation of developed instrument. Comparative analysis revealed that the readings obtained from the developed instrument have been non-significant ($P>0.05$) when compared to the readings obtained from the existing electronic fiber bundle strength tester implying a close similarity in results. Gage evaluation of repeatability in nested gage repeatability and reproducibility has shown variation of 25.09% which is well within the acceptable limit. The developed instrument is capable of being powered by a 24V, 16A battery, providing up to 6 hours of continuous testing operation. This newly developed testing device offers advantages such as reduced cost, smaller size and light weight compared to existing instruments.

Keywords: Tenacity, Breaking load, Jute, Mesta, Nested R

1 Introduction

Over the decade, there has been a significant increase in the demand for natural fiber based products, driven by their environmental friendliness and economic advantages. This has resulted in a compound annual growth rate (CAGR) of 7.6% expected from 2024 to 2031. Moreover, the market is anticipated to achieve a value of $102,712.91 million by the year 2031. Long lignocellulosic fibers such as jute, mesta, ramie, hemp, flax, sisal, and banana are highly sought after among natural fibers for the production of value-added items like upholstery, furnishings, decorations, and secondary apparel[1]. The quality of the final product relies on the quality of fibres used to make it. The bundle strength of natural fibres is a crucial parameter significantly impacting the strength and longevity of the end product. Further, it is important for maximizing the lifespan and usefulness of natural fiber products, reducing the need for frequent replacements and minimizing environmental impact[2]. Notably, it is evident that the higher the bundle strength of fibre, the better the end product. [1]

Assessing the bundle strength prior to manufacturing/processing in the machine for yarn production not only provides insight into the final product's strength but also facilitates blending with other natural fibers of comparable strength to achieve desired quality. In the natural fibre industry, bundle strength is also commonly referred to as tenacity (g/tex). To measure the bundle strength of natural fibres, (Bandyopadhyay [3] and Saha et al.,[4]) have developed mechanical bundle strength tester to measure the breaking load of fibre utilizing components like analog display unit, manual load imparting system and clamp for fibre holding. Manual calculation is necessary to determine the tenacity of the fiber, a process that is both time-consuming and susceptible to errors. Apart from these, there are a few commercially available analog bundle strength testers designed specifically for natural fibers. To expedite the measurement of bundle strength and alleviate manual error, (Roy *et al.* [5]) designed and developed a semiautomatic digital fiber bundle strength tester for jute fibre and other natural fibres which comprised motorized loading system (three motors), clamp and clamp holder. The instrument provides breaking strength (g/tex), breaking load (kg) and elongation (%) in digital form. Further, it eliminates the manual calculation of bundle strength. Nevertheless, this

*Corresponding author (Email: nagesha.kumar88@gmail.com)

instrument consumes a significant amount of power, need continuous power, weighs between 40 and 50 kg and expensive. Due to these problems, still natural fibres are purchased from the growers by checking its strength by manual method. Currently, investigating and identifying suitable natural fibers across various forming or non-forming locations poses significant challenges due to mobility limitations and the associated costs of equipment. Hence, there is a need to develop portable, compact and digital bundle strength tester to test fibre at field, remote locations and laboratory conditions.

With light of above factors, the current study aimed to design, develop, and assess the performance of portable digital bundle strength tester. Further, developed instrument was compared with existing digital instrument.

2 Materials and Methods

The instrument has been developed in the Quality Evaluation and Improvement Division, ICAR-NINFET, Kolkata. The developed instrument comprises of fibre breaking unit and embedded system. The instruments mechanical fibre breaking unit was designed to exert constant rate of loading to break a bundle. An embedded system was designed to handle tasks such as reading, amplifying, storing, and displaying data from both a load cell and limit switch.

2.1 Design of mechanical fibre breaking unit

The proposed system aimed to exert a constant rate of loading to break the fiber bundle. Initial testing of the system revealed that with a driving torque on the feed screw ranging from 55 N.mm to 60 N.mm, the system could generate an axial force of 4.15-4.50 kg/s. To meet the specifications, a 12V, 16 A motor capable of producing a torque of 76.6 N·m at rated load with a speed of 40 rpm was selected. This motor applies its torque to a gear (A) mounted on the shaft, with the driver gear having 20 teeth and the driven gear (B) having 15 teeth.

The torque available on the gear provided on the feed screw shaft is calculated using formula (1)

$$\mathrm{Tf} = \mathrm{GR} \times \text{torque avaiable at gear A} \qquad ...(1)$$

$$\mathrm{Tf} = 0.75 \times 76.6 = 57.42\ \mathrm{N.m}$$

After studying the existing instruments based on constant rate of loading, it is found that feed screw is most effective to exert axial force to fibres[5]. One of the movable jaws is driven by a feed screw, which receives torque from the motor via a gear drive mechanism. The torque produced when force is exerted on the feed screw is determined by a formula recommended by Rizal *et al.* [6].

$$T = \frac{ph \times F_a}{2\pi \times n} \qquad (2)$$

Where, ph= Feed screw lead; F_a = Frictional resistance on the guide surface; n= Efficiency of Feed screw (0.96 assumed)

$$F = \mu \times mg \qquad (3)$$

Where, μ = frictional coefficient of the guide surface (0.003 for feed screw); g= gravitational acceleration (9.8 m/s^2); m= mass of the transferred object (kg)

$$T = \frac{10 \times 34.78}{2 \times 3.14 \times 0.96} = 57.7\ \mathrm{N.mm} \qquad ...(4)$$

Based on the above design, feed screw of 100 mm length and width 20 mm diameter with 15 mm pitch was selected.

2.2 Fabrication of mechanical fibre breaking unit

The fibre breaking unit comprises base frame, jaws, clamping unit, feed screw and gear drive. The rectangular base frame, having 300 mm length and 100 mm width was fabricated using 20 mm stainless steel. To enable jaw movement, a square slot measuring 20 mm width and 100 mm length has been provided. Two jaws made of stainless steel having 50 mm height and 30 mm width were positioned on base frame (Fig. 1). One of these jaw bases, S-type load cell is attached and another one is moved forward and backward by dc motor (12 V 16A) using feed screw and nylon gear drive. In order to pull the sample, feed screw with internal thread of jaw converts motor rotation into linear motion. One of the movable jaws features an internal worm thread pitch of 15 mm and mounted on feed screw of 15 mm pitch with 100 mm thread length. As the gears are turned, the feed screw revolves, causing the jaw to move and exert a consistent load. The sample holder consists of a fixed lower clamp and an upper clamp that is adjustable using a T-shaped handle screw (Fig. 2). The designed clamp should be able to hold the sample tightly without breaking them at the grip faces. Therefore, rubber strips are affixed to the clamps in a configuration resembling male and female arrangements.

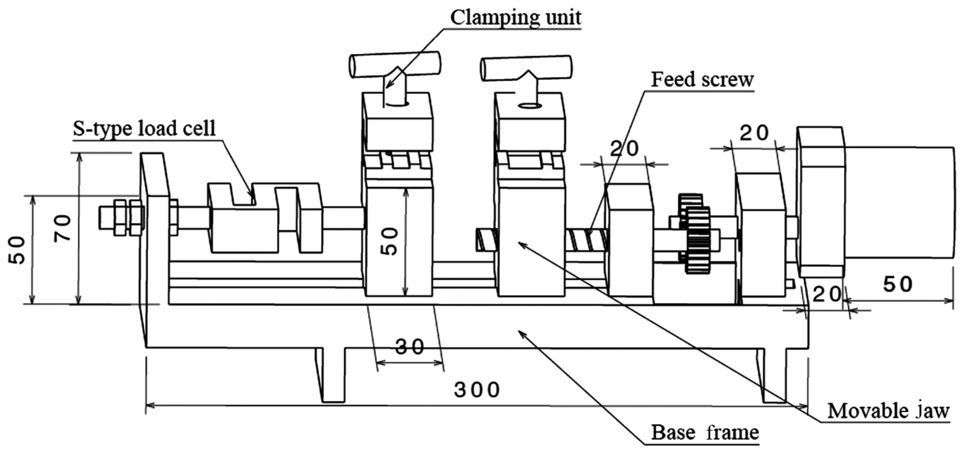

Fig. 1 — Designed mechanical fiber breaking unit with dimensions in mm.

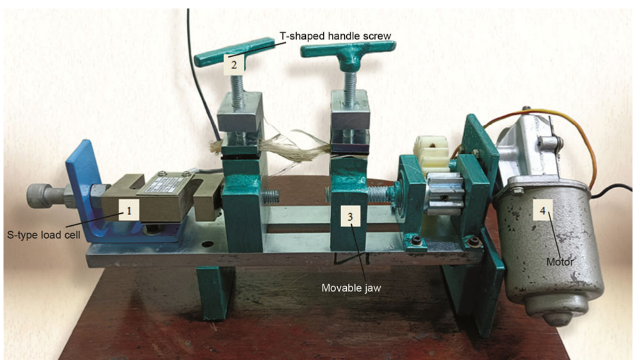

Fig. 2 — Development mechanical fiber breaking unit.

2.3 Embedded system

Embedded system is composed of several components, including an Arduino Mega 2560, limit switch, load cell with HX711 interface, motor driver, buck converter, and potentiometer (Fig. 3). The components used to develop embedded system are presented in Table 1. The Arduino Mega consists of 54 digital input/output pins (with 15 available for PWM output), 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, USB connectivity, a power jack, an ICSP header, and a reset button. For measuring breaking load, an industrial S-type load cell was mounted between the frame and the fixed jaw base. According to previous studies, the maximum breaking load of jute fibre bundles ranging from 300 to 600 mg typically varies between 60 and 100 kg for strong fibers[3, 5]. Hence, an S-type load cell, with a capacity of 200 kgf and an accuracy of 0.1 kg, was utilized for measuring the breaking load of fibre. Due to the extremely low magnitude of the output signals from the load cell, it becomes impractical to directly interpret such low

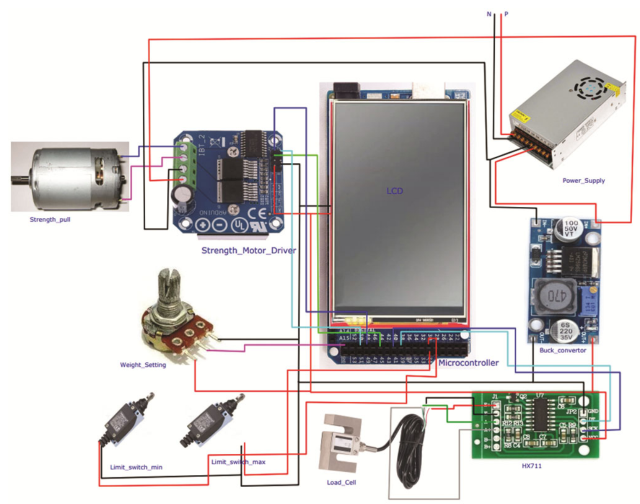

Fig. 3 — Circuit diagram of the developed embedded system.

voltage output values with the microprocessor during signal processing. Therefore, the output from the load cell was amplified further by a differential amplifier (HX711, a 24-bit precision amplifier designed for load cells), which offers a digital output. After recording the maximum breaking load, the microcontroller calculates the tenacity (g/tex) using the formula (4)

$$\text{Tenacity}(\text{g/tex}) = \frac{125 \times \text{breaking load (kg)}}{\text{Weight of sample (g)}} \quad ...(5)$$

Limit switches were incorporated to restrict the further movement of the jaw base and to deactivate the power to the motor post fibre breakage. To wary bundle weight of fibre, potentiometer was provided in the embedded system and output of potentiometer was connected with A15 of Arduino board.

Table 1 — Components used in the embedded system of bundle strength tester.

Sl. No	Components	Specifications
1	Microcontroller	Arduino Mega 2560 Total pins: 54 , operating voltage: 5V, operating speed: 16 MHz
2	S-beam type load cell	MAXLOAD, model: SL, output: 2±0.004 Mv/v
3	Load cell amplifier	HX711 24 Bit precision amplifier
4	Rotary limit switch	Jai Balaji, Current:10 A, voltage: 500 V, operating frequency: 60 Hz
5	Display	3.5 TFD LCD White background blue colour font Resolution: 480x320(Pixel), I/O Voltage: 3.3V/5V
6	Motor driver	BTS7960 Input Voltage: 6 ~ 27Vdc, PWM capability of up to 25 kHz,
6	Buck converter	LM 2596S Input Voltage: 3-40 V, Rated current: 2A
7	Power distribution unit	12VDC, 17A SMPS

Since this instrument is developed for onsite testing of natural fibre, a thin-film-transistor liquid-crystal touch display was used in the embedded system to display results of breaking load (kg) and breaking strength (g/tex). The TFT LCD offers superior advantages over traditional LCD displays, including faster response time and lower power consumption[7]. The 3.5 inch LCD had a white backlight with blue font with pixel of 480×320 that helped to display results. The BTS7960 motor driver, a fully integrated high-current half bridge, controlled both the direction of rotation and the speed of the motor. The motor received power from a 16 amp supply through the motor controller. The input power supply of 230 AC was converted to DC power within two different ranges. The motor operated on 12V DC 16 A, drawing from a SMPS, while the remaining components operated on 5V DC, 1A through a buck converter (LM 2596S).

The Arduino Mega 2560 comprise microcontroller that is capable of being programmed to detect and manipulate objects within the physical world. Once all circuits were prepared and finalized, the Arduino code was uploaded. This coding comprises instructions dictating the board what function it needs to perform

2.4 Sample preparation and testing of fibres

To assess the performance of the developed portable digital bundle strength tester, instrument was tested with selected thirty samples of each of jute, mesta, bimli and banana fibre. From each sample, a clean section measuring 200 mm in length was randomly taken from middle region of the reeds, excluding any root bottom, defect and crappy end as per BIS standard[8, 9]. These samples were manually cleaned for dust and removed short fibres, were cut to the recommended length of 125 mm and positioned between the clamping units. Subsequently, they were then securely tightened using a T-shaped screw, followed by adjustment of the sample weight using potentiometer knob. Upon pressing "start" command, fibres were broken and results were recorded for analysis.

2.5 Nested Gauge Repeatability and Reproducibility

Gauge repeatability and reproducibility are crucial performance characteristics of any instrument, vital for guaranteeing measurement reliability. It depends on various factors such as the precision of instrument components, calibration procedure, environmental conditions, operator and sample to be tested[10]. Gauge repeatability and reproducibility (Gauge R&R) is a statistical technique employed to evaluate the variability in measurements conducted by a gauge or measurement system. Further, it includes part-to-part or process variation, appraiser variation (reproducibility), and measurement system variation (repeatability). Two methods for evaluating gauge R&R: crossed gauge R&R and nested Gauge R&R. The crossed method is typically applied to reusable samples, while the nested method is preferred when working with destructive testing samples. In the current study, the nested method was chosen due to the nature of the instrument, where the samples are irreversibly altered and cannot be reused for subsequent tests. In this study, a total of 27 jute samples are tested by three operators with two replications. Data were analysed in the Minitab® software at 95% confidence interval.

2.6 Statistical analysis

To analyze the difference between developed portable tester and existing bundle strength tester, an independent sample T-test has been conducted in SPSS software (IBM, SPSS statistics, version 25) at 95 % confidence level.

3 Results and Discussion

Prior to conducting fibre testing with this instrument, it was crucial to assess its performance. Of utmost importance is the calibration of the load cell, a pivotal

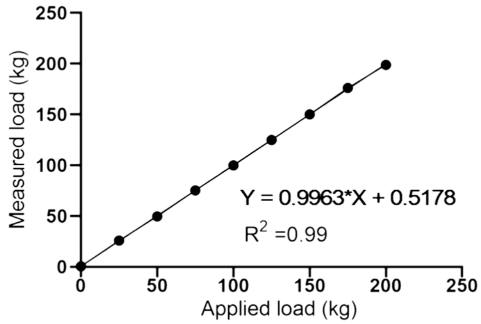

Fig. 4 — Calibration curve for S-type load cell in tension mode.

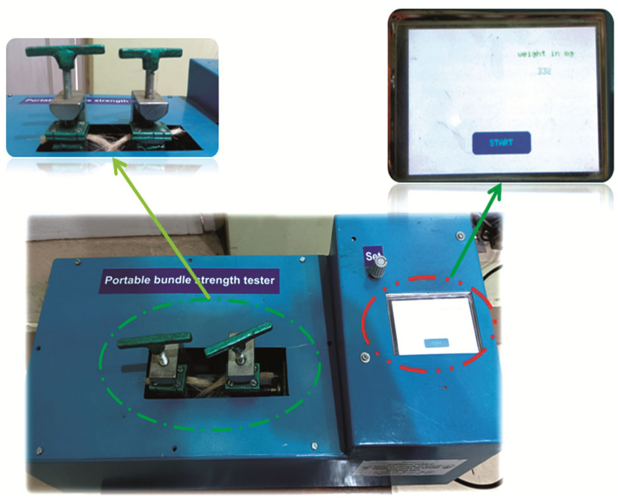

Fig. 5 — Developed portable digital bundle strength tester.

component of the developed portable instrument. S-type load cell of 200 kg is available in the commercial market. However, to ensure precision, calibration before usage is imperative[11]. Consequently, the load cell was calibrated by gathering data from various known applied loads and observing their corresponding output loads. Fig. 4 shows the obtained linear behaviour between applied voltage and measured load from the load cell with R^2 value of 0.99.

Portable digital bundle strength tester has been successfully developed to measure the strength of lignocellulosic fibres. This portable tester, depicted in Fig. 5, underwent preliminary trials to evaluate its performance in breaking fibers. These trials revealed that the instrument operated satisfactorily, providing results within 1600 milliseconds after breaking the sample. A delay of 4000 milliseconds has been provided to reset the jaws to their original position.

To validate the developed portable digital bundle strength tester, thirty samples each of jute, mesta, bimli, and banana fiber were tested. Additionally, another set of thirty samples was tested using the

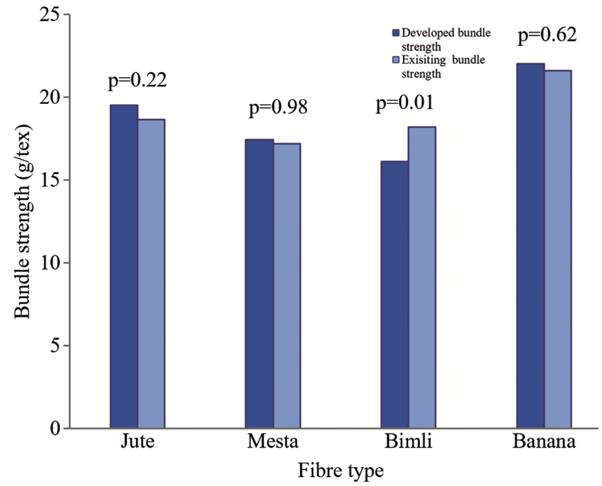

Fig. 6 — Comparison between average values obtained from developed bundle strength tester and existing bundle strength tester ($p>0.05$ indicates significant difference).

existing electronic bundle strength tester for comparison. All the tests have been performed with same loading rate (4.25 kg/s) and gauge length (50 mm), so the results from newly developed instrument can be compared with existing instrument. The results are shown in Fig. 6. It is clear from the figure that, aside from bimli, the results obtained with the developed instrument are not statistically significant ($P>0.05$) compared to those from the existing electronic bundle strength tester, implying a close similarity in results. This implies that the developed instrument is suitable for achieving reliable outcomes. During instrument testing, one of the issues observed was the possibility of slippage if the clamps were not adequately tightened. Ensuring sufficient grip on the sample is essential for obtaining accurate readings.

The portable digital bundle strength tester characteristics were compared with existing electronic bundle strength tester (Table 2). The weight of the newly developed instrument is 74% lighter compared to the existing machine, which primarily utilizes mild steel components, contributing to its heavier weight. The lightweight design enables experiments to be conducted in field, remote locations, and laboratory conditions. The newly developed instrument requires 20% more time to test 30 samples compared to the existing electronic bundle strength tester due to the manual tightening of the fiber clamping system. As most of the components utilized in the fabrication of the portable unit are commercially available, including the S-type load cell, it becomes less expensive than the existing system. Additionally,

Table 2 — Portable digital bundle strength tester characteristics compared to existing electronic bundle strength tester

Parameter	Portable digital bundle strength	Existing electronic bundle strength tester
Load cell (kg)	200	200
Weight of the instrument (kg)	11.5	45
Time required for testing (30 samples), Minute	60	50
Manufacturing cost (Rs.)	50,000	1,80,000
Floor area, cm^2	900	2600

Table 3 — Anova of nested gauge R and R.

Source	df	SS	MS	F	P
Operators	2	1.64	0.82	0.02	0.97
Part (appraiser)	6	198.51	33.08	45.64	0.00
Repeatability	18	13.04	0.72		
Total	26	213.21			

Table 4 — Variance Components of Nested gauge R and R.

Source	Var Comp	%Contribution (of Var Comp)
Total Gage R&R	0.72	6.30
Repeatability	0.72	6.30
Reproducibility	0.00	0.00
Part-To-Part	10.78	93.70
Total Variation	11.51	100.00

unlike the existing machine which utilizes three DC motors, the developed instrument comprises a single motor. Because it is a first prototype, future development incurs very low cost.

3.1 Nested gauge repeatability and reproducibility

Analysis of nested gauge repeatability and reproducibility of the developed instrument was carried out in Minitab Software and corresponding ANOVA is presented in Table 3. The results indicate that the operators' influence on the total variation is statistically insignificant (p value of 0.976), suggesting that the average bundle strength of jute fiber remains consistent regardless of the operator conducting the measurement. The small p-value of part in analysis indicates that the part-to-part variation (sample) was statistically significant. The number of distinct categories was 5.

The variance components analysis of the nested gauge repeatability and reproducibility (R&R), as presented in Table 4, reveals that the reproducibility component is 0.00, indicating that no two operators tested the same part. The part-to-part components are the largest contributors to the variance component of R&R, accounting for 93.70% of the total variation. This highlights the substantial influence of part-to-part variability on the overall variation observed in the measurement system.

Table 5 — Gage evaluation of nested gauge R and R.

Source	Std Dev (SD)	Study Var (6 × SD)	%Study Var (%SV)
Total Gage R&R	0.85	5.10	25.09
Repeatability	0.85	5.10	25.09
Reproducibility	0.00	0.00	0.00
Part-To-Part	3.28	19.70	96.80
Total Variation	3.39	20.35	100.00

Table 5 illustrates that the largest contributor to study variation is part-to-part variation, comprising 96.80%. Additionally, both total gage R&R and repeatability contribute equally to 25.09% of the total variation observed in the study. An acceptable level of study variation for repeatability is 30% or lower for the digital instruments[12]. Consequently, the study variation in repeatability for the developed instrument falls within acceptable limits

4 Conclusion

The present study aimed to design and develop a portable bundle strength tester for testing of long lignocellulosic fibres. Utilizing commercially available materials, the instrument comprised a fiber breaking unit and an embedded system. Calibration of load cell shows linear behaviour between applied voltage and measured load from the load cell with R^2 value of 0.99. Comparative analysis revealed that the readings obtained from the developed instrument were non-significant (P>0.05) when compared to the mean obtained from the existing electronic fiber bundle strength tester, except for bimli. The reported results and performance of the developed instrument suggest its suitability for testing lignocellulosic fiber. This testing device offers advantages such as low cost and smaller size compared to existing devices, with the newly developed instrument weighing 74% less than the existing instrument. Results of nested gage R and R indicate that the operators' influence on the total variation is statistically insignificant. The fabrication cost of this instrument amounted to Rs. 50,000=00. The developed instrument is capable of being powered by a 24V, 16A battery, providing up to 6 hours of continuous testing operation. This instrument can be used to measure the bundle strength of natural fibres at remote location using battery. Further research may be conducted to reduce the weight of the instrument with light weight materials and utilizing a solar photovoltaic system for operation.

Acknowledgment

Authors would like to thank Director, ICAR-National Institute of Natural Fibre Engineering and Technology for financial support to carry out this project.

References

1 Elfaleh I, Abbassi F, Habibi M, Ahmad F, Guedri M, Nasri M, & Garnier C, *Results Eng*, (2023)101271.
2 Girijappa T, Gowda Y, Rangappa S M, Parameswaranpillai J, & Siengchin S, *Frontiers in Materials* (6) (2019) 226.
3 Bandyopadhyaya S B, *Text Res J,* 38: (1986). 310-314.
4 Saha B, Nageshkumar T, Saha SC, Roy G, Sarkar A, Sardar G, & Mondal J, *J Sci Indust Res*, 81(02) (2022)113.
5 Roy, G., Bhattacharya, G. K., Sengupta, S. & Mukherjee, M. *IEI (I) Journal-TX*, 89 (2009).
6 Rizal, M., Aulia, U., & Yudiansyah, R.. *Aceh Int J Scie Tech*, *12*(1) (2023)25.
7 Mayr, S., & Buchner, A.. *Ergonomics*, *53*(7) (2010) 914.
8 IS 271 Indian Standard textiles — grading of white, tossa and daisee uncut indian jute published by Bureau of Indian Standards, Newdehli. (2020)1.
9 IS 7032 (1 to 8) Physical methods of test for uncut Indian jute, Mesta and Bimli published by Bureau of Indian Standards, Newdehli, (1986)1.
10 Snee, R. D. *Qual Eng*, *33*(3) (2021) 395.
11 Shrivastava, P., Nageshkumar, T., Jagadale, M., Shambhu, V.B. and Nayak, L.K, *J Nat Fibers*, 20(2) (2023) 2200986.
12 Gao, Z., Moore, T., Smith, A. P., Doub, W., Westenberger, B., & Buhse, L. *AAPS Pharm Sci Tech*, *8* (2007)11.