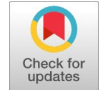


Bio-Surfactant for Sustainable Textile Processing

Sangeeta Patil, Ashok Athalye



Abstract: Enforcing environmental preservation and addressing climate change for future generations presents various issues for modern society. Microorganisms produce a family of surface-active molecules called biosurfactants, which have garnered considerable interest due to their environmentally beneficial properties and potential to replace synthetic surfactants in various industries. Traditional textile wet processing, which includes pretreatment, dyeing, and finishing, often employs synthetic surfactants that raise concerns regarding their biodegradability, toxicity, and potential for water pollution. On the contrary, biosurfactants are biodegradable, non-toxic, and can work in various environmental circumstances, providing a sustainable option. Among the different types of surfactants, glycolipids are particularly highlighted, with sophorolipids (SLs) being low-molecular-weight compounds that have garnered significant attention. This study compares the effectiveness of SLs with conventional surfactants in various textile wet processing steps, such as pretreatment and dyeing. According to the findings, SLs not only outperform their synthetic counterparts in terms of surfactant qualities (wetting, emulsifying, and foaming) but also lessen the process's total environmental impact. The results suggest that incorporating SLs into textile wet processing can facilitate the industry's transition to more sustainable technologies, leading to greener production methods.

Keywords: Bio-based Surfactant, Bio-degradable, Cotton Processing, Environmental Impact, Effluent Treatment

Abbreviations:

SLs: sophorolipids

FTIR: Fourier Transform Infrared

HPLC: High-performance Liquid Chromatography

ANOVA: Analysis of Variance

I. INTRODUCTION

The textile industry is one of the largest and most resource-intensive sectors globally, consuming vast amounts of water, energy, and chemicals during various wet processing stages. Conventional textile processing methods heavily rely on synthetic surfactants to achieve desirable fabric properties, such as wettability and detergency [1]. However, the widespread use of artificial surfactants poses significant environmental challenges, as many of these substances are not biodegradable.

chemicals are non-biodegradable and toxic, contributing to water pollution, soil contamination, and ecological degradation. In response to the increasing demand for sustainable practices in textile manufacturing, biosurfactants have emerged as promising alternatives due to their environmentally friendly characteristics. Biosurfactants, derived from microbial sources, provide eco-friendly alternatives to synthetic surfactants. They exhibit low toxicity and biodegradability and are gaining traction across various industrial applications. The frequent use and subsequent release of this surfactant into the environment have become a growing concern. In recent years, there has been a significant increase in interest in microbial surfactants due to their unique properties and diverse range of applications in various environmental contexts. Biosurfactants are surface-active agents produced by microorganisms, classified into different types based on their molecular weight and structure [2].

High-molecular-weight biosurfactants encompass polymeric and particulate surfactants, often utilised in environmental applications due to their stability and biodegradability. Glycolipids, lipopeptides, and phospholipids are examples of low molecular weight biosurfactants that are well-known for their capacity to improve emulsification and lower surface tension. SLs are regarded as natural compounds and green glycolipid surfactants. Since about 45 years ago, SLs have been recognized as biosurfactants that some yeast strains can make. They combine green chemistry with a reduced carbon footprint, making them environmentally beneficial. They exhibit low ecotoxicity and are biodegradable, making them commercially appealing [3].

This study demonstrates the application of SLs in textile wet processing applications. Among the notable characteristics that the biosurfactants display are surface tension lowering, emulsification, wetting, and foaming [4]. Surface tension reduction, emulsification, wetting, and foaming are some of the prominent properties exhibited by biosurfactants. A biologically generated chemical known as SLs-biosurfactant is produced when microorganisms (bacteria, fungi, and yeast) are cultivated in aqueous environments and provided with a carbon source as a feedstock, such as blends of carbohydrates, fats, oils, and hydrocarbons [5]. SLs, a glycolipid biosurfactant produced by yeast species such as *Starmerella bombicola*, have garnered interest due to their potential applications in various industries, including cosmetics, pharmaceuticals, and food processing. In recent years, their use in textile applications has been explored due to their unique surface-active properties, low toxicity, and biodegradability. SLs can be produced from renewable resources, making them an attractive alternative to petrochemical-based surfactants in textile wet processing [6]. SLs are known for their rapid breakdown in the environment, which is a crucial factor in reducing

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pollution. Studies indicate that SLs exhibit minimal cytotoxicity, comparable to that of conventional solvents, thereby enhancing their safety profile [7].

This study aims to investigate the application of biosurfactants from SLs in various stages of textile wet processing, including scouring, bleaching, and dyeing, with a focus on their effectiveness compared to traditional synthetic surfactants. The research will examine the impact of SLs on fabric quality, dye uptake, and colour fastness. By reviewing the performance and environmental benefits of SLs in textile applications, this study aims to contribute to the growing body of knowledge on sustainable practices in the textile industry. It provides insights into the viability of bio-surfactant SLs as a greener alternative to conventional surfactants.

II. EXPERIMENTAL

A. Material

SLs Received from Rossari Biotech Limited. Caustic flakes, sodium chloride, and soda ash are sourced from SD Fine Chem. Reactive dyes are sourced from Rossari Biotech Limited. Single jersey 30s cotton was sourced from Vijay and Sons, Tirupur. The greige cotton fabric, with a quality of 40 ComX 40 Cw / 132 x 72 - 1/1, was sourced from Gimatex.

B. Wetting Test (Drave's Test -AATCC 17)

A surfactant's effectiveness is evaluated by measuring how long it takes for a standard cotton yarn skein with a standard weight to sink in a solution of a wetting agent in water. The more quickly the skein wets out, the more effective the surfactant is at doing so.

C. Foaming Test

The method involves manually shaking the cylinder with the Product under study and measuring the column of the resulting foam. The graduated cylinder is 2-2-250 as per GOST 1770-74, and the stopwatch is as per GOST 5072-72. Prepare a solution of 1.0 g/L of the product under study and shake the graduated cylinder with horizontal swinging motions, using an amplitude of 70 cm, for 1 minute. Then, the cylinder is put on a tabletop immediately after shaking, and the difference between the foam's surface and the emulsion's meniscus is determined, which numerically expresses the foaming tendency. Allow it to settle for 1 minute and measure the foam's volume again to assess its settling.

D. Surface Tension (Pendant Drop Method)

Adding surfactant to water reduces the surface tension of water from 72 dynes/cm to approximately 30 dynes/cm. The pendant drop method, which involves finding a drop of water at the tip of a needle, is used to measure surface tension. A camera captures a picture of the drop, which is then imported into the drop shape analysis program. The first step in contour recognition is to analyze a greyscale image. Optical contact angle measuring and contour analysis systems (Model No. OCA 25 15EC) of Data Physics are used for the evaluation.

E. Cloud Point (DIN EN 1890)

The cloud point is the temperature at which the surfactant's solubility is significantly decreased, resulting in phase separation and making the solution cloudy. At this temperature, the surfactant separates the hydrophobic part

from its soluble phase and forms micelles. These micelles aggregate, making the clear solution turbid. A higher cloud point indicates the stability of the surfactant at high temperatures, allowing it to exhibit properties under those conditions.

F. Emulsifying Index

The emulsification index test determines the surfactant's emulsifying properties. The emulsification index test calculates the ratio of the height of the stable emulsion layer to the total height of the liquid generated after vortexing and allowing it to stand for 24 hours. This helps determine whether the surfactant possesses emulsifying properties. The activity of emulsification was computed by applying the formula.

$E24 (\%) = \text{height of the liquid layer} / \text{height of the emulsified layer}$.

G. Specific Gravity (ASTM D792)

Specific gravity is a measure of the ratio of the mass of a given volume of material at 30°C to the same volume of deionised water.

H. Ionic Nature

Ionic nature refers to the characteristics of a chemical compound, which determines whether a chemical is non-ionic, anionic, or cationic. The ionic nature of surfactants is crucial, as it determines their performance in various applications and compliance with environmental standards.

I. pH Value

A Universal digital pH meter was used to check the pH of the products. Prepared a solution with 10 g of product in 100 ml of distilled water and tested for the pH value of the surfactant under study.

J. Solid Content

The solid content is a measure of the amount of active ingredients or non-volatile components in the liquid. It is determined by measuring the weight loss of the liquid when the volatile components evaporate. It is an essential parameter for understanding the strength of the product.

K. Absorbency by Drop Test

The absorbency of scoured fabric is measured using the drop test, as specified in AATCC 79. Wetting time refers to the amount of time required for a water drop to disappear from the surface of the fabric, and it is also used to determine the shape of the drop on treated fabric.

L. Sinking Test

The sinking test is checked by JIS 1907. The sinking time test determines how long it takes for the scoured test specimen to be completely wetted by water when placed on its surface.

M. Wicking Test

Standard vertical wicking test techniques, as outlined in AATCC 197, are used. The specimen's bottom comes into contact with water, and then the wicking distance is measured after 15 minutes.

N. Weight Loss:

The weight loss of the scoured fabric is calculated

according to ISO 1383:1977 (BIS 1982). W_a and W_b are the weights of the unscoured and the scoured fabric, respectively
Weight loss % = $(W_a - W_b)/W_a \times 100$

O. TEGEWA Rating

The TEGEWA scale is used to measure desizing efficiency. A tiny piece of resized cloth was cut out and submerged in an iodine solution in a beaker. 0.6358 g of iodine and 10 g of potassium iodide (KI) are combined in 100 ml of water, and the mixture is thoroughly shaken to dissolve. Crystals of iodine. After that, 800 mL of distilled water is added, followed by 1000 mL of ethanol. Following a thorough water rinse and a dab with filter paper, the fabric is instantly compared to the TEGEWA scale, which has a rating range of 1 to 9. Nearly no size removal is indicated by a grade of 1, while total size removal from the fabric is indicated by a value of 9.

P. Desizing Efficiency

W_1 is the initial weight of the greige fabric, and note down the weight of the fabric after desizing. This is W_2 . This desized fabric is further desized with a Concentrated amylase enzyme at a high dosage, ensuring complete size removal. The TEGEWA rating can assess this. The TEGEW rating is 8-9, which denotes complete size removal from the fabric. Weigh the fabric after completely removing the size. This reading is W_3 .

$$\text{Total size content} = W_1 - W_3$$

$$\text{Residual size} = W_2 - W_3$$

$$\text{Desizing Efficiency} = (\text{Total size} - \text{Residual size}) / \text{Total size} \times 100$$

Q. Whiteness Index and Colour Strength Measurement

The spectrophotometer X-Rite Colour Ci7450 Model Spectrophotometer was used to measure the whiteness of scoured and colour intensity (K/S), colour indices (L^* , a^* , b^*) values of dyed cotton fabric at the maximum wavelength. The CIE scale was used to calculate whiteness. D65 was set as illuminated at 10 standard observers for determining K/S using the Kubelka–Munk equation,

$$K/S = \frac{(1-R)^2}{2R}$$

Additionally, the colored samples were assessed using L^* , a^* , b^* , C, h, and dE. The distance between the standard or reference point and the sample points shown in the $L^*a^*b^*$ colour space is known as the colour difference (dE). L^* values vary from 0 to 100, where 0 denotes darkness or black and 100 denotes lightness or white. Green is indicated by negative values of " a^* ," whereas positive values indicate red; blue is indicated by negative values of " b^* ," and yellow by positive values. The most widely used system today is the $L^*a^*b^*$ system, which was derived from the CIE in 1976.

Where DL: L (standard) – L (sample), Da: a (standard) – a (sample), Db: b (standard) – b (sample). From the CIELAB coordinates, one may compute C (chroma) and h (hue). The distance between the achromatic point and the colour is known as the chroma or saturation (C), and it is computed from " a^* " and " b^* " using the following formula: The chromaticity diagram's centre is located at $a = 0$ and $b = 0$. Higher achromaticity and poorer purity are indicated by

lower values of " a^* " and " b^* ." Conversely, the purer, more saturated, or brighter the colour, the higher the values of " a^* " and " b^* " (disregard the negative signs). More saturated colour, or brighter, is indicated by positive chroma (or saturation) numbers, whereas less saturated colour, or duller, is indicated by negative values. Hue, also known as colour purity, is an angle measured in degrees [8].

R. Experimental Design

The scouring process was optimised using the response surface methodology to investigate the effects of three selected variables on absorbency, sinking, and the drop test. Box–Behnken statistical experimental design contained three factors,

Factor 1 A – Temperature (Degree Celsius)

Factor 2 B – SLs Concentration (% On weight of fabric)

Factor 3 C –Caustic Soda Concentration (% On weight of fabric)

Each component was put on three levels, regularly spaced out according to the scheme shown in Table 1.

Table-I: Process Variables with Range for SLs Scouring of Cotton

Variable	Code	Variable level		
Temperature- Degree Celsius	A	85	92.5	100
SLs - %	B	0.5	1.75	3
Caustic soda -%	C	1	3	5

The preliminary scouring experiment was used to determine the variable levels for SL concentration (%) and Caustic concentration (%). In contrast, data from a prior study on alkaline scouring of cotton were used to determine the third parameter. A total of 17 combinations were found. Using Design-Expert software, analysis of variance (ANOVA) statistics, response surface plots, and model analysis were conducted at a 95% confidence interval ($p < 0.05$). During the optimization process, "minimize" was the stated goal for each variable's answer and objective [9].

III. CHARACTERIZATION

A. Fourier Transform Infrared (FTIR)

Several functional groups found in the SLs are confirmed by IR spectrometry using a Thermo Nicolet FTIR spectrometer with a diamond ATR.

B. High-performance Liquid Chromatography (HPLC)

The Shimadzu LC-2030C NT Model is used to identify and quantify the components of SLs

C. Statistical Data Analysis

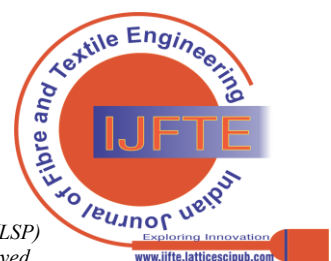
Analysis of variance (ANOVA) was used to estimate the statistical variance of the experimental data.

D. Surface Activity

Optical contact angle measuring and contour analysis systems (Model No. OCA 25 15EC) of Data Physics are used for the evaluation.

E. Rota Dyer

Rota Dyer Machine Model
12 x 100 CC: Qty-12nos.J.K.
Electronics manufactured



the device used in this study. This instrument enables the simultaneous conduct of 12 trials while maintaining a consistent temperature and rate of temperature rise for all experiments. They are embedded with a special Temperature Control Mechanism and an indicator. This was used for desizing, scouring, and dyeing applications.

F. Spectrophotometer

The X-Rite Colour Ci7450 Model was used to measure the whiteness of the scoured material and to measure colour intensity.

G. Laundrometer (Wash Fastness)

The R.B. Electronic wash fastness tester is used to determine the resistance of textiles to colour fading and staining during repeated washing cycles.

IV. TESTING AND ANALYSIS

A. Desizing

Gimatex's greige cotton fabric, of quality 40 ComX 40 Cw / 132 x 72 - 1/1, is utilised for this application. The fabric is desized using a commercially available and widely used Amylase enzyme, which breaks down the 1-4 glycosidic bonds between the amylose and amylopectin molecules in the starch. The alpha-amylase enzyme Rexsize NCG liquid then transforms it into water-soluble fructose, glucose, or maltose, which is easily removed from the fabric. The bacterial reaction, a biological process, produces the amylase enzyme, a bio-catalyst. Enzymes work on specific substances in a particular way [10].

A small amount of an enzyme can break down a significant amount of the chemical it acts on because enzymes have a specialised mechanism of action. Acetic acid maintains the pH at 6.5, and the enzyme concentration is 0.5% of the fabric's weight. The temperature is increased to 85^o C and held for 45 minutes. Following the process, the bath is drained, and a 10-minute hot wash at 95^oC is administered. The item is then allowed to air dry and examined for characteristics, including weight reduction, TEGEWA rating, and desizing efficiency. Additionally, surfactants help lower the water's surface tension, making it easier to remove sizing agents from textiles. Conventional surfactant (Keenox CBR) was tested against SLs in desizing applications. Desizing results are compiled in Section 6.1, Table 7.

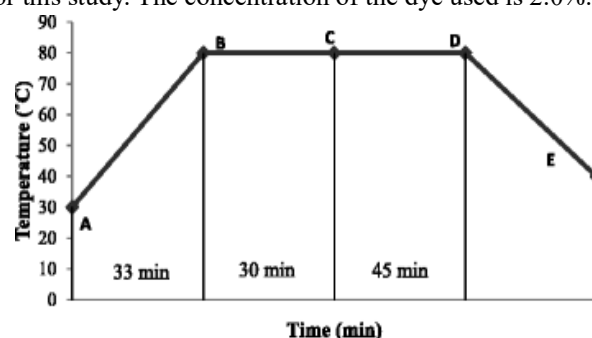
B. Scouring and Bleaching

Greig hosiery fabric was treated with scouring and bleaching to remove impurities and enhance its functionality. Traditional scouring and bleaching methods involve alkali treatment with surfactant and bleaching agent. The Scouring bath is prepared with Caustic at 2.0%, H₂O₂ at 3.0%, Surfactant at 0.6%, and Stabiliser for peroxide at 0.3%. The chemicals mentioned below are based on the weight of the fabric. The MLR was maintained at a 1:10 ratio, and the temperature was maintained at 98^oC. The run time is 45 minutes. After the process, the bath is drained, and the fabric under study is washed at 85 °C for 10 minutes, followed by

drying. Treated fabrics are tested for properties such as absorbency, capillary rise, sinking test, and whiteness index. Swatches are then further taken for reactive dyeing to assess the effect of the surfactant on dyeing performance.

C. Reactive Dyeing: The Scoured and Bleached Fabric is Dyed with Reactive Dyes

The fabric, 5.0 g, is scoured and bleached with Kleenox CBR and SLs, and then dyed with reactive dyes. The study was done on three reactive dyes. Rosareact G Yellow HER, Rosareact N Blue HE2G, Rosareact Red HE4B H/C are used for this study. The concentration of the dye used is 2.0%.



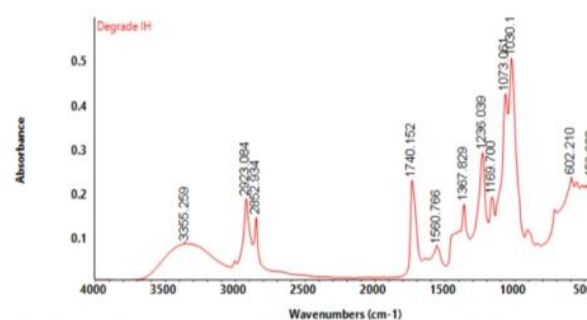
[Fig.1: Graphical Representation of the Reactive Dyeing Process]

A time-temperature graph illustrates the traditional reactive HE dyeing procedure. Where A: Fabric, the necessary quantity of dye, and room-temperature salt (40 g/L), A–B: Increase the temperature by 1.5^oC each minute to 80^oC. B–C: Run the bath at 80^oC for 30 minutes. C: Adding 20 g/l of sodium carbonate, C–D: 45 minutes of dyeing, E: Rinsing and washing [11].

V. RESULTS AND DISCUSSION

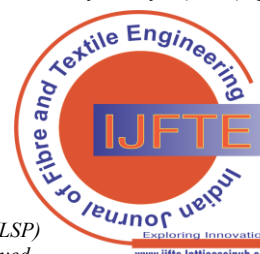
A. Fourier-Transform Infrared Spectroscopy (FTIR)

FTIR spectra in Figure 3 typically show characteristic peaks corresponding to hydroxyl (-OH), carbonyl (C=O), and ester (C-O) groups, which are essential for the surfactant activity of SLs [12].



[Fig.2: FTIR Spectra of SLs]

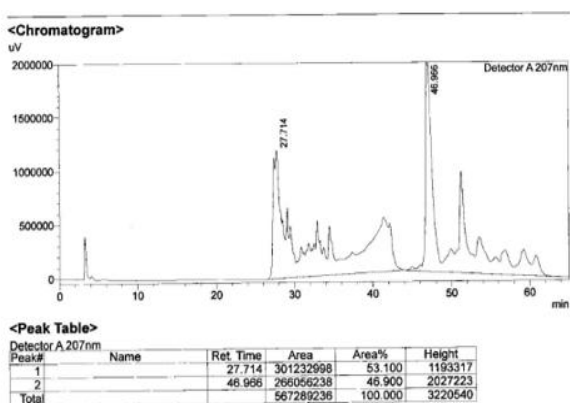
- Hydroxyl Groups: FTIR spectra typically show broad absorption bands around 3200-3450 cm⁻¹, indicating the presence of hydroxyl (-OH) groups, which are essential for the surfactant properties of SLs [13].



- C-H Stretching: Peaks in the range of 2800-3000 cm^{-1} correspond to C-H stretching vibrations from the fatty acid chains, confirming the glycolipid nature of SLs
- C=O Stretching: A peak around 1740 cm^{-1} is indicative of carbonyl (C=O) stretching, which is characteristic of the ester bonds formed between the fatty acids and the sophorose moiety.
- Alkyl Groups: A deformation vibration at 1367 cm^{-1} indicates alkyl groups.
- FTIR spectra reveal characteristic peaks corresponding to hydroxyl (-OH), carbonyl (C=O), and ether (C-O-C) groups, essential for understanding the molecular structure of SLs.

B. High-Pressure High-Performance Chromatography

SLs were examined using an HPLC analytical symmetric C18 column (250 x 4.6 mm^2). The following gradient solvent elution profile was employed: a 95:5 v/v water/acetonitrile mixture was held for 10 minutes, resulting in a final composition of 50 minutes of linear gradient water/acetonitrile (5:95, v/v), followed by a 10-minute holding period. The flow rate was 0.5 ml/min. At 220 nm, the peaks were found. In numerous runs, fractions from various peaks were gathered and pooled independently.



[Fig.3: HPLC Chromatogram of SLs]

The analysis of SLs using high-performance liquid chromatography (HPLC) reveals their complex composition and diverse derivatives. SLs are categorized into acidic and lactonic types, each exhibiting unique properties.

(i) Peaks: Peak 1, at a retention time of 27.714 minutes, has an area percentage of 53.1% and a height of 1,193,317. Peak 2, at a retention time of 46.986 minutes, has an area percentage of 46.9% and a higher peak height of 2,027,223. This indicates that there are two primary components in the SLs sample, contributing almost equally to the total area.

(ii) Retention Times: The retention times of around 27.7 and 47 minutes suggest that the sample likely contains

different SL variants, such as lactonic and acidic forms. SLs often show varied retention based on structural differences (e.g., acetylation and chain length of fatty acids).

Peak 1 (Retention time: 27.714 min) represents lactonic SLs, which elute earlier due to their more hydrophobic nature, allowing them to interact less with the stationary phase in reverse-phase chromatography.

Peak 2 (Retention time 46.986 min) represents acidic SLs. Acidic SLs are more hydrophilic due to a free carboxylic acid group, making them elute later as they interact more with the stationary phase [12].

C. Physical Properties of SLs

The SLs have a surface tension value of 30.56, a wetting time of 23 seconds by Drave's test, and an emulsification index of approximately 86. Wetting fabric and emulsifying wax are crucial steps in the scouring process. Since SLs have both emulsification and wettability qualities, they will be a superior green surfactant for scouring cotton.

Table-II: Physical Properties of SLs

Properties	SLs
Appearance	Clear Liquid
pH of 10 %	5.36
Solid Content at 110 ° for 2 hours	50 %
Wetting by Drave's test-1.0 ml in water	23 sec
Foaming by the Cylinder method	150 ml Collapsed to 120 ml in 1 min
Specific gravity	1.023
Ionic Nature	Anionic
Emulsifying index	86
Surface Tension of 0.1 % Solution	34.56

D. Response Surface Methodology Statistical Optimization

The experimental data were analysed using the 'Design Expert 12' statistical program, with an ANOVA used to estimate statistical parameters. Table 3 provides the experimental range, coded level of variables, and outcomes. The quadratic model was proposed for the drop test (Equation 1) and the sinking test (Equation 2), while the linear model was suggested for capillary rise (Equation 3). Equations (1 to 3) display the final empirical model as a coded factor for the response of the drop test (in seconds), sinking test, and wicking test. The process is run for 45 minutes.

Factor 1 A – Temperature (Degree Celsius)

Factor 2 B – SLS Concentration (% On weight of fabric)

Factor 3 C -Caustic Concentration (% On weight of fabric)

$$\text{Drop Test} = +4-2.06A-5.56B - 1.75C+1.38AB+0.25AC+1.25BC+0.1875A^2+4.19B^2+1.56C$$

$$\text{Sinking Test} = +40.08-9.59A-32.13B-1.84C-5.1AB-2.98AC-5.15BC+1.67A^2+21.6B^2+1.67C$$

$$\text{Capillary Rise} = +2.42+0.2875A+0.625B+0.3625C$$



Table-III: Experimental Variables for Scouring of Cotton

Std	Run	Factor 1 Temp	Factor 2 SL conc in % owf*	Factor 3 Caustic Conc in %owf	Response 1 Sinking in sec	Response 2 Drop test in sec	Responses 3 Capillary rise in cm for 5 mins
4	1	100	3	3	21.5	2.0.0	3.1
12	2	92.5	3	5	20.7	3 sec	3.4
1	3	85	0.5	3	95.0	17.5	1.3
6	4	100	1.75	1	37.5	5.0	2.1
8	5	100	1.75	5	27.6	3.0	3.4
17	6	92.5	1.75	3	37.5	5.0	2.4
5	7	85	1.75	1	53.3	9.0	1.6
10	8	92.5	3	1	34.4	5.0	2.8
16	9	92.5	1.75	3	29.3	2.	2.5
13	10	92.5	1.75	3	32.3	2.0	2.7
3	11	85	3	3	48.3	4.0	2.7
11	12	92.5	0.5	5	102.6	12.0	1.8
15	13	92.5	1.75	3	51.3	6.0	2.4
14	14	92.5	1.75	3	50.0	5.0	2.3
2	15	100	0.5	3	88.6 sec	10.0	2.0
7	16	85	1.75	5	55.3 sec	6.0	2.7
9	17	92.5	0.5	1	95.7sec	19.0	1.9

*On the weight of the fabric

Table-IV: ANOVA for the Response Surface Quadratic Model for the Drop Test

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Response	408.47	9	45.39	18.62	0.0004	significant
A-Temperature	34.03	1	34.03	13.96	0.0073	
B-concentration	247.53	1	247.53	101.55	< 0.0001	
C-Caustic conc	24.5	1	24.5	10.05	0.0157	
AB	7.56	1	7.56	3.1	0.1216	
AC	0.25	1	0.25	0.1026	0.7581	
BC	6.25	1	6.25	2.56	0.1533	
A ²	0.148	1	0.148	0.0457	0.8124	
B ²	73.83	1	73.83	30.29	0.0009	
C ²	10.28	1	10.28	4.22	0.0791	
Residual	17.06	7	2.44			
Lack of Fit	3.06	3	1.02	0.2917	0.8304	not significant
Pure Error	14	4	3.5			
Cor Total	425.53	16				
Source	Sum of Squares	df	Mean Square	F-value	p-value	

The factor is coded. Type III: Partial sum of squares. The significance of the model is indicated by its F-value of 18.62. This large F-value could only result from noise in 0.04% of cases. Model terms are considered significant when the P-value is less than 0.0500. A, B, C, and B2 are essential model terms. The model terms are not important if the values are higher than 0.1000. Model reduction can enhance your model

if it contains many unnecessary terms (apart from those necessary to maintain the hierarchy). Compared to pure mistakes, the lack of fit is not substantial, as indicated by the lack of fit F-value of 0.29. A significant Lack of Fit F-value has an 83.04% probability of being caused by noise. Good is a non-significant lack of fit.

E. Response to Sinking Test

Table-V: ANOVA for the Response Surface Quadratic Model for the Sinking Test

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	11298.6	9	1255.4	16.61	0.0006	significant
A-Temperature	735.36	1	735.36	9.73	0.0169	
B-concentration	8256.13	1	8256.13	109.22	< 0.0001	
C-Caustic conc	27.01	1	27.01	0.3573	0.5688	
AB	104.04	1	104.04	1.38	0.2791	
AC	35.4	1	35.4	0.4683	0.5158	
BC	106.09	1	106.09	1.4	0.2748	
A ²	11.78	1	11.78	0.1558	0.7048	
B ²	1964.01	1	1964.01	25.98	0.0014	
C ²	11.78	1	11.78	0.1558	0.7048	
Residual	529.15	7	75.59			
Lack of Fit	121.46	3	40.49	0.3972	0.7629	not significant
Pure Error	407.69	4	101.92			
Cor Total	11827.74	16				

The sum of squares factor coding is Type III-Partial. The significance of the model is indicated by its F-value of 16.61. An F-value of this level could only result from noise in 0.06% of cases. Model terms are considered significant when the P-

value is less than 0.0500. A, B, and B2 are essential model terms in this instance. Regarding the pure error, the



lack of fit is not considerable, as indicated by the F-value of 0.40 for the lack of fit. A significant Lack of Fit F-value has

a 76.29% probability of being caused by noise. Inconsequential absence of fit is good.

F. Response for Wicking Test

Table-VI: ANOVA for a Linear Model for Wicking

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	4.84	3	1.61	25.97	< 0.0001	significant
A-Temperature	0.6612	1	0.6612	10.65	0.0062	
B-concentration	3.13	1	3.13	50.33	< 0.0001	
C-Caustic conc	1.05	1	1.05	16.93	0.0012	
Residual	0.8072	13	0.0621			
Lack of Fit	0.7152	9	0.0795	3.46	0.1224	not significant
Pure Error	0.092	4	0.023			
Cor Total	5.64	16				

The significance of the model is indicated by its F-value of 25.97. An F-value this enormous could only result from noise in 0.01% of cases. Model terms are considered significant when the P-value is less than 0.0500. A, B, and C are essential model terms in this instance. Values above 0.1000 indicate that the model terms are not significant. Model reduction can enhance your model if it contains many unnecessary terms (apart from those necessary to maintain the hierarchy). Regarding the pure error, the Lack of Fit is not substantial, as indicated by the Lack of Fit F-value of 3.46. A significant Lack of Fit F-value has a 12.24% probability of being caused by noise. A negligible loss of fit is desirable; we want the model to fit.

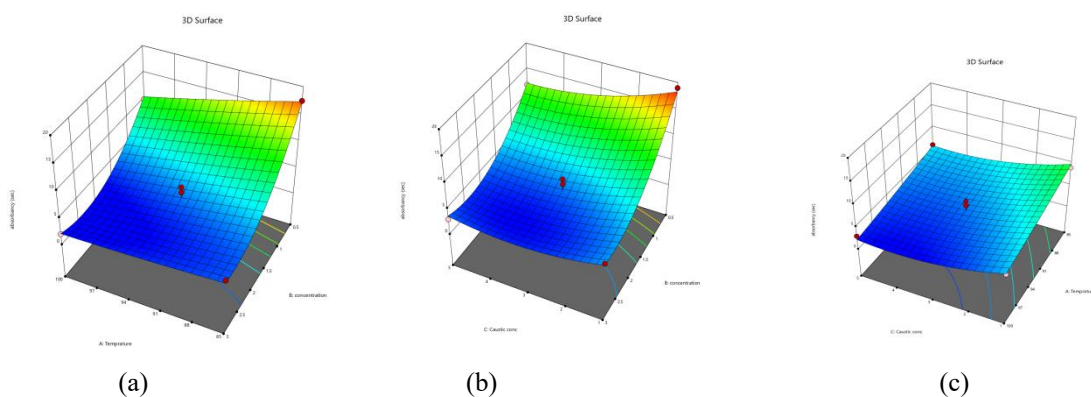
G. Combined Effect of Temp, SLs, and Caustic Concentration on Absorbency

The response surface approach was employed to investigate the individual and combined effects of the three factors on the absorbency of scoured fabric. ANOVA was used to analyse the results, and three-dimensional response surface plots illustrated the impact of experimental conditions. The basic processes of alkaline scouring in cotton include the saponification of oils and fats, the emulsification of waxes,

and the breakdown of proteins and pectins into sodium salts of smaller molecular fragments. According to the response surface analysis approach in Table 3, the SL concentration, caustic concentration, and temperature have a substantial impact on the absorbency of the scoured fabric.

As indicated in Table 2, the response surface analysis approach demonstrated that the scouring parameters have a considerable impact on the fabric's absorbency. With absolute values on the axes, Figures 5-7 display the relationships between variables in three-dimensional response surface plots. Figure 4(a) illustrates how the drop test of scoured cloth is affected by the concentration of SLs, caustic, and temperature at a fixed 45-minute interval.

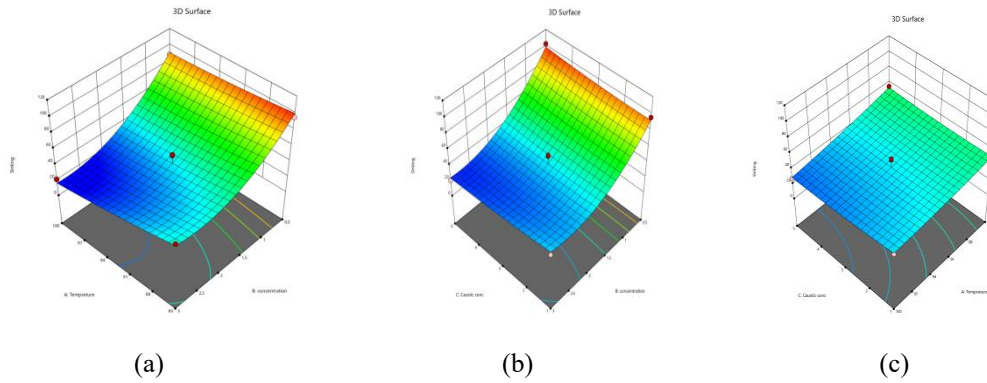
According to the study, the absorbency of the scoured fabric increases linearly with the concentration of SLs (SL), and it significantly increases as the temperature and SL concentration rise. Temperature enhances wettability, as shown in Figure 4(b), presumably due to an increased saponification rate and wax melting. Figure 4(c) shows that saponification increases absorbency, as measured by the drop test, with rising temperature and caustic concentration.



[Fig. 4: (a, b, and c) – Impact of SLs Conc by Drop Test of the Scoured Fabric]

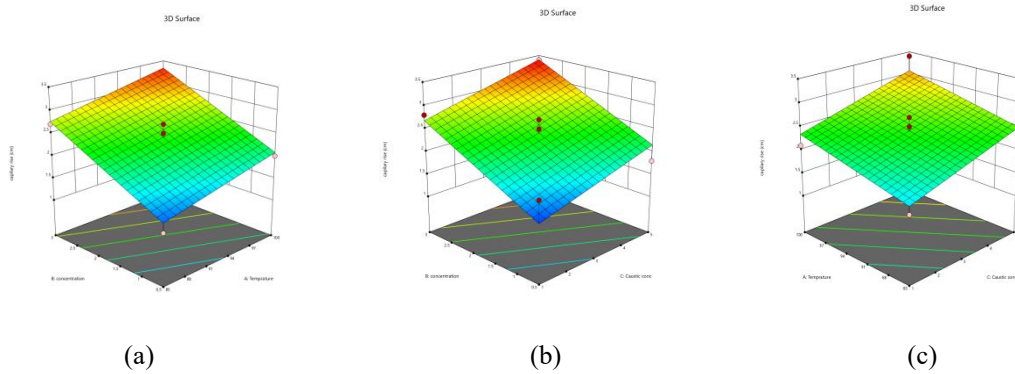
Figures 5 (a, b and c) show the impact of variables on the sinking test of scoured cotton fabric. The study reveals that the sinking of scoured fabric showed a linear improvement with an increase in SL concentration, caustic concentration, and temperature at a fixed time of 45 minutes.

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[Fig. 5: (a, b, and c) – Impact of SLs Conc on the Sinking Test of Scoured Fabric]

Figures 6A, B, and C disclose the impact of variables on the wicking of scoured cotton fabric. The Wicking of fabric increases with rising temperature, SLs concentration, caustic concentration, and temperature at a fixed time of 45 mins.



[Fig.6: (a, Band c) – Impact of Temperature and SLs Concentration on the Capillary Test]

According to the study, an optimal recipe can result in high capillary, low sinking time, and the lowest absorbency. Section 5.4.3's numerical optimization provides a highly desirable formula with precise scouring parameter values.

H. Optimization and Validation of the Model

Table 7 presents the optimisation constraints for a Box-Behnken design, detailing the goals, limits, weights, and importance of each parameter. The chart defines optimization goals for process parameters.

Table-VII: Common Constraints

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A: Temperature	minimize	85	100	1	1	3
B: SL- Concentration	minimize	0.5	3	1	1	3
C: Caustic conc	minimize	1	5	1	1	3
Absorbency	minimize	2	19	1	1	3
Sinking	minimize	20.7	102.6	1	1	3
Capillary rise	maximize	1.3	3.4	1	1	3

An optimised recipe is achieved by optimising the scouring process parameter to minimise absorbency, as measured by the drop test, sinking, and the higher wicking-capillary test, which is a crucial component of the study. A numerical optimisation method was employed to optimise the scouring variable parameter. The numerical optimization suggested the

optimal scouring conditions for good wettability were temperature 88°C, SLs concentration 2.0 %, and caustic 2.0 % As shown in Table 8, the predicted and experimental values for drop test, sinking test, and wicking loss were very close, indicating that the developed model accurately predicted the result.

Table-VIII: Predicted and Experimental Response of Numerically Optimized Recipe

Temperature	SLs concentration	Caustic conc	Absorbency (Drop Test)		Sinking		Capillary rise	
			Pred	Exp	Pred	Exp	Pred	Exp
88	2.00%	2.00%	5.1	5	41	40	2.2	2.1

Abbreviations: Pred- Predicted and Exp- Experimental

VI. PRETREATMENT AND DYEING PERFORMANCE

A. Desizing

The Desizing application, performed with conventional and SL surfactants, is compiled in Table 9. The lesser absorbency, desizing efficiency, and TEGEWA rating might be due to the low wetting properties of the SLs.

Table-IX: Comparative Results after Desizing Application of Conventional and SLs

	TEGEWA Rating	Desizing Efficiency (%)	Absorbency	Whiteness Index-CIE	Weight Loss
			(Seconds)		
Conventional Surfactant	4-5	88	12-15 sec	15.63	11.23%
SLs	4	86	20-25 sec	15.67	10.56%

B. Scouring and Bleaching

The scouring and bleaching performance of SLs against conventional scoured fabric is shown in Table 10. The capillary rise, drop test, sinking test, and weight loss of traditional surfactants are better due to their higher wetting action and detergency.

Table-X: Comparative Pretreatment Performance of Conventional and SLs

Recipe	Capillary rise	Drop test	Sinking test	Weight loss	Whiteness index
Convention surfactant-	4.4 cm	Less than 1 sec	13 sec	2.66%	64.32
SLs	3 cm	1 sec	35.6 sec	2.58%	63.18

C. Performance of Scoured and Bleached Fabric in Dyeing by Spectrophotometer

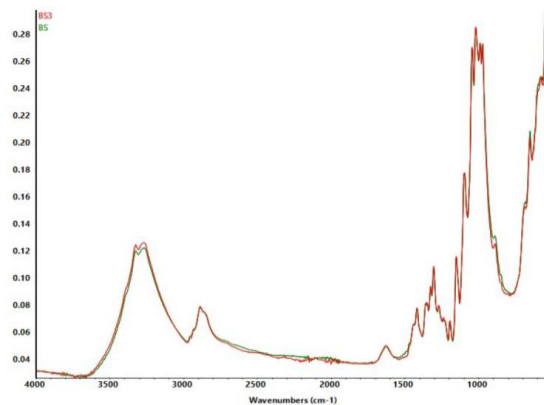
The preparation of fabric for dyeing is a crucial responsibility for textile processors; uneven pre-processing can result in uneven colouration. Considering the importance of dyeing performance, the fabric was scoured with SLs and dyed with reactive dye, and the dyeing results L*, a*, b*, and K/S were investigated, as shown in Tables 11, 12 and 13. The conventional surfactant-pretreated and dyed fabric is considered the standard, and the comparison of strength and K/S is made with the SL-pretreated, dyed sample.

i. Yellow Shade

Rosareact G Yellow HER- As shown in Table 11, the colour strength of SL-treated fabric is similar to that of conventional wetting agent-treated fabric. DE 0.28 indicates that the tonal variation falls within an acceptable range of 0.5. No structural changes were observed in either fabric on FTIR scanning.

Table-XI: Spectro Reading for Rosareact G Yellow HER 2.0% Shade

Standard	L*	a*	b*	C*	h		
G. Yellow (CBR)	44.55	59.96	0.99	59.97	0.94		
SLs surfactant – pretreated and dyed	DL*	Da*	Db*	DC*	DH*	%STR WSUM	DEcmc
	-0.36 D	0.36 R	0.64 Y	0.73 B	-0.8 R	102.84	0.28



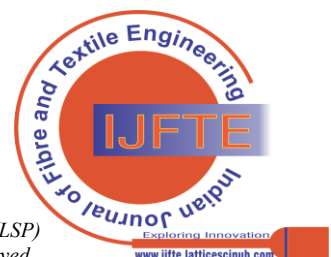
[Fig.7: FTIR of Conventional and SLs Pretreated and Dyed with Rosareact G Yellow HER]

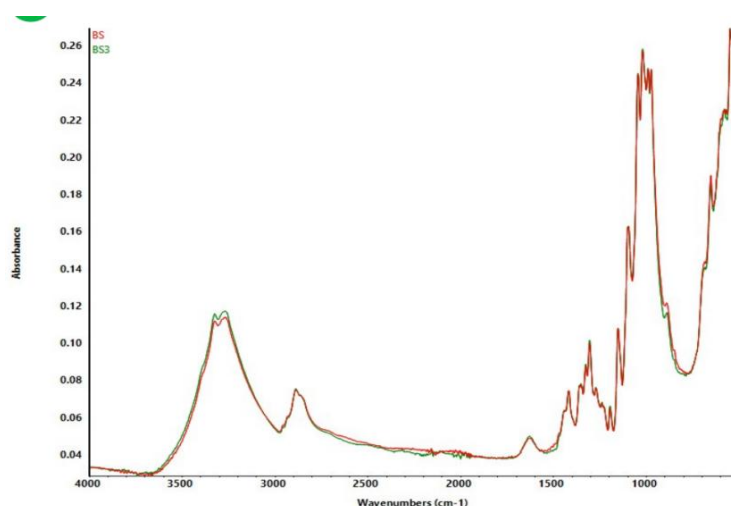
ii. Red Shade

Table-XII: Spectro Reading for Rosareact Red HE4B H/C-2.0% Shade

Standard	L*	a*	b*	C*	h		
Conventional Surfactant – pretreated and dyed	44.55	59.96	0.99	59.97	0.94		
SLs surfactant – pretreated and dyed	DL*	Da*	Db*	DC*	DH*	%STR WSUM	DE CMC
	-0.43D	0.28R	0.39 Y	0.29 B	0.39 Y	101.46	0.31

According to the data in Table 9, the colour strength of the conventional and SL samples is comparable. The tonal variation is within the acceptable range of DE -0.5. The treated fabrics' FTIR was performed to check for any changes in the functional properties of the fabric after treatment. Figure 7 shows identical peaks, indicating no structural change.





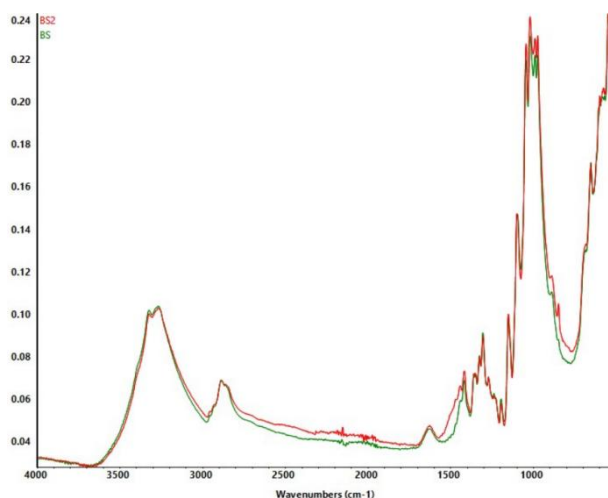
[Fig.8: FTIR of Conventional and SLs Pretreated and Dyed with Rosareact Red HE4B H/C]

iii. Blue Shade

According to the reading in Table 12, the colour strength of the conventional and SL samples is comparable. The tonal variation is within the acceptable range of DE -0.5. The treated fabrics' FTIR was performed to check for any changes in the functional properties of the fabric after treatment. Figure 8 shows identical peaks, indicating no structural change.

Table-XIII: Spectro Reading for Rosareact N Blue HE2G -2.0% Shade

Standard	L*	a*	b*	C*	h		
Conventional surfactant – pretreated and dyed	33.10	-6.26	-19.07	20.07	251.83		
SLs surfactant – pretreated and dyed	DL*	Da*	Db*	DC*	DH*	%STR WSUM	DEcmc
	-0.42 D	0.13 R	0.01	-0.05 D	0.12 R	101.27	0.55



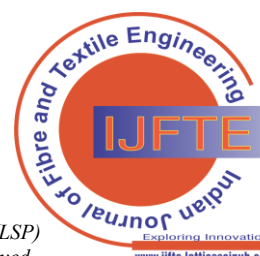
[Fig.9: FTIR of Conventional and SLs Pretreated and Dyed with Rosareact N Blue HE2G]

D. Colour Fastness Data

Dyed fabric is tested for wash fastness ISO 3. The results in Table 14 indicate that the fastness properties of conventionally treated and SL-treated dyed fabrics are similar.

Table-XIV: Colour Fastness Performance of Conventional and SL-Treated Dyed Fabric

Details	Staining on Multifibre Strip					
	Acetate	Cotton	Nylon	Polyester	Acrylic	Wool
Yellow shade - Conventionally treated	4-5	4	4-5	4-5	4-5	4-5
Yellow shade - SLs treated	4-5	4	4-5	4-5	4-5	4-5
Red shade - Conventionally treated	4-5	4	4-5	4-5	4-5	4-5
Red shade - SLs treated	4-5	4	4-5	4-5	4-5	4-5
Blue shade - Conventionally treated	4-5	4	4-5	4-5	4-5	4-5
Blue shade - SLs treated	4-5	4	4-5	4-5	4-5	4-5





[Fig.10: Picture of Reactive Dyed Fabric]

VII. CONCLUSION

The pretreatment performance, in terms of wettability, weight loss, and whiteness, improved after SL scouring. The SLs concentration, caustic concentration, and temperature process parameters were optimized using the response surface approach. Regarding pretreatment, comparisons against conventional dyeing effectiveness yield identical outcomes. This study demonstrated that SLs are an effective and environmentally friendly alternative to petroleum-based synthetic surfactants. SLs, a subtype of glycolipid biosurfactants, have shown significant potential as an environmentally benign alternative to conventional synthetic surfactants due to their natural, biodegradable, and low-toxicity properties. SLs showed improved emulsifying, wetting, and foaming properties, which are critical in textile processing. By proposing the substitution of SLs for synthetic surfactants, this study promotes a shift toward sustainable practices in the production of textiles and beyond.

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