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Optimising the process of fibre extraction from Himalayan nettle (*Girardinia diversifolia*) using response surface methodology

Vishwajeet, Abhijit Majumdar & Deepti Gupta[a]

Department of Textile & Fibre Engineering, Indian Institute of Technology Delhi, New Delhi 110 016, India

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This study investigates the effect of alkaline treatment conditions on the yield and quality of fibres extracted from Himalayan nettle bark. Process parameters are systematically optimised, revealing that fibre characteristics are highly sensitive to alkali concentration, temperature, and duration. Mild conditions result in poor fibre separation, while harsh conditions lead to fibre degradation or redeposition of impurities. Optimal conditions (8 % NaOH, 1 h, 85 °C) yield fibres with superior properties — 56.65 % yield, 1.91 tex linear density, 6.23 gf/den tenacity, 4.13 % elongation, and 204.07 gf/den modulus — significantly outperforming traditional extraction methods. The developed method is simple and can be used for large-scale extraction of nettle fibres with superior and consistent properties.

Keywords: Alkaline retting, Box-Behnken design, Lignocellulose, Nettle fibre, Sustainable fibre

1 Introduction

The growing ecological and sustainability concerns have led to a shift in consumer demands toward sustainable products. This has encouraged the search for non-toxic, renewable, biodegradable fibres that are abundant and easily available. Lignocellulosic fibres extracted from plants can fulfil this criterion. Significant investigations are being carried out to obtain lignocellulosic fibres from various plant materials including jute[1], flax[2], ramie[3] and hemp[4], and explore their potential applications.

In this context, the Himalayan nettle (*Girardinia diversifolia)* plant, being abundant in India, presents an underutilised yet promising source of cellulosic fibres[5,6]. Known locally by various names such as *Bichhu Buti, Kandali, Dolan, Nilgiri*[7] and *Khujalli patta*[8] in India, and *Puwa and Allo*[9] in Nepal, this wild perennial plant is insect resistant and has virulent and stinging hairs[7]. The fibres obtained from this plant are being traditionally used as ropes, bags, sacks, fishing nets and mats[10]. Their other applications such as blended yarns and fabrics[11–13], oil spill cleaning[14,15], sound absorption[16,17] and composites[18–20] are being explored.

Despite this potential, the commercial exploitation of Himalayan nettle fibres remains limited, as they are still obtained using traditional methods. These involve boiling the bark with wood wash for 3-4 hours, washing in running water followed by beating with a wooden mallet, and finally, treatment with local clay (*kamedu mitti*) or rice husk, followed by sun drying for 2-3 days[7,8]. Such methods are labour-, water-, and energy-intensive, lack process control, and often result in non-uniform and poor-quality fibres with inconsistent mechanical properties.

The quality as well as quantity of fibres extracted are highly dependent on the method of extraction and their process parameters. Various methods of fibre extraction are reported from lignocellulosic materials, namely dew and water retting, mechanical process, enzymatic, microbial and alkali treatment. Among these, chemical treatments are rapid, cost-effective and easy to control[21,22]. Some methods have been explored for the extraction of Himalayan nettle fibres by some researchers. Sett *et al.*[23] used a combination of chemical, mechanical and enzymatic methods to extract fibres from Himalayan nettle ribbons, yielding fibres with linear density of 1.4 tex, tenacity of 4.9 gf/den, elongation of 1.5 % and modulus of 967 gf/den. Samanta *et al.*[24] used microbial retting on nettle stems to extract fibres, exhibiting linear density of 2.4 tex, tenacity of 2.5 gf/den, elongation of 1.6 % and modulus of 288 gf/den. Deepa & Kumaresan[25] extracted fibres by treating nettle barks with NaOH (4%) at 100°C for 60 min and reported tenacity (635 MPa), elongation (0.95 %) and modulus (36 GPa). The methods employed in the above

[a]Corresponding author.
E-mail: deepti@textile.iitd.ac.in

Fig. 1 — Himalayan nettle (a) plant, (b) freshly harvested bark, (c) bark ribbons and (d) cleaned ribbons

studies, other than Deepa & Kumaresan[25], are very tedious and time-consuming. It can be seen from the above studies that there is no consistency in reported values of properties of fibres and the method used for extraction of fibres. The reported studies even did not optimise the process parameters using statistically relevant experimental design. Therefore, there is a need to develop an optimum method that is simple, rapid, cost-effective and scalable.

In the present study, an optimisation exercise is being carried out to identify the conditions for fibre extraction that give the best combination of fibre yield, fibre strength and linear density. The experiments are performed using a three-factor, three-level Box-Behnken design. The key process parameters - alkali concentration, treatment time and temperature- are varied to evaluate their effects on fibre yield, linear density, and tensile properties. Statistical analyses are performed to assess the significance of these parameters. Fibre morphology and chemical compositions are also examined to study the effect of process parameters on extracted fibres.

2 Materials and Methods

2.1 Materials

Dry ribbons of Himalayan nettle barks were obtained from the Biodiversity Management Committee (Naugaon, Uttarakhand, India). The plants were harvested, followed by removal of leaves from the stalks. The bark was peeled off from the stalks and sun-dried. Sodium hydroxide (NaOH) pellets (assay≥97 %) and glacial acetic acid (assay≥99 %) were procured from EMLURA (Merck Life Science Private Limited, Mumbai, India). All chemicals were used as received without further purification. Deionised water was used throughout all experiments.

The received Himalayan nettle ribbons were manually cleaned to remove visible impurities such as dust and extraneous plant matter. The cleaned ribbons were uniformly cut to a length of 15 cm. Figure 1 shows the stages of sample preparation, including the Himalayan nettle plant, freshly harvested bark, ribbons of bark and clean ribbons.

Table 1 — Details of process factors and their levels

Process factor	Level		
	-1	0	+1
NaOH conc., %	1	4.5	8
Time, h	1	2.5	4
Temperature, °C	70	85	100

2.2 Experimental Design

A Box–Behnken design (three-factor, three-level) was employed to investigate and optimise fibre extraction conditions. The three process factors were NaOH concentration, treatment time, and temperature. The levels of each process factor (Table 1) were based on the preliminary experiments, where the effect of each variable on yield, linear density and mechanical properties was observed individually, while keeping the other two constant. The low level (-1) corresponded to conditions where fibre extraction was ineffective, while the high level (+1) represented conditions beyond which fibre degradation or redeposition of non-cellulosic material occurred.

Fifteen experimental runs were generated by the design, and each experiment was performed in triplicate to account for experimental variability. The measured responses included yield (%), linear density (tex), tenacity (gf/den), elongation (%) and modulus (gf/den).

2.3 Fibre Extraction

The prepared nettle ribbons were dried in the hot air oven at 100°C for 4 h to achieve a constant dry weight. Subsequently, they were treated with NaOH solution under an M:L ratio of 1:40. The concentration, time and temperature were varied

according to the experimental design. The alkali-treated nettle ribbons were thoroughly washed with tap water to remove the residual blackish-brown liquor and other non-cellulosic impurities. The extracted fibres were then neutralised with 1 % (v/v) acetic acid at 60°C for 10 min, followed by multiple washing with tap water. Final drying was carried out in a hot air oven at 100°C till a constant dry weight was achieved. The dried fibres were stored under standard atmospheric conditions as per ASTM D1776/D1776M-20 standard.

2.4 Fibre Yield Calculation

The yield of extracted nettle fibre was calculated based on the constant dry weight of the ribbon and extracted fibre using Eq. 1:

$$\text{Yield (\%)} = \left(\frac{W_2}{W_1}\right) \times 100 \quad \ldots(1)$$

where W_1 is the constant dry weight of nettle ribbons (g); and W_2, constant dry weight of the extracted nettle fibres (g).

2.5 Linear Density

Linear density of the fibres (tex, g/km) was determined as per ASTM D1577-07(2018). Individual fibres were measured for length using the standard ruler and weighed using an electronic balance (least count: 0.1 mg). An average of ten fibres was reported.

2.6 Mechanical Properties

The tensile properties of the extracted fibres were determined as per the single fibre tensile testing method (ASTM D3822/D3822M-14(2020)) using a Universal Testing Machine (Instron, Model-3365, USA). The gauge length, load cell capacity and rate of extension were kept constant at 25 mm, 50 N and 50 mm/min, respectively. Fibres were mounted on a paper window using adhesive and mounted on the jaws of the tensile tester. Tenacity (gf/den), elongation (%) and modulus (gf/den) were calculated from 10 replicates and averaged.

2.7 Surface Morphology

The surface morphology of extracted fibres was examined using an optical microscope (Leica, DM2700 M, Germany) equipped with universal white light LED illumination and a scanning electron microscope (ZEISS, EVO 18, Germany). For optical microscopy, individual fibres were mounted on glass slides and their surface morphology was examined at a 5x magnification level. For scanning electron microscopy (SEM), the samples were prepared by cutting fibres into 5 mm lengths, mounting them on aluminium stubs, and coating them with gold. The SEM images were taken at 1000-2000x magnification.

2.8 Chemical Composition

The cellulose, hemicellulose, and lignin content of extracted fibres were determined following the NREL/TP-510-42618 (2012) protocol. Fibre samples were dried, powdered, and subjected to acid hydrolysis using 72 % H_2SO_4 (3 mL, 1 h at 30 °C), followed by dilution to 4 % acid and autoclaving (1 h at 121 °C). Vacuum filtration separated the liquid and solid fractions. The liquid fraction was used for the determination of sugar content and acid-soluble lignin. The solid residue was used to determine acid-insoluble lignin and ash content.

The cellulose and hemicellulose content were determined using HPLC (Agilent, 1260 Infinity II, USA), equipped with an Aminex 87 H column and a refractive index detector (RID), kept at 50 °C. The mobile phase utilised for this was 5 mM H_2SO_4, with a flow rate of 0.6 ml/min. The acid-soluble lignin was determined using a UV-Vis spectrophotometer (Agilent, Cary 4000, USA). After the filtrate was suitably diluted, the absorbance at 280 nm was measured. The acid-soluble lignin (ASL) of samples was calculated using Eq. 2.

$$\text{ASL (\%)} = \left[\frac{(\text{O.D. at 280 nm} \times \text{dilution} \times V)}{(\epsilon \times \text{path length} \times W)}\right] \times 100 \quad \ldots(2)$$

where *O.D.* is the optical density; *V,* volume of filtrate; ε , molar extinction coefficient (24.7); and W , dry sample weight (300 mg).

The residue was oven-dried at 105 °C and combusted in a muffle furnace at 575 °C for 4 h to determine ash content. The acid-insoluble lignin (AIL) was calculated using the Eq. 3:

$$\text{AIL (\%)} = \left[\frac{(W_1 - W_2)}{W}\right] \times 100 \quad \ldots(3)$$

where W_1 is the dried weight of acid-insoluble residue; W_2, weight of ash; and W, dry sample weight (300 mg).

The total amount of lignin was calculated using Eq.4.

$$\text{Lignin (\%)} = \text{ASL (\%)} + \text{AIL (\%)} \quad \ldots(4)$$

2.9 Statistical Analysis

Analysis of variance (ANOVA) was used to determine the statistical significance of each process parameter and their interactions on the measured responses. Insignificant interaction or quadratic terms were systematically excluded based on *p*-values to refine the model. The Design-Expert® software (ver 11.1.2.0) was used to design the experiments and statistical analysis.

3 Results and Discussion

The fibre yield, linear density, tenacity, elongation and modulus for all the experimental runs are reported in Table 2. To determine the significance of process factors on each response, analysis of variance (ANOVA) was performed. Statistically significant factors were further modelled using regression equations, and their effects were illustrated through three-dimensional (3D) response surface plots. These results are discussed in the following subsections.

3.1 Fibre Yield

Table 2 indicates that the maximum yield (63.64 %) of nettle fibre is achieved when the ribbons are treated with 1 % NaOH at 85°C for 1 h. Conversely, the lowest yield (46.70 %) occurs under treatment with 4.5% NaOH at 100°C for the same duration. The yield ratio between these conditions is 1.36:1.

ANOVA results for fibre yield (Table 3) show that the model is significant (p=0.024). Among the process variables, the linear and quadratic effects of NaOH concentration are statistically significant ($p<0.05$), while the effects of time and temperature are not. The developed regression model to predict yield, based on coded variables, is as follows:

$$\text{Yield (\%)} = 51.40 - 3.11\times A - 1.50\times B - 2.19\times C + 5.28\times A^2 \quad \ldots(5)$$

$$R^2 = 0.64$$

where A, B and C represent NaOH concentration, time, and temperature, respectively.

Table 2 — Details of experimental runs and corresponding responses

Std	Run	Factors			Response				
		A NaOH conc. (%)	B Time (h)	C Temp. (°C)	Yield (%)	Linear density (tex)	Tenacity (gf/den)	Elongation (%)	Modulus (gf/den)
9	1	4.5	1.0	70	58.08	2.36	5.26	3.24	228.28
10	2	4.5	4.0	70	54.49	2.12	4.43	3.09	250.82
15	3	4.5	2.5	85	49.13	1.71	5.61	3.30	250.72
14	4	4.5	2.5	85	49.04	1.80	6.01	3.09	275.16
12	5	4.5	4.0	100	53.17	3.10	4.37	2.88	238.55
13	6	4.5	2.5	85	49.22	1.62	5.21	3.52	226.28
1	7	1.0	1.0	85	63.64	2.26	5.50	2.95	257.31
2	8	8.0	1.0	85	56.65	1.91	6.23	4.13	204.07
7	9	1.0	2.5	100	55.67	1.73	6.60	2.94	268.64
5	10	1.0	2.5	70	61.70	1.79	4.62	2.49	249.93
11	11	4.5	1.0	100	46.70	1.79	5.11	3.00	236.40
4	12	8.0	4.0	85	47.28	1.76	3.92	2.59	249.51
8	13	8.0	2.5	100	55.80	3.07	4.30	2.97	241.04
3	14	1.0	4.0	85	58.16	1.54	5.13	2.54	269.81
6	15	8.0	2.5	70	54.58	2.15	5.06	3.54	215.22

Table 3 — ANOVA for yield of nettle fibre

Source	Sum of squares	df	Mean square	*F*-value	*p*-value	Significance
Model	237.600	4	59.400	4.51	0.024	Significant
A-NaOH conc.	77.250	1	77.250	5.86	0.036	Significant
B-Time	17.910	1	17.910	1.36	0.271	Not significant
C-Temperature	38.330	1	38.330	2.91	0.119	Not significant
A^2	104.110	1	104.110	7.90	0.018	Significant
Residual	131.780	10	13.180			
Cor. Total	369.370	14				

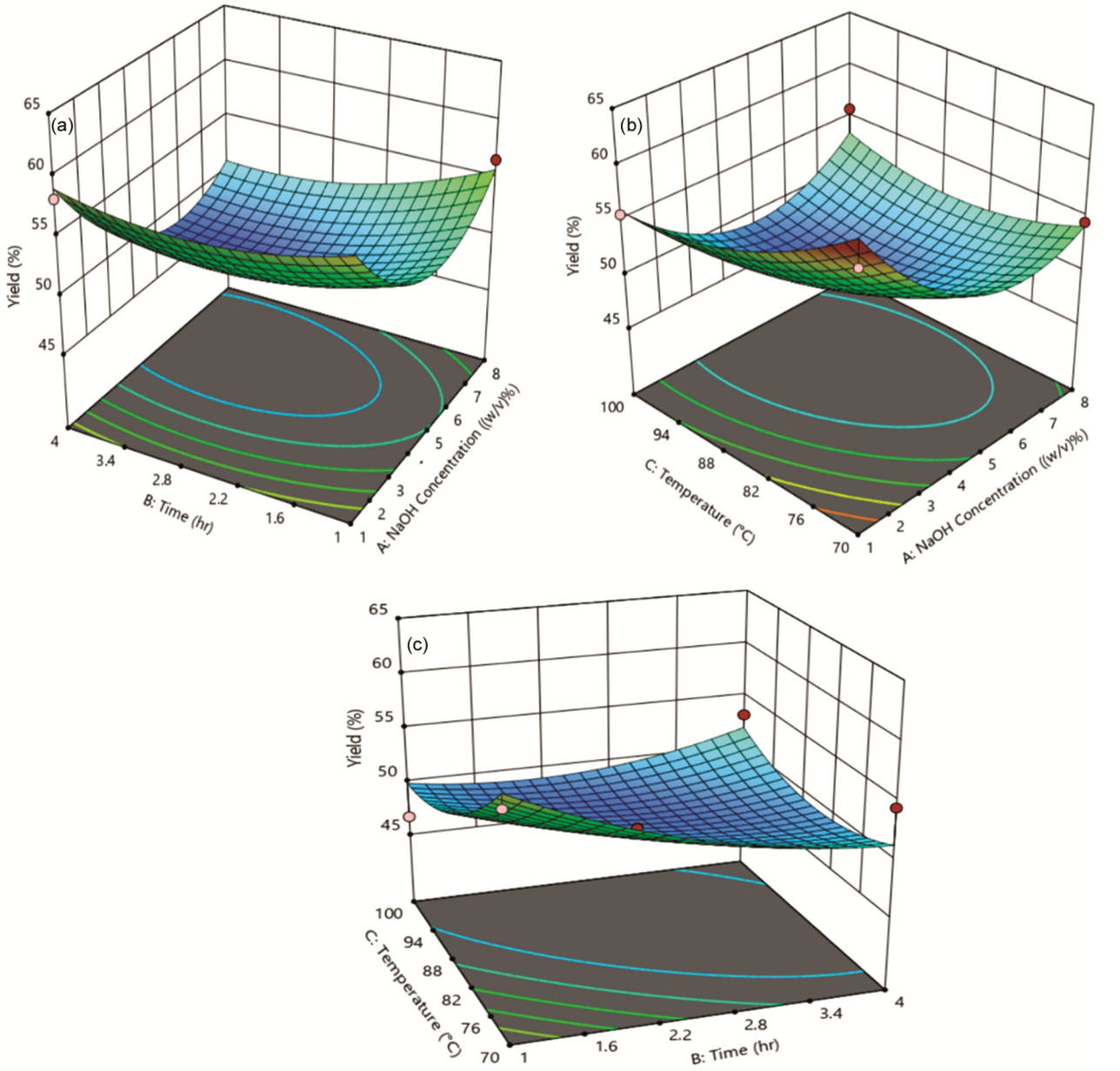

Fig. 2 — Effects of process factors on yield (a) 85°C, (b) 2.5 h and (c) 4.5 % NaOH

The three-dimensional response surface plots showing the effects of process factors on the yield of nettle fibre are represented in Fig. 2 (a-c) at the central points. They indicate that the yield initially decreases and then increases with an increase in each process factor.

3.2 Fibre Linear Density

The highest linear density (3.10 tex) is observed for fibres treated with 4.5 % NaOH at 100°C for 4 h (Table 2). The lowest linear density (1.54 tex) results from 1 % NaOH treatment at 85°C for 4 hours, giving a ratio of 2.01:1. The statistical model for linear density is found to be insignificant (p = 0.104), as shown in Table 4. The influence of linear terms (concentration, time and temperature) is also insignificant (p>0.1). Although the interaction between time and temperature (BC) and the quadratic effect of temperature (C^2) are individually significant, the overall model is not robust enough. This implies that the linear density of the extracted Himalayan nettle fibre does not follow statistical relationship with the process factors. The inherent variability of the linear density was so high that any variability in linear density induced by the

Table 4 — ANOVA for linear density of nettle fibres

Source	Sum of squares	df	Mean square	*F*-value	*p*-value	Significance
Model	1.920	5	0.384	2.57	0.104	Not significant
A- NaOH conc.	0.308	1	0.308	2.06	0.185	Not significant
B- Time	0.005	1	0.005	0.03	0.859	Not significant
C- Temperature	0.202	1	0.202	1.35	0.275	Not significant
BC	0.601	1	0.601	4.02	0.076	Significant
C^2	0.803	1	0.803	5.38	0.046	Significant
Residual	1.340	9	0.149			
Cor. total	3.260	14				

Table 5 — ANOVA for tenacity of nettle fibre

Source	Sum of squares	df	Mean square	*F*-value	*p*-value	Significance
Model	7.040	7	1.010	7.23	0.009	Significant
A-NaOH conc.	0.684	1	0.684	4.92	0.062	Significant
B-Time	2.260	1	2.260	16.24	0.005	Significant
C-Temperature	0.128	1	0.128	0.92	0.370	Not significant
AB	0.941	1	0.941	6.77	0.035	Significant
AC	1.880	1	1.880	13.50	0.008	Significant
B^2	0.540	1	0.540	3.88	0.089	Significant
C^2	0.691	1	0.691	4.97	0.061	Significant
Residual	0.973	7	0.139			
Cor. total	8.010	14				

process factors could not be statistically ratified. Hence, the corresponding mathematical model and 3D plots were not studied further.

3.3 Fibre Tenacity

The maximum tenacity (6.60 gf/den) is recorded for ribbons treated with 1 % NaOH at 100°C for 2.5 hours, whereas the minimum (3.92 gf/den) is obtained with 8 % NaOH at 85°C for 4 hours, resulting in a ratio of 1.68:1. ANOVA results (Table 5) confirm the statistical significance of the model (p = 0.009). NaOH concentration and treatment time have significant linear effects, while temperature shows significance only in interaction with concentration and in quadratic form. The value of R^2 is 0.88, which is the highest among all the responses, indicating the highest correlation of tenacity with process factors. The statistical model to predict the tenacity of the extracted fibre is depicted in Eq. 6.

$$\text{Tenacity (gf/den)} = 5.59 - 0.2925\times A - 0.5313\times B + 0.1263\times C - 0.4850\times AB - 0.6850\times AC - 0.3813\times B^2 - 0.4313\times C^2 \quad \ldots(6)$$

$$R^2 = 0.88$$

Figure 3 represents the three-dimensional response surface plots, which show the effects of process factors on the tenacity of nettle fibre at central points. For the lowest extreme of time and temperature, their tenacity increases with NaOH conc., but the reverse is observed in the case of another extreme of time and temperature. At high alkali concentration, the tenacity continuously decreases with time as well as temperature.

3.4 Fibre Elongation

As seen in Table 2, the highest elongation (4.13%) is achieved with 8 % NaOH at 85°C for 1 hour, and the lowest (2.49 %) with 1 % NaOH at 70°C for 2.5 hours—a ratio of 1.66:1, similar to that observed for tenacity. The ANOVA results (Table 6) show that the model is statistically significant (p = 0.016). NaOH concentration, time, and their interactions significantly affect elongation, while temperature alone does not. The statistical model to envisage the elongation of the nettle fibre in terms of the coded factors is indicated in Eq.7.

$$\text{Elongation (\%)} = 3.08+0.2885\times A-0.2781\times B-0.0686\times C-0.2812\times AB-0.2548\times AC \quad \ldots(7)$$

$$R^2 = 0.74$$

The response plots [Fig. 4 (a–c)] reveal that at low time and temperature, elongation increases with NaOH concentration, whereas at high time and temperature, elongation increases initially and then decreases with further alkali increase.

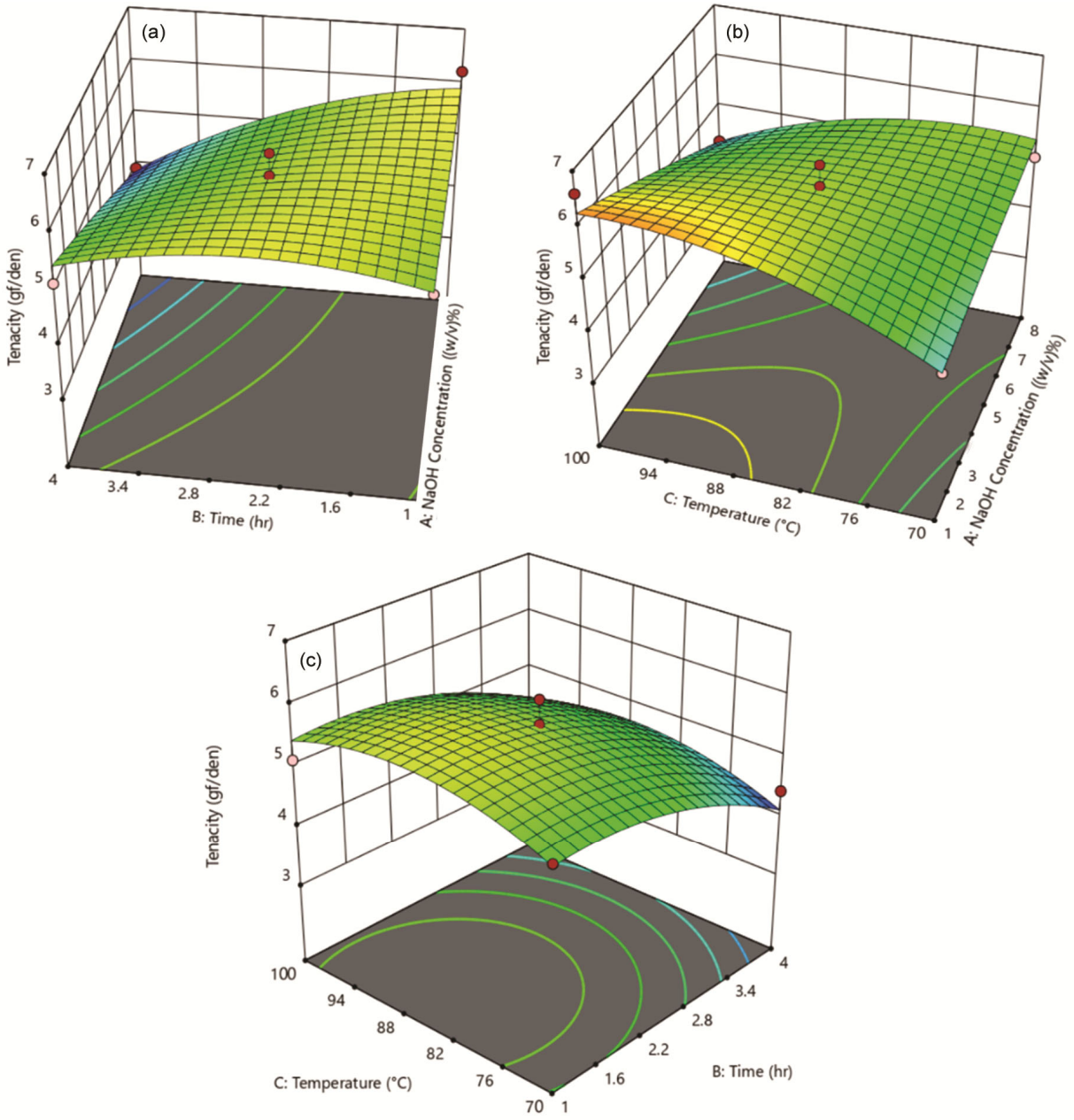

Fig. 3 — Effects of factors on tenacity (a) 85°C, (b) 2.5 h and (c) 4.5 % NaOH

Table 6 — ANOVA for elongation of nettle fibre

Source	Sum of squares	df	Mean square	*F*-value	*p*-value	Significance
Model	1.900	5	0.380	5.18	0.016	Significant
A-NaOH conc.	0.666	1	0.666	9.08	0.015	Significant
B-Time	0.619	1	0.619	8.44	0.017	Significant
C-Temperature	0.038	1	0.038	0.51	0.492	Not significant
AB	0.316	1	0.316	4.32	0.068	Significant
AC	0.260	1	0.260	3.54	0.092	Significant
Residual	0.660	9	0.073			
Cor. total	2.560	14				

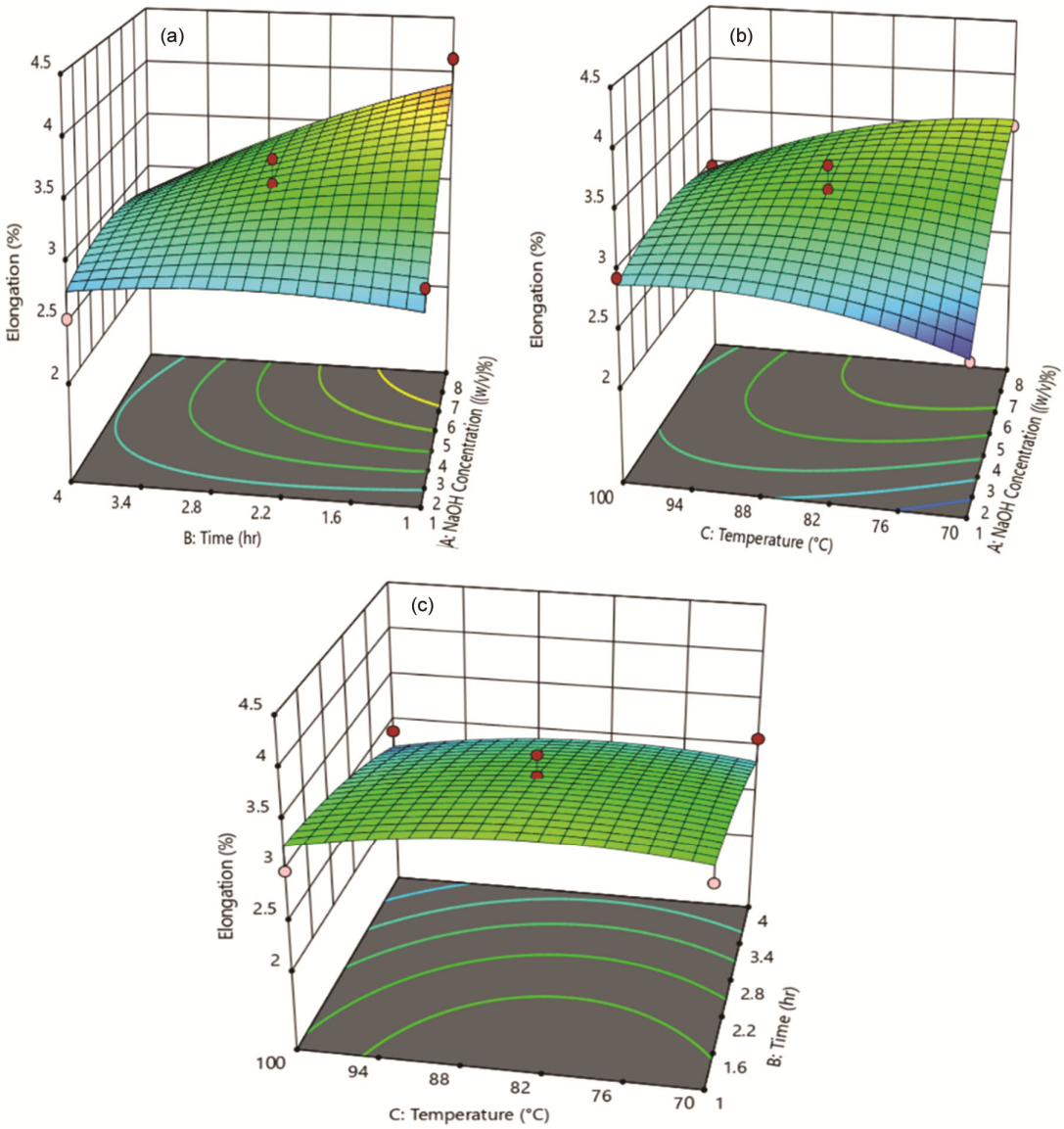

Fig. 4 — Effects of factors on elongation (a) 85°C, (b) 2.5 h and (c) 4.5 % NaOH

Table 7 — ANOVA for modulus of nettle Fibre

Source	Sum of squares	df	Mean square	*F*-value	*p*-value	Significance
Model	3363.890	3	1121.300	5.38	0.016	Significant
A-NaOH conc.	2306.770	1	2306.770	11.06	0.007	Significant
B-Time	853.240	1	853.240	4.09	0.068	Significant
C-Temperature	203.890	1	203.890	0.98	0.344	Not significant
Residual	2293.660	11	208.510			
Cor. total	5657.550	14				

3.5 Fibre Modulus

The highest modulus (275.16 gf/den) is recorded at 4.5% NaOH, 85°C, and 2.5 hours. The lowest modulus (204.07 gf/den) is associated with 8 % NaOH, 85°C, and 1 hour—yielding a ratio of 1.35:1. As shown in Table 7, the model is statistically significant (p = 0.016). NaOH concentration has a highly significant effect, while time is moderately significant and temperature is not. The value of R^2 is 0.59, which is least among all the responses indicating

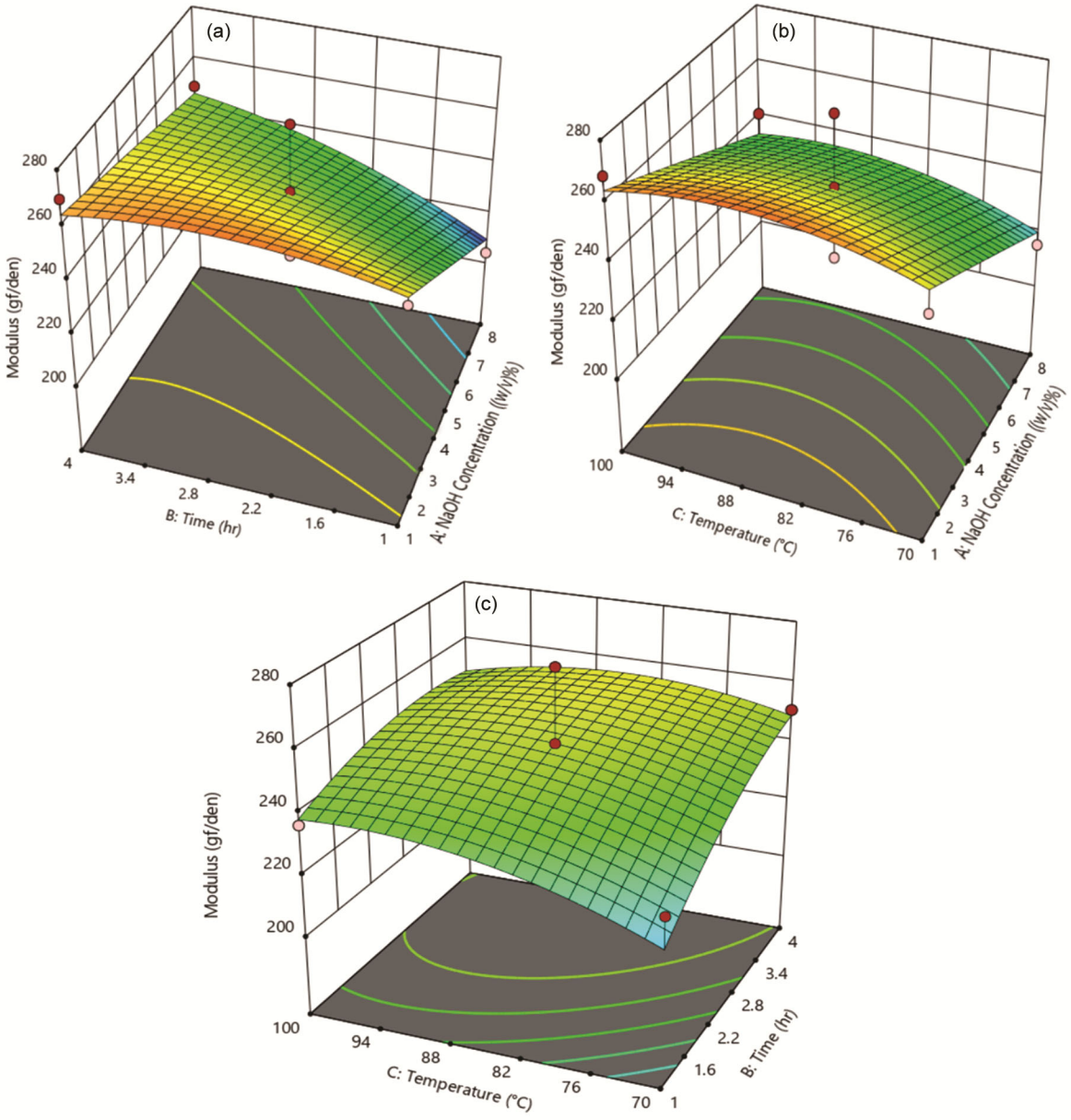

Fig. 5 — Effects of factors on modulus (a) 85°C, (b) 2.5 h and (c) 4.5 % NaOH

the lowest sensitivity of modulus with process factors. A mathematical model for the same is shown in Eq. 8.

$$\text{Modulus (gf/den)} = 244.12 - 16.98\times A + 10.33\times B + 5.05\times C \quad ...(8)$$

$$R^2 = 0.59$$

According to the 3D plots [Fig. 5 (a–c)], modulus decreases with increasing alkali concentration. However, this reduction is less pronounced at higher time and temperature. An increase in either time or temperature generally results in higher modulus values.

3.6 Optimum Process Conditions

The optimisation of process conditions for fibre extraction from Himalayan nettle was needed as the maximum to the minimum ratio for responses, namely yield, linear density, tenacity, elongation, and modulus, were in the range of 1.35-2.01. The optimisation exercise was carried out with the objective of maximum yield, tenacity and elongation while minimising linear density (tex) and modulus of the extracted nettle fibres, keeping in the mind the sustainability with the lowest NaOH concentration, time, and temperature. The minimum linear density

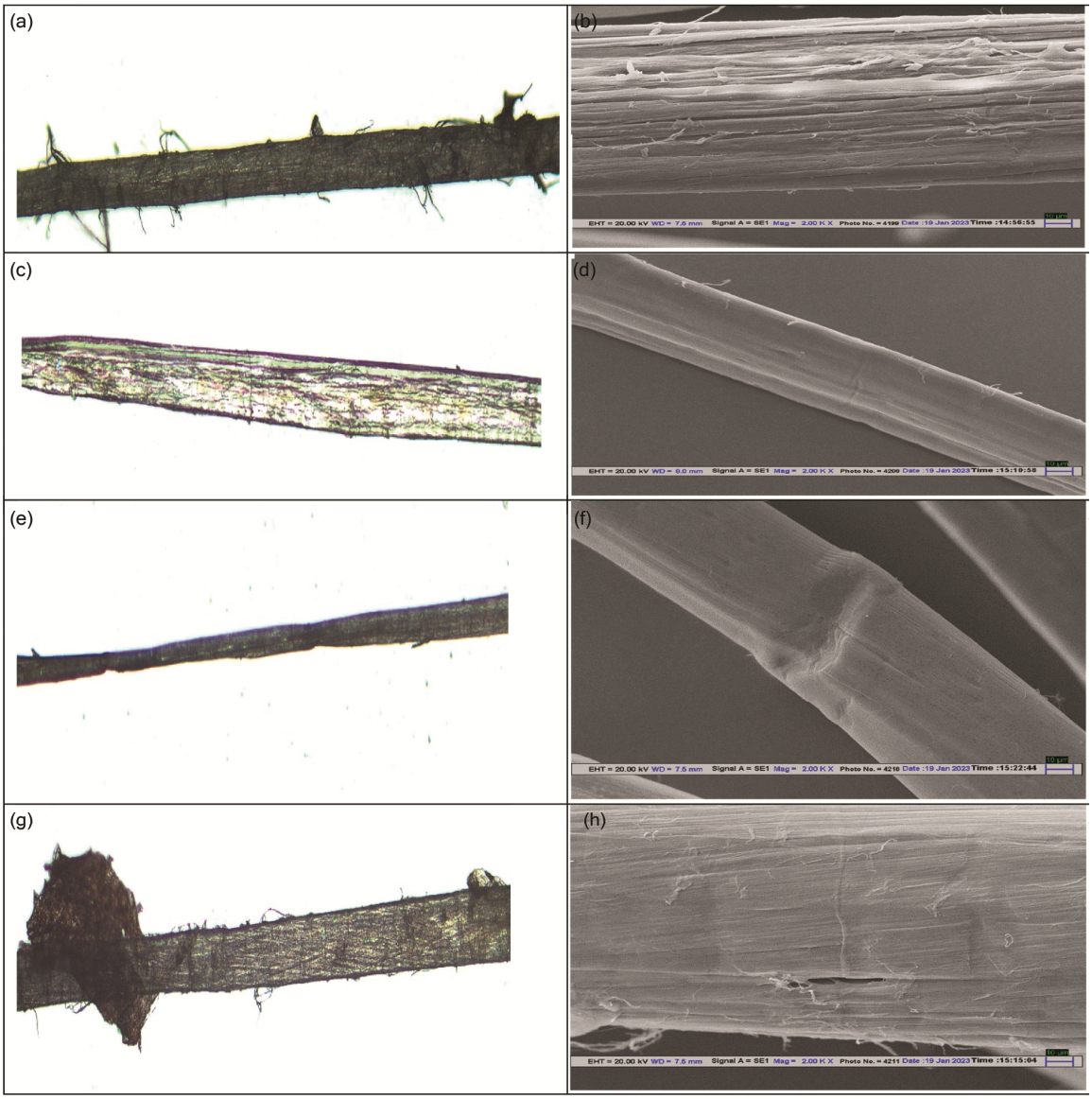

Fig. 6 — Optical microscopic and SEM images of fibres subjected to (a, b) mild treatment, (c, d) optimal treatment, (e, f) aggressive alkalisation and (g, h) high time and temperature

and modulus are desirable for processing them for textile applications. From all the experimental runs, Run 8—comprising 8 % NaOH, 85°C, and 1 hour—emerges as the optimal condition. This setup yields fibres with desirable characteristics: yield (56.65 %), linear density (1.91 tex), tenacity (6.23 gf/den), elongation (4.13 %), and modulus (204.07 gf/den). The tenacity and elongation of the extracted nettle fibres using these conditions were significantly higher than the reported values (1.26 - 4.10 gf/den) and (1.70 – 2.93 %) respectively for fibres procured from local sources in Uttarakhand, which uses traditional methods to extract the fibres [26–28]. The fibres extracted under these conditions exhibited significantly superior mechanical properties compared to those obtained through previously reported extraction methods for Himalayan nettle fibre[23-25]. Additionally, this condition supports sustainability through minimal processing time and moderate temperature.

3.7 Surface Morphology

Optical and scanning electron microscopy (SEM) are employed to assess morphological changes in fibres subjected to different treatments (Fig. 6). Fibres

Table 8 — Chemical composition of Himalayan nettle barks and extracted fibres

Alkali treatment	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Ash (%)
-	69.24	5.29	15.79	9.68
Mild (1% NaOH, 2.5 h and 70°C)	81.94	3.55	10.94	3.57
Optimal (8% NaOH, 1 h, 85°C)	89.73	1.26	7.73	1.28
Aggressive (8% NaOH, 4 h, 85°C)	93.82	0.00	6.18	0.00
Highest time & temperature (4.5% NaOH, 4 h, 100°C)	86.95	1.96	9.16	1.93

subjected to the mildest treatment conditions, run 10 (1 % NaOH, 2.5 h and 70 °C) are shown in Fig. 6 (a) and (b). These fibres exhibit a rough, non-uniform surface with fibrous projections, suggesting that the treatment was insufficient for effective fibre extraction. Fibres obtained under optimal treatment conditions — run 8 (8 % NaOH, 1 h, 85 °C) — are depicted in Figures 6(c) and 8(d). The fibres display a smooth surface and well-defined edges, indicating the effective removal of non-cellulosic components and successful fibre extraction. Figures 6(e) and 8(f) illustrate the effect of aggressive alkalisation — run 12 (8 % NaOH, 4 h, 85 °C). The fibres show a non-uniform diameter with severely degraded edges, suggesting excessive degradation due to prolonged exposure to high alkali concentrations. In run 5 (4.5 % NaOH, 4 h, 100°C), where the time and temperature of treatment were the highest resulting fibres, as seen in Figures 6(g) and 8(h), exhibit a rough surface with small, lumpy deposits. This may indicate partial degradation and redeposition of non-cellulosic materials.

3.8 Chemical Composition

The chemical compositions of Himalayan nettle fibres extracted using NaOH are given in Table 8. The Himalayan nettle barks' cellulose, hemicellulose, lignin, and ash content are 69.24, 5.29, 15.79 and 9.68 %, respectively. Under optimal treatment conditions, an increase in cellulose content is observed, indicating effective removal of non-cellulosic components such as hemicellulose, lignin, and ash. However, under aggressive alkalisation (e.g., high NaOH concentration and extended treatment duration), further removal of non-cellulosic material occurs, including high-molecular-weight lignin complexes. These conditions can lead to fibre degradation, as noted by Chen *et al.*[29], who highlighted the need for harsh conditions to remove complex lignin structures. Under extreme time and temperature conditions, non-cellulosic content tends to increase again. This is likely due to the redeposition of solubilized non-cellulosic materials onto the fibre surfaces, adversely affecting the purity and quality of the final fibres.

4 Conclusion

This study demonstrates that both the yield and properties other than linear density of fibres extracted from Himalayan nettle bark are highly sensitive to the conditions employed during the alkaline extraction process. The optimisation of treatment parameters is thus critical. If the conditions are milder than optimal, the fibre extraction is ineffective. Above optimal conditions, either the fibre is degraded, or the impurities may redeposit on the fibre. At the optimum conditions (8 % NaOH, 1 h, 85°C) identified for extraction of fibres, the fibre yield was 56.65 %, and the extracted fibres had mean linear density of 1.91 tex, tenacity of 6.23 gf/den, elongation of 4.13 % and modulus of 204.07 gf/den. The tenacity and elongation of the extracted nettle fibres using optimum process conditions were significantly higher than the traditional method. The proposed method is simple, reproducible, and scalable, and yields fibres of the best and most consistent quality. The development of the optimised process will go a long way in making the large-scale production of nettle fibre with improved properties possible for use by the industrial sector.

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