ADVANCED PHYSICO-CHEMICAL METHODS IN RAW MULBERRY SILK DEGUMMING: EFFICIENCY, FIBER INTEGRITY, AND ENVIRONMENTAL IMPACT

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Abstract. The degumming process, which involves the removal of sericin from raw mulberry silk fibroin, is a critical and determinant step in silk processing. Traditional alkaline-based degumming, while effective, poses significant environmental challenges and can compromise the intrinsic mechanical properties of silk fibers. This scientific-analytical article provides a comprehensive review and analysis of advanced physico-chemical degumming methodologies. It evaluates the efficacy, fiber quality preservation, and environmental sustainability of emerging techniques such as ultrasonic-assisted, enzymatic, plasma, and supercritical CO2 degumming against conventional methods. The analysis is based on a systematic review of recent scientific literature, focusing on parameters such as degumming efficiency (sericin removal yield), tensile strength retention, weight loss, fiber morphology, and the ecological footprint of each process. The findings indicate that hybrid methods, particularly ultrasonic-enzymatic and plasma-assisted processes, offer a superior balance between high sericin removal, excellent preservation of fibroin's mechanical integrity, and reduced consumption of water, energy, and chemicals. The article concludes that the future of sustainable and high-quality silk processing lies in the optimization and industrial-scale adoption of these integrated physico-chemical approaches.

Keywords: Mulberry Silk, Degumming, Sericin, Fibroin, Ultrasonic, Enzymatic, Plasma Treatment, Supercritical CO2, Sustainability, Fiber Properties.

Annotatsiya. Ipni qayta ishlashda xom pilladan seritsinni ajratib olish - bu ipak mahsulotlarining sifatini belgilovchi muhim bosqichdir. An'anaviy ishqor asosida seritsinni ajratish samarali bo'lishiga qaramay, atrof-muhitga jiddiy zarar yetkazishi va ipak tolalarining tabiiy mexanik xususiyatlarini susaytirishi mumkin. Ushbu ilmiy-tahliliy maqolada zamonaviy fizik-kimyoviy seritsin ajratish usullari keng ko'lamda o'rganilgan va tahli qilingan. Yangi paydo bo'lgan ultratovushli, fermentli, plazmali va superkritik CO_2 usullarining samaradorligi, tola sifati va ekologik barqarorligi an'anaviy usullar bilan solishtirgan holda baholangan. Tahlil so'nggi ilmiy adabiyotlar asosida amalga oshirilgan bo'lib, seritsin ajratish samaradorligi, cho'zilish kuchini saqlab qolish, tola morfologiyasi va har bir jarayonning ekologik izi kabi parametrlar diqqat markazida bo'lgan. Tadqiqot natijalari shuni ko'rsatadiki, ayniqsa ultratovushli-fermentli va plazma bilan qo'shilgan jarayonlar kabi gibrid usullar yuqori seritsin ajratish, fibroin mexanik mustahkamligini a'lo darajada saqlash va suv, energiya va kimyoviy moddalar sarfini kamaytirish o'rtasida eng yaxshi muvozanatni ta'minlaydi. Maqolada yuqori

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sifatli va barqaror ipak mahsulotlarini ishlab chiqarishning kelajagi ushbu integratsiyalashgan fizik-kimyoviy usullarni sanoat miqyosida optimallashtirish va qo'llashdan iborat ekanligi xulosasiga kelinadi.

Kalit so'zlar: Pillapoya ipagi, Seritsin ajratish, Seritsin, Fibroin, Ultratovushli, Fermentli, Plazma ishlov berish, Superkritik CO2, Barqarorlik, Tola xususiyatlari.

Аннотация. Процесс удаления серицина из сырого фиброина шелкопряда тутового шелкопряда является критически важным и определяющим этапом в переработке шелка. Традиционное щелочное удаление серицина, будучи эффективным, создает значительные экологические проблемы и может нарушить внутренние механические свойства шелковых волокон. Данная научно-аналитическая статья предоставляет всесторонний обзор и анализ передовых физико-химических методов удаления серицина. Оценивается эффективность, сохранение качества волокна и экологическая устойчивость таких новых методов, как ультразвуковая, ферментативная, плазменная обработка и удаление серицина с помощью сверхкритического CO2, в сравнении с традиционными методами. Анализ основан на систематическом обзоре научной литературы с фокусом на такие параметры, как эффективность удаления серицина, сохранение прочности на растяжение, потеря веса, морфология волокна и экологический след каждого процесса. Результаты указывают, что гибридные методы, в частности ультразвуково-ферментативные и процессы с плазменной активацией, предлагают превосходный баланс между высоким уровнем удаления серицина, отличным сохранением механической целостности фиброина и сниженным потреблением воды, энергии и химикатов. В статье делается вывод, что будущее устойчивой и высококачественной переработки шелка лежит в оптимизации и внедрении на промышленном уровне этих интегрированных физико-химических подходов.

Ключевые слова: Шелк тутового шелкопряда, Удаление серицина, Серицин, Фиброин, Ультразвуковой, Ферментативный, Плазменная обработка, Сверхкритический CO2, Устойчивость, Свойства волокна.

Introduction

Mulberry silk, produced by the domesticated silkworm *Bombyx mori*, is renowned for its exceptional luster, tactile smoothness, high tensile strength, and biocompatibility. These properties are primarily attributed to its two main protein components: fibroin, the structural core filament (approximately 70-80% of the cocoon's weight), and sericin, the gum-like protein (20-30%) that cements the fibroins together. The primary objective of the degumming process is to completely remove sericin to unveil the inherent qualities of the fibroin fiber, thereby facilitating subsequent dyeing, printing, and finishing operations with uniform and high-quality results [1-3].

Conventional industrial degumming predominantly relies on hot aqueous solutions of alkali, most commonly sodium carbonate (Na_2CO_3), often

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supplemented with soap. While this method is cost-effective and provides rapid sericin removal, it has several drawbacks. The high pH and temperature can lead to hydrolysis of the fibroin chains, resulting in a reduction of tensile strength, loss of weight, and a harsher hand feel. Furthermore, the process generates large volumes of alkaline effluent with high Chemical Oxygen Demand (COD) and Biological Oxygen Demand (BOD) from the dissolved sericin, presenting a serious environmental pollution problem and increasing wastewater treatment costs [4-5].

Consequently, the global silk industry and research community are actively seeking alternative degumming technologies that are not only efficient but also environmentally benign and gentle on the silk fiber. This article aims to provide a detailed scientific analysis of the most promising advanced physico-chemical degumming methods, evaluating their mechanisms, operational parameters, and overall impact on fiber quality and the environment [6].

CONVENTIONAL ALKALINE DEGUMMING: A CRITICAL ANALYSIS

The traditional method involves treating silk yarn or fabric in a bath containing 0.5-2.0 g/L of sodium carbonate and 5-10 g/L of Marseille soap at a temperature of 95-100°C for 60-120 minutes. The mechanism is primarily saponification and hydrolysis of sericin [7-8].

Advantages:

High efficiency and reliability.

Low cost and readily available chemicals.

Well-established and understood process.

Disadvantages:

Fiber Damage: Prolonged exposure to strong alkali weakens the fibroin by breaking peptide bonds, leading to a 15-25% loss in tensile strength.

Weight Loss: Beyond sericin removal, fibroin itself is attacked, causing an overall weight loss higher than the actual sericin content.

Environmental Impact: The effluent is highly alkaline (pH 9-11) and contains degraded protein, leading to high COD (5000-10,000 mg/L) and BOD, depleting oxygen in water bodies.

Resource Intensity: High water and energy consumption.

ADVANCED PHYSICO-CHEMICAL DEGUMMING METHODS

This technique utilizes high-frequency sound waves (typically 20-40 kHz) to create cavitation bubbles in the degumming solution. The implosion of these microbubbles generates intense local microjets, shockwaves, and turbulence.

Mechanism:The physical forces disrupt the sericin layer, increasing its surface area and enhancing the diffusion of chemicals or enzymes into the gum, thereby accelerating the hydrolysis process [9-10].

Process Parameters: Can be combined with either alkaline or enzymatic solutions. Temperature and chemical concentration can often be reduced.

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Impact on Fiber Quality: Studies show that ultrasonic-assisted degumming results in more uniform sericin removal with less fiber damage compared to conventional methods. The tensile strength retention is significantly higher.

Environmental Impact: Reduces processing time, energy consumption, and chemical usage by 20-40%, leading to lower effluent load.

This is a bio-based approach using specific proteolytic enzymes (e.g., alkaline, neutral, or serine proteases) that selectively hydrolyze sericin without attacking fibroin.

Mechanism: Enzymes act as biocatalysts, cleaving the peptide bonds in sericin with high specificity. The process is sensitive to pH, temperature, and enzyme concentration.

Process Parameters: Typically conducted at milder temperatures (50-60°C) and near-neutral pH, depending on the enzyme. Requires careful control to prevent enzyme denaturation.

Impact on Fiber Quality: Considered the gentlest method. It excellently preserves the mechanical properties of fibroin, resulting in silk with superior strength, luster, and softness. The weight loss is closer to the actual sericin content.

Environmental Impact: The effluent is biodegradable, less alkaline, and has a lower environmental footprint. The main challenge is the relatively high cost of enzymes and longer processing times compared to alkaline degumming.

Low-temperature plasma (e.g., atmospheric pressure plasma with air, oxygen, or argon gases) is a dry, eco-friendly surface modification technique.

Mechanism: Plasma generates a cocktail of reactive species (ions, electrons, radicals, UV photons) that etch and oxidize the surface sericin layer, making it more hydrophilic and fragile. This pre-treatment can significantly enhance subsequent wet degumming.

Process Parameters: A short-duration (seconds to minutes) dry process.

Impact on Fiber Quality: As a surface treatment, it does not affect the bulk properties of fibroin. It can improve dye uptake and wettability after degumming.

Environmental Impact: Extremely low water and chemical consumption. No wastewater generation from the plasma process itself.

This method employs carbon dioxide above its critical temperature and pressure (31.1 C, 73.8 bar) as a non-toxic, non-flammable solvent.

Mechanism: Supercritical CO2 has gas-like diffusivity and liquid-like density. It can penetrate the silk fiber and, when combined with a co-solvent like water or ethanol, facilitate the extraction and hydrolysis of sericin.

Process Parameters: Requires high-pressure equipment. Process efficiency depends on pressure, temperature, and co-solvent.

Impact on Fiber Quality: Operates at moderate temperatures, preserving fiber strength. The process is very clean and leaves no solvent residue.

Environmental Impact: CO2 is recyclable, and the process generates minimal waste. It is a closed-loop system, representing a pinnacle of green processing.

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COMPARATIVE ANALYSIS AND DISCUSSION

A comparative analysis of the different methods based on key performance indicators is presented below:

Table 1

Comparative Analysis of Mulberry Silk Degumming Methods

Parameter	Conventional Alkaline	Ultrasonic-Alkaline	Enzymatic	Plasma + Wet Process	Supercritical CO2
Sericin Removal (%)	98-99	98-99	95-98	95-98 (after mild bath)	90-95
Fiber Strength Retention (%)	75-85	85-90	92-98	90-95	90-95
Process Time (minutes)	60-120	30-60	90-180	5-10 (Plasma) + 30-60	60-120
Water Consumption (L/kg silk)	30-50	20-35	25-40	10-20	5-10 (co-solvent)
Chemical Oxygen Demand (COD) of Effluent	Very High (5000-10000 mg/L)	High (3000-7000 mg/L)	Moderate (1500-3000 mg/L)	Low (500-1500 mg/L)	Very Low (<100 mg/L)
Relative Cost	Low	Low-Medium	Medium-High	Medium	High

Graphical representation of key parameters:

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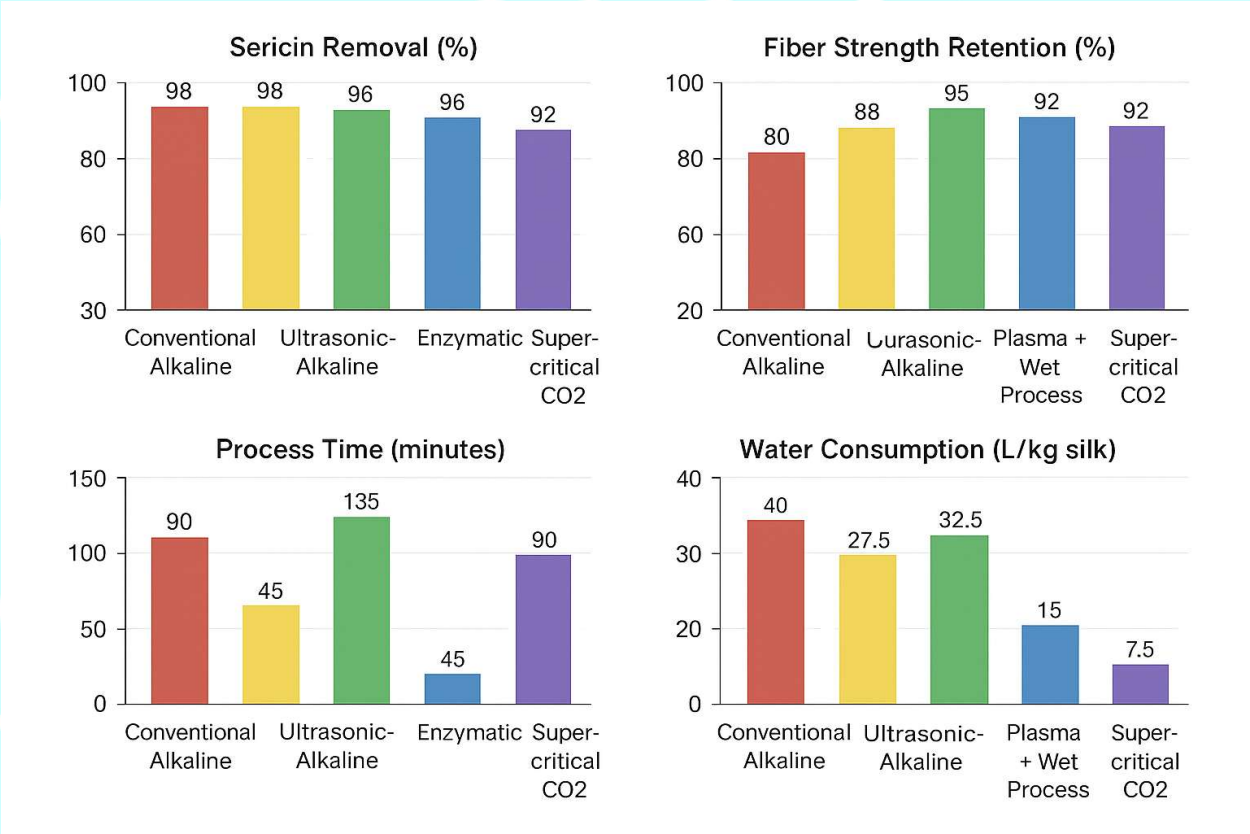


Figure 1. A comparative histogram for mulberry silk degumming methods

Analysis: The table and histogram clearly illustrate the trade-offs. While conventional degumming is cheap and fast, its environmental and quality costs are high. Enzymatic degumming offers the best fiber quality but at a higher operational cost and longer duration. Ultrasonic-assisted degumming strikes a practical balance, enhancing conventional processes by making them faster, more efficient, and less damaging. Plasma treatment is an excellent pre-treatment step that can drastically reduce the chemical and time requirements of a subsequent mild degumming bath. Supercritical CO2, though currently expensive for large-scale implementation, represents the future of zero-discharge textile processing.

CONCLUSION AND FUTURE PERSPECTIVES

The move away from traditional alkaline degumming is not just a trend but a necessity for the sustainable future of the silk industry. Advanced physico-chemical methods offer viable, efficient, and greener alternatives. No single method is a panacea; the choice depends on a balance between desired fiber quality, production capacity, cost constraints, and environmental regulations.

The most promising direction appears to be the development of hybrid technologies. For instance:

Ultrasonic-Enzymatic Degumming: Combining ultrasound can reduce enzymatic degumming time and enzyme dosage, making the process more economical.

Plasma-Assisted Mild Alkaline Degumming: A brief plasma pre-treatment can allow for a subsequent alkaline degumming process with much lower alkali concentration, temperature, and time, minimizing fiber damage and effluent load.

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Future research should focus on scaling up these hybrid processes, optimizing parameters for industrial machinery, and conducting full life-cycle assessments (LCA) to quantify their environmental and economic benefits accurately. By embracing these advanced technologies, the silk industry can ensure the production of premium quality silk while upholding its commitment to environmental stewardship.

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