# Valorisation of Silk Textile Industry Wastewater for Sustainable Agriculture: Life Cycle Assessment and Life Cycle Costing of Sericin Biostimulant Application in Lettuce Cultivation

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***Abstract*—The silk textile industry produces high volumes of wastewater during the degumming process, which removes sericin, a water-soluble protein coating raw silk fibres. Most of this sericin is currently lost in effluents, with limited reuse for cosmetics and biomedical solutions. Given the promising results of sericin in promoting seed germination, enhancing plant growth, and improving tolerance to abiotic stress, this study explores its novel agricultural application by assessing the recovery and reuse of sericin as a biostimulant in lettuce cultivation. Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) studies are conducted to evaluate the environmental and economic feasibility of three scenarios, using 1 kg of lettuce as the functional unit. The first scenario reflects the current system: wastewater is treated conventionally, and lettuce is grown using standard methods. In the second scenario, sericin is concentrated via ultrafiltration to a 5% w/v solution, then stabilised, diluted, transported, and applied to crops. The third scenario proposes a simplified route: the degumming wastewater is diluted and directly applied to the field, bypassing other processing steps. Findings reveal that the third scenario achieves the best results both in terms of environmental performance and economic viability, showing a 40% improvement over the second scenario on selected impact indicators. Sensitivity analysis confirms its benefits within a reasonable transport distance. Beyond replacing wastewater treatment, this approach converts a waste stream into an agricultural resource, aligning with circular economy principle The study also highlights the processes that contribute most to overall impacts and demonstrates the potential of sericin valorisation as a sustainable solution in the agricultural sector.**

***Keywords*—sustainability, circular economy, life cycle assessment, life cycle costing, Sericin, wastewater treatment, agriculture**

## I. Introduction

### *A. Sustainability and Textile Wastewater*

In recent decades, the linear economic paradigm, which follows the extract-produce-use-dispose model, has increasingly been recognised as unsustainable. Its nature is marked by excessive resource consumption, high volumes of waste generation, and significant environmental impacts, including greenhouse gas emissions and water pollution [1]. In this context, the textile industry contributes to these pressures through its intensive use of water and energy [2]. Wastewater from textile processing, particularly in silk manufacturing, presents a notable case for concern and opportunity. Among the various textile processes, silk production involves a degumming stage in which the fibres are treated to remove sericin, a hydrophilic protein that accounts for approximately 20 to 30% of the cocoon weight [3]. The removal of sericin during degumming generates a sericin-rich wastewater stream, which is typically discharged in wastewater treatment plants and presents high organic loads, thus elevated chemical and biological oxygen demand (COD and BOD) levels and significant treating challenges [4].

Moreover, the transition from a linear to a circular economy (CE) has been increasingly linked not only to environmental efficiency but also to issues of environmental justice and sustainable agriculture. Circular strategies are expected to reduce environmental burdens while also redistributing the benefits and costs of resource use more equitably across industrial and agricultural sectors. In this sense, industrial wastewater valorisation represents a concrete opportunity to strengthen local value chains, enhance resilience in agro-industrial systems, and contribute to the United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), and SDG 12 (Responsible Consumption and Production) [5]. Moreover, this wasteful disposal practice stands in contrast to the growing emphasis on CE strategies, which aim to enhance resource efficiency and close material loops across production systems [6]. In this perspective, industrial wastewater is increasingly recognized as a secondary source of raw materials. Recent policy frameworks and scientific research have highlighted the importance of recovering valuable compounds from process effluents, aligning industrial practices with sustainability and zero-waste objectives [7]. Within this perspective, the valorisation of sericin offers a compelling example of how a compound traditionally regarded as a contaminant can instead be repurposed into high-value applications across various sectors, including pharmaceuticals, cosmetics [8], biomedicine, and, here explored, agriculture [9, 10]. More specifically, sericin is water-soluble, biodegradable, and exhibits a wide range of biofunctional properties such as antioxidant, antimicrobial, moisturizing, and metal chelating activities, which make it an attractive biopolymer for both technological and agronomic uses [11, 12].

Additionally, the commercial value of sericin is non-negligible, as prices vary greatly depending on its purity and intended use, from standard industrial formulations to highly refined products used in research or healthcare contexts [13]. Despite its potential, sericin is still largely discarded in current industrial practices, representing not only a source of pollution but also a lost economic opportunity.

Considering that the global silk industry, with China and India as leading producers, generates tens of thousands of tonnes of wastewater containing high concentrations of sericin each year, the development and implementation of efficient recovery processes is necessary [14]. Techniques such as membrane filtration, flocculation, enzymatic treatments, and hybrid systems have shown promising results in recovering sericin at both laboratory and pilot scales [15], exemplifying how traditional waste streams can be reimagined as resource flows in the transition toward a circular and sustainable bioeconomy.

Building on these considerations, this study aims to advance current knowledge by investigating an innovative application of sericin in the agricultural sector, specifically through its recovery and reuse in lettuce cultivation. From a broader perspective, sericin can be considered an alternative protein recovered from waste and used as a biostimulant: A shift that exemplifies eco-innovation in agro-industrial systems. Such a transition is consistent with the growing literature on bio-based innovations, where biostimulants obtained from industrial by-products are emerging as tools to increase crop productivity while reducing dependence on conventional chemical inputs. Hence, sericin valorisation contributes not only to closing material loops in the textile industry but also to reinforcing sustainable and circular agro-industrial systems.

The analysis focuses on a combined LCA and LCC approach, to identify both the environmental and economic impacts, as well as the key hotspots along the value chain. To this end, the study aims to address the following Research Questions (RQs):

1. *To what extent does the valorisation of sericin from silk degumming wastewater reduce the environmental impacts of lettuce cultivation compared to conventional practices?*
2. *To what extent do transportation costs affect the economic feasibility of valorising sericin-rich wastewater in local agricultural systems?*

To achieve the research objective, the article is structured as follows: Section II reviews previous studies on the recovery and application of sericin in various sectors, as well as research addressing environmental impacts along the value chain. Section III presents the case study, detailing the analysed scenarios and the evaluation methods adopted through LCA and LCC approaches. Section IV reports the results and offers a critical discussion of the findings. Finally, Section V outlines the conclusions and provides recommendations for future research.

## II. Literature Review

The potential for sericin recovery from silk degumming wastewater has been extensively explored, with various studies focusing on enhancing extraction efficiency and product quality through diverse process configurations [16]. Traditional methods, such as hot water extraction and ethanol precipitation, have been complemented by advanced techniques like membrane filtration, ultrafiltration, and hybrid processes, offering improved selectivity and scalability. For instance, membrane-based recovery systems utilising polysulfone membranes have demonstrated the ability to concentrate and retain sericin with high molecular weight fractions, which are particularly relevant for applications requiring specific biofunctional properties [17]. Similarly, precipitation methods involving calcium chloride have shown potential for economically viable recovery while preserving the structural integrity of the protein [18]. Process integration strategies, such as flocculation combined with nanofiltration and low-energy drying steps, have also been investigated to reduce energy consumption and operational costs [19].

Recovered sericin has attracted growing interest across multiple sectors due to its multifunctional bioactivity. In the biomedical field, it has been studied for its applications in wound dressings, tissue engineering, and drug delivery systems, owing to its biocompatibility, low immunogenicity, and regenerative potential [20]. In the cosmetic industry, sericin is widely recognised for its moisturising, anti-ageing, and antioxidant effects, and is commonly used in formulations for skin care and hair treatment [21]. In the food sector, its antioxidant and antimicrobial properties enable its use as a natural preservative or functional protein additive [22]. Additionally, recent research has begun to highlight the relevance of sericin in agriculture, where it has shown potential as a biostimulant capable of promoting seed germination, enhancing root and shoot development, and improving resistance to abiotic stress [23]. This broad applicability, combined with the significant volume of sericin-rich wastewater generated in major silk-producing countries, such as China and India, reinforces the importance of valorising this protein rather than discarding it.

Several studies have adopted LCA methodologies to assess the sustainability of sericin recovery pathways [24–26]. These analyses have revealed that, while sericin recovery can reduce the environmental burden associated with conventional wastewater treatment, it also introduces new impacts, primarily related to energy-intensive steps such as lyophilisation and chemical usage in precipitation [25]. A comparative LCA by [19] has demonstrated that scenarios including ethanol precipitation and lyophilisation exhibit notably higher impacts in categories such as global warming potential and non-renewable energy use compared to simpler process chains, suggesting that process simplification can substantially improve sustainability performance [27].

In parallel, LCC has been used to assess the economic viability of sericin recovery. One comprehensive study has examined eight alternative process configurations, combining different pre-treatment, concentration, and drying technologies. It found that the unit cost of recovered sericin ranged from €89 to €1300 per kilogram, with the lowest costs associated with minimal processing (e.g., pre-treatment and oven drying only), and the highest costs driven by lyophilisation and ethanol use [19]. Staff and energy expenses have been identified as the most significant operational cost items. Importantly, the economic feasibility of these systems has improved substantially when targeting high-purity or specialised sericin applications, suggesting a strong link between end-use value and process optimisation [28].

While previous studies have demonstrated the technical feasibility of sericin recovery and have highlighted its potential applications across various sectors, research integrating both environmental and economic performance assessments remains limited. In particular, few studies have conducted comparative evaluations of different valorisation routes, especially in the context of agricultural applications. Moreover, existing LCA and LCC studies often focus on process optimisation or single end-use applications, without addressing the trade-offs between different recovery scenarios within a circular economy framework. By combining LCA and LCC to evaluate multiple valorisation strategies in the agricultural context, this study aims to bridge these gaps. It offers a novel contribution by quantifying not only the environmental and economic benefits of sericin reuse in crop production but also the broader implications of shifting from a waste treatment paradigm to one based on material recovery and functional reuse.

## III. Materials and Methods

### A. Case Study

In the silk manufacturing process, degumming is a critical phase in the raw silk processing, which involves the removal of sericin from the silk to give the filament its characteristic softness and sheen. Conventionally, the degumming process is performed at a boiling temperature using a solution of soap and soda at alkaline pH [25]. Most updated routes minimize the use of additives, only tuning water temperature.

As a by-product of degumming, large volumes of wastewater containing sericin are generated and typically discharged as pure waste. Treating this wastewater in the appropriate facilities requires electricity in multiple phases and the addition of chemicals according to the COD and BOD levels of the incoming sample. Chemicals used in the wastewater treatment process are aluminum sulfate ($Al_2(SO_4)_3$), ozone ($O_3$), and polyelectrolytes.

For silk sericin recovery and valorisation, an ultrafiltration module is used, allowing the solution derived from the degumming process to be concentrated through a membrane, resulting in a product with a higher sericin concentration, called serigel. The ultrafiltration process generates two outputs: a retentate, consisting of the serigel concentrated at 5% w/v sericin, and a permeate, which is the fraction of the solution containing only minimal residual amounts of sericin and that must still be sent to the wastewater treatment facility, although it requires a reduced input of chemicals for treatment. The ultrafiltration process enables the concentration of an initial 1.2% w/v sericin solution to 5% w/v in two hours, relying exclusively on electricity. Each cycle of the process yields 20 kg of solution at 5% w/v, starting from approximately 83 kg of the initial 1.2% w/v solution.

Once recovered, the sericin solution undergoes additional steps before its application on crops: on-site transportation using a tank truck and stabilisation with specific additives. The stabilisation of the solution is essential both to prolong its shelf life and to neutralise it to a pH 7, making it suitable for agricultural use. The additives used for this purpose are sodium benzoate, sulphuric acid, and potassium hydroxide.

Subsequently, the sericin solution is applied to lettuce crops during the conventional fertilisation phase, diluted to a final concentration of 0.25%w/v in a 1:20 ratio and adjusted to a pH of 7.

Prior to field application of the degumming wastewater, a mineral ionic profile was conducted to confirm the environmental safety of the solution, revealing the absence of heavy metal pollutants and a non-toxic Na level.

### B. Description of the Scenarios

To assess the recovery and reuse of degumming wastewater in lettuce production, three scenarios were considered in Fig. 1.

The first scenario (S1) represented the as-is state, in which wastewater from the degumming process, containing sericin at a concentration of 1.2% w/v, was sent to wastewater treatment facilities, while lettuce was cultivated in parallel using conventional methods.

The second scenario (S2) introduced an ultrafiltration step for the degumming water to concentrate sericin to 5% w/v, followed by transportation of serigel to the field using tank trucks, on-site stabilisation before use, dilution to a final sericin concentration of 0.25% w/v, and foliar application on crops during the fertilisation phase. While serigel underwent these steps, the permeate generated by the ultrafiltration process was sent to wastewater treatment facilities.

The third scenario (S3) explored a simplified alternative to the second one, excluding the ultrafiltration step and, as a result, eliminating the generation of permeate and its subsequent treatment at the wastewater facility. In this case, wastewater from the degumming process was directly transported to the application site using tank trucks, then stabilised on-site and applied directly to the field through foliar spraying during the fertilisation phase.

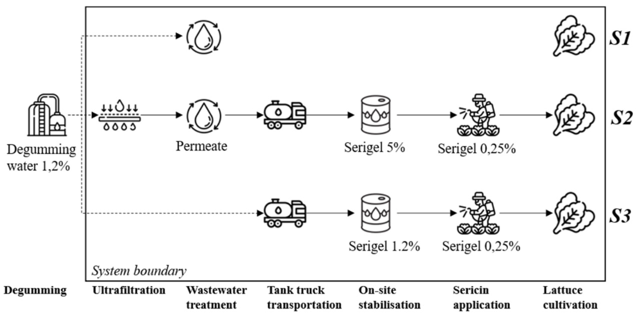


Fig. 1. System boundaries and life cycle phases considered in the LCA of the three scenarios.

### C. LCA and LCC Analysis

#### 1) LCA and LCC methodology

In line with recent contributions in the circular economy literature [29], the integration of LCA and LCC in this study responds to the need for hybrid environmental-economic assessments capable of capturing trade-offs between resource recovery strategies, environmental impacts, and economic feasibility. This combined approach allows the modelling of sericin valorisation not only as an environmental intervention, but also as an eco-innovative circular pathway where environmental burdens and economic constraints must be jointly assessed to inform sustainable decision-making.

Both LCA and LCC methodologies follow established international standards to ensure robustness, comparability, and transparency of results.

The environmental analysis was conducted according to the ISO 14040 and ISO 14044 standards [30], which define the principles and framework for LCA. This includes four interconnected phases: (i) goal and scope definition, (ii) life cycle inventory (LCI), (iii) life cycle impact assessment (LCIA), and (iv) interpretation. LCA provides a comprehensive evaluation of potential environmental impacts throughout the entire life cycle of a product or system, from resource extraction and processing to end-of-life. In this study, environmental impacts were calculated using a proprietary tool developed by SUPSI, which complies with ISO requirements and integrates the Environmental Footprint (EF) method, enabling midpoint characterisation of multiple impact categories.

The economic dimension was addressed through Life Cycle Costing, based on the framework proposed in the ILCD Handbook. LCC is used to quantify all relevant cost flows associated with the life cycle of a product or service, including capital, operational, maintenance, and end-of-life costs. Unlike conventional cost accounting, LCC captures long-term economic performance and enables cost comparison between alternative scenarios from a life cycle perspective.

*2) Goal and scope*

In this combined LCA and LCC study, the Functional Unit (FU) was set as the cultivation of 1 kg of fresh lettuce in Northern Italy under conventional greenhouse conditions during the autumn 2024 cultivation season, excluding harvesting and post-harvest operations. The system boundaries, illustrated in Fig. 2, were defined according to a cradle-to-grave approach, extending from the entry of degumming wastewater into the system to the production of lettuce. Within this configuration, the degumming process itself was omitted from the analysis, as it does not induce differential impacts across the three scenarios. Given the comparative nature of the study, excluding non-differentiating processes ensured that the assessment focused exclusively on the environmental and economic differences generated by alternative management pathways for sericin-rich wastewater recovery and reuse in lettuce cultivation.

The reference flow was defined as a fixed amount of sericin corresponding to the selected FU. While the quantity of sericin remained constant across scenarios, the associated flows, such as wastewater volume, energy consumption, and chemical inputs, varied depending on the processes involved.

To fulfil the FU, defined as the cultivation of 1 kg of lettuce, 1.335 L of sericin solution at a concentration of 0.25% w/v was used, corresponding to 4.34 g of sericin, assuming a solution density of 1.30 kg/L. This amount represented the application dose identified through experimental trials, resulting in a biomass yield increase, expressed as fresh weight of the usable product, of approximately 45%. This biomass increase was observed under both normal and saline stress conditions. It is important to highlight that, as experimental trials on lettuce were still in their early stages, the results obtained on crop growth were not considered sufficiently robust to be included in the assessment conducted in this study.

The initial volume of degumming wastewater, identical across all three scenarios, was therefore 0.278 L of solution at a concentration of 1.2% w/v. This initial volume of the solution changed from one step to another in S2, since it underwent ultrafiltration.

The amount of sericin required to satisfy the FU was calculated as follows: 1 kg of lettuce corresponded to approximately 7 lettuce crops weighing 150 g each. During the lettuce life cycle of 21 days, each crop received two applications of sericin solution, for a total of 200 mL, concentrated at 0.25% w/v.

*3) Life cycle inventory*

The LCI data used in this study are presented in Table 1, grouped by process, reported for each scenario, and with the corresponding data source.

Table 1. LCI input-output data for each scenario

| Process | LCI data | Unit | S1 | S2 | S3 | Source |
|---|---|---|---|---|---|---|
| Ultrafiltration | electricity, low voltage | kWh | - | 0.0501 | - | Plant data |
| Wastewater treatment | electricity, low voltage | kWh | 0.002 | 0.0016 | - | Plant data |
| | chemicals mix | g | 0.116 | 0.0658 | - | |
| | sewage sludge | g | 9.509 | 3.5715 | - | |
| Transportation | lorry 3.5-7.5 metric ton, EURO5 | kg * km | - | 3.3871 | 13.971 | Ecoinvent |
| Stabilisation | benzoic acid production | g | - | 0.203 | 0.201 | Plant data |
| | sulfuric acid production | g | - | 0.211 | 0.209 | |
| | potassium hydroxide production | g | - | 0.233 | 0.231 | |
| Sericin application | tap water (dilution to 0.25% w/v) | L | - | 1.2679 | 1.058 | Plant data |
| | diesel, burned in agricultural machinery | kWh | - | 0.005 | 0.005 | |
| Lettuce cultivation | water pump operation, electric | MJ | 0.022 | 0.021 | 0.021 | Plant data + Ecoinvent |
| | water pump operation, diesel | MJ | 0.016 | 0.015 | 0.015 | |
| | tap water | L | 70 | 68.665 | 68.663 | |

The study primarily relied on technical data directly collected from the field, referred to as foreground data. When such data were not available, secondary data or background data from the Ecoinvent v3.11 database were used by disaggregating the relevant processes. Since data were collected in Northern Italy, Ecoinvent processes belonging to Italy (IT) origin were selected and, if not available, the ones with European origin (RER).

Technical data on lettuce cultivation, including the amount of sericin required, solution stabilisers, and fertilisers, were directly collected from the current use in the field. Fertiliser data, for instance, were derived from the technical sheet of the product used, ensuring consistency with real-case agricultural practices.

Additionally, samples of degumming water, with a sericin concentration of 1.2% w/v, and ultrafiltration permeate, containing negligible amounts of sericin, were sent to the wastewater treatment plant for analysis. These samples were used to determine both the chemicals involved and the specific electricity consumption as a function of the sericin solution concentration.

To further improve the accuracy of the study, the actual electricity mixes of the ultrafiltration and wastewater treatment facilities, derived from plant-specific data, were used instead of the national electricity mix provided by Ecoinvent v3.11.

As stated in the goal of the study, since this was a comparative LCA, input data that were non-differential across the scenarios were not included, as they did not provide any relevant information for the purpose of the assessment.

The following assumptions were made during the inventory analysis:

- The average weight of a lettuce head was approximately 150 g; therefore, around 7 heads were associated with the 1 kg functional unit, and the calculation of inputs and outputs was primarily based on this assumption.
- The volume of tap water applied per cultivation cycle (21 days), with or without sericin, to satisfy the FU, ranged from 1500 to 2000 $m^3$/ha. Considering that the surface area required to cultivate 1 kg of lettuce was approximately 0.4 $m^2$, it was assumed that around 70 L of tap water was needed per kilogram of lettuce.
- The solution at a concentration of 0.25% w/v of sericin was applied to the crop during the standard fertilisation phase, thereby eliminating the need for a dedicated application process and preventing additional fuel consumption. The application was performed twice during its cultivation cycle.
- Irrigation was assumed to be 50% drip and 50% sprinkler-based.
- In calculating the quantities of water and fertilisers required for lettuce cultivation, no differences were assumed between treatments with or without the sericin solution, as the experimental trial applied identical amounts in both cases. However, in the future, these quantities could be reduced where the solution is applied, based on the positive effects of sericin on crop growth.
- The transportation distance from the extraction site to the point of use was initially set at 50 km, based on a case-specific assumption that reflected the actual distance between companies located in Northern Italy.
- Electricity consumption at the wastewater treatment facility was calculated based on specific formulas corresponding to the treatment phases required. Calculations include both fixed and volume-dependent components; fixed values were excluded, as they were non-differentiating and could have biased the results.
- The specific amount of additives used to stabilise the sericin solution prior to use was determined experimentally on a 5% w/v concentration sample. For the 1.2% w/v concentration sample, the required amounts were calculated proportionally to the first sample, based on the sericin content per litre of solution.

### *D. Assessment Approach*

#### *1) Life cycle impact assessment and interpretation*

The LCIA phase was conducted following the characterisation method defined by the Environmental Footprint 3.1 (EF 3.1), as recommended by the European.

Commission for harmonised environmental assessments [31]. This method enabled a midpoint-based evaluation across a set of impact categories, ensuring consistency with current EU policy frameworks and comparability across studies. Unlike traditional LCIA approaches with limited focus, the EF 3.1 offered an extended set of indicators that captured a broader range of environmental mechanisms and pressures.

The selected impact categories included climate change, ozone depletion, human toxicity (cancer and non-cancer effects), particulate matter, ionising radiation (human health), acidification, eutrophication (terrestrial, freshwater, marine), ecotoxicity (freshwater), land use, water use, energy resources (non-renewable). These categories were chosen to provide a detailed and multidimensional assessment of the environmental burdens associated with the recovery and application of sericin in agriculture.

Impact calculations were carried out using a proprietary LCA tool developed by SUPSI, fully compliant with ISO 14040/44 standards and capable of implementing EF-compliant LCIA modelling. The analysis was performed at the midpoint level, and results were reported without normalisation or weighting, in line with current best practices for transparent, non-subjective environmental evaluation.

The final phase of the LCA, interpretation, was conducted in accordance with ISO 14044 guidelines, ensuring that the results from the inventory and impact assessment phases were critically analysed in relation to the defined goal and scope of the study. This step involved identifying significant contributions, evaluating data quality and consistency, and assessing the robustness of the results. Special attention was given to potential trade-offs between environmental benefits and burdens across the different scenarios. Furthermore, sensitivity analyses were performed to examine the influence of key parameters, such as transport distance and sericin concentration, on the overall impact profile. These insights supported a transparent and well-founded evaluation of the most sustainable valorisation strategy, reinforcing the credibility of the study's conclusions.

#### *2) Life cycle costing*

The cost assessment was conducted in parallel with the environmental assessment to quantify the economic burdens associated with the recovery and agricultural use of sericin as a biostimulant. The LCC approach incorporated economic data related to energy and material inputs, transportation, treatment, and field application. The analysis focused on direct costs borne by stakeholders, with particular emphasis on the transportation of the degumming wastewater, identified as a key economic bottleneck.

Unit costs were assigned to each process based on real data from the pilot plant and official sources (e.g., the Italian Ministry of Infrastructure and Transport for freight costs). The analysis compared scenarios S1 and S2, representing different strategies for processing and applying the by-product. For each scenario, total costs were calculated per FU, enabling a direct comparison of alternatives.

Integrating LCC results with those from the LCA allowed for the identification of the most sustainable solutions from both environmental and economic perspectives. Notably, the analysis highlighted the critical role of transport distance in determining the economic viability of this path of sericin recovery, reinforcing the need for optimized logistics or financial incentives to support the broader adoption of this circular practice.

## IV. Results and Discussion

### A. LCA Impacts Assessment

#### 1) Midpoint impacts

The midpoint impacts, based on the characterisation method defined by EF 3.1, for the first scenario (S1), the second scenario (S2), and the third scenario (S3) are reported in Table 2.

Table 2. Life cycle environmental impacts per kg of cultivated lettuce for each scenario

| Impact category | Unit | Impact values | | |
|---|---|---|---|---|
| | | S1 | S2 | S3 |
| Climate change | kg $CO_2$-Eq | **2.74E-2** | 7.73E-2 | 3.35E-2 |
| Water use | $m^3$ world Eq deprived | 1.83E-2 | 3.50E-2 | **1.58E-2** |
| Acidification | mol H+-Eq | **1.59E-4** | 2.99E-4 | 1.79E-4 |
| Land use | dimensionless | **1.00E-1** | 2.02E-1 | 1.43E-1 |
| Human toxicity: carcinogenic | CTUh | **1.04E-11** | 1.62E-11 | 1.16E-11 |
| Human toxicity: non-carcinogenic | CTUh | **3.28E-10** | 5.29E-10 | 3.86E-10 |
| Ionising radiation: human health | kBq U235-Eq | **9.38E-3** | 1.99E-2 | 9.40E-3 |
| Ozone depletion | kg CFC-11-Eq | **4.61E-10** | 1.67E-9 | 6.06E-10 |
| Eutrophication: freshwater | kg P-Eq | 1.81E-5 | 2.81E-5 | **1.78E-5** |
| Eutrophication: terrestrial | mol N-Eq | **2.63E-4** | 5.63E-4 | 3.28E-4 |
| Eutrophication: marine | kg N-Eq | **2.81E-5** | 5.74E-5 | 3.35E-5 |
| Ecotoxicity: freshwater | CTUe | **8.52E-2** | 1.77E-1 | 1.21E-1 |
| Energy resources: non-renewable | net calorific value | **4.92E-1** | 1.28E0 | 5.80E-1 |
| Particulate matter formation | disease incidence | **1.02E-9** | 1.67E-9 | 1.48E-9 |

Across all three scenarios, the overall order of magnitude of impact values remained consistent, indicating the absence of substantial differences at the midpoint level.

Within this context, S2 exhibited the highest impact values across most categories. S3, on the other hand, presented an environmental profile closely aligned with S1, showing only slight increases in selected indicators such as acidification, carcinogenic human toxicity, non-carcinogenic human toxicity, ionising radiation, ozone depletion, and particulate matter formation. For this latter scenario, slight reductions were also observed in water use (-13.7%) and freshwater eutrophication (-1.7%) compared to S1.

Although the circular economy approach proposed in S2 and S3 promoted resource recovery, it was important to consider that such a strategy could involve increased energy demand due to additional treatment steps, as reflected in the impact values [25].

Regarding the impact categories, climate change was the most widely considered impact category in environmental assessments. To better understand how each process contributed to this impact, the climate change category was analysed across the three scenarios, highlighting the percentage contribution of the processes involved, as illustrated in Fig. 2.

Scenario-specific differences clearly emerged in the distribution of these contributions across the various process stages.

The impact value in the climate change category for S1 was overwhelmingly dominated by lettuce cultivation, which accounted for more than 91% of the total impact. This predominance was primarily due to the high tap water consumption required for irrigation, a parameter that significantly exceeded the contribution of wastewater treatment, which accounted for 8.87% of the impact.

When considering S2 and S3, lettuce cultivation still accounted for a substantial portion of the climate change impact, even though the inclusion of further processing phases led to a more diversified and distributed impact profile.

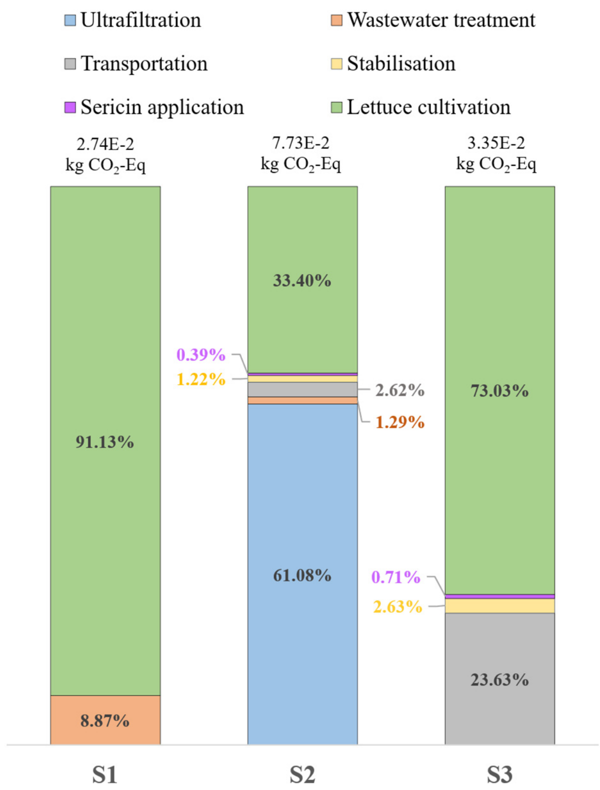


Fig. 2. Climate Change impact contribution of each phase in the three scenarios.

Taking into account S2, the impact became more fragmented due to the presence of additional treatment steps. In this case, the ultrafiltration phase emerged as the dominant contributor (61.08%), mainly because of the energy consumption required to concentrate the degumming water.

Compared to S1, the relative contribution of lettuce cultivation decreased to 33.40%. This reduction was not primarily due to a decrease in tap water consumption, which remained comparable, but rather to the significant weight of the ultrafiltration process, which led to a redistribution of impact shared across the different phases. The remaining impact was distributed among transportation (2.62%), stabilisation (1.22%), wastewater treatment (1.29%), and sericin application (0.39%), all of which contributed only marginally.

The S3 presented an intermediate impact profile between S1 and S2. Lettuce cultivation remained the main contributor (73.03%), yet a notable increase in the contribution from the transportation phase was observed (23.63%). This shift could be attributed to the fact that, unlike in S2, no concentration process was performed after degumming, but the sericin solution was transported directly at a low concentration of 1.2% w/v, which entailed a larger volume being moved and, consequently, a higher environmental load associated with transportation. Stabilisation and sericin application, accounting for 2.63% and 0.71% respectively, continued to contribute only marginally to the overall climate change impact.

*2) Sensitivity analysis*

Sensitivity analysis is an essential part of the final interpretation of the LCA model, as mentioned in the ISO 14044 standard. Sensitivity analysis can be performed using a One-at-A-Time Approach (OAT), meaning that a subset of the input parameters is changed one at a time to see how much influence it has on the results [32]. It is common practice to focus on the impact categories that are most relevant to the context of the analysis [33]. Therefore, the subset of indicators selected for this sensitivity analysis included only the following: climate change, land use, water use, acidification, freshwater eutrophication, and carcinogenic human toxicity.

In this comparative LCA, transportation distance (km) and solution volume ($m^3$) were identified as sensitivity parameters. This sensitivity analysis aimed to validate the three scenarios and determine threshold conditions under which one outperformed the others, providing practical applicability limits for real-world implementation.

Varying the transportation distance parameter enabled the determination of the critical thresholds at which the environmental performance of S2 (5% sericin solution transported) or S3 (1.2% sericin solution transported) matched or surpassed that of S1 (no transport). This analysis provided insight into the maximum transportation range within which the field application of the sericin solution became environmentally advantageous for the selected subset of impact categories. It also enabled the identification of the conditions under which it was preferable to transport either the non-concentrated solution (S3) or the concentrated serigel (S2), depending on the required transportation distance.

The sensitivity analysis conducted on the transportation distance parameter revealed that transporting the sericin solution at 1.2% w/v (S2) was environmentally advantageous within a range of 15 km, when compared to S1. For the selected subset of six impact categories, S3 outperformed S1 in 2 out of 6 categories, with reductions observed particularly in water use (15.85%), and freshwater eutrophication (3.87%). It showed equal performance in 3 out of 6 categories, including climate change, acidification, and carcinogenic human toxicity. The only category where it performed worse than the S1 is land use, which increased by 11.00%.

The second scenario (S2), on the other hand, still performed worse than S1 across all impact categories, even when the transport distance was limited to 15 km.

By comparing S2 and S3, substantial advantages could be observed in favour of S3 for the selected subset of impact categories. On average, S3 showed an improvement of approximately 45% across all six categories considered.

The comparative visualisation of the three scenarios is presented in Fig. 3, where the blue line represents S1, the yellow line corresponds to S2, and the purple line represents S3, all evaluated at a transportation distance of 15 km.

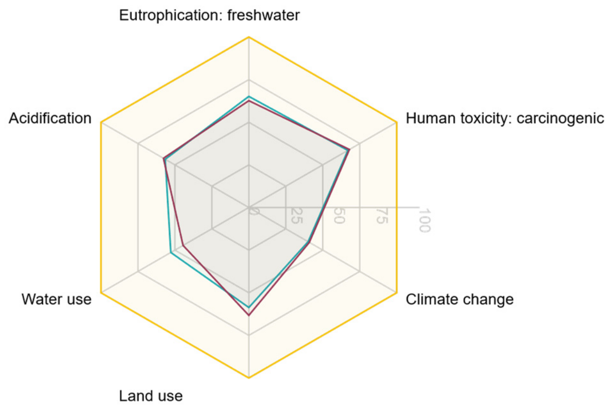


Fig. 3. Comparative visualisation of scenarios (S1 – blue line, S2 – yellow line, S3 – purple line) based on the selected subset of impact categories, considering a transportation distance of 15 km.

A second comparative analysis conducted between S2 and S3 allowed the identification of a second threshold at approximately 400 km, beyond which the transportation of the concentrated serigel at 5% w/v (S2) became more environmentally favourable than the non-concentrated solution at 1.2% w/v (S3). In more detail, 4 out of 6 categories showed better performance in S2, including carcinogenic human toxicity, which improved by 13.89%, and land use, which showed a reduction of 39.52%. Additionally, both scenarios presented equivalent impact values for climate change and acidification. However, S2 remained less favourable than S3 in terms of freshwater eutrophication and water use.

In summary, this sensitivity analysis suggested that:

- If the sericin solution were to be transported within 15 km, ultrafiltration has to be avoided and the degumming wastewater applied directly on crops, making S3 the best performing scenario in terms of environmental impact.
- Conversely, if the transportation distance exceeded 400 km, concentrating the solution to 5% w/v (S2) becomes more sustainable than S3, even though its impacts remained significantly higher than S1.

After evaluating the transportation distance, the analysis explored the effect of changing the solution volume. By varying this parameter, it was possible to evaluate how changes in application volume affected the environmental trade-offs among the scenarios. Given the normalization to the FU, the environmental impacts associated with using 1 $m^3$ of solution to produce 3593 kilograms of lettuce were expected to scale proportionally with those calculated for 2.78E-4 $m^3$ per kilogram of lettuce. This proportionality ensured model consistency, enabling a coherent interpretation of results across different application volumes. The results demonstrated that the assumed proportional relationship held, as variations in solution volume led to proportional changes in environmental impacts.

### *B. Cost Evaluation*

The wastewater resulting from the degumming of raw silk concentrated at 1.2% w/v represents a potentially valuable by-product for agricultural use, particularly as a biostimulant for leafy vegetable crops such as lettuce. However, the economic feasibility of this valorisation pathway is significantly constrained by the logistical costs associated with transporting the solution. Currently, the company partner of the project, which provided empirical data, generates approximately 5 $m^3$ of degumming water per day, which is discharged into the public sewer system along with other industrial wastewater streams. Cost calculations were performed on a reference volume of 1 $m^3$ of solution, rather than on the volume defined by the FU in the LCA analysis, as this approach was considered more representative of a real-world situation and did not influence the overall assessment, given the proportional relationship of the results.

The disposal cost was estimated at around 3-4€/$m^3$, totalling approximately €20 per day. This amount represented the maximum budget available to cover transportation costs in the absence of a structured market capable of absorbing such expenses. According to official rates provided by the Italian Ministry of Infrastructure and Transport for vehicles in the 3.5 to 12-ton category (Category B), the cost per kilometre ranges from a minimum of 1.104€/km to a maximum of 2.065 €/km. Based on Eqs. (1) and (2), where $C_{disposal}$ represents the unit cost of wastewater disposal and $C_{unit}$ the transportation cost per kilometre, the maximum economically viable transport distance per day ranges from 9.7 km (at the highest cost) to 18.1 km (at the lowest cost). Beyond these thresholds, transportation costs exceed the savings from avoided disposal, making the operation economically unfeasible.

$$\frac{C_{disposal}}{C_{unit}} = \frac{20\ €}{1.104\ €/km} = 18.116\ km \quad (1)$$

$$\frac{C_{disposal}}{C_{unit}} = \frac{20\ €}{2.065\ €/km} = 9.685\ km \quad (2)$$

This geographical constraint implies that only farms located in the immediate proximity of the production site can benefit from the use of the liquid biostimulant. As a result, the development of a local valorisation chain is challenging unless structural interventions are implemented to reduce transport costs (e.g., product concentration, shared logistics) or economic incentives are introduced to support the reuse of the by-product.

Ultimately, the results on feasible transportation distance obtained from the cost evaluation are consistent with those from the sensitivity analysis of the environmental assessment. Both results indicate that the valorisation of the sericin solution is only viable within a limited range from the extraction site, being economically viable up to around 18 km and environmentally sustainable up to 15 km when direct application of degumming wastewater (S3) is adopted. Beyond these thresholds, transportation costs and impacts outweigh the benefits.

## V. Conclusion

This study has assessed the environmental and economic implications of valorising sericin from silk degumming wastewater through its reuse as a biostimulant in lettuce cultivation, applying a combined LCA and LCC approach within a circular economy framework. The analysis of three scenarios demonstrated that, while additional processing steps such as ultrafiltration and stabilisation generally increase environmental burdens, the direct application of non-concentrated sericin wastewater within short transport distances can deliver comparable or even superior sustainability outcomes relative to conventional wastewater treatment. Sensitivity analysis further confirmed that transportation distance is a critical factor, with economic viability constrained to a radius of approximately 18 km around the production site unless new logistic or financial mechanisms are introduced.

Beyond the quantitative findings, this study highlights the broader significance of sericin valorisation as an eco-innovative waste-to-resource strategy that contributes to the circular economy transition in agriculture. By recovering a protein traditionally treated as waste and repurposing it as a biostimulant, the approach supports multiple SDGs, notably SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), and SDG 12 (Responsible Consumption and Production). Such integration of industrial by-products into agro-industrial systems strengthens resource efficiency, reduces reliance on synthetic inputs, and fosters sustainable production practices.

From a policy perspective, the results underscore the need for supportive regulatory frameworks and targeted incentives to enhance the scalability of biostimulant uptake from industrial waste streams. Potential measures include subsidies for on-farm application, shared logistics schemes to mitigate transport costs, and certification schemes that recognise the environmental benefits of circular biostimulants. Moreover, integrating agronomic performance data, such as biomass yield improvements and reduced fertiliser requirements, into environmental and economic assessments will provide a more complete picture of their long-term sustainability potential.

In conclusion, sericin valorisation exemplifies how circular economy strategies can bridge industrial and agricultural sectors, converting a wastewater challenge into a resource for sustainable food production. With adequate policy support and further research, this pathway could serve as a scalable model for coupling waste valorisation with agro-industrial sustainability.

## Conflict of Interest

The authors declare no conflict of interest.

## Author Contributions

C.C. and V.B.F. contributed to the life cycle assessment analyses and the preparation of the manuscript. S.C.

conducted the economic analysis. GB carried out chemical analyses to determine the wastewater composition. M.S. reviewed the manuscript and supervised the overall activities. All authors approved the final version of the paper.

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