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Techno-economic and life cycle assessment of tannin production from spruce bark for leather industry applications

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Bark, which is currently far from being utilised to the maximum, has the potential to be a sustainable source of chemicals in the future. For instance, bark contains a significant amount of tannins, which has a wide range of applications in various industries. Tannins extracted from spruce bark have been proposed for use in the leather industry to achieve more sustainable and environmentally friendly tanning processes. In this work, a novel industrial-scale extraction process for tannins from spruce bark is described and its feasibility and environmental impacts evaluated. The process concept includes hot water extraction of tannins from spruce bark and after-treatment sections, with the final product being a powder with a high concentration of polyphenolic compounds. The process and its equipment were dimensioned based on the estimated available bark volume of a pulp mill located in the Nordic countries. The study included a techno-economic analysis and sensitivity study, and the plant project to be implemented using this tannin extraction process was assessed to be feasible in terms of dimensions, raw material and consumption of utilities. Based on the techno-economic analysis, tannins extracted from Norway spruce bark for leather industry applications show promising economic potential. The minimum selling price for the tannin product was 2.1 € per kg, and the most prominent economic risks within said plant project stemmed from achieving a high enough overall process yield. The global warming potential of the extracted spruce bark tannin was 4.5 kg CO_2-eq per kg of tannin product. The most significant contributor to the global warming potential was process steam, meaning that optimising the energy consumption of the process would be important for increased environmental benefits. If the extraction of tannin from spruce bark can be successfully scaled up to industrial level, there is significant potential for the future, improving the value of underutilised biomass fractions and thus providing an alternative to the most commonly used, environmentally harmful tanning agents.

Green foundation

1. This work advances the field of green chemistry by valorising spruce bark, an underutilised industrial side stream, into a renewable and non-toxic alternative to chromium-based tanning agents. The combined approach of techno-economic analysis and LCA has not previously been conducted for this type of process utilising spruce bark as the feedstock.
2. The key green chemistry achievement is the industrial-scale production of bio-based tannins using hot-water extraction under mild conditions, avoiding organic solvents and generating negligible waste, as spent bark is reused for energy. The process was deemed to be both economically feasible (minimum product selling price 2.1 € per kg) and environmentally quantified (4.6 kg CO_2-eq per kg product).
3. Further research could enhance sustainability by reducing steam demand through heat integration, improving extraction yield, lowering chemical and enzyme use through recycle systems, and expanding the process toward a multi-product biorefinery.

Introduction

In the shift towards a more sustainable world economy, there is an ever-growing need for sustainable solutions in chemical production. Forests, in addition to acting as carbon sinks, supply large volumes of renewable raw material for a variety of industrial applications. Trees, and their separable fractions, contain a wide variety of valuable chemical compounds with a multitude of applications across many industries.

In the wood processing industry of today, tree bark is an underutilised fraction used mainly as an energy source, and a multitude of functional chemical fractions are lost in the current processing chains. For example, in Canada, around

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17 million cubic metres of bark ends up incinerated or as waste,[1] indicating the lost potential of valuable extractives in the forest industry. Furthermore, debarking is a process step already existing in almost all forest industry processes, where the tree bark is separated for further processing.[2]

Tannins are a group of polyphenolic chemicals that are widely distributed in nature with substantial concentrations in various tree barks. They can be extracted from bark using a variety of methods, such as hot water extraction.[3,4] Tannins are used as coagulants in environmental applications[5] in adhesives where they substitute formaldehyde[6] and in the leather industry as tanning agents.[4]

In the literature, some techno-economic assessments (TEAs) have been conducted on the extraction of spruce bark tannin with different production capacities and plant configurations. For example, Wijeyekoon *et al.*[7] explored tannin extraction and its application in on-site adhesive production, while Ajao *et al.*[8] examined its general applications. Their overall findings suggest that tannin production from spruce bark can be economically feasible on an industrial scale; however, the tannin product analysed in these studies was not specifically intended for use in leather tanning. One of the key findings of Wijeyekoon *et al.*[7] was that only a brownfield solution implemented alongside an existing plant site was profitable.

Chromium-based tanning agents still dominate the leather industry and are used in over 80% of global leather production due to their efficiency and cost-effectiveness,[9] although there is a growing trend towards more sustainable, chromium-free alternatives.

Other plant-derived tannins, such as chestnut and quebracho, are used in the leather industry, and are produced from the wood material itself.[10,11] Unlike these tannins, spruce bark tannin would be produced from a wood processing side stream, utilising pre-processing chains already in existence at pulp mill sites. The utilisation of this side stream is expected to result in lower land occupation per unit of tannin than tannins derived from purpose-harvested wood[10,11] although the exact magnitude depends on extraction yield and process assumptions. Extracting value from side streams can open up more sources of income for companies in the forest industry, and the extracted natural products would shift other industries in a more sustainable direction.

The global tannin market volume was estimated at 1.1 million metric tons 2017, with leather tanning accounting for approximately 62% of total turnover.[12] According to estimations based on a compound annual growth rate (CAGR) of between 4.5% and 6.6%, the tannin market should reach €3.2 billion in 2025, with leather manufacturing and winemaking expected to be the key drivers of growth.[12–14] Based on these figures, the market conditions will most likely be favourable for extracting tannin product from spruce bark, and targeting the leather industry is a logical choice due to its large market share.

Tannins extracted from spruce bark could offer a more environmentally friendly and benign alternative to chrome as a tanning agent. This work aims to develop a novel industrial-scale process concept for extracting tannins, specifically tailored for the leather tanning industry. The feasibility of the developed process is evaluated by performing a TEA and sensitivity analysis. Additionally, a life cycle assessment (LCA) is conducted to identify the processing steps, raw materials, utilities and generated waste materials that have the most significant environmental impacts on the tannin production process. To the best of the authors' knowledge, this integrated approach, combining TEA and LCA, has not previously been conducted for tannins extracted from spruce bark for use in the leather tanning industry. Considerations for improving the profitability of the proposed process are presented based on the results.

Methodology

The plant capacity, mass and energy balances, and process yield were used as the basis for the TEA and LCA calculations. The capacity of the industrial-scale plant was set at 25 kt per a of Norway spruce bark on a dry matter basis (50% moisture content). The production capacity estimate was based on the potential bark volume of one Nordic pulp and paper mill.[15–17] The tannin extraction plant was designed to be situated on an existing pulp mill site, in order to take advantage of the close proximity of the feedstock, as well as the utilities required for the process. Pretreatment of the spruce bark feedstock, and the packaging and handling of the final product were not included in the detailed design. Mass and energy balances and equipment sizing were performed using Microsoft Excel. The energy usage of the plant was calculated from the heating and cooling requirements, as well as the electricity required to run the process equipment.[18–21]

Production plant investment costs were estimated using the Aspen process economic analyser (APEA), version 14.2, and operating costs were determined from the mass balance with cost figures found from the literature and chemical market data. The profitability of the process was evaluated based on the investment and operating costs. The effect of key process parameters was evaluated by sensitivity analysis. Finally, life cycle inventories were developed based on material and energy balances to conduct a life cycle impact assessment of the proposed process. The detailed methodology and assumptions for both the TEA and LCA are detailed below.

Techno-economic assessment

The total capital investment was estimated as the sum of fixed capital investment (FCI) and working capital. Working capital was defined as three months of operational expenses. Fixed capital investment is the sum of direct and indirect costs and was estimated using the percentages of the delivered equipment method,[22] listed in Table S1. Some of the percentages were modified from the base values presented by Peters,[22] to better represent the addition of the plant to an existing industrial site. The land-related costs were assumed to be negligible, aside from land modifications, which were included in the FCI.

The direct costs of the plant included the total process of procuring and installing the equipment, and the indirect costs comprised engineering, construction expenses and contingency for the plant project. The equipment costs were estimated using APEA version 14.2 with price basis from the first quarter of 2022. The delivered equipment cost (DEC) was derived by multiplying the base equipment cost by a factor of 1.1. The total equipment price was adjusted using the chemical engineering plant cost index value from 2022 to the level of 2024.[23] The APEA equipment database did not include all the specific equipment listed for the process, thus some simplifications were made in order to obtain approximate prices for selected process equipment: the extractors were estimated as simple screw conveyors and falling-film evaporator columns as long tube evaporators. The nanofiltration equipment cost was calculated based on investment costs ranges as a function of feed capacity, interpolated from three available cost data points.[24]

Operating costs were determined as the sum of fixed operating costs (FOC) and variable operating costs (VOC). VOC include raw materials, utilities and operating supplies, which are calculated based on the mass and energy balance of the process. The cost of operating supplies was assumed to be 0.5% of the plant FCI. Raw material costs comprised spruce bark, extraction aid chemicals, enzymes and buffer solution. The price of the spruce bark could not be determined directly on a per tonne basis, as it is recycled back to the energy production process after extraction. Instead, the price was based on a combination of the energy cost of drying the bark back to 50% moisture content after the extraction step, and the heating value loss from extracting around 10% of the solids in the bark mass. Dewatering energy consumption, bark heating values and the price of heat used in the calculations are based on values by Jinze *et al.*[25] The prices of the process utilities are listed in Table 1. Air for the spray drying unit is taken directly from the atmosphere with a compressor system, so the only costs in air use result from running the necessary equipment.

The FOC include salaries, quality control operation (excluding salaries), maintenance and repairs, insurance and security. Operation salary costs were calculated based on per-process-unit per shift worker requirements,[35] and assumed values of 1 and 0.5 workers for the extractor unit and spray drying unit respectively. The plant was set to be operated in five shifts with four workers including a supervisor for each shift. In addition, the plant has mechanical and quality control personnel on site. Average salaries for plant personnel in Finland[36] were used, with the assumption that quality control personnel have the same wage as process operators. Administration, healthcare, quality control, plant maintenance, insurance and security costs were estimated as percentages of personnel and plant size-related figures, listed in Table 2.

Once the investment and operating costs had been calculated, the profitability of the process was evaluated using the assumptions listed in Table 3. Eqn (1)–(4) are used to calculate key economic indicators.

$$\mathrm{NPV} = \sum_{t=0}^{n} \frac{C_\mathrm{t}}{(1+i)^t} \tag{1}$$

where NPV is the net present value of the plant project, C_t is the yearly revenue after tax, i is the discount rate, and t is the number of time periods.

$$0 = \mathrm{NPV} = \sum_{t=1}^{n} \frac{C_\mathrm{t}}{(1+\mathrm{IRR})^t} - \mathrm{TCI} \tag{2}$$

Table 1 Process utility prices used in OPEX calculation

Utility	Unit	Price (€ per unit)
Process steam	t	40 [26]
Process water	t	1.1 [27]
Cooling water	t	0.24 [27]
Electricity	kWh	0.08 [28]
Wastewater treatment	m^3	1.5 [29]
Sodium carbonate	t	250 [30]
Sodium sulfate	t	350 [31]
Sodium acetate	t	500 [32]
Enzyme mixture	t	30 000[a] [33,34]
Spruce bark	t	2

[a] Total enzyme mixture price based on available price data for food-grade enzymes.

Table 2 OPEX cost components determined with personnel and plant size figures

Cost component	Calculation basis
Administration salaries	15% of total labor cost
Healthcare and benefits	25% of total labor cost
Quality control operation	1% of FCI
Maintenance and repairs	10% of DEC
Insurance	4% of direct FCI
Security	2% of DEC

Table 3 Techno-economic assessment assumptions

Component	Assumed basis
Basis year for evaluation	2024
Plant operating lifetime	25 years
Annual plant operating time	340 days
Decommissioning cost	30% of FCI
Plant salvage value	10% of delivered equipment cost
Working capital	3 months OPEX
Discount rate	10%
Equity	0%
Term of loan	10 years
Loan interest	5%
Depreciation factor	8.8%
Tax rate	20%
Administration	15% of labour costs
Employee healthcare and benefits	25% of labour costs
Quality control operation	1% of FCI
Plant maintenance	2.5% of FCI
Insurance	4% of direct FCI
Plant security	0.5% of FCI

where C_t is the yearly revenue after tax, IRR is the internal rate of return, t is the number of time periods, and TCI is the total capital investment.

$$\mathrm{ROI} = \frac{C}{\mathrm{TCI}} \quad (3)$$

where ROI is the return on investment value of the plant project, C is the average yearly income after tax, and TCI is the fixed capital investment.

$$\mathrm{PBP} = \frac{\mathrm{TCI}}{C} \quad (4)$$

where PBP is the period of time it takes for the plant to earn back its investment cost through its cash flow, TCI is the total capital investment, and C is the average yearly income after tax.

The selling price range for the tannin product was determined from averages of global shipment data[37,38] and total yearly imports of vegetable-derived tanning agents in the EU area[39] for various tannin types. The prices were derived by dividing the total value of the imports by the total import volume. The net present value (NPV) of the plant project was calculated using the low and high ends of the selling price range. The minimum selling price (MSP) for the tannin product was calculated to achieve an NPV of zero for the entire operating life of the plant.

Life cycle assessment

LCA was conducted according to the ISO 14040 and ISO 14044 standards using Simapro v. 9.6.01 software. The purpose of the LCA was to identify which processing steps, as well as raw materials, utilities and generated waste materials, have the most significant impact on the tannin product production process.

The system boundary of the LCA is cradle-to-gate, encompassing the manufacturing and distribution of feedstocks, utilities and the generation and processing of waste, as well as the production of the tannin product, as presented in Fig. 1. The infrastructure emissions of the biorefinery were excluded from this research due to lack of data. The unit-specific inventory data in Table S2 used to model the biorefinery were obtained from the material and energy balances and scaled using 1 kg of tannin product per dry basis as the functional unit. Characterisation data, presented in Table S3, were extracted from the Ecoinvent v. 3.10 database except for sodium acetate, for which the data were retrieved from a report by Jungbluth.[40] The ReCiPe 2016 midpoint (H) v. 109 method was used to quantify the 17 environmental impacts. However, the discussion focuses on five key indicators: global warming potential (kg CO_2-eq), stratospheric ozone depletion (kg CFC11-eq), terrestrial acidification (kg SO_2-eq), land use (m^2a crop-eq) and fossil resource scarcity (kg oil-eq); the scores for all environmental indicators are reported in the SI.

Results and discussion

Process design

The continuous process for tannin extraction comprises four main steps: (1) extraction, (2) concentration, (3) filtration and (4) spray drying, as shown in Fig. 1. Overall, the process utilised a bark feed of 50 kt per a, including 50% moisture, to yield 3.5 kt per a of tannin powder with a solid content of 94%, based on a yield of 7.6%. The yield was calculated from the mass balance with assumed intermediary yields and solids losses.[41,42]

The process flow diagram of the extraction process is presented in Fig. 2. The primary process equipment was sized based on the mass balance, with the inputs outlined in Table 4. The parameters are a combination of estimates, and values from previous research on similar process solutions for tannin extraction. The stream mass balances, equipment list and utility demands are provided in Tables S4, S5 and S6, respectively.

As shown in Fig. 2, the process starts with hot water extraction, where the bark is fed to a continuous flow impregnator, in which steam-heated 90 °C water flows counter-currently to the shredded bark, which is moved with an auger conveyor lengthwise through horizontally placed extractor tubes. Bark residence time in the extractors is set at 30 minutes, and the solid-to-liquid ratio in the extraction is 0.4. The extraction design parameters are presented in Table S7. A solids yield of 10% is assumed in the extraction step, based on experimental results.[41] To maintain a constant temperature along the extrac-

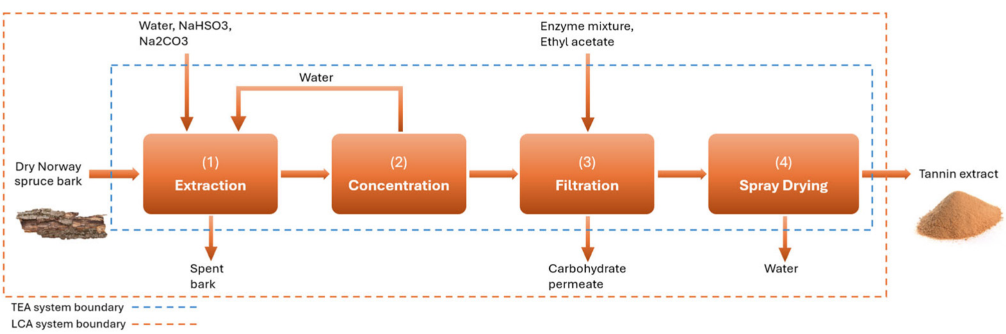

Fig. 1 Block flow diagram of the process with TEA and LCA system boundary.

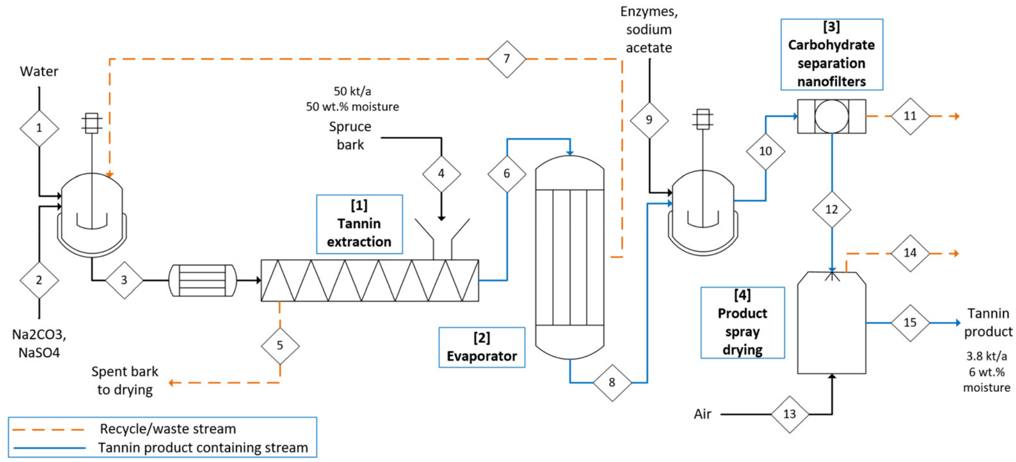

Fig. 2 Simplified process flow diagram of the tannin extraction process.

Table 4 Mass balance inputs

Input	Value	Reference
Dry bark feed (t per a)	50 000	This design
Relative bark volume (%)	12.8	13
Dry bark solids content (%)	50	Estimate
Screening reject amount (%)	1	Estimate
Extraction solid to liquid ratio	0.4	This design
Extraction solids yield (%)	10.2	41
Extraction aid amount (m-%)	2.5	41
Powdered extract moisture content (%)	6	This design
Buffer solution amount (% of product-containing stream water content)	1	42
Filtration solids loss (%)	23.5	42
Spray drying solids loss (%)	5	Estimate

tor tubes, steam coils are used to offset the heat losses from the tube surfaces. Extraction aid chemicals (Na_2SO_3 and Na_2CO_3), amounting to 1% of the dry bark mass weight, are added to the water to make the extraction process more efficient. From the end of the final extractor pass, the product-containing stream is routed to an intermediary vessel through a filter to remove any larger solids.

The product-containing stream is fed to a falling-film evaporator (step 2), operating at 1 atm and 100 °C, to reduce the water content of the product-containing stream down to 65%, resulting in an evaporation rate of 24 900 kg h^{-1}. It is assumed that no solid content is lost during concentration. The falling-film evaporator is designed as a two-stage evaporator with mechanical vapour compression and thermal vapour compression systems,[21] as specified in Table S8. The product-containing stream is circulated in the columns, both to increase the concentration and to ensure that a constant film is maintained in the column tubes. Water recovered from the evaporator system is recycled to extraction (step 1) to decrease the amount of fresh water required for the process.

After concentration, the product-containing stream is sent to a stirred vessel, where enzymes are added to liberate carbohydrates from the feed stream. The amount of added enzymes is 5 mg g^{-1} of total solids in the feed stream.[42] To maintain a stable pH in the stirred vessel, a buffer solution of 0.1 M sodium acetate is also added to the enzyme mixture. Once the enzymatic process is complete and sugar fractions liberated, they are separated from the rest of the solution through nanofiltration (step 3). The refined product-containing stream is recovered as the retentate. The recovered product is further concentrated in this step, with an assumed moisture content of 50%. Solid matter loss occurs at this process step as part of the carbohydrate fraction goes to the permeate.[42] The liberated carbohydrate fraction is intended to be removed at this stage, although a minor loss of the tannin fraction from the product-containing stream also takes place.

The retentate is further processed in a spray dryer (step 4), where it is dried using steam-heated 140 °C air to obtain a powdered tannin product with 94% solid concentration. A wheel atomiser is used to atomise the feed solution. The residence time of the feed solution is set at 10 seconds, which is suitable for a fine-to-coarse spray when drying to a low final moisture.[43] A 5% solid matter vessel loss is assumed to occur in this process step. The energy usage of the plant results from heating and cooling requirements, as well as the electricity required to run the process equipment. Based on the energy balance, the total energy consumption of the plant is 2100 kW, of which 630 kW is electrical power.

CAPEX and OPEX

With a 25 kt per a bark feedstock capacity on a dry matter basis, the FCI of the tannin production plant is 8.1 M€. As presented in Fig. 3, process equipment and installation are the largest contributors to the overall FCI. The total delivered equipment cost is 1.98 M€. The TCI of the tannin extraction plant is 9.57 M€. The equipment costs are presented in Table S9 and a CAPEX breakdown is provided in Table S10.

The dewatering energy consumption for the bark resulted in a cost of 14.6 k€ per a, and the potential heating value loss a cost of 169 k€ per a, totalling a spruce bark feed price of 1.98

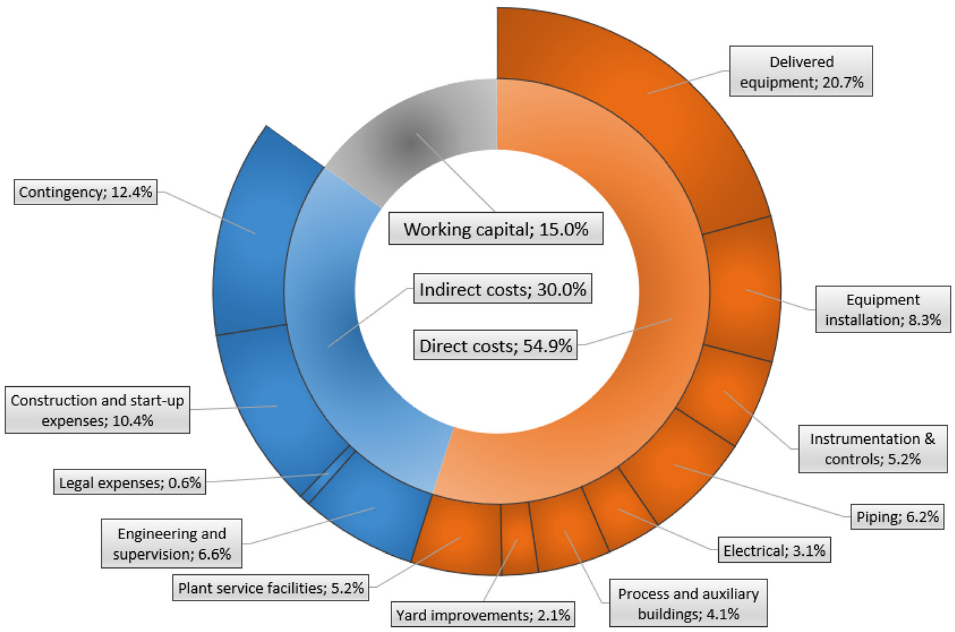

Fig. 3 Tannin extraction plant TCI breakdown.

€ per t. The total OPEX for the tannin extraction plant is 5.8 M€ per a, with a VOC of 3.4 M€ per a VOC and a FOC of 2.4 M€ per a. A detailed breakdown of the total OPEX is presented in Table S11. As shown in Fig. 4, process steam and extraction aid chemicals account for the largest operational expenditures of the VOC, and plant operator salaries the largest of the FOC. The single largest factor in the OPEX was determined to be 4.8 bar process steam, at a cost of 1.3 M€ per a. The spruce bark pricing mechanism discussed above led to the bark being a comparably small factor in the total OPEX.

Profitability analysis

If the total OPEX of the tannin extraction plant remains relatively constant, the gross operating margin of the plant will be heavily dependent on the selling price of the final product. The minimum selling price of the tannin product, which

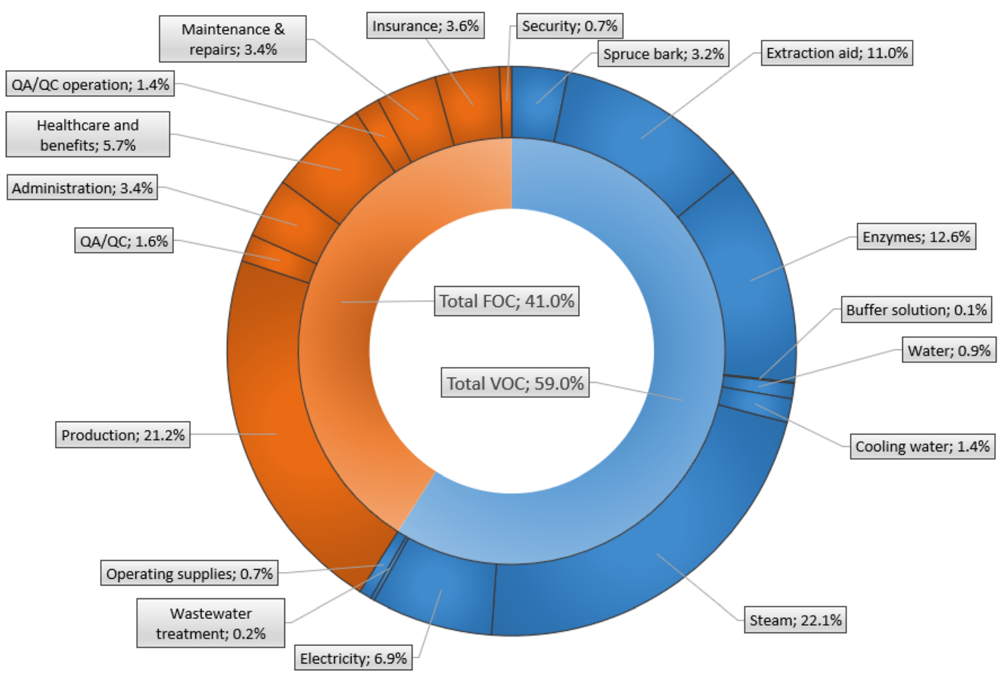

Fig. 4 Tannin extraction plant OPEX breakdown.

results in an NPV of zero at the end of the project lifetime, was determined to be 2.1 € per kg.

With a lower selling price (1.6 k€ per t) scenario, the gross operating margin is −109 k€ per a, and with a higher selling price (2.3 k€ per t), the margin is around 2400 k€ per a. With the low-end price, the plant project NPV would be −12 800 k€, so the lower selling price scenario was not analysed further due to economic unfeasibility. Table 5 presents the key profitability indicators for the proposed process, based on a selling price of 2.3 € per kg for the tannin product. The NPV of the plant project was found to reach zero during the 11th year of operation, as presented in Fig. 5. The payback period of the plant project would be around 5.5 years.

Table 5 Economic analysis key indicators

Key figure	Value
NPV (k€)	5200
Internal rate of return (%)	16.2
Return on investment (%)	17.4
Payback period (a)	5.5

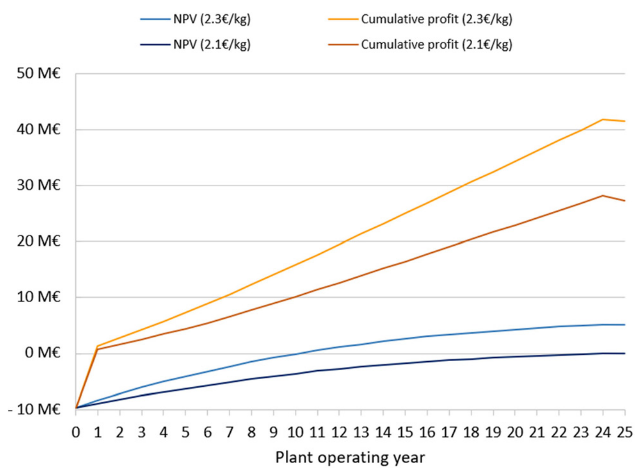

Fig. 5 NPV and cumulative revenue for the plant operating lifetime with MSP and 2.3 € per kg selling price.

Sensitivity analysis

The effects of the overall process yield, costs of process steam, enzymes and chemicals (including extraction aid chemicals and sodium acetate), discount rate and CAPEX on the NPV and MSP of tannin product, presented in Fig. 6, were examined through a sensitivity analysis. Overall process yield was found to be the most significant factor affecting plant profitability. With a yield change of −10% from the base value, the MSP increases to around 2.3 € per kg. The steep profitability fluctuation caused by changes in overall yield means that yield optimisation is crucial in future development work on this type of process. Conversely, the price of the process utilities was found to have a relatively minor impact on the MSP, the range being 2.0–2.1 € per kg even with ±30% variance from the base values.

LCA and environmental aspects

The global warming potential was estimated to be 4.5 kg CO_2-eq per kg of tannin product, stratospheric ozone depletion 6×10^{-6} kg CFC11-eq and terrestrial acidification 0.01 kg SO_2-eq. The impacts on land use were 4.7 m^2 crop-eq, and fossil resource scarcity was 1.3 kg oil-eq. The stage-by-stage breakdown of the environmental impacts is presented in Fig. 7, and characterisation scores are detailed in Table S12.

Notably, most of the environmental impacts originate from the extraction stage, which is explained by the fact that the majority of the feedstocks, such as bark, water and extraction aid chemicals, are introduced at this stage. Furthermore, spent bark is generated during this stage. The second most significant impact is from the concentration stage due to the con-

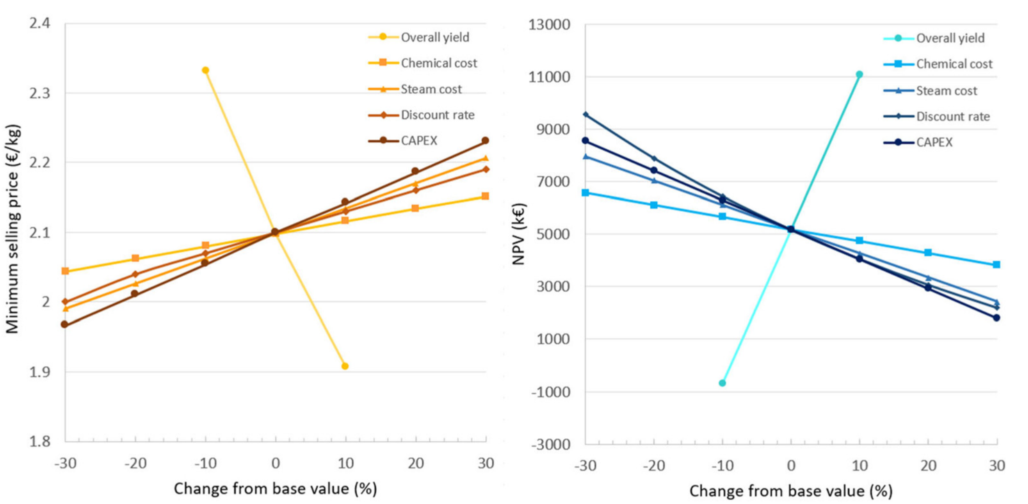

Fig. 6 Sensitivity analysis for the effect of process (tannin product) yield, chemicals and utilities, and discount rate and CAPEX on the minimum selling price (left), and NPV (right).

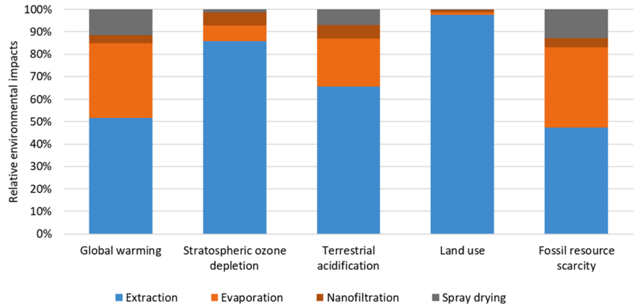

Fig. 7 Relative environmental impacts of each processing stage of the tannin product production process. The impact of raw materials, utilities and waste processing is embedded in the production process.

siderable utility consumption in the form of steam and electricity.

The environmental impacts of the feedstock and waste materials of the tannin product production process are presented in Fig. 8, and the characterisation scores are given in Table S13. The use of steam has the highest effect on global warming potential, at 39%. It also has a significant impact on terrestrial acidification and fossil resource scarcity impact categories. Therefore, to achieve increased environmental benefits it would be important to optimise energy consumption and to select lower carbon energy sources. Utilizing natural gas for process steam generation instead of the current European chemical industry steam supply would decrease the GWP to 4.0 kg CO_2-eq per kg of tannin product and reduce the steam contribution to 31%. Using wood pellets for process steam would further decrease the GWP to 3.0 kg CO_2-eq per kg of tannin product, with steam accounting for only 8% of impacts; in this scenario, the main environmental impacts would arise from bark use (25%) and spent bark (29%).

Bark as a feedstock and spent bark as a waste also have a significant impact on all the above-mentioned categories. In addition, bark, as a feedstock, accounts for 97% of the impact on land use. To minimise the environmental impacts per functional unit (1 kg tannin product), it is essential to maximise product yield. A 10% relative decrease in yield from 7.6% to 6.8%, with bark input held constant and the lower extraction rate reflected in the product mass, increases the global warming potential from 4.5 to 4.7 kg CO_2-eq per kg tannin. This can be addressed by further developing the extraction process, for example through cascade extraction.

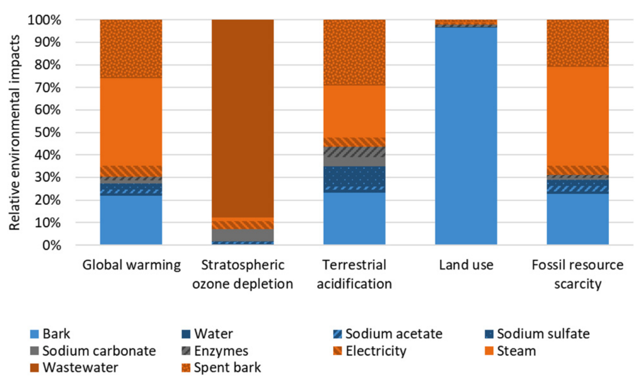

Fig. 8 Environmental impacts of the feedstock and waste of the tannin extract production process.

Challenges and future outlook in commercial scaling

Feedstock variability, transportation and storage

As a natural material, tree bark can have significant variability in its composition,[44] which may have an effect on the process yield. Compared to natural variability, an even more significant effect stems from the conditions in which the logs and bark material are stored. The longer the logs spend in storage, and the bark spends in storage after debarking, the more the polyphenolic compounds will decompose.[44] Warmer temperatures during the summer accelerate the breakdown of the valuable polyphenolic compounds. These factors may result in the fluctuating quality and yield of the final product. As discussed in the sensitivity analysis, the overall process yield heavily dictates the economic feasibility of the tannin production plant. Special attention must be paid to the supply chain and ensuring that the time between debarking and the extraction process is as short as possible. Although the bark supply logistics are critical in terms of bark compound decomposition, the bark supply itself is stable under normal pulp mill operation, as the debarking takes place on site.

Competition in the tanning agent market and leather industry

From the consumption data in leather tanning processes and the price of the various tanning agents presented in Table S14, it can be seen that vegetable-derived tannins are most likely unable to compete with chromium sulfate in terms of leather production cost. Chromium-based tanning agents are in most cases cheaper and less chemical is required to complete the tanning process. In addition, they often have a shorter processing time than vegetable tanning, resulting in a more economically favourable process.[45] However, the chromium tanning agents are fossil-based and the effluents from chromium-based tanning processes are in general more toxic to human and the environment, due to the existence of hexavalent chromium Cr(VI). The health and environmental factors of the chromium tanning agents can be seen as an advantage for the tannin product derived from spruce bark.

Considering other vegetable-derived tannins, such as from mimosa and quebracho, the spruce bark tannin product is most likely competitive in terms of price. The definitive advantage of the spruce bark tannin product is that the raw material is readily available as a side stream, not only in the Nordic countries, with little additional investment requirements for transporting the raw material to be used in the extraction process. Vegetable- and chrome-tanned leathers differ in terms of their general characteristics, and currently over 85% of the leather produced in the world is chrome-tanned.[9,45] The market growth of vegetable-tanned leather will in part dictate how much demand, and in turn how much economic potential, there will be for a spruce bark tannin product in the tanning agent context.

Global market characteristics also vary between vegetable-tanned and chrome-tanned leather products, and since the tannin product is aimed for use in the leather industry, the demand for the tannin product is directly tied to the demand of vegetable-tanned leather. This factor may affect the selling price of the tannin product and the key economic indicators of the plant project. Since the viable selling price range is quite narrow, price fluctuations should be considered when scaling up to an industrial-scale production plant.

Tannin extraction plant integration to an existing pulp mill

Another critical factor is the environmental permit of the pulp mill to which the tannin extraction plant is to be integrated: the permit most likely requires expanding, as the tannin extraction plant produces additional waste and wastewater treatment requirements. Modifying the environmental permit will most likely result in additional costs which have not been considered in the economic figures calculations. Site logistics and infrastructure for transporting the bark from debarking to the tannin production plant must also be considered, resulting in additional costs.

Increasing the economic potential of tannin extraction from spruce bark

A way of increasing the profitability of the plant project would be to extract other valuable compounds, such as the stilbenes present in the bark,[46] as their market has an estimated CAGR of 6.2% from 2025 to 2034.[47] The wide range of applications across industries for stilbenes could open additional sources of income for the plant, assuming they can be separated efficiently. Larger plant capacities should also be examined, as sufficient volumes of bark material would be available for processing.[2] A larger production capacity could leverage better economies of scale in production, assuming a supply chain can be established to provide the plant with the required amount of bark in addition to that of a single pulp mill.

Conclusions

This research lays out a technically and economically feasible process for extracting tannins from Norway spruce bark on an industrial scale. The extracted tannin product is most likely readily applicable in the leather industry for the tanning of leather, although more research on the tanning application would be beneficial. The production plant is intended to be integrated into an existing pulp mill, and the process would be able to produce a highly concentrated tannin product, with a minimum selling price of 2.1 € per kg by utilising the residue bark from the main pulp mill. The sensitivity analysis showed that the overall yield has a significant effect on profitability, meaning that a yield of at least 8% should be the main goal when scaling up this process for an industrial plant. The other parameters investigated in the sensitivity analysis were found to have a much smaller impact on MSP and NPV. A change of ±10% in the yield resulted in an MSP range of 1.9 to 2.3 € per kg, meaning there is also significant gain to be achieved with a relatively small increase in the yield. If the target yield is not reached, the production cost per kilogram of tannin product becomes higher, and the economic feasibility of the plant lower. A selling price of 2.3 € per kg, which results in an overall profitable plant project, is reasonable based on existing import and export data.

The process uses advanced and widely used process solutions and saves energy and costs by utilising steam recycling and a nearly closed water system. The process produces negligible waste, as after the tannin extraction, the bark can be used for energy production. In addition, the calorific value of the extracted bark is not significantly reduced in the extraction process.

In the tannin market, the major competitors of spruce bark tannin are other vegetable-derived tannins, produced from trees such as quebracho and chestnut. The reasonably low production cost of the tannin product is an advantage in the vegetable-derived tannins market, and the tannin product is not limited for use in the leather industry alone. Although economically feasible, it is unlikely that the spruce tannin product would be able to compete against the chrome-based tanning agents based purely on pricing.

The global warming potential of the tannin product is estimated to be 4.5 kg CO_2-eq per kg of dry tannin extract. The usage of steam has the highest impact on global warming potential, which can be mitigated by heat integration to reduce steam demand and by switching to another heat source such as biomass to the reduce the GWP. In addition to heat integration, the energy needs can be covered by the pulp mills excess energy generation from the side streams,[48] and in this case the steam required by the tannin plant would most likely be produced utilising biomass. Bark as a feedstock and spent bark as a waste material also have a significant impact on the global warming potential, and thus it would be important to maximise the product yield by optimising the operating conditions during the extraction stage.

In addition to steam, the addition of extraction aid chemicals and enzymes to the process proved to be major cost components, at 11% and 13% of the total OPEX, respectively. For this reason, special attention must be paid to optimising the level of chemical use in the respective process steps, and in the case of extraction aid chemicals, some form of recovery system should be implemented. The usefulness of the concentration step before nanofiltration can be questioned: more dilute tannin solution could be fed directly through nanofilters, essentially trading a lower amount of process equipment for higher filter investment and operating costs.

Based on this techno-economic assessment of the tannin extraction process from spruce bark, it can be concluded that the extracts produced with the planned process and the selected capacity have significant economic potential. In addition to generating economic value, the spruce-based extract shows good promise for increasing the degree of refinement in the forest industry value chain and would help enable more sustainable processes in the leather industry.

Author contributions

IN: conceptualisation, methodology, formal analysis, writing – original draft, writing – review & editing, visualisation. SF: conceptualisation, methodology, formal analysis, writing – original draft, writing – review & editing, visualisation. PO: conceptualisation, supervision, writing – review & editing. RD: methodology, supervision, writing – review & editing.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work presented in this paper.

Data availability

The data supporting this article have been included as part of the supplementary information (SI). Supplementary information is available. See DOI: https://doi.org/10.1039/d6gc00120c.

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References

1 Z. Pasztory, *et al.*, The utilization of tree bark, *BioResources*, 2016, **11**(3), 7859–7888.
2 CEforestry, *O.2.1. R1 Methodology of spruce extracts as biocides replacement in a wastewater system*, 2025 [cited 2025 12.11.]; Available from:https://interreg-baltic.eu/project/ceforestry/.
3 M. Fraga-Corral, *et al.*, Technological Application of Tannin-Based Extracts, *Molecules*, 2020, **25**(3), 614.
4 A. Pizzi, Chapter 8 - Tannins: Major Sources, Properties and Applications, in *Monomers, Polymers and Composites from Renewable Resources*, ed. M. N. Belgacem and A. Gandini, Elsevier, Amsterdam, 2008, pp. 179–199.
5 N. Graham, *et al.*, Characterisation and coagulation performance of a tannin-based cationic polymer: A preliminary assessment, *Colloids Surf., A*, 2008, **327**(1), 9–16.
6 J. Zhang, *et al.*, Tannin-based adhesive cross-linked by furfuryl alcohol-glyoxal and epoxy resins, *Int. J. Adhes. Adhes.*, 2019, **94**, 47–52.
7 S. Wijeyekoon, *et al.*, Techno–economic analysis of tannin and briquette co–production from bark waste: a case study quantifying symbiosis benefits in biorefinery, *Biofuels, Bioprod. Biorefin.*, 2021, **15**(5), 1332–1344.
8 O. Ajao, *et al.*, Multi-product biorefinery system for woodbarks valorization into tannins extracts, lignin-based polyurethane foam and cellulose-based composites: Techno-economic evaluation, *Ind. Crops Prod.*, 2021, **167**, 113435.
9 J. Zhang and W. Chen, A rapid and cleaner chrome tanning technology based on ultrasound and microwave, *J. Cleaner Prod.*, 2020, **247**, 119452.
10 R. Ciriminna, *et al.*, Chestnut tannin: New use, research and bioeconomy, *J. Bioresour. Bioprod.*, 2024, **9**(3), 246–252.
11 V. Caprarulo, C. Giromini and L. Rossi, Review: Chestnut and quebracho tannins in pig nutrition: the effects on performance and intestinal health, *Animal*, 2021, **15**(1), 100064.
12 Grand View Research, *Tannin Market Size and Trends*, 2022 [cited 2025 14.2]; Available from: https://www.grandviewresearch.com/industry-analysis/tannin-market.
13 R. Muilu-Mäkelä, *et al.*, Valuable biochemicals of the future, *Nat. Resour. Bioecon. Stud.*, 2024, **85/2024**, 85.
14 ECB. *US dollar (USD)*, 2025 [cited 2025 1.12]; Available from: https://www.ecb.Europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html.
15 UPM. *UPM Pulp*, 2025 [cited 2025 3.2]; Available from: https://www.upmpulp.com/pulp-production/.
16 Södra. *Mönsterås site*, 2025 [cited 2025 3.11]; Available from: https://www.sodra.com/en/global/about-us/organisation/facilities/monsteras-site/.
17 Södra. *Värö site*, 2025 [cited 2025 3.11]; Available from: https://www.sodra.com/en/global/about-us/organisation/facilities/varo-site/.
18 K. I. Keskinen, *Taulukoita ja piirroksia kemian laitetekniikkaan - Tables and Drawings for Chemical Engineering*, Otatieto, 2 edn, 2015, vol. 170.
19 CheCalc, *Pump Sizing Calculation*, 2025 [cited 2025 25.3.]; Available from: https://checalc.com/calc/pump.html.
20 Checalc, *Blower & Fan Calculation*, 2025 [cited 2025 1.4.]; Available from: https://checalc.com/fan.html.
21 Tetra Pak, *Tetra Pak Evaporator Falling FILM MVR*, 2022 [cited 2025 14.5.]; Available from:https://www.tetrapak.com/solutions/integrated-solutions-equipment/processing-equipment/evaporation/tetra-pak-evaporator-mvr.
22 M. S. Peters, K. D. Timmerhaus and R. E. West, *Plant Design and Economics for Chemical Engineers*, McGraw-Hill, 5 edn, 2003, p. 987.
23 Towering Skills, *Cost Indices*, 2025 [cited 2025 4.4.]; Available from: https://toweringskills.com/financial-analysis/cost-indices/.
24 C. Peyrelasse, M. Jacob and A. Lallement, *Comparison and predesign cost assessment of ozonation, membrane filtration*

and activated carbon for the treatment of recalcitrant organics, a conceptual study. 2021.
25 D. Jinze, *et al.*, Valorization of long-neglected spruce bark and bark-press effluents through integrated utilization of stilbenoids and pectin, *Chem. Eng. J.*, 2023, **470**, 144122.
26 R. P. Bangalore Ashok, *et al.*, Techno-economic assessment for the large-scale production of colloidal lignin particles, *Green Chem.*, 2018, **20**(21), 4911–4919.
27 R. P. Bangalore Ashok, P. Oinas and S. Forssell, Techno-economic evaluation of a biorefinery to produce γ-valerolactone (GVL), 2-methyltetrahydrofuran (2-MTHF) and 5-hydroxymethylfurfural (5-HMF) from spruce, *Renewable Energy*, 2022, **190**, 396–407.
28 eurostat, *Electricity price statistics*, 2024 [cited 2025 13.5.]; Available from: https://ec.Europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics#Electricity_prices_for_non-household_consumers.
29 Äänekosken energia, *Vesihuollon hinnasto*, 2025 [cited 2025 13.5.]; Available from: https://www.aanekoskenenergia.fi/hinnasto/vesi/.
30 Chemanalyst, *Soda Ash Price Trend and Forecast*, 2024 [cited 2025 10.4.]; Available from: https://www.chemanalyst.com/Pricing-data/soda-ash-76.
31 Tradewheel, *96% 97% sodium sulphate anhydrous price*, 2025 [cited 2025 10.4.]; Available from: https://www.tradewheel.com/p/96-97-sodium-sulphate-anhydrous-price-521676/.
32 Made-in-China, *Factory Price Wholesale Sodium Acetate Anhydrous CAS 127-09-3 Sodium Acetate Trihydrate*, 2025 [cited 2025 9.9.2025]; Available from: https://hbkenbin.en.made-in-china.com/product/OpeUHfPlXRcw/China-Factory-Price-Wholesale-Sodium-Acetate-Anhydrous-CAS-127-09-3-Sodium-Acetate-Trihydrate.html?pv_id=1j4nfeal5386&faw_id=1j4nfeqrl576&bv_id=1j4nfh2o84b5&pbv_id=1j4nfe18d997h.
33 Made-in-China, *Sowu Supply Beta-Glucanase/Dextranasecas 9025-70-1*, 2025 [cited 2025 9.4.2025]; Available from: https://cnsonwu.en.made-in-china.com/product/WnLYtiNAaypS/China-Sowu-Supply-Beta-Glucanase-Dextranasecas-9025-70-1.html?pv_id=1jc26cki22ef&faw_id=1jc26e5nhb30&bv_id=1jc26e5nk093.
34 Alibaba, *Food Grade Pectinase Enzyme Liquid Enzima 99% Pectinase Powder CAS 9032–75–1*, 2025 [cited 2025 9.4.2025]; Available from: https://www.alibaba.com/product-detail/Food-Grade-Pectinase-Enzyme-Liquid-Enzima_1601634290265.html?spm=a2700.7724857.0.0.4d632c46Z0NXiC.
35 N. I. S. Muhammad and K. Rosentrater, Techno-Economic Evaluation of Food Waste Fermentation for Value-Added Products, *Energies*, 2020, **13**, 436.
36 Salaryexpert, *Process Plant Operator*, 2025 [cited 2025 18.5.]; Available from: https://www.salaryexpert.com/salary/job/process-plant-operator/finland.
37 Volza, *Vegetable Tanning Agents Imports in World - Market Size & Demand based on Import Trade Data*, 2024 [cited 2025 14.4.]; Available from: https://www.volza.com/p/vegetable-tanning-agents/import/.
38 Zauba, *Tanning Agent Tara Imports*, 2016 [cited 2025 14.4.]; Available from: https://www.zauba.com/import-tanning%2Bagent%2Btara-hs-code.html.
39 WITS, *European Union Quebracho extract imports by country in 2023*, 2023 [cited 2025 14.4.]; Available from: https://wits.worldbank.org/trade/comtrade/en/country/EUN/year/2023/tradeflow/Imports/partner/ALL/product/320110.
40 N. Jungbluth and B. Nguyen, *Life cycle inventory of sodium acetate and expanded graphite: Short report*, Switzerland, 2008.
41 K. Kemppainen, , *et al.*, Spruce bark as an industrial source of condensed tannins and non-cellulosic sugars, *Ind. Crops Prod.*, 2014, **52**, 158–168.
42 H. Kyllönen, *et al.*, Enzyme-assisted nanofiltration to enrich tannins from softwood bark extract, *Ind. Crops Prod.*, 2023, **205**, 117441.
43 A. S. Mujumdar, *Handbook of Industrial Drying*, Taylor & Francis, 4th edn, 2014.
44 T. Jyske, *et al.*, Fate of Antioxidative Compounds within Bark during Storage: A Case of Norway Spruce Logs, *Molecules*, 2020, **25**(18), 4228.
45 D. Ahmed, K. M. Maraz and R. A. Khan, Prospects and challenges of chrome tanning: approach a greener technology in leather industry, *Sci. Rev.*, 2021, **7**(3), 42–49.
46 J. Tienaho, *et al.*, Pilot scale hydrodynamic cavitation and hot-water extraction of Norway spruce bark yield antimicrobial and polyphenol-rich fractions, *Sep. Purif. Technol.*, 2025, **360**, 130925.
47 GMI, *Stilbene Market Size - By Type, Purity, Application Analysis, Share, Growth Forecast, 2025–2034*, 2024 [cited 2025 23.5.]; Available from: https://www.gminsights.com/industry-analysis/stilbene-market.
48 M. A. Hubbe, Energy efficiency challenges in pulp and paper manufacturing: a tutorial review, *BioResources*, 2021, **16**(4), 8567.