Studies on Degumming Eri Silk Cocoons Cultivated in Ethiopia

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ABSTRACT

Background: Eri silk (Samia ricini) is a valuable non-mulberry silk with growing potential for sustainable textile production. Effective degumming is essential for removing sericin and other non-fibrous constituents while maintaining the desirable properties of the silk fibre. However, information on suitable degumming conditions for Eri silk cultivated in Ethiopia remains limited.

Objective: This study investigated the effects of sodium carbonate (Na_2CO_3) concentration, neutral soap concentration, and boiling duration on the degumming loss of Ethiopian Eri silk, focusing on Borduar white and Kokrajhar brick-red cocoon types.

Methods: A three-factor, three-level response surface design based on the Box–Behnken approach was employed. Na_2CO_3 concentration, neutral soap concentration, and boiling duration were varied within the ranges of 10–20%, 10–20%, and 0.5–1.5 h, respectively. Degumming loss was determined from the mass loss following treatment. The experimental data were analyzed using Design-Expert 13 through analysis of variance (ANOVA), regression modeling, response surface analysis, and residual diagnostics.

Results: The linear models were statistically significant for both Borduar white ($p=0.0033$) and Kokrajhar brick-red ($p=0.0034$). Na_2CO_3 concentration was the most influential factor, followed by boiling duration, whereas neutral soap concentration had no significant linear effect. The models explained approximately 64.0% and 63.7% of the variation in degumming loss for Borduar white and Kokrajhar brick-red, respectively. The predicted responses showed close agreement with the experimental results, with mean absolute errors of approximately 0.28 percentage points for both cocoon types. Kokrajhar brick-red exhibited consistently higher degumming loss than Borduar white, with predicted center-point values of 13.72% and 10.71%, respectively.

Conclusion: Na_2CO_3 concentration and boiling duration are the principal processing variables governing degumming loss of the investigated Ethiopian Eri silk cocoons. The findings provide a quantitative basis for optimizing Eri silk degumming, while further studies incorporating residual sericin and fibre-quality properties are recommended.

Keywords: Eri silk; Samia ricini; degumming; sodium carbonate; neutral soap; response surface methodology; Box–Behnken design; Ethiopia.

Introduction

Eri silk (*Samia ricini*), widely known as "Ahimsa" or peace silk, is an important non-mulberry silk with growing potential for sustainable textile and biomaterial applications. The silk fibroin of *S. ricini* has attracted considerable interest because of its favourable biological and functional characteristics, including biocompatibility and potential for biomedical applications (Pal *et al.*, 2013). Unlike conventional mulberry silk, which is generally obtained by reeling continuous filaments from intact cocoons, Eri silk is produced from open-ended cocoons. This allows the adult moth to emerge naturally before the silk is harvested and is the principal basis for its designation as "Ahimsa" or peace silk (Sangannavar *et al.*, 2023; Central Silk Board, n.d.). Eri silk is also recognized for properties such as softness, breathability, heat retention and biodegradability, which contribute to its potential for eco-friendly textile applications (Rajan *et al.*, 2026).

Eri silk is produced primarily by the domesticated Eri silkworm *Samia ricini* (also reported in the literature as *Samia cynthia ricini*). The species is traditionally associated with several host plants, among which castor (*Ricinus communis* L.) is particularly important. Research conducted in southwest Ethiopia has demonstrated the suitability of different castor genotypes for Eri silkworm rearing and has confirmed the importance of host-plant characteristics in determining silkworm and cocoon performance (Tulu *et al.*, 2022). Eri silkworm culture is traditionally concentrated in northeastern India and neighbouring regions, where several ecoraces have been maintained. Among these, **Borduar and Kokrajhar** are recognized Eri ecoraces, and comparative studies have demonstrated differences in their rearing and economic characteristics (Bora *et al.*, 2024). Differences between white and brick-red Eri silk have also been reported in terms of fibre diameter, tensile properties, thermal behaviour, crystallinity, surface characteristics and weight loss after treatment, indicating that cocoon type can influence subsequent fibre-processing behaviour (Brahma, Kalita and Baruah, 2025).

The production of high-quality Eri silk requires appropriate post-cocoon processing. Because Eri cocoons are open-ended and contain discontinuous silk fibres, the material is generally processed through operations such as degumming, opening, carding and spinning rather than conventional filament reeling. The raw silk fibre consists principally of fibroin surrounded and bound by sericin, together with smaller quantities of other non-fibrous constituents. Sericin is a hydrophilic protein that surrounds the fibroin and contributes substantially to the characteristics of the raw silk. Consequently, controlled removal of sericin is an essential step in producing cleaner, softer and more processable silk fibres. Studies of Ethiopian Eri silk have demonstrated significant differences in its physical, mechanical, structural and thermal properties, emphasizing the importance of appropriate processing conditions for fibre utilization (Melesse, Atalie and Koyrita, 2020).

Degumming involves the removal of sericin and associated non-fibrous substances through chemical, enzymatic or physical treatments. Among conventional chemical methods, alkaline degumming using sodium carbonate is widely used because of its effectiveness and relative simplicity. Neutral soap may be incorporated into the degumming bath to assist wetting and the removal of solubilized non-fibrous substances. However, the severity of degumming must be carefully controlled because excessive alkaline concentration and prolonged thermal treatment can increase weight loss and adversely affect the mechanical properties of silk fibroin. Recent research on Ethiopian Eri silk has shown that sodium-carbonate treatment can effectively remove sericin but may also alter fibre structure, whereas enzymatic treatment can provide effective sericin removal with less structural disturbance (Rajan *et al.*, 2026).

An important earlier investigation specifically addressed the optimization of Eri silk degumming using response surface methodology. Chattopadhyay, Chakraborty and Chatterjee (2017) investigated three concentrations of sodium carbonate and neutral soap together with three boiling durations using a **Box–Behnken experimental design**. Their results showed that degumming loss increased with increasing sodium carbonate concentration and boiling duration for both white and brick-red Eri cocoons, whereas neutral soap concentration had no significant effect on degumming loss or single-fibre tensile characteristics. The authors reported that approximately 10% sodium carbonate, 10% neutral soap and 1 h of boiling provided relatively uniform degumming under their experimental conditions. These findings provide an important methodological basis for investigating the influence of the same principal processing variables under Ethiopian production conditions.

More recently, research specifically addressing Ethiopian Eri silk has further demonstrated the importance of degumming conditions in determining fibre quality. Rajan *et al.* (2026) investigated alkaline, enzymatic and hot-water degumming treatments using Eri silk cocoons obtained from Addis Ababa, Arba Minch and Hawassa. The study evaluated the resulting fibres using scanning electron microscopy, Fourier-transform infrared spectroscopy, differential scanning calorimetry and mechanical testing. The authors reported that degumming treatment substantially influenced sericin removal, fibre surface morphology and mechanical characteristics, and identified enzymatic treatment as a promising approach for maintaining fibre structure while achieving effective sericin removal (Rajan *et al.*, 2026).

Eri sericulture is also emerging as an opportunity for diversification of Ethiopia's natural-fibre and textile sector. Research on Eri silkworm rearing in Ethiopia has demonstrated the feasibility of utilizing locally available host plants and has generated information on silkworm and cocoon performance under Ethiopian conditions (Tulu *et al.*, 2022). In parallel, characterization studies have demonstrated that Ethiopian Eri silk possesses distinct physical, mechanical and thermal characteristics and therefore has potential for value-added textile and other applications (Melesse, Atalie and Koyrita, 2020). The development of Eri sericulture and silk processing in Ethiopia consequently creates a need for locally generated scientific information on cocoon characteristics and suitable post-cocoon processing technologies.

Despite these developments, systematic information on the response of Eri cocoons cultivated in Ethiopia to controlled combinations of **alkaline concentration, neutral soap concentration and thermal treatment duration** remains limited. Differences in ecorace, cocoon characteristics, host plant, rearing environment and production conditions may influence the response of the cocoon material to degumming. Furthermore, although previous research has established the importance of sodium carbonate concentration and boiling duration in Eri silk degumming (Chattopadhyay, Chakraborty and Chatterjee, 2017), the applicability of those conditions to Eri cocoons cultivated under Ethiopian conditions requires experimental verification. This need is particularly relevant given the recent expansion of Ethiopian Eri sericulture and the demonstrated variation in the characteristics of

Eri silk produced in different Ethiopian locations (Melesse, Atalie and Koyrita, 2020; Rajan *et al.*, 2026).

Therefore, the present study was undertaken to investigate the effects of selected degumming variables on Eri silk cocoons cultivated in Ethiopia and processed at the **Ethiopian Institute of Textile and Fashion Technology (EiTEX) fibre laboratory**. The study focuses on three important process variables—**sodium carbonate concentration, neutral soap concentration and boiling duration**—and evaluates their effects on degumming loss of selected Eri cocoon types, including **Borduar white and Kokrajhar brick-red**. Response surface methodology based on a three-factor, three-level **Box–Behnken design** was employed to systematically evaluate the effects of the processing variables within the selected experimental domain. The findings are intended to provide an experimental basis for establishing suitable degumming conditions for Ethiopian Eri silk and to contribute to improved fibre processing, value addition and sustainable development of Eri silk production in Ethiopia.

Materials and Methods

Eri silk cocoons

The Eri silk cocoons used in this study were obtained from Eri silkworms (*Samia ricini*) cultivated in Ethiopia. The cocoons were reared and harvested under the Eri sericulture activities associated with the Ethiopian Institute of Textile and Fashion Technology (EiTEX), Bahir Dar University, Ethiopia (Figure 1). The selected cocoons represented the Eri ecoraces cultivated under the Ethiopian rearing conditions and included white and brick-red cocoon types.

Figure 1 Castor plant farm (part of Eri sericulture activities) found in the Selam campus of Ethiopian Institute of Textile and Fashion Technology (EiTEX): Bahir Dar University

The principal cocoon types investigated in the present study were the **Borduar white** and **Kokrajhar brick-red** types. The characteristic appearance of the two cocoon types is presented in Figure 2. The cocoons were carefully harvested after completion of the cocooning stage and sorted to remove damaged, contaminated, or abnormal cocoons. The samples were subsequently transported to the EiTEX Fibre Laboratory for degumming experiments.

(a) (b)

Figure 2 Eri silk cocoon types used in the study: (a) Borduar white and (b) Kokrajhar brick-red.

Before degumming, visible foreign matter and adhering impurities were removed manually. The cocoons were prepared under identical laboratory conditions to minimize variation arising from sample preparation.

Chemicals and reagents

Analytical/laboratory-grade **sodium carbonate (Na_2CO_3)** was used as the principal alkaline degumming agent. A **neutral soap** was used as the auxiliary washing and degumming agent. Distilled water was used for preparation of the degumming solutions and subsequent washing of the treated cocoons.

The concentrations of sodium carbonate and neutral soap were selected as experimental factors according to the response surface experimental design described below. The concentrations were expressed as percentages based on the mass of the cocoon material and/or liquor formulation used in the experiment, and the same basis was maintained throughout all experimental runs.

Experimental design

The degumming experiments were designed using **Response Surface Methodology (RSM)** with a three-factor, three-level **Box–Behnken design** originally proposed by Box and Behnken [8]. The design was selected because it permits estimation of the main effects, two-factor interactions, and quadratic effects of the process variables while requiring fewer experimental runs than a full three-level factorial design.

Three independent variables were considered:

X_1: sodium carbonate concentration (%)
X_2: neutral soap concentration (%)
X_3: boiling duration (h)

Table 1 Independent variables and experimental levels used in the Box–Behnken design.

Factor	Independent variable	−1	0	1
X_1	Sodium carbonate concentration (%)	20	10	0
X_2	Neutral soap concentration (%)	20	10	0
X_3	Boiling duration (h)	1.5	1.0	0.5

Degumming procedure

A measured quantity of Eri silk cocoons was used for each experimental run. The required quantity of sodium carbonate and neutral soap was calculated according to the treatment conditions specified by the experimental design. The chemicals were dissolved in the required quantity of distilled water to prepare the degumming liquor.

The cocoon samples were immersed in the prepared degumming bath and heated to boiling under controlled laboratory conditions. The treatment was maintained for the specified duration corresponding to the experimental run. The combination of sodium carbonate concentration, neutral soap concentration, and boiling duration was varied according to the Box–Behnken design.

At the end of the specified boiling period, the treated cocoons were removed from the degumming bath and thoroughly washed with warm distilled water to remove dissolved sericin, residual chemicals, and other soluble impurities. A subsequent cold-water washing was carried out to remove remaining alkali and soap. The washed material was then dried under controlled laboratory conditions until a constant or stable mass was obtained.

The same material-to-liquor ratio, washing procedure, heating conditions, and drying procedure were maintained for all experimental runs unless otherwise specified by the experimental design.

Determination of degumming loss

The effectiveness of degumming was evaluated primarily in terms of degumming loss, which represents the percentage reduction in mass of the cocoon material resulting from the removal of sericin and other non-fibrous substances during degumming.

The initial dry mass of the sample before degumming (W_1) and the dry mass after degumming and washing (W_2) were determined using a laboratory balance. Degumming loss was calculated using Equation (1):

$$\text{Degumming loss (\%)} = \frac{W_1 - W_2}{W_1} \times 100; \ldots(1)$$

Where:

W_1 = dry mass of the sample before degumming (g), and

W_2 = dry mass of the sample after degumming (g)

A higher degumming loss generally indicates greater removal of sericin and associated non-fibrous substances; however, excessive weight loss may also indicate undesirable degradation or loss of fibroin. Therefore, degumming loss was interpreted together with the relevant fibre-quality characteristics.

Experimental reproducibility

All experimental procedures were conducted using standardized laboratory protocols. The same procedure for sample preparation, chemical preparation, degumming, washing, and drying was followed for all treatment combinations.

Replicate measurements/experimental runs were used where applicable to improve the reliability of the experimental results. The mean values and corresponding variability were used for subsequent statistical analysis.

Degumming Loss of **Borduar white Eri Silk Variety**

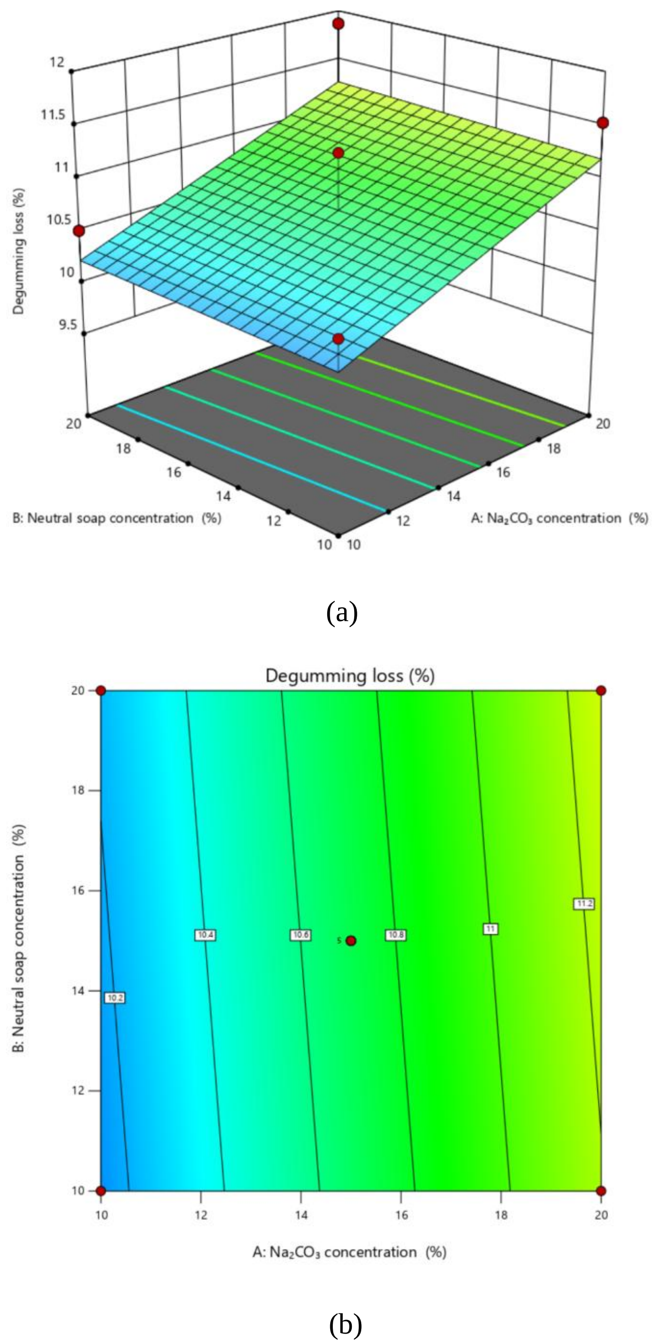

Figure 3 Three-dimensional response surface (a) and corresponding contour plot (b): Effect of sodium carbonate and neutral soap concentrations on degumming loss

Table 2 Analysis of Variance (ANOVA): Factors affecting Degumming Loss; Borduar white Eri silk

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	3.37	3	1.12	7.71	0.0033	significant
A-Na_2CO_3 concentration	2.2	1	2.2	15.13	0.0019	
B-Neutral soap concentration	0.0128	1	0.0128	0.0878	0.7716	
C-Boiling duration	1.16	1	1.16	7.93	0.0146	
Residual	1.89	13	0.1457			
Lack of Fit	1.49	9	0.1659	1.65	0.3313	not significant
Pure Error	0.4017	4	0.1004			
Cor Total	5.27	16				

Effect of sodium carbonate and neutral soap concentrations on degumming loss of Borduar white Eri silk

The three-dimensional response surface and corresponding contour plot (Figure 3) illustrate the effects of sodium carbonate and neutral soap concentrations on the degumming loss of Borduar white Eri silk at a constant boiling duration of 1.0 h. The response surface exhibited a predominantly planar and increasing trend, with the predicted degumming loss increasing from approximately 10.2% in the lower concentration region to approximately 11.2% toward the higher sodium carbonate concentration region. The relatively pronounced gradient in the sodium carbonate direction compared with the neutral soap direction indicates that sodium carbonate concentration was the dominant factor affecting degumming loss within the investigated experimental region.

The ANOVA results (Table 2) confirmed the graphical observation. Sodium carbonate concentration exhibited a highly significant effect on degumming loss ($F = 15.13$, $p = 0.0019$), with the largest sum of squares among the investigated factors (SS = 2.20). The positive effect of sodium carbonate can be attributed to

its alkaline action, which promotes the swelling and solubilization of sericin and facilitates the removal of sericin and other non-fibrous constituents from the raw Eri silk. The positive regression coefficient for sodium carbonate (+0.525 in coded units) further indicates that increasing its concentration from 10 to 20% was associated with an estimated increase of approximately 1.05 percentage points in degumming loss, with the other factors held constant.

In contrast, neutral soap concentration did not have a statistically significant effect on degumming loss ($F = 0.0878$, $p = 0.7716$). Its very small regression coefficient (+0.040) corresponds to an estimated change of only approximately 0.08 percentage points when the concentration is increased from 10 to 20%. Although neutral soap may contribute to wetting, penetration, emulsification, and removal of solubilized impurities during degumming, its concentration within the investigated range did not significantly affect the measured mass loss of the Borduar white Eri silk.

Boiling duration exhibited a statistically significant positive effect on degumming loss ($F = 7.93$, $p = 0.0146$), with a regression coefficient of +0.380. The model therefore predicts an increase of approximately 0.76 percentage points in degumming loss when the boiling duration is increased from 0.5 to 1.5 h, with the chemical concentrations held constant. The effect of boiling duration is not directly represented in the A–B response surface because the latter was generated at the center level of boiling duration (1.0 h); therefore, its interaction with sodium carbonate concentration is examined separately using the corresponding A–C response surface.

The fitted linear model was statistically significant (F = 7.71, p = 0.0033), while the lack-of-fit test was not significant (F = 1.65, p = 0.3313), indicating no statistically significant evidence of model inadequacy relative to the experimental error. The model explained approximately 64.0% of the variation in degumming loss (R^2=0.6403). Overall, the results indicate that sodium carbonate concentration was the principal factor affecting degumming loss of Borduar white Eri silk, followed by boiling duration, whereas neutral soap concentration had a comparatively negligible linear effect within the investigated range.

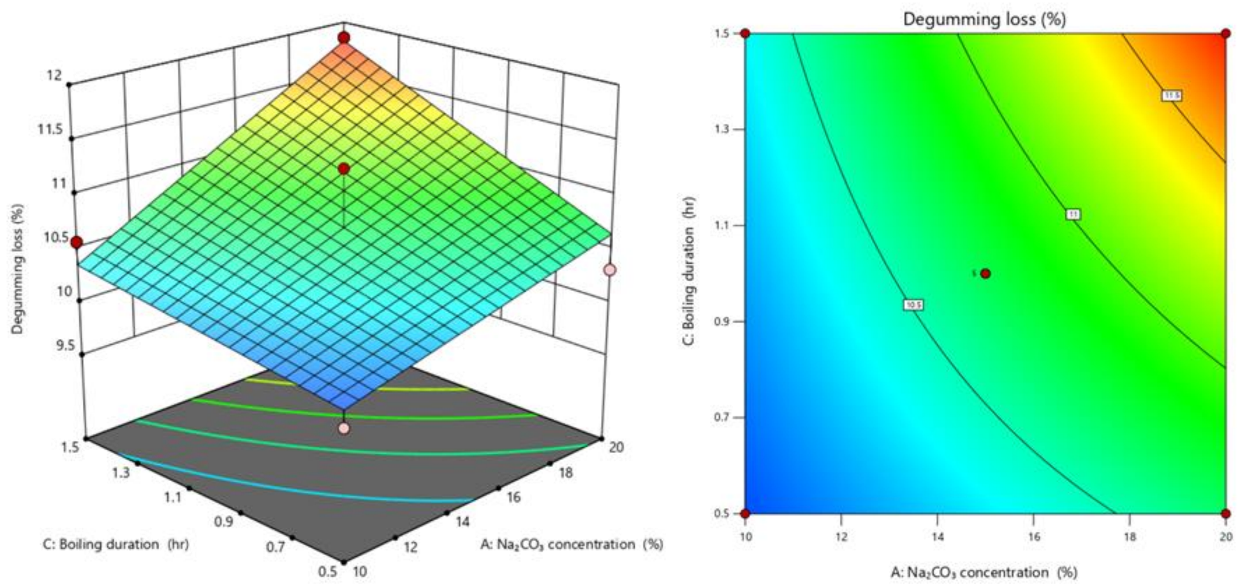

Figure 4 Three-dimensional response surface and corresponding contour plot: Effect of sodium carbonate concentration and boiling duration on degumming loss

Effect of sodium carbonate concentration and boiling duration on degumming loss of Borduar white Eri silk

The three-dimensional response surface and corresponding contour plot illustrate the effects of sodium carbonate concentration and boiling duration on the degumming loss of Borduar white Eri silk at a constant neutral soap concentration of 15% (Figure 4). The response surface exhibited a clear positive trend with both sodium carbonate concentration and boiling duration. The predicted degumming loss increased from approximately 10% at the lower levels of the two factors to approximately 11.6–11.8% toward the region of high sodium carbonate concentration and prolonged boiling duration.

The positive response to sodium carbonate concentration is consistent with its alkaline action, which facilitates the swelling, solubilization, and removal of sericin and other non-fibrous constituents associated with the raw Eri silk. The increase in degumming loss with boiling duration indicates that prolonged thermal exposure enhances the effectiveness of the degumming treatment, presumably by increasing the time available for penetration of the degumming liquor and alkaline action on the sericin layer.

The graphical observations are consistent with the ANOVA results, which identified both sodium carbonate concentration ($F = 15.13$, $p = 0.0019$) and boiling duration ($F = 7.93$, $p = 0.0146$) as statistically significant linear factors affecting degumming loss. The corresponding regression coefficients were positive (+0.525 and +0.380, respectively), confirming that increasing either factor increased the predicted response within the investigated experimental domain. Based on the coded regression model, increasing sodium carbonate concentration from 10 to 20% was associated with an estimated increase of 1.05 percentage points in degumming loss, whereas increasing boiling duration from 0.5 to 1.5 h was associated with an estimated increase of 0.76 percentage points, with the remaining factor held constant.

The contour plot showed increasing response levels toward the combined high-concentration and long-duration region. Although some curvature of the contour lines was apparent, statistical significance of a possible sodium carbonate concentration × boiling duration interaction cannot be established from the graphical representation alone. Nevertheless, the response surface clearly demonstrates that the two statistically significant factors acted in the same positive direction. The results indicate that sodium carbonate concentration and boiling duration were important processing variables controlling the extent of degumming of the Borduar white Eri silk sample.

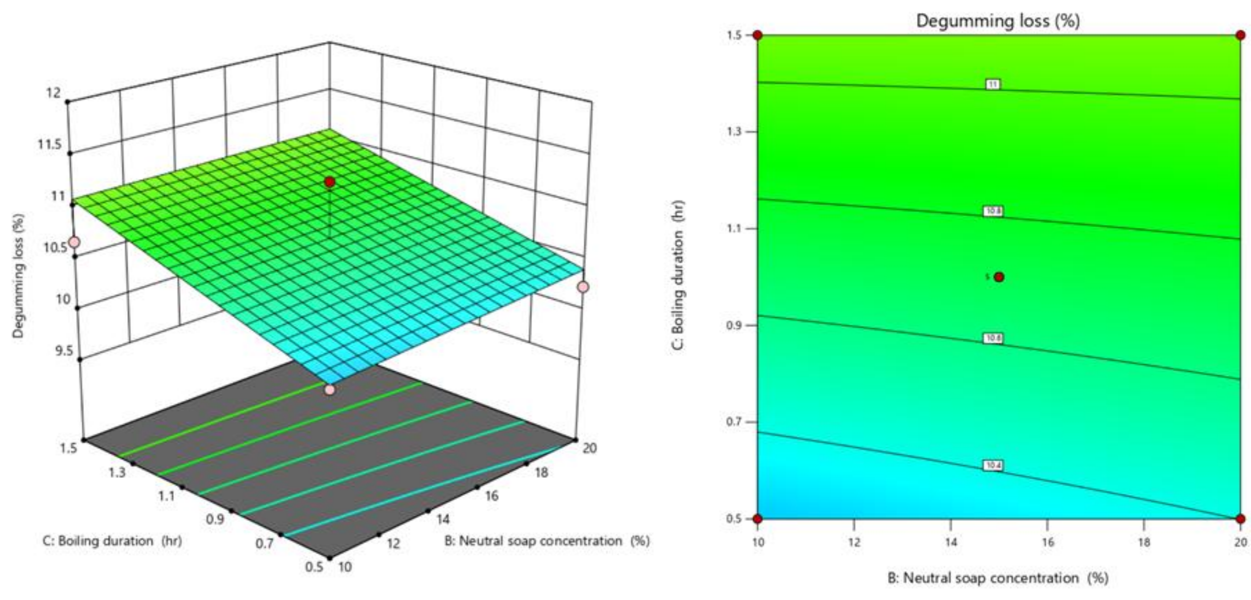

Figure 5 Three-dimensional response surface and corresponding contour plot: Effect neutral soap concentration and boiling duration

Effect of neutral soap concentration and boiling duration on degumming loss of Borduar white Eri silk

The response surface and contour plots demonstrated that boiling duration exerted a substantially greater influence on degumming loss than neutral soap concentration. Increasing the boiling duration from 0.5 to 1.5 h resulted in a progressive increase in predicted degumming loss, as indicated by the upward-sloping response surface and the displacement of the contour levels toward higher response values. This observation was confirmed by ANOVA, where boiling duration exhibited a statistically significant effect ($F=7.34$, $p=0.0190$). In contrast, neutral soap concentration had no significant effect on degumming loss within the investigated range of 10–20% ($F=0.0813$, $p=0.7804$). The very small sum of squares associated with neutral soap concentration (0.0128) further indicates its comparatively minor contribution to the variation in degumming loss. The interaction between neutral soap concentration and boiling duration was also statistically insignificant (F=0.0311, p=0.8629), indicating that the effect of boiling duration was essentially independent of neutral soap concentration within the experimental domain. The reduced 2FI model was statistically significant (F=5.36, p=0.0103), while its lack of fit was non-significant (F=1.85, p=0.2887), demonstrating adequate model fit to the experimental data. Overall, the results indicate that **thermal treatment duration, rather than neutral soap concentration, was the principal factor controlling degumming loss in this factor combination for Borduar white Eri silk**. The observed trend is consistent with previous research on Eri silk, which reported increasing degumming loss with increasing boiling duration but no significant effect of neutral soap concentration (Chattopadhyay, Chakraborty and Chatterjee, 2017).

Degumming Loss of **Kokrajhar brick-red Eri Silk Variety**

Effect of sodium carbonate and neutral soap concentrations on degumming loss of Kokrajhar brick-red Eri silk

The three-dimensional response surface and corresponding contour plot illustrate the effects of sodium carbonate concentration and neutral soap concentration on the degumming loss of Kokrajhar brick-red Eri silk at a constant boiling duration of 1.0 h. The response surface exhibited a predominantly planar increasing trend, with the predicted degumming loss increasing from approximately 13.2% in the lower sodium carbonate concentration region to approximately 14.2% at higher sodium carbonate concentrations. The relatively steep gradient in the sodium carbonate direction compared with the neutral soap direction indicates that sodium carbonate concentration was the dominant factor affecting degumming loss within the investigated experimental region.

The ANOVA results confirmed this graphical observation. Sodium carbonate concentration had a highly significant effect on degumming loss (F = 15.01, p = 0.0019), with the largest sum of squares among the three investigated factors (SS = 2.24).

Table 3 Analysis of Variance (ANOVA): Factors affecting Degumming Loss; Kokrajhar brick-red Eri Silk

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	3.41	4	0.8537	5.3	0.0108	significant
A-Na_2CO_3 concentration	2.24	1	2.24	13.89	0.0029	
B-Neutral soap concentration	0.0113	1	0.0113	0.0699	0.796	
C-Boiling duration	1.16	1	1.16	7.22	0.0198	
BC	0.0042	1	0.0042	0.0262	0.874	
Residual	1.93	12	0.161			
Lack of Fit	1.51	8	0.1891	1.8	0.298	not significant
Pure Error	0.4195	4	0.1049			
Core Total	5.35	16				

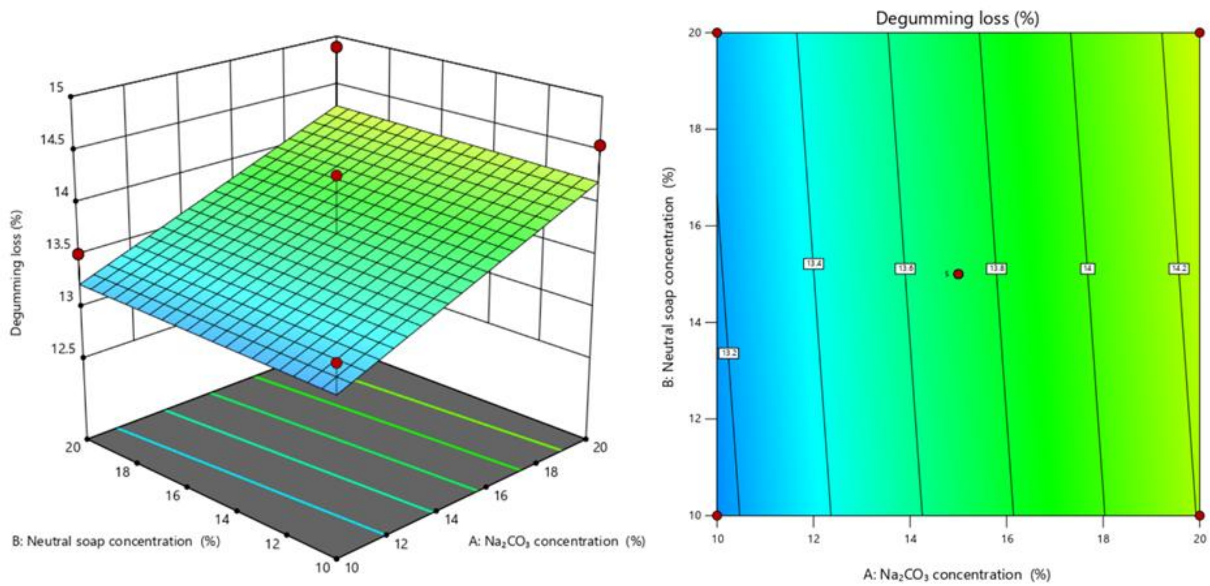

Figure 6 Three-dimensional response surface and corresponding contour plot: Effect of sodium carbonate and neutral soap concentrations on degumming loss

The positive response to increasing Na_2CO_3 concentration can be attributed to its alkaline action, which promotes swelling and solubilization of sericin and facilitates the removal of non-fibrous constituents from the Eri silk cocoon. In contrast, neutral soap concentration did not have a statistically significant effect on degumming loss (F = 0.0755, p = 0.7878). The very small sum of squares associated with neutral soap concentration (SS = 0.0113) indicates that its variation contributed negligibly to the observed response within the investigated range.

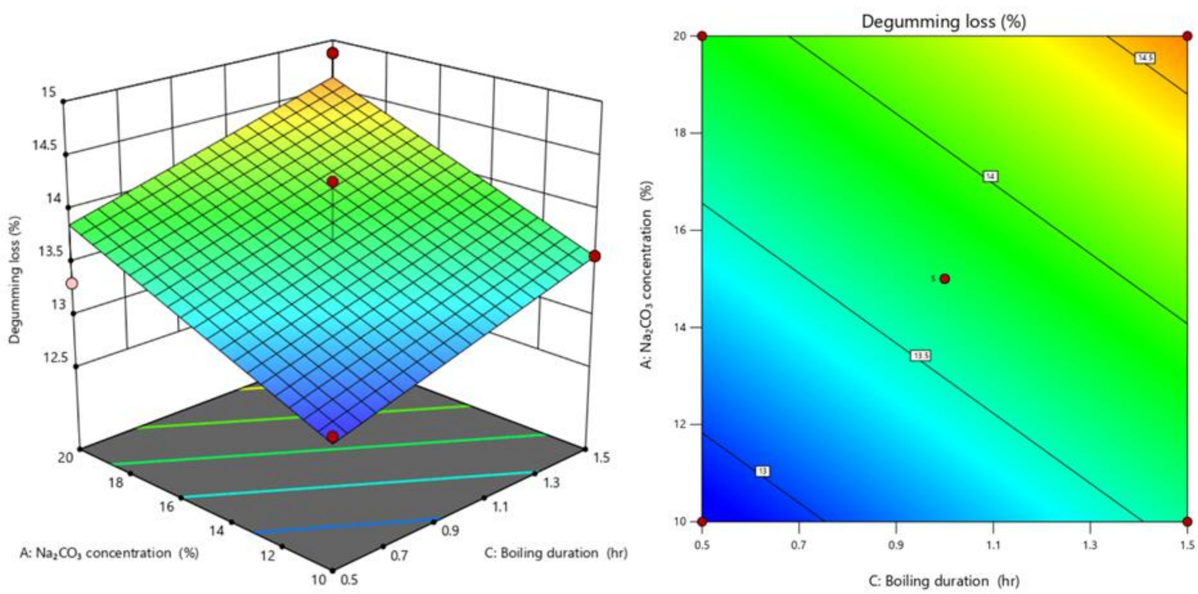

Figure 7 Three-dimensional response surface and corresponding contour plot: Effect of sodium carbonate and boiling duration on degumming loss

Effect of sodium carbonate concentration and boiling duration on degumming loss of Kokrajhar brick-red Eri silk

The three-dimensional response surface and corresponding contour plot illustrate the effects of sodium carbonate concentration and boiling duration on the degumming loss of Kokrajhar brick-red Eri silk at a constant neutral soap concentration of 15%. The response surface exhibited a clear positive trend with both sodium carbonate concentration and boiling duration. The predicted degumming loss increased from approximately 13.0% at the lower levels of the two factors to approximately 14.5% toward the region of higher sodium carbonate concentration and longer boiling duration.

The increase in degumming loss with sodium carbonate concentration is attributable to the enhanced alkaline action of Na_2CO_3, which promotes swelling, solubilization, and removal of sericin and other non-fibrous constituents from the cocoon. The response also increased with boiling duration, indicating that prolonged thermal exposure enhanced the extent of degumming, presumably by providing additional time for penetration of the degumming liquor and alkaline action on the sericin layer.

The graphical observations were consistent with the ANOVA results, which showed that sodium carbonate concentration had a highly significant effect on degumming loss ($F = 15.01$, $p = 0.0019$), while boiling duration also exerted a significant effect ($F = 7.81$, $p = 0.0152$). The larger F-value and sum of squares for sodium carbonate concentration ($SS = 2.24$) compared with boiling duration ($SS = 1.16$) indicate that sodium carbonate concentration was the more influential of the two factors. The response increased toward the combined high-concentration/high-duration region, demonstrating that the two significant factors acted in the same positive direction.

Some curvature was apparent in the contour lines; however, the statistical significance of a possible sodium carbonate × boiling duration interaction cannot be established from the response surface alone. The corresponding interaction term would need to be evaluated using an appropriate interaction or quadratic model. Overall, the response surface confirms that sodium carbonate concentration and boiling duration were important processing variables governing degumming loss of the Kokrajhar brick-red Eri silk sample.

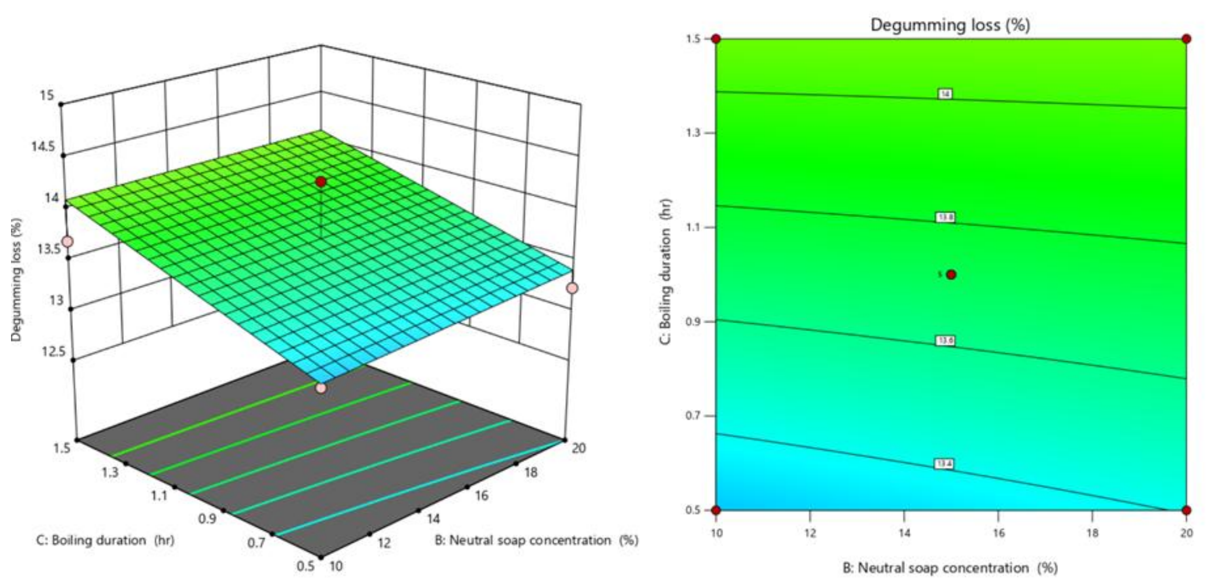

Figure 8 Three-dimensional response surface and corresponding contour plot: Effect of neutral soap concentrations and boiling duration on degumming loss

Effect of neutral soap concentration and boiling duration on degumming loss of Kokrajhar brick-red Eri silk

The three-dimensional response surface and corresponding contour plot illustrate the effects of neutral soap concentration and boiling duration on the degumming loss of Kokrajhar brick-red Eri silk at a constant sodium carbonate concentration of 15%. The response surface exhibited a predominantly planar trend, with degumming loss increasing primarily with boiling duration, whereas variation in neutral soap concentration produced only a minor change in the response. The predicted degumming loss increased from approximately 13.3% at the lower boiling duration to approximately 14.0% at the higher boiling duration.

The graphical observation was consistent with the ANOVA results. Boiling duration had a statistically significant effect on degumming loss ($F = 7.81$, $p = 0.0152$), whereas neutral soap concentration was not statistically significant ($F = 0.0755$, $p = 0.7878$). The very small sum of squares associated with neutral soap concentration ($SS = 0.0113$) further indicates that variation in soap concentration contributed negligibly to the observed response within the investigated range. The increasing response with boiling duration is attributable to the longer exposure of the cocoon material to the alkaline degumming liquor, facilitating the removal of sericin and other non-fibrous constituents.

The contour lines were approximately horizontal and relatively regular, indicating that the response was considerably more sensitive to boiling duration than to neutral soap concentration. No pronounced interaction between the two factors was visually apparent from the response surface. Overall, the B–C response surface confirms the dominant role of boiling duration and the comparatively minor contribution of neutral soap concentration to degumming loss of the Kokrajhar brick-red Eri silk sample.

Regression prediction of degumming loss

The fitted linear regression models quantified the influence of the three degumming variables on the two Eri silk cocoon types. For Borduar white, the predicted degumming loss was expressed in terms of coded factors as:

$$Y=10.7100+0.5250A+0.0400B+0.3800C,$$

Whereas for Kokrajhar brick-red it was:

$$Y=13.7200+0.5288A+0.0375B+0.3812C.$$

In both varieties, Na_2CO_3 concentration had the largest positive coefficient, followed by boiling duration, while the coefficient for neutral soap concentration was very small. This ranking was consistent with the ANOVA results and response-surface analyses. At the center point of the experimental region (15% Na_2CO_3, 15% neutral soap and 1.0 h boiling), the predicted degumming losses were 10.71% for Borduar white and 13.72% for Kokrajhar brick-red. The corresponding difference of approximately 3.01 percentage points was maintained across the experimental region because the estimated main-effect coefficients were remarkably similar between the two cocoon types. These results suggest that the two Eri silk types have comparable sensitivity to the investigated processing variables but differ substantially in their baseline degumming response.

Actual versus predicted degumming loss

Run	A Na_2CO_3 (%)	B Soap (%)	C Time (h)	Borduar Actual (%)	Borduar Predicted (%)	Residual	Kokrajhar Actual (%)	Kokrajhar Predicted (%)	Residual
1	10	15	1.5	10.57	10.565	0.005	13.57	13.572	−0.002
2	15	15	1	10.52	10.71	−0.190	13.52	13.72	−0.200

3	15	15	1	10.54	10.71	−0.170	13.54	13.72	−0.180
4	15	15	1	11.25	10.71	0.54	14.27	13.72	0.55
5	10	10	1	10.43	10.145	0.285	13.43	13.154	0.276
6	20	10	1	11.53	11.195	0.335	14.55	14.211	0.339
7	15	15	1	10.57	10.71	−0.140	13.58	13.72	−0.140
8	15	20	1.5	10.55	11.13	−0.580	13.56	14.139	−0.579
9	20	15	1.5	11.85	11.615	0.235	14.87	14.63	0.24
10	15	10	1.5	10.67	11.05	−0.380	13.69	14.064	−0.374
11	20	15	0.5	10.31	10.855	−0.545	13.31	13.868	−0.558
12	15	15	1	10.54	10.71	−0.170	13.55	13.72	−0.170
13	15	10	0.5	10.21	10.29	−0.080	13.23	13.301	−0.071
14	20	20	1	11.87	11.275	0.595	14.89	14.286	0.604
15	15	20	0.5	10.23	10.37	−0.140	13.23	13.376	−0.146
16	10	20	1	10.51	10.225	0.285	13.52	13.229	0.291
17	10	15	0.5	9.85	9.805	0.045	12.87	12.81	0.06

Conclusion

This study investigated the effect of sodium carbonate concentration, neutral soap concentration, and boiling duration on the degumming loss of Eri silk cocoons cultivated in

Ethiopia, with particular consideration of the **Borduar white** and **Kokrajhar brick-red** Eri silk types. A three-factor experimental design was employed, and the experimental data were analyzed using Design-Expert 13 through response surface methodology and linear regression modeling.

The results demonstrated that **sodium carbonate concentration was the most influential processing variable affecting degumming loss**, followed by **boiling duration**, whereas **neutral soap concentration did not exert a statistically significant linear effect** within the investigated range. For Borduar white, the fitted model was:

YB=10.7100+0.5250A+0.0400B+0.3800C

while for Kokrajhar brick-red:

YK=13.7200+0.5288A+0.0375B+0.3812C

where A, B, and C represent the coded levels of Na_2CO_3 concentration, neutral soap concentration, and boiling duration, respectively. The remarkably similar coefficients for the two cocoon types indicate that their responses to changes in the investigated processing variables were broadly comparable.

For both Eri silk types, increasing **Na_2CO_3 concentration** resulted in an increase in degumming loss, which can be attributed to enhanced alkaline action and removal of sericin and other non-fibrous constituents. Similarly, increasing **boiling duration** increased degumming loss, reflecting the greater duration available for penetration and action of the degumming liquor. In contrast, changes in neutral soap concentration from 10 to 20% produced only a minor change in degumming loss and were statistically non-significant.

The fitted models were statistically significant for both cocoon types, with p=0.0033 for Borduar white and p=0.0034 for Kokrajhar brick-red. Moreover, the lack-of-fit tests were non-significant (p=0.3313 and p=0.3417, respectively), indicating that the linear models provided an adequate representation of the experimental responses within the investigated factor ranges. The models explained approximately **64.0% and 63.7%** of the variation in degumming loss for Borduar white and Kokrajhar brick-red, respectively.

The experimental-versus-predicted comparison further demonstrated similar model performance for the two cocoon types. The mean absolute prediction errors were approximately **0.28 percentage points** for both varieties, while the mean residuals were close to zero, indicating negligible systematic prediction bias. Thus, the fitted models adequately represented the principal trends in degumming loss within the experimental domain, although their predictive capability should be regarded as moderate rather than excellent.

A notable difference was observed between the two Eri cocoon types. **Kokrajhar brick-red consistently exhibited higher degumming loss than Borduar white**, with the fitted center responses being 13.72% and 10.71%, respectively. The approximately **3.01 percentage-point difference** between the center responses, together with the remarkably similar regression coefficients, suggests that the principal difference between the two cocoon types lies in their baseline susceptibility to mass loss during degumming rather than in their sensitivity to the investigated processing variables. This difference may be associated with inherent differences in cocoon structure and composition, although confirmation of specific compositional causes would require further physicochemical characterization.

Overall, the findings demonstrate that **alkaline concentration and thermal treatment duration are the principal process variables governing degumming loss of the investigated Ethiopian Eri silk cocoons**. The results provide a useful quantitative basis for developing controlled degumming conditions for Eri silk cultivated in Ethiopia. However, maximizing degumming loss alone should not be considered synonymous with obtaining the optimum silk quality. Further optimization should therefore incorporate additional responses such as **residual sericin content, fibre tenacity, elongation, fineness, whiteness, handle, and other relevant quality characteristics** to identify processing conditions that achieve effective degumming while preserving the desirable properties of Eri silk.

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