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Research Article

Techno-economic analysis of sericin recovery from waste cocoons

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Abstract

This study evaluates the techno-economic feasibility of sericin recovery from waste silk cocoons by comparing hot-water extraction and citric acid–assisted fractionation processes. Sericin was extracted from *Bombyx mori* cocoons under autoclave conditions (105-125 °C, 15-75 min) using water and 1.25% citric acid. Process optimization was performed via response surface methodology. Molecular-weight fractions were obtained by dialysis, and bioactivity was assessed using antioxidant and α-glucosidase inhibition assays. Techno-economic analysis included mass/energy balances, capital and operating costs, and profitability indicators. Hot-water extraction produced ~34,255 kg yr^{-1} sericin with moderate profitability (ROI: 21.55%). In contrast, the fractionation-based process generated multiple high-value products, achieving ~36.87 M$ annual revenue and significantly higher profitability (ROI: 109.2%, payback <1 year). Economic performance shifted from feedstock-driven to value-driven due to product diversification. The results highlight that process design and product portfolio, rather than extraction yield alone, determine economic viability. Fractionation-based strategies enable transformation of sericin recovery into a high-value biorefinery system.

Keywords: Sericin, SuperPro Designer, Extraction, Bioactivity, Techno-economic analysis

Introduction

Sericulture and silk textile production generate significant quantities of solid and liquid waste throughout cocoon harvesting, reeling, and degumming processes. A considerable portion of this waste consists of defective or non-reelable cocoons and sericin-rich effluents, which are commonly discarded despite their high biochemical and economic potential (Qadir *et al.,* 2025). Seri-biological wastes are particularly abundant in cocoon processing, where sericin—accounting for approximately 20-30% of the cocoon mass—is removed to obtain fibroin fibers with desirable textile properties (Saha *et al.,* 2019; Aad *et al.,* 2024). On a global scale, this practice results in the loss of tens of thousands of tons of recoverable sericin annually and contributes to elevated chemical and biological oxygen demand in wastewater streams (Yuan *et al.,* 2024; Orlandi *et al.,* 2020).

Silk sericin is a globular, glue-like protein that envelopes fibroin fibers and ensures the cohesion and mechanical integrity of the cocoon. Its distribution within the cocoon is heterogeneous, with higher sericin content in the outer layers, which play a crucial protective role against environmental stressors, particularly ultraviolet (UV) radiation (Zhou *et al.,* 2023). Structurally, sericin is composed of 18 amino acids, predominantly serine, glycine, and aspartic acid, resulting in high polarity, hydrophilicity, and strong moisture-binding capacity (Aad *et al.,* 2024; Yuan *et al.,* 2024). These intrinsic features underpin sericin's natural photoprotective, adhesive, and barrier-forming functions.

The molecular weight (MW) of sericin spans a wide range, typically from below 10 kDa to above 400 kDa, and is strongly influenced by extraction and purification conditions (da Silva *et al.,* 2014; Capar & Aygün, 2015). This MW variability governs its physicochemical behavior, solubility, film-forming ability, and biological activity. Low-molecular-weight sericin fractions are generally preferred for cosmetic and skincare applications, while high-molecular-weight sericin is more suitable for biomedical materials, membranes, and structural biomaterials (Paladini *et al.,* 2025; Veiga *et al.,* 2025). Therefore, precise control of extraction severity and downstream processing is essential to tailor sericin for specific end-use applications.

Over the past decade, sericin has undergone a paradigm shift from an undervalued degumming by-product to a multifunctional biopolymer with demonstrated antioxidant, antimicrobial, anti-inflammatory, anti-tyrosinase, anti-elastase, moisturizing, and UV-protective properties (Orlandi *et al.,* 2020; Mathew *et al.,* 2024; Chetia *et al.,* 2025). These attributes have enabled its utilization in clean beauty and cosmetic formulations, biomedical and pharmaceutical systems, tissue engineering scaffolds, drug delivery platforms, food packaging, edible coatings, and environmentally responsive materials (Aad *et al.,* 2024; Paladini *et al.,* 2025). As a result, sericin recovery has become closely associated with waste-to-wealth and circular bioeconomy strategies.

The extraction route plays a decisive role in determining both the quality and usability of recovered sericin. Conventional alkaline degumming processes, although effective for fibroin purification, often lead to extensive hydrolytic degradation of sericin, loss of molecular integrity, and diminished bioactivity, in addition to generating chemically intensive effluents (Orlandi *et al.,* 2020; Sincar *et al.,* 2026). To overcome these limitations, alternative extraction strategies such as hot-water extraction, autoclave-assisted hydrothermal treatment, organic acid-based

methods—particularly citric acid extraction—and membrane-based recovery have been developed to preserve bioactivity while reducing environmental impact (Saha *et al.,* 2019; Capar & Pilevneli, 2024; Sincar *et al.,* 2026).

Beyond extraction, downstream concentration and stabilization steps—including ethanol precipitation, freeze–thawing, ultrafiltration and nanofiltration, dialysis, lyophilization, spray drying, oven drying, and advanced cryo-lyophilization—significantly influence yield, molecular weight distribution, storage stability, and industrial applicability (da Silva *et al.,* 2014; Capar & Pilevneli, 2024; Veiga *et al.,* 2025). Importantly, sericin recovered directly from industrial degumming wastewater has been shown to exhibit physicochemical and biological properties comparable to laboratory-grade sericin, supporting its classification as a valuable industrial raw material rather than a downgraded waste stream (Capar & Aygün, 2015; Orlandi *et al.,* 2020).

Despite the extensive literature on sericin structure, extraction technologies, and functional applications, large-scale implementation of sericin recovery remains limited. A critical gap persists in the integration of technical performance with economic feasibility. Existing studies indicate that capital investment, energy demand, labor requirements, and drying technology selection dominate the overall cost structure, leading to substantial variability in unit sericin production costs depending on process configuration (Capar & Pilevneli, 2024). This techno-economic uncertainty represents a major barrier to industrial adoption, particularly in sericulture-intensive regions generating large volumes of waste cocoons.

Therefore, a comprehensive techno-economic analysis is essential to bridge the gap between laboratory-scale feasibility and industrial realization of sericin recovery processes. In this study, sericin recovery from waste cocoons is systematically evaluated by integrating extraction efficiency, downstream processing strategies, cost structure, and market competitiveness. The findings aim to identify economically viable processing scenarios and cost-critical unit operations that can support scalable, sustainable, and circular valorization of sericulture waste streams.

Materials and methods

Silk cocoons derived from *Bombyx mori* were obtained from local sericulture farms in İzmir, Turkey, and stored under dry, light-protected conditions at room temperature until use. Prior to extraction, the cocoons were manually cut into small pieces (approximately 0.5-1 cm^2). Deionized water was used as the primary extraction solvent. Citric acid monohydrate (≥99.5%) was used for acidic extraction experiments. Analytical reagents including Trolox, ABTS, α-glucosidase enzyme, and 4-nitrophenyl-α-D-glucopyranoside were procured from standard commercial suppliers.

For water-based extraction, cocoon samples were mixed with deionized water at a solid-to-liquid ratio of 1:50 (w/v) and subjected to autoclave treatment at controlled temperatures (105-125 °C) and durations (15-75 min) under saturated steam pressure (~3 bar). Following extraction, the mixtures were cooled to room temperature and filtered to remove insoluble residues. The resulting solutions were either directly analyzed or subjected to drying using a SpeedVac concentrator (40 °C, 3000 rpm, 4 h) and subsequent freeze-drying to obtain powdered sericin. This approach enabled efficient solvent removal while preserving the structural integrity of the protein (Sincar *et al.,* 2026).

In parallel, acidic extraction was performed under identical experimental conditions, with the addition of 1.25% (w/v) citric acid to the extraction medium. This modification allowed evaluation of the synergistic effect of heat and mild organic acid treatment on sericin solubilization and bioactivity preservation. The acidic extraction approach was found to significantly enhance sericin purity and enzyme inhibition activity compared to water-based extraction, while maintaining comparable yields (Sincar *et al.,* 2026).

To further investigate molecular weight-dependent bioactivity, sericin fractions (>3.5, >7, and >10 kDa) were separated using dialysis over a period of three days. Dialysis effectively removed residual citric acid and low-molecular-weight impurities while preserving bioactive fractions. The purified fractions were subsequently dried and used for analytical characterization (Sincar *et al.,* 2026).

Extraction yield was calculated as the percentage ratio of recovered sericin mass to the initial cocoon mass. Sericin purity was determined using UV–Vis spectrophotometry at 275 nm based on calibration with standard sericin. Molecular weight distribution and polydispersity index (PDI) were analyzed using size exclusion chromatography (SEC) (Sincar *et al.,* 2026).

The antioxidant capacity of sericin extracts was evaluated using the ABTS radical scavenging assay, with results expressed as IC_{50} values. Lower IC_{50} values indicated higher antioxidant activity. The α-glucosidase inhibition assay was conducted using a microplate-based method, and inhibitory activity was similarly expressed as IC_{50} values (Sincar *et al.,* 2026).

The simulations for both processes were carried out using SuperPro Designer v13.

Results and discussion

Comparative evaluation of extraction methods

The extraction of sericin using hot-water and citric acid–assisted processes revealed distinct differences in both physicochemical and biological properties. Although hot-water extraction resulted in a broader yield range (8.51-26.96%), citric acid extraction provided consistently higher purity levels (up to 100%), indicating its effectiveness in removing non-sericin impurities and promoting selective solubilization of target proteins.

This observation is consistent with previous studies reporting that mild acidic environments facilitate the hydrolysis of intermolecular interactions between fibroin and sericin, thereby enhancing extraction selectivity and purity. In contrast, hot-water extraction, while simpler and more environmentally benign, may co-extract additional non-protein components, leading to lower purity.

From a functional perspective, the two extraction methods exhibited complementary bioactivity profiles. Hot-water extracts demonstrated significantly stronger antioxidant activity ($IC_{50:}$ 0.15-0.24 mg/mL), whereas citric acid extracts showed markedly enhanced α-glucosidase inhibition (IC_{50}: 0.67-3.06 mg/mL).

Table 1 presents a comparative analysis of sericin extraction using hot water and citric acid-assisted methods. While hot water extraction demonstrated a wider range of yield and superior antioxidant activity (lower IC_{50} values), citric acid extraction provided significantly higher purity and enhanced α-glucosidase inhibitory activity. These findings indicate that extraction method selection should be guided by the targeted functional property, as water extraction favors antioxidant potential, whereas citric acid extraction enhances purity and antidiabetic performance.

This divergence can be attributed to differences in peptide composition and structural integrity. Hot-water extraction likely preserves native amino acid sequences responsible for radical scavenging, such as tyrosine and serine-rich domains. On the other hand, citric acid treatment may promote controlled hydrolysis, generating smaller bioactive peptides that are more effective in enzyme inhibition, particularly in antidiabetic applications. Similar trends have been reported in protein hydrolysates, where moderate hydrolysis enhances enzyme inhibitory activity due to increased accessibility of active sites.

Influence of process parameters on yield and bioactivity

Table 2 summarizes the optimal extraction conditions determined via response surface methodology (RSM) for maximizing yield, bioactivity, and purity of sericin obtained under water and citric acid-assisted extraction systems. The results reveal that maximum yield is achieved at higher temperatures and longer extraction times, whereas antioxidant activity is favored under milder conditions, particularly in water extraction. In contrast, citric acid-assisted extraction enhances both α-glucosidase inhibitory activity and purity, indicating its effectiveness in selective fractionation and functional enrichment. These findings highlight the critical role of extraction parameters in tailoring sericin properties for specific biomedical and cosmeceutical applications.

Table 1: Comparative evaluation of hot water and citric acid extraction methods in terms of yield, purity, antioxidant, and antidiabetic activities

Parameter	Hot water extraction	Citric acid extraction
Yield (%)	8.51-26.96	16.46-24.00
Purity (%)	53.88-76.50	70.69-100.00
Antioxidant (IC_{50} mg/mL)	0.15-0.24 (lower is better)	0.54-3.26
α-glucosidase (IC_{50} mg/mL)	1.63-27.69	0.67-3.06 (significantly better)

Table 2: Optimization of extraction conditions for sericin: yield, antioxidant, antidiabetic activity, and purity outcomes

Objective	Optimal condition	Result
Maximum yield (water)	125°C - 75 min	26.96%
Maximum yield (acid)	105°C - 75 min	24.00%
Best antioxidant activity (water)	105°C - 15 min	IC_{50}=0.15
Best antidiabetic activity (acid)	115°C - 45 min	IC_{50}=0.67
Best purity (acid)	115°C - 15 min	100%

Temperature-dependent behavior

Temperature was identified as a critical parameter influencing both extraction efficiency and bioactivity. Increasing temperature enhanced sericin yield, with maximum values observed at 125 °C (hot water) and 105 °C (citric acid). This is primarily due to improved protein solubilization and disruption of hydrogen bonding within the silk matrix.

However, excessive temperatures led to a decline in biological activity, indicating thermal degradation of functional amino acid residues. This phenomenon has been widely reported in protein-based systems, where high temperatures induce denaturation, peptide fragmentation, and loss of functional groups critical for bioactivity.

Time-dependent behavior

Extraction time showed a similar dual effect. Prolonged extraction increased yield but negatively impacted antioxidant capacity. Short extraction times (15 min) preserved bioactivity, whereas extended durations (75 min) likely caused oxidative degradation and structural modification of bioactive peptides.

These findings suggest that both temperature and time must be carefully controlled to avoid over-processing, which can compromise the functional quality of sericin.

Multi-response optimization strategy

A key outcome of this study is the identification of a multi-response optimum at 115 °C for 45 min, where yield, purity, antioxidant activity, and antidiabetic activity were simultaneously balanced.

This condition represents a critical compromise between extraction efficiency and functional preservation. Unlike conventional optimization approaches that prioritize yield alone, this study demonstrates that a multi-objective strategy is essential for developing high-value bioactive products.

Such optimization approaches are increasingly emphasized in bioprocess design, particularly for functional biomaterials, where product performance is determined by a combination of physicochemical and biological properties rather than a single metric.

Molecular weight–bioactivity relationship

The molecular weight distribution of sericin (38.15-172.36 kDa) and its fractionation via dialysis (>3.5, >7, and >10 kDa) revealed a strong positive correlation between molecular size and bioactivity.

Higher molecular weight fractions (>10 kDa) exhibited the most potent biological activity, as indicated by lower IC_{50} values in both antioxidant and α-glucosidase inhibition assays. Intermediate fractions (>7 kDa) showed moderate activity, while lower molecular weight fractions (>3.5 kDa) displayed relatively weak performance.

This trend can be explained by the structural and functional characteristics of sericin. Larger molecular weight fractions retain longer peptide chains and more intact functional domains, which enhance their ability to interact with free radicals and enzyme active sites. Additionally, these fractions exhibit greater conformational stability, which may contribute to sustained bioactivity.

Interestingly, while enzymatic hydrolysis is often reported to improve bioactivity in protein systems, the present results indicate that excessive fragmentation may reduce functional performance in sericin. This suggests that maintaining an optimal molecular size range is critical, rather than maximizing hydrolysis.

Furthermore, the results indicate that extraction conditions indirectly influence bioactivity through their effect on molecular weight distribution. Harsh conditions may increase apparent molecular weight due to aggregation or cross-linking but do not necessarily improve bioactivity, highlighting the importance of controlled processing.

Integrated process–structure–function relationship

Overall, this study demonstrates that sericin extraction is governed by a complex interplay between process conditions, molecular structure, and functional properties. While higher temperatures and longer extraction times improve yield, they may simultaneously compromise bioactivity due to structural degradation.

Citric acid extraction enhances purity and antidiabetic activity, whereas hot-water extraction better preserves antioxidant functionality. In addition, molecular weight emerges as a key determinant of bioactivity, with higher molecular weight fractions showing superior performance.

These findings emphasize that process design should be application-driven, focusing on the desired biofunctional outcome rather than solely maximizing extraction yield. This approach is particularly relevant for the development of sericin-based biomaterials in cosmetic and biomedical applications, where functionality is the primary determinant of product value.

Process configuration and operational capacity

The techno-economic evaluation was conducted for two sericin recovery configurations based on autoclave-assisted extraction of waste silk cocoons operated under batch conditions (Table 3). In the baseline configuration, sericin is recovered through a hot-water autoclave extraction process consisting of cocoon shredding, solid–liquid extraction (leaching), phase separation, thin-film evaporation, condensation, and final spray drying (Figure 1). This configuration produces powdered sericin as the main product while fibroin is simultaneously recovered as a secondary co-product stream.

The plant was simulated with an annual operating time of 7,920 h, corresponding to continuous availability throughout the year. Considering a batch cycle time of approximately 6 h, the process can perform 1,320 batches annually. Under these conditions, each batch yields approximately 25.95 kg of sericin, resulting in a total annual production capacity of about 34,255 kg of sericin powder. This production scale corresponds to a small-to-medium industrial facility and is particularly suitable for integration into existing sericulture or textile processing infrastructures.

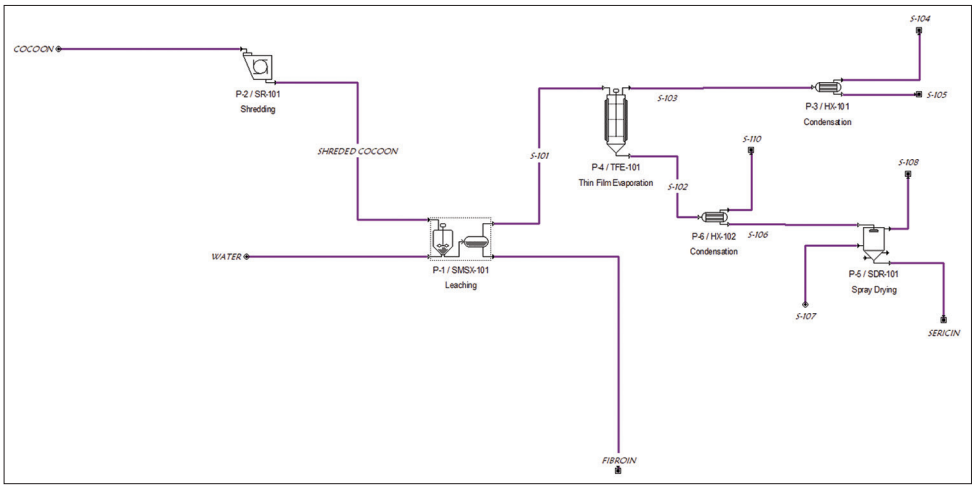


Figure 1: Flow diagram of hot water extraction of sericin

Table 3: Techno-economic comparison of hot water and hot water–citric acid autoclave extraction scenarios

Parameter	Scenario I Hot Water Autoclave	Scenario II Hot Water–Citric Acid+MW Fractionation
Process philosophy	Single-product recovery	Biorefinery-oriented, multi-product
Main product (MP)	Bulk sericin powder	Sericin 7-10 kDa (powder)
Batch operation (h/batch)	~6 h	~10 h (diafiltration-limited)
Batches per year	1,320	792
MP production (kg/yr)	34,255	5,224.9
Additional sericin fractions	None	<3.5 kDa, 3.5-7 kDa, >10 kDa
Fibroin recovery	Yes	Yes
Total capital investment (TCI)	4.74 M$	12.78 M$
Annual operating cost (AOC)	9.02 M$/yr	15.39 M$/yr
Dominant OPEX driver	Raw material (cocoon)	Labor+membranes
Utilities share of AOC	0.33%	0.08%
Total annual revenue	10.12 M$/yr	36.87 M$/yr
Revenue from MP	5.14 M$/yr	0.78 M$/yr
Revenue from co-products	~49%	>97%
Unit production cost (MP)	263 $/kg	2,946 $/kg
Unit production revenue (MP)	295 $/kg	7,057 $/kg
Gross margin	10.84%	58.26%
ROI	21.55%	109.19%
Payback time	4.64 years	0.92 years
IRR (after tax)	13.61%	60.18%
NPV (7%)	2.30 M$	82.98 M$
Economic risk profile	Feedstock-sensitive	Operation-intensive but resilient
Best industrial fit	Low-complexity bulk production	High-value biorefinery platform
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In the second configuration (Figure 2), the process was redesigned to incorporate citric acid–assisted hydrolysis and downstream molecular-weight fractionation to increase product value. In this approach, shredded cocoons are subjected to pressurized autoclave treatment using a 1.25% (w/w) citric acid solution, followed by centrifugation to separate fibroin and hydrolyzed sericin fractions. The liquid phase is then processed through multi-stage diafiltration, enabling the separation of sericin into different molecular-weight classes prior to concentration by thin-film evaporation and final spray drying.

Due to the additional separation steps, this configuration operates with a longer batch cycle and therefore lower annual batch throughput. The plant was simulated for the same annual operating time of 7,920 h but with 792 batches per year. Each batch produces approximately 6.60 kg of sericin in the 7-10 kDa molecular-weight range, resulting in an annual production capacity of 5,224.9 kg of this fraction, which was defined as the main product due to its higher functional and commercial value.

Besides the main product, the process generates significant quantities of additional sericin fractions and fibroin as value-added co-products. These include approximately 59,470 kg yr^{-1} of fibroin, 29,541 kg yr^{-1} of sericin with molecular weight below 3.5 kDa, 31,251 kg yr^{-1} of sericin in the 3.5-7 kDa range, and 601,520 kg yr^{-1} of sericin fractions above 10 kDa. The presence of these multiple product streams represents a major distinguishing feature of the citric-acid-assisted process and forms the basis of its improved economic performance, as the diversified product portfolio allows the process to access different market segments and significantly increases the overall value generated from waste cocoons.

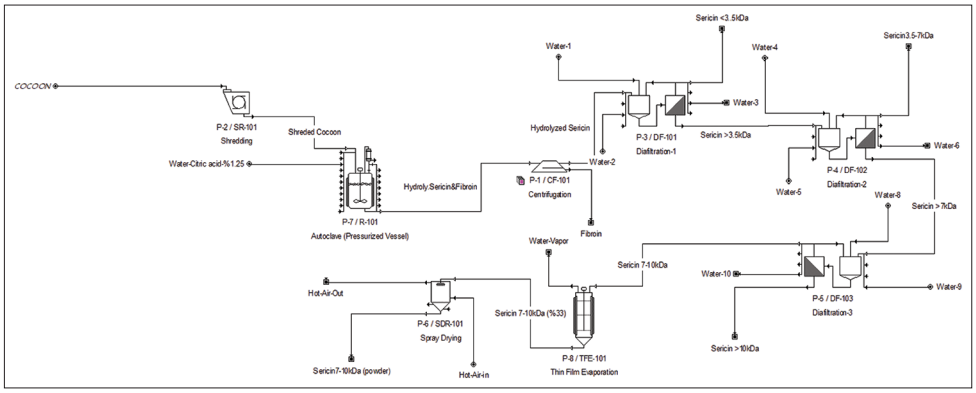


Figure 2: Flow diagram of hot water-citric acid extraction of sericin

Material balance and resource consumption

The material balance analysis confirms that both extraction configurations exhibit stable and closed mass flows throughout the system. For the hot-water autoclave extraction scenario, each batch processes 100 kg of shredded cocoon using 397.88 kg of water as the extraction medium. When process air required for spray drying is included, the total batch input reaches approximately 2,176.91 kg. The simulation results indicate that from the cocoon biomass, approximately 25 kg of sericin and 75 kg of fibroin are recovered per batch, corresponding to the complete valorization of the protein components of the cocoon. The overall mass balance achieves 100% component closure without accumulation or losses, demonstrating the robustness and internal consistency of the process simulation.

At the annual operating capacity of 1,320 batches, the hot-water extraction process consumes approximately 132,000 kg of cocoon feedstock, 525,204 kg of water, and 2,216,322 kg of process air used primarily during spray drying. When normalized to sericin production, the specific raw material consumption corresponds to approximately 3.85 kg cocoon per kg of sericin and 15.33 kg water per kg of sericin. These values fall within the expected range for aqueous protein extraction systems. An important advantage of this configuration is that no chemical reagents are required during extraction, thereby eliminating additional chemical costs and reducing potential environmental burdens associated with acid or alkaline treatments.

In the citric-acid-assisted extraction configuration, the material balance reflects the additional process steps required for molecular-weight fractionation. The annual raw material consumption in this scenario consists of approximately 79,200 kg of cocoon feedstock, 4,946 kg of citric acid, 4,277,496 kg of water, and 234,999 kg of air used mainly in drying operations. Although citric acid is introduced to facilitate hydrolysis and improve sericin fractionation efficiency, its contribution to overall raw material costs remains negligible within the system boundary assumptions. Economic evaluation indicates that cocoon feedstock overwhelmingly dominates the raw material cost structure, accounting for approximately 99.89% of total raw material expenses and corresponding to an annual cost of about 3.96 M$ at an assumed price of 50 $ kg^{-1}.

Overall, the material balance highlights two key characteristics of the evaluated systems. First, both processes achieve complete protein recovery from cocoon biomass, ensuring full utilization of the sericin and fibroin components. Second, while the citric-acid-assisted process requires larger water throughput due to diafiltration operations, the additional reagent input remains economically insignificant compared with the cost of the primary biomass feedstock. This observation confirms that the economic performance of sericin recovery systems is primarily governed by cocoon feedstock pricing rather than by auxiliary reagents used in the extraction process.

Energy demand and utility distribution

The energy balance analysis indicates that thermal operations constitute the primary source of utility consumption within the process. The total annual utility cost was estimated at approximately 30,218 $ yr^{-1}, distributed among chilled water, steam, electricity, and glycol. Among these utilities, chilled water represents the dominant demand, accounting for approximately 53,273 MT yr^{-1} (70.5% of total utility consumption). This high cooling requirement is mainly associated with condensation stages following thin-film evaporation and the recovery of exhaust streams from the spray-drying unit. Steam consumption amounts to approximately 634 MT yr^{-1} (25.2%), primarily required for autoclave extraction and evaporation processes where elevated temperatures are necessary for efficient protein solubilization and solvent removal.

Electricity demand is relatively modest, totaling 8,264 kWh yr^{-1} (2.7%), and is mainly associated with equipment operation such as shredding, pumping, centrifugation, and spray-drying auxiliary systems. In addition, glycol usage reaches approximately 586 MT yr^{-1} (1.6%), serving as a secondary heat-transfer medium within the thermal management system.

Despite the relatively high thermal demand associated with extraction and evaporation steps, the overall economic impact of utilities remains minimal. Utility costs account for only about 0.33% of the total annual operating cost, indicating that energy consumption does not represent a critical economic driver for the process. Instead, the techno-economic performance of the system is primarily governed

by raw material costs and labor-related expenses, which dominate the operating cost structure.

Capital investment analysis

The capital investment requirements differ substantially between the two evaluated process configurations. For the hot-water autoclave extraction scenario, the total capital investment (TCI) is estimated at approximately 4.737 M$, which includes fixed capital, working capital, and start-up costs. Within this amount, the direct fixed capital (DFC) represents 3.811 M$, covering equipment purchase, installation, piping, instrumentation, buildings, and auxiliary facilities required for plant operation.

The total equipment purchase cost for this configuration is estimated at 626,000 $. The largest contributions originate from the thin-film evaporator (152,000 $) and the spray dryer (136,000 $), both of which are critical units responsible for solvent removal and final product formation. Additional significant equipment investments include the cocoon shredder (99,000 $) and the condensation and extraction units (114,000 $) that enable efficient thermal extraction and vapor recovery. Although the direct equipment cost appears relatively moderate, indirect expenses substantially increase the overall plant cost. Engineering costs account for approximately 518,000 $, while construction expenses contribute 725,000 $, reflecting the infrastructure requirements associated with thermal processing and industrial-scale drying operations.

In comparison, the hot water–citric acid autoclave extraction process requires a significantly higher capital investment due to the inclusion of additional separation technologies aimed at molecular-weight fractionation. The total capital investment for this configuration is estimated at approximately 12.78 M$, representing a nearly threefold increase relative to the hot-water-only scenario. The higher investment is primarily driven by the addition of centrifugation and multi-stage diafiltration units, which substantially increase equipment complexity and downstream processing requirements.

In this scenario, the total equipment purchase cost reaches 1.823 M$. The largest contribution arises from the installation of two industrial centrifuges (876,000 $) used for efficient solid–liquid separation of fibroin and sericin fractions. Other key equipment includes the spray dryer (136,000 $) and thin-film evaporator (126,000 $) for concentration and drying operations, the autoclave reactor (107,000 $) used for citric-acid-assisted hydrolysis, and the three diafiltration units (DF-101, DF-102, DF-103) with a combined cost of approximately 114,000 $, which enable the separation of sericin into distinct molecular-weight fractions.

When installation, piping, instrumentation, buildings, and other auxiliary systems are included, the total plant direct cost (TPDC) for the citric-acid-assisted process increases to approximately 6.10 M$. Additional indirect costs, including engineering and construction, contribute about 3.66 M$, and after accounting for contractor fees and contingency factors, the direct fixed capital (DFC) reaches 11.23 M$.

Overall, the capital investment analysis highlights a clear trade-off between process simplicity and product value creation. While the hot-water extraction configuration requires relatively modest capital investment and relies on a simpler equipment layout, the citric-acid-assisted process introduces additional separation technologies that substantially increase capital requirements. However, this higher investment enables molecular-weight-resolved fractionation and a diversified product portfolio, which ultimately enhances the economic potential of the process in subsequent profitability analyses.

Operating cost structure

The annual operating cost (AOC) differs significantly between the two evaluated process configurations due to differences in process complexity and downstream separation requirements. For the hot-water autoclave extraction scenario, the AOC is estimated at approximately 9.024 M$ yr^{-1}. The cost structure is strongly dominated by raw materials, which account for 6.601 M$ (73.15%) of the total operating expenses. This high contribution originates almost entirely from cocoon feedstock, assuming a cocoon price of 50 $ kg^{-1}. Labor-dependent costs represent 1.457 M$ (16.15%), followed by facility-dependent costs of 0.717 M$ (7.95%), while laboratory, quality control, and quality assurance activities contribute 0.219 M$ (2.42%) to the total annual expenses. Utilities, consumables, and waste treatment costs remain relatively insignificant in this configuration, indicating that the economic performance of the hot-water extraction process is primarily governed by feedstock pricing and supply stability.

In contrast, the hot water–citric acid autoclave extraction process with molecular-weight fractionation exhibits a substantially higher annual operating cost of approximately 15.39 M$ yr^{-1}. The cost structure in this configuration is markedly different from the baseline scenario. Labor-dependent costs become the largest contributor, reaching 6.95 M$ (45.1%), reflecting the increased operational complexity associated with multi-stage diafiltration and additional downstream processing steps. Raw material costs decrease in relative importance, accounting for 3.96 M$ (25.8%), although cocoon feedstock remains the primary contributor within this category.

Facility-dependent costs increase to 2.11 M$ (13.7%), reflecting the higher capital investment and infrastructure requirements of the fractionation-based process. Laboratory, quality control, and quality assurance activities contribute 1.04 M$ (6.8%), while consumables, particularly centrifuge components and membrane replacement for diafiltration units, represent an additional 1.30 M$ (8.4%) of the total operating cost. In contrast to these dominant cost categories, utilities (0.012 M$, 0.08%) and waste treatment (0.018 M$, 0.12%) remain negligible despite the presence of energy-intensive thermal operations.

Overall, the comparison reveals a fundamental shift in cost drivers between the two process configurations. While the hot-water extraction process is largely feedstock-driven, the citric-acid-assisted fractionation process becomes operation-driven, where labor intensity and consumable requirements associated with membrane-based separation dominate the operating expenses. This structural change in cost distribution highlights the economic trade-off between process simplicity and value-added product diversification in advanced sericin biorefinery systems.

Revenue streams and co-product valorization

The revenue generation patterns differ considerably between the two evaluated process configurations due to differences in product portfolio and value density. In the hot-water autoclave extraction scenario, revenue is generated from two main product streams: bulk sericin powder and fibroin recovered as a co-product. The process produces approximately 34,255 kg yr^{-1} of sericin, which, assuming a market price of 150 \$ kg^{-1}, generates an annual revenue of approximately 5.138 M\$ yr^{-1}. In addition, 99,657 kg yr^{-1} of fibroin is recovered and sold at 50 \$ kg^{-1}, yielding an additional 4.983 M\$ yr^{-1}. Consequently, the total annual revenue for this configuration reaches approximately 10.121 M\$ yr^{-1}. Notably, fibroin recovery contributes nearly 49% of the total revenue, highlighting the critical role of co-product valorization in ensuring the economic feasibility of the process. Without the recovery and commercialization of fibroin, the profitability of the hot-water extraction scenario would be significantly reduced.

In contrast, the hot water–citric acid autoclave extraction process with molecular-weight fractionation generates revenue from a diversified portfolio of sericin fractions in addition to fibroin. In this configuration, the 7-10 kDa sericin fraction, selected as the main product due to its higher functional value, generates approximately 783,735 \$ yr^{-1}. However, the major economic contribution arises from the >10 kDa sericin fraction, which yields approximately 30.08 M\$ yr^{-1}. Additional revenues are obtained from the 3.5-7 kDa fraction (1.56 M\$ yr^{-1}) and the <3.5 kDa fraction (1.48 M\$ yr^{-1}), while fibroin recovery contributes approximately 2.97 M\$ yr^{-1}.

As a result, the total annual revenue for the fractionation-based process reaches approximately 36.87 M\$, which is more than three times higher than that of the hot-water-only extraction scenario. Importantly, more than 81% of the total revenue originates from the >10 kDa sericin fraction, demonstrating the strong economic leverage associated with molecular-weight-resolved sericin valorization. This diversified product portfolio significantly enhances the value extracted from cocoon biomass and illustrates how fractionation strategies can transform sericin recovery from a bulk protein extraction process into a high-value biorefinery system.

Profitability indicators and economic performance

The techno-economic evaluation reveals substantial differences in profitability between the two investigated process configurations. For the hot-water autoclave extraction scenario, the process achieves a unit production cost of 263.42 \$ kg^{-1} sericin, while the unit production revenue reaches 295.46 \$ kg^{-1}, resulting in a gross margin of 10.84%. The overall economic indicators show a return on investment (ROI) of 21.55%, with a payback period of approximately 4.64 years. The internal rate of return (IRR, after tax) is estimated at 13.61%, and the net present value (NPV) at a discount rate of 7% reaches 2.30 M\$. These indicators confirm that the hot-water extraction process is economically feasible, particularly when fibroin co-production is considered as an additional revenue stream. The positive NPV and moderate payback time suggest that this configuration represents a viable option for medium-scale industrial implementation, especially in facilities already integrated with sericulture or textile production chains.

In contrast, the hot water–citric acid autoclave extraction process combined with molecular-weight fractionation demonstrates significantly stronger economic performance. In this configuration, the unit production cost of the main product (7-10 kDa sericin) is estimated at 2,945.6 \$ kg^{-1}, while the unit production revenue reaches 7,057.1 \$·kg^{-1}, resulting in a substantially higher gross margin of 58.26%. The investment performance indicators are also markedly improved, with an ROI of 109.2% and a remarkably short payback period of approximately 0.92 years. The IRR (after tax) increases to 60.18%, while the NPV at a 7% discount rate reaches 82.98 M\$, indicating strong long-term economic value generation.

Overall, the comparison highlights a clear distinction between the two process strategies. While the hot-water extraction process offers stable but moderate profitability suitable for conventional protein recovery operations, the citric-acid-assisted fractionation process enables substantially higher economic returns through value-added product diversification. The exceptional ROI and rapid capital recovery observed in the fractionation-based scenario indicate strong resilience against market fluctuations and demonstrate the economic advantages of transforming sericin recovery into a multi-product biorefinery platform.

Discussion and industrial ımplications

The results demonstrate that the hot-water autoclave extraction process provides a chemically clean and technically reliable route for sericin recovery from waste silk cocoons. Although thermal operations increase capital requirements and energy demand, these disadvantages are largely offset by the absence of chemical reagents, the elimination of waste-treatment costs, and the additional revenue generated through fibroin co-production. Compared with conventional acid- or alkali-based extraction methods, the hot-water approach offers improved environmental compatibility and simpler downstream purification, making it an attractive option for facilities seeking low-complexity and environmentally benign sericin recovery technologies.

However, the economic performance of the hot-water-only configuration remains strongly dependent on cocoon

feedstock price and drying energy demand. Since cocoon procurement represents the dominant cost component, fluctuations in feedstock pricing can significantly influence profitability. Therefore, future optimization strategies should focus on improving raw material sourcing, increasing water recycling efficiency, and exploring alternative drying technologies to reduce energy demand and further enhance economic performance.

In contrast, the citric-acid-assisted autoclave extraction process combined with molecular-weight fractionation demonstrates a fundamentally different economic structure. While this configuration requires higher capital investment and operating costs due to the integration of centrifugation and diafiltration units, it simultaneously enables a much more diversified product portfolio. The separation of sericin into multiple molecular-weight fractions significantly increases the value density of the recovered biomolecules, leading to substantially higher total revenue and markedly improved profitability indicators.

Overall, the comparative analysis confirms that molecular-weight fractionation transforms sericin recovery from a relatively low-margin commodity extraction process into a high-value biorefinery platform. This approach maximizes the utilization of cocoon biomass and aligns strongly with circular bioeconomy principles by converting sericulture waste streams into multiple value-added bioproducts.

While the hot-water autoclave process demonstrates baseline technical feasibility and environmental compatibility, the integration of citric-acid-assisted extraction with diafiltration enables true biorefinery-scale valorization of waste cocoons, achieving significantly superior economic performance through molecular-weight-resolved product streams.

Sensitivity and risk perspective

Sensitivity analysis indicates that Scenario I is highly vulnerable to cocoon price fluctuations, as raw materials dominate its cost structure. Conversely, Scenario II exhibits greater resilience to feedstock price volatility due to diversified revenue streams and higher value density.

However, Scenario II introduces new operational risks, including membrane fouling, higher labor dependency, and tighter process control requirements. These risks are mitigated by the rapid payback period and strong cash flow, suggesting that Scenario II is better suited for technologically mature operators rather than entry-level facilities.

Environmental and sustainability considerations

From an environmental standpoint, both scenarios benefit from the absence of hazardous chemicals and full biomass valorization. Scenario II, despite higher water and operational intensity, achieves lower effective carbon footprint per unit of revenue due to economic allocation across multiple high-value products. This reinforces the concept that value maximization can indirectly improve environmental performance in biorefinery systems.

Strategic ımplications for industrial deployment

Taken together, the comparative analysis indicates that Scenario I is suitable for low-complexity, feedstock-integrated installations aiming for bulk sericin production with moderate profitability. In contrast, Scenario II represents a next-generation sericin biorefinery, capable of delivering superior economic returns through molecular-weight fractionation and product diversification. Process complexity increases cost, but strategic fractionation multiplies value.

Conclusion and industrial outlook

This study presents a comprehensive techno-economic evaluation of two distinct sericin recovery strategies from waste silk cocoons: a conventional hot water autoclave extraction route and an advanced hot water–citric acid autoclave process coupled with molecular-weight fractionation. The comparative analysis clearly demonstrates that process design philosophy—rather than extraction chemistry alone—plays a decisive role in determining economic viability.

The hot water autoclave process represents a technically robust and environmentally benign baseline scenario, characterized by low process complexity, moderate capital investment, and stable operation. However, its economic performance is constrained by a commodity-driven product portfolio, resulting in limited margins and high sensitivity to cocoon feedstock prices. This configuration is therefore best suited for integrated sericulture or textile facilities seeking incremental value recovery with minimal technological risk.

In contrast, the hot water–citric acid autoclave process with diafiltration transforms sericin recovery into a high-value biorefinery system. Although this scenario requires higher capital investment and operational sophistication, the ability to fractionate sericin into multiple molecular-weight-defined products enables access to premium markets and dramatically enhances profitability. The resulting economic indicators ROI exceeding 100%, payback time below one year, and a strongly positive NPV underscore the transformative impact of molecular-weight-resolved valorization.

Increasing process complexity can be economically justified when it enables disproportionate value creation.

Furthermore, when combined with full biomass utilization (fibroin recovery) and chemical-light processing, the biorefinery-oriented scenario aligns strongly with circular bioeconomy principles. The integrated TEA–LCA perspective suggests that maximizing value density per unit biomass not only improves economic resilience but also reduces the effective environmental burden per unit revenue.

Overall, this work provides a quantitative framework for selecting sericin recovery strategies based on investment capacity, technical maturity, and target market positioning. The findings support the industrial deployment of advanced fractionation-based sericin biorefineries as a next-generation pathway for sustainable valorization of sericulture waste streams.

This study demonstrates that sericin recovery economics are not governed by extraction yield alone, but by the ability to engineer molecular-weight-defined product portfolios that unlock high-value markets.

Author contributions

Bahar Sincar: Conceived the research idea, conducted the simulations, recorded observations, analyzed the data, and prepared the initial manuscript draft. Oguz Bayraktar: Provided scientific guidance throughout the study, supervised the simulations and data analysis, and critically reviewed and revised the manuscript. All authors approved the final manuscript.

References

Aad, R., Dragojlov, I., & Vesentini, S. (2024). Sericin protein: Structure, properties, and applications. *Journal of Functional Biomaterials, 15*(11), 322. https://doi.org/10.3390/jfb15110322

Capar, G., & Aygün, S. S. (2015). Characterization of sericin protein recovered from silk wastewaters. *Türk Hijyen ve Deneysel Biyoloji Dergisi, 72*(3), 219-234.

Capar, G., & Pilevneli, T. (2024). Cost-effective process development for sericin recovery from silk degumming wastewater. *Sustainable Chemistry and Pharmacy, 37*, 101405. https://doi.org/10.1016/j.scp.2023.101405

Chetia, P., Kashyap, B., Bora, S., Kaushik, A., Sut, R., Naan, T., & Bharathi, S. A. B. (2025). Upcycling silk waste into clean beauty: Sericin as a green skincare ingredient. *Journal of Advances in Biology & Biotechnology, 28*(8), 1038-1046. https://doi.org/10.9734/jabb/2025/v28i82777

da Silva, T. L., da Silva Junior, A. C., Ribani, M., Vieira, M. G. A., Gimenes, M. L., & da Silva, M. G. C. (2014). Evaluation of molecular weight distribution of sericin in solutions concentrated via precipitation by ethanol and precipitation by freezing/thawing. *Chemical Engineering Transactions, 38*, 103-108. https://doi.org/10.3303/CET1438018

Mathew, S. S., Maria, H. J., Allardyce, B. J., Rajkhowa, R., & Thomas, S. (2024). Waste to wealth: Exploring the versatile prospects of discarded silk sericin. *ACS Sustainable Chemistry & Engineering, 12*(3), 1165-1184. https://doi.org/10.1021/acssuschemeng.3c04264

Orlandi, G., Faragò, S., Menato, S., Sorlini, M., Butti, F., Mocchi, M., Donelli, I., Catenacci, L., Sorrenti, M. L., Croce, S., Segale, L., Torre, M. L., & Perteghella, S. (2020). Eco-sustainable silk sericin from by-product of textile industry can be employed for cosmetic, dermatology and drug delivery. *Journal of Chemical Technology & Biotechnology, 95*(9), 2549-2560. https://doi.org/10.1002/jctb.6441

Paladini, F., D'Urso, F., Panico, A., Lanzillotti, C., Broccolo, F., & Pollini, M. (2025). Comparative analysis of highly purified sericin and waste-derived sericin: Implications for biomedical applications. *Biomimetics, 10*(6), 387. https://doi.org/10.3390/biomimetics10060387

Qadir, J., Islam, T., Gupta, R. K., Bali, K., Sharma, M., Gupta, S. K., & Samnotra, R. K. (2025). Quantification of sericin extracted from different seri bio-waste sources. *Journal of Scientific Agriculture, 9*, 66-68. https://doi.org/10.25081/jsa.2025.v9.9502

Saha, J., Mondal, M. I. H., Sheikh, M. R. K., & Habib, M. A. (2019). Extraction, structural and functional properties of silk sericin biopolymer from Bombyx mori silk cocoon waste. *Journal of Textile Science & Engineering, 9*(1), 1000390. https://doi.org/10.4172/2165-8064.1000390

Sincar, B., Özdemir, F., Bıçakcı, B. T., Erdem, C., Yalçın, D., Alamri, A. S., Galanakis, C. M., & Bayraktar, O. (2026). Comparative optimization of hot water and citric acid extraction methods for sericin recovery from silk cocoons. *Journal of Pharmaceutical Innovation, 21*, 95. https://doi.org/10.1007/s12247-025-10189-z

Veiga, A., Ramírez-Jiménez, R. A., Santos-Rosales, V., García-González, C. A., Aguilar, M. R., Rojo, L., & Oliveira, A. L. (2025). Innovative processing and sterilization techniques to unlock the potential of silk sericin for biomedical applications. *Gels, 11*(2), 114. https://doi.org/10.3390/gels11020114

Yuan, Y., Nasri, M., Manayi, A., Zhang, J., Wu, C., Jeon, T.-J., & Kang, L. (2024). Sericin coats of silk fibres, a degumming waste or future material? *Materials Today Bio, 29*, 101306. https://doi.org/10.1016/j.mtbio.2024.101306

Zhou, B., Wang, H., Zhao, J., Chen, J., & Zhou, H. (2023). Study on structure and anti-UV properties of sericin cocoons. *Autex Research Journal, 23*(2), 193-199. https://doi.org/10.2478/aut-2021-0058