

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

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Supporting Information content

Number of pages: 16

Number of tables: 14

Contents

1	Methodology.....	3
2	Process design.....	6
3	CAPEX and OPEX.....	9
4	LCA and environmental aspects.....	12
5	Challenges and future outlook in commercial scaling.....	15
6	References.....	16

Table S1. Percentages for the FCI calculation with the percentages of delivered equipment method.....	S3
Table S2. Inventory data for conversion and transportation of inputs and outputs to the LCA scaled based on the functional unit of 1 kg of spruce bark extract.....	S4
Table S3. Selected databases for the life cycle impact assessment.....	S5
Table S4. Mass flows and component fractions in the tannin extraction process.....	S6
Table S5. Extractor design parameters.....	S7
Table S6. Tetra Pak FFE system specifications.....	S8
Table S7. Equipment list.....	S8
Table S8. Equipment costs.....	S8
Table S9. Capital investment cost components.....	S9
Table S10. OPEX breakdown.....	S10
Table S11. Utility consumption of process units.....	S11
Table S12. Tanning agent economic comparison.....	S12
Table S13. The stagewise environmental impacts for the tannin extract production process.....	S13
Table S14. Environmental impacts of feedstocks and waste of the tannin extract production process.....	S15

1 Methodology

The percentages of delivered equipment cost on which the FCI calculation is based are listed in Table S1.

Table S1. Percentages for the FCI calculation with the percentages of delivered equipment method.

Cost component	% of DEC
Direct costs	
Delivered equipment	100
Equipment installation	40
Instrumentation & controls	25
Piping	30
Electrical	15
Process and auxiliary buildings	20
Yard improvements	10
Plant service facilities	25
Total direct costs	265
Indirect costs	
Engineering and supervision	32
Legal expenses	3
Construction and start-up Expenses	50
Contingency	60
Total indirect costs	145
Land	0
Working capital	75
Fixed capital investment	410
Total capital investment	485

The unit specific inventory data scaled to the functional unit of 1kg tannin extract product is presented in Table S2, and the databases selected for the life cycle impact assessment are presented in Table S3.

Table S2. Inventory data for conversion and transportation of inputs and outputs to the LCA scaled based on the functional unit of 1 kg of spruce bark extract.

Item	Extraction	Evaporation	Nanofiltration	Spray drying
Spruce bark	27.8	-	-	-
Water	69.1	98.3	-	-
Sodium carbonate	0.2	-	-	-
Sodium sulphate	0.2	-	-	-
Electricity	0.01	-	0.1	0.09
Steam	-	4.0	-	1.6
Enzymes	-	-	0.007	-
Sodium acetate	-	-	0.03	-
Spent bark	32.0	-	-	-
Wastewater	-	0.06	0.002	0.001
Tannin extract	-	-	-	1

Table S3. Selected databases for the life cycle impact assessment.

Input	Process	Database
<i>Inputs from technosphere: materials/fuels</i>		
Bark	Bark chips, wet, measured as dry mass (Europe without Switzerland) market for bark chips, wet, measured as dry mass Cut-off, U	Ecoinvent 3.10
Water	Tap water (RER) market group for tap water Cut-off, U	Ecoinvent 3.10
Sodium sulphate	Sodium sulfate, anhydrite (RER) market for sodium sulfate, anhydrite Cut-off, U	Ecoinvent 3.10
Sodium carbonate	Soda ash, light (RER) market for soda ash, light Cut-off, U	Ecoinvent 3.10
Enzymes	Enzymes (RER) , enzymes production Cut-off, U	Ecoinvent 3.10
Transportation	Transport, freight, lorry >32 metric ton, EURO6 (RER) market for transport, freight, lorry >32 metric ton, EURO6 Cut-off, U	Ecoinvent 3.10
Sodium acetate	Sodium acetate	Jungbluth, 2008
<i>Inputs from technosphere: electricity/heat</i>		
Steam	Steam, in chemical industry (RER) market for steam, in chemical industry Cut-off, U	Ecoinvent 3.10
Electricity	Electricity, medium voltage (FI) market for electricity, medium voltage Cut-off, U	Ecoinvent 3.10
Heat*	Heat, central or small scale, other than natural gas (Europe without Switzerland) heat production, wood pellet, at furnace 9 kW Cut-off, U	Ecoinvent 3.10
Heat*	Heat, central or small scale, natural gas (Europe without Switzerland) heat production, natural gas, at boiler modulating <100kW Cut-off, U	Ecoinvent 3.10
<i>Outputs to technosphere: waste and emissions to treatment</i>		
Spent bark	Waste wood, untreated (FI) market for waste wood, untreated Cut-off, U	Ecoinvent 3.10
Wastewater	Wastewater, average market for wastewater, average Cut-off, U (Europe without Switzerland)	Ecoinvent 3.10

*Used for scenario analysis only, not included in the base case model.

2 Process design

In the mass flows and component fractions presented in Table S4, the solids are not divided into further components, and are instead considered as bark dry matter before extraction and as biomass after extraction.

Table S4. Mass flows and component fractions in the tannin extraction process

Stream	Mass flow (kg/h)	Water	Bark dry matter	Bio-mass	Sodium carbonate	Sodium sulphate	Sodium acetate	Enzyme mixture	Air
1	3248	1	-	-	-	-	-	-	-
2	141	-	-	-	0.5	0.5	-	-	-
3	28112	0.995	-	-	0.0025	0.0025	-	-	-
4	11301	0.5	0.5	-	-	-	-	-	-
5	13003	0.6	0.4	-	-	-	-	-	-
6	26552	0.978	-	0.022	<0.001	<0.001	-	-	-
7	24864	1	-	-	-	-	-	-	-
8	1688	0.65	-	0.342	0.004	0.004	-	-	-
9	14	0.71	-	-	-	-	0.078	0.212	-
10	1702	0.65	-	0.338	0.004	0.004	<0.001	0.002	-
11	845	0.804	-	0.173	0.009	0.009	0.001	0.004	-
12	857	0.5	-	0.5	-	-	-	-	-
13	12464	-	-	-	-	-	-	-	1
14	424	0.95	-	0.05	-	-	-	-	-
15	433	0.06	-	0.94	-	-	-	-	-

The equipment list of the process is in Table S5. The list along with the equipment sizing parameters were used as the input for Aspen Process Economic Analyzer.

Table S5. Equipment list.

Code	Equipment description	Amount	Area	Details
DB-001/2/3/4/5	extractor	5		d = 0.8 m, l = 7.9 m
M-001/2/3/4/5	Extractor screw motor	5		0.2 kW
GA-001	Water feed pump	1		centrifugal, 1.5 kW
FA-001	Water feed vessel	1		d = 1.2 m, h = 3.6 m
EA-001	Water heater	1	Extraction	3 m ² , 830 kW
FB-001/2/3/4/5	Bark hopper	5		-
HA-001/2	Tannin extract sieve	2		-
FA-002	Tannin extract vessel	1		d = 2 m, h = 4 m
GA-002	Tannin extract pump	1		centrifugal, 1 kW
CB-101/2	Falling-film evaporator column	2		d = 1.5 m, h = 15 m*, 550 kW
GA-101/2	Circulation pump	2		centrifugal, 1 kW
FA-101/2	Flash drum	2		d = 0.85 m, h = 2.6 m*
EA-101/2	Vapor condenser	2	Evaporation	700 kW
GA-103	Cooling water pump	1		centrifugal, 1 kW
GA-104	Condensate pump	1		centrifugal, 2 kW
FA-104	Mixing vessel	1		d = 1.3 m, h = 3.7 m
GA-105	Concentrated tannin Extract pump	1		centrifugal, 0.2 kW
HX-201/2/3	Nanofilter	3		600-800 Da, 40 bar
GA-201	Filter pump	1		centrifugal, 3.5 kW
GA-202	Concentrated tannin Extract pump	1	Filtration	centrifugal, 0.2 kW
GA-203	Permeate pump	1		centrifugal, 0.3 kW
CA-301/2/3	Spray drying column	3		d = 1.5, h = 6.5 m, 322 kW
HE-301/2/3	Cyclone separator	3		-
GB-301	Air blower	1	Drying	p = 13 kW
EA-301	Air heater	1		60 m ² , 385 kW
FA-301	Tannin product Container	1		-

*Design values calculated to accommodate the volume flows; actual dimensions are from the selected equipment package by Tetra Pak.

The utility consumption of the process units in Table S6 were determined from the mass balance and the characteristics of the process units.

Table S6. Utility consumption of process units.

Process unit	Water (kg/h)	Cooling water (kg/h)	Steam (kg/h)	Air (kg/h)	Electricity (kW)
Extractors	3248	-	1644	-	5.5
Evaporation	2500	40 000	1625	-	555.2
Filtration	-	-	-	-	40
Spray drying	-	-	655	12 464	36.3
Total	5748	40 000	3924	12 464	634

The extractor unit design parameters in Table S7 were based on the mass balance, with the required capacity and material flow speeds dictating the dimensions of the unit.

Table S7. Extractor design parameters.

Parameter	Value
required volume (m ³)	18.8
residence time (h)	0.5
L/D ratio	10
n:o of extractor tubes	5
bark flow velocity (cm/s)	0.5
water flow velocity (cm/s)	1.5
conveyor screw speed (rpm)	2

The required equipment specifications for the evaporation step were first determined from the mass balance and the amount of water to be removed from the product containing stream, and a suitable falling-film evaporator system by Tetra Pak [7] was deemed suitable for the design. The falling-film evaporator column specifications are in Table S8.

Table S8. Tetra Pak FFE system specifications.

Parameter	Value	Notes
temperature	>100 °C	The system is at minimum in the boiling point of the concentrated fluid
pressure	1 atm	-
processing capacity	48 000 kg/h	Originally for skim milk, assumed to be compatible with other fluids
required steam	1625 kg/h	-
electrical power	550 KW	for MVR and pumps
cooling water	40 m ³ /h	30 °C in, 45 °C out
ring and sealing water	2.5 m ³ /h	-

3 CAPEX and OPEX

Equipment costs for the process are listed in Table S9. The CEPCI-adjusted equipment costs were multiplied with 1.1 to get the delivered equipment cost. The nanofilter equipment cost was interpolated from existing datapoints [8].

Table S9. Equipment costs.

Code	Equipment description	CEPCI adjusted equipment cost (k€)	Delivered equipment cost (k€)
DB-001/2/3/4/5	extractor	165	181
M-001/2/3/4/5	extractor screw motor	4	4
GA-001	water feed pump	8	9
FA-001	water feed vessel	25	28
EA-001	water heater	21	23
FB-001/2/3/4/5	bark hopper	49	54
HA-001/2	Dilute tannin extract filter	5	5
FA-002	Dilute tannin extract vessel	34	37
GA-002	Dilute tannin extract pump	8	9
CB-101/2	Falling-film evaporator column	371	409
GA-101/2	circulation pump	13	14
FA-101/2	flash drum	29	32
EA-101/2	vapor condenser	27	30
GA-103	cooling water pump	9	9
GA-104	condensate pump	6	7
FA-104	Concentrated tannin extract vessel	55	60
GA-105	Concentrated tannin extract pump	5	6
HX-201	nanofilter	239	263
GA-201	filter pump	12	13
GA-202	Concentrated tannin extract pump	5	6
GA-203	permeate pump	6	6
CA-301/2/3	spray drying column	471	518
HE-301/2/3	cyclone separator	53	58
GB-301	air compressor	147	161
EA-301	air heater	24	26
FA-301	Tannin product container	14	16
Total		1803	1983

Table S10 below includes all the cost components of the plant project, calculated as percentages of delivered equipment cost. The delivered equipment cost is 1984 k€, and it is assumed to be the cost when all equipment have been procured and delivered at the site. The land-related costs were assumed to be zero due to the plant project being carried out within an existing pulp mill site.

Table S10. Capital investment cost components.

Cost component	Cost (k€)	% of DEC	% of TCI
Direct costs			
Delivered equipment	1984	100	20.7
Equipment installation	793	40	8.3
Instrumentation & controls	496	25	5.2
Piping	595	30	6.2
Electrical	198	15	2.1
Process and auxiliary buildings	397	20	4.1
Yard improvements	198	10	2.1
Plant service facilities	595	25	6.2
Total direct costs	5256	265	54.9
Indirect costs			
Engineering and supervision	635	32	6.6
Legal expenses	60	3	0.6
Construction and start-up Expenses	992	50	10.4
Contingency	1190	60	12.4
Total indirect costs	2876	145	30.0
Land	0	0	0.0
Working capital	1440	75	15
Fixed capital investment	8133	410	
Total capital investment	9626	485	100.00

Table S11 shows the detailed OPEX breakdown of the plant. The usage time for all the VOC components was assumed to be the same, and their amounts were based on the mass balance of the process. The prices for the utilities were based on available sources, except for the spruce bark, for which the price was determined based on the post-processing energy consumption and heating value loss. The FOC components were calculated either based on the total salary costs, or as a percentage of another suitable cost component. The cost components on which the FOC are based are listed in the table. The number of workers per shift was determined to be 4, and with a five-shift operation, the total number of production workers is 20, including a supervisor for each shift. In addition, the plant has three mechanical staff on site, and two Quality control personnel.

Table S11. OPEX breakdown.

	Amount (kg/h)	Usage (h/a)	Price per unit (k€)	Cost (k€/a)	% of OPEX
VOC					
Spruce bark	11.4	8160	0.00198	184.01	3.2
Extraction aid chemicals	0.14	8160	0.55	634.01	11.0
Enzymes	0.003	8160	30	723.11	12.6
Buffer solution	0.001	8160	0.5	4.49	0.1
Water	5.75	8160	0.00105	49.40	0.9
Cooling water	40.0	8160	0.00024	78.34	1.4
Steam	3.92	8160	0.04	1272.50	22.1
Electricity	634	8160	0.000078	396.78	6.9
Air	12.46	8160	0	0	0
Wastewater treatment	1.082	8160	0.0015	13.25	0.23
Operating supplies	-	-	-	41	0.71
			Total VOC	3397	59.0
FOC					
Production salaries				1221	21.2
Quality control salaries				90	1.6
Administration salaries (15% of the total labor cost)				197	3.4
Healthcare and benefits (25% of the total labor cost)				328	5.7
Quality control operation (1% of FCI)				81	1.4
Maintenance and repairs (10% of DEC)				198	3.4
Insurance (4% of direct CAPEX)				210	3.6
Security (2% of DEC)				40	0.7
			Total FOC	2364	41.0
			Total OPEX	5761	100

4 LCA and environmental aspects

The detailed environmental impacts for the tannin extract production process are presented stagewise in Table S12 and for each feedstock and raw material in Table S13.

Table S12. The stagewise environmental impacts for the tannin extract production process.

Category	Unit	Total	Extraction	Evaporation	Nanofiltration	Spray drying
Global warming	kg CO ₂ -eq	4.54	2.35	1.51	0.16	0.52
Stratospheric ozone depletion	kg FCF11-eq	6.4x10 ⁻⁶	5.4x10 ⁻⁶	4.6x10 ⁻⁶	3.7x10 ⁻⁷	7.3x10 ⁻⁸
Ionizing radiation	kBq Co-60-eq	0.67	0.67	0.17	0.41	0.054
Ozone formation, human health	kg NO _x -eq	0.017	0.014	0.0020	0.00039	0.00065
Fine particulate matter formation	kg PM2.5-eq	0.0053	0.0036	0.0011	0.00023	0.00033
Ozone formation, terrestrial ecosystems	kg NO _x -eq	0.017	0.014	0.0022	0.00041	0.00071
Terrestrial acidification	kg SO ₂ eq	0.014	0.0089	0.0029	0.00083	0.00094
Freshwater eutrophication	kg P-eq	0.0094	0.0088	0.00040	0.00011	7.0x10 ⁻⁵
Marine eutrophication	kg N-eq	0.0012	0.00070	0.00039	0.00014	1.4x10 ⁻⁵
Terrestrial ecotoxicity	kg 1,4-DCB-eq	76.4	55.8	14.3	2.15	4.06
Freshwater ecotoxicity	kg 1,4-DCB-eq	0.18	0.14	0.026	0.011	0.0042
Marine ecotoxicity	kg 1,4-DCB-eq	0.31	0.24	0.048	0.014	0.0093
Human carcinogenic toxicity	kg 1,4-DCB-eq	1.04	0.77	0.21	0.031	0.030
Human non-carcinogenic toxicity	kg 1,4-DCB-eq	6.03	4.91	0.73	0.27	0.13
Land use	m ² a crop-eq	4.65	4.54	0.043	0.058	0.0074
Mineral resource scarcity	kg Cu-eq	0.013	0.010	0.0021	0.00077	0.00034
Fossil resource scarcity	kg oil-eq	1.32	0.62	0.47	0.054	0.17

Table S13. Environmental impacts of feedstocks and waste of the tannin extract production process.

Category	Unit	Total	Bark	Water	Sodium acetate	Sodium Sulphate	Sodium carbonate
Global warming	kg CO ₂ -eq	4.54	0.99	0.052	0.070	0.12	0.060
Stratospheric ozone depletion	kg FCF11-eq	6.4x10 ⁻⁶	3.3x10 ⁻⁷	1.86x10 ⁻⁸	2.2x10 ⁻⁸	3.5x10 ⁻⁸	1.7x10 ⁻⁸
Ionizing radiation	kBq Co-60-eq	0.67	0.12	0.017	0.016	0.018	0.0038
Ozone formation, human health	kg NO _x -eq	0.017	0.0047	0.00012	0.00012	0.00029	1.7x10 ⁻⁴
Fine particulate matter formation	kg PM2.5-eq	0.0053	0.0014	8.1x10 ⁻⁵	6.8·10 ⁻⁵	0.00041	1.5x10 ⁻⁴
Ozone formation, terrestrial ecosystems	kg NO _x -eq	0.017	0.0050	0.00012	0.00013	0.00030	1.7x10 ⁻⁴
Terrestrial acidification	kg SO ₂ eq	0.014	0.0032	0.00018	0.00017	0.0013	5.6x10 ⁻⁴
Freshwater eutrophication	kg P-eq	0.0094	4.5x10 ⁻⁴	3.4x10 ⁻⁵	3.7x10 ⁻⁵	6.2x10 ⁻⁵	4.1x10 ⁻⁵
Marine eutrophication	kg N-eq	0.0012	4.8x10 ⁻⁵	3.4x10 ⁻⁶	9.0x10 ⁻⁶	7.6x10 ⁻⁶	5.9x10 ⁻⁶
Terrestrial ecotoxicity	kg 1,4-DCB-eq	76.4	19.5	3.65	0.69	2.17	0.91
Freshwater ecotoxicity	kg 1,4-DCB-eq	0.18	0.032	0.0043	0.0041	0.012	0.0082
Marine ecotoxicity	kg 1,4-DCB-eq	0.31	0.059	0.0099	0.0060	0.017	0.011
Human carcinogenic toxicity	kg 1,4-DCB-eq	1.04	0.24	0.16	0.015	0.036	0.023
Human non-carcinogenic toxicity	kg 1,4-DCB-eq	6.03	0.87	0.064	0.083	0.23	0.15
Land use	m ² a crop-eq	4.65	4.49	0.0018	0.0022	0.0053	0.0054
Mineral resource scarcity	kg Cu-eq	0.013	0.0028	0.00063	0.00031	0.00085	0.00061
Fossil resource scarcity	kg oil-eq	1.32	0.30	0.014	0.032	0.035	0.014

Table S13 (continued). Environmental impacts of feedstocks and waste of the tannin extract production process.

Category	Unit	Total	Enzymes	Transport	Electricity	Steam	Wastewater	Spent bark
Global warming	kg CO ₂ -eq	4.54	0.079	1.59·10 ⁻⁴	0.23	1.76	0.026	1.15
Stratospheric ozone depletion	kg FCF11-eq	6.4x10 ⁻⁶	3.3x10 ⁻⁷	7.0x10 ⁻¹¹	2.3x10 ⁻⁷	2.0x10 ⁻⁷	1.04x10 ⁻⁷	5.16x10 ⁻⁶
Ionizing radiation	kBq Co-60-eq	0.67	0.011	2.5x10 ⁻⁶	0.43	0.037	0.0039	0.013
Ozone formation, human health	kg NO _x -eq	0.017	2.4x10 ⁻⁴	3.1x10 ⁻⁷	4.1x10 ⁻⁴	0.0022	6.0x10 ⁻⁵	0.0085
Fine particulate matter formation	kg PM2.5-eq	0.0053	1.5x10 ⁻⁴	1.3x10 ⁻⁷	2.5x10 ⁻⁴	0.0011	3.0x10 ⁻⁵	0.0016
Ozone formation, terrestrial ecosystems	kg NO _x -eq	0.017	2.5x10 ⁻⁴	3.5x10 ⁻⁷	4.2x10 ⁻⁴	0.0024	6.3x10 ⁻⁵	0.0086
Terrestrial acidification	kg SO ₂ -eq	0.014	6.3x10 ⁻⁴	2.3x10 ⁻⁷	5.4x10 ⁻⁴	0.0032	7.7x10 ⁻⁵	0.0039
Freshwater eutrophication	kg P-eq	0.0094	6.0x10 ⁻⁵	1.4x10 ⁻⁸	6.6x10 ⁻⁵	2.2x10 ⁻⁴	1.7x10 ⁻⁴	0.0082
Marine eutrophication	kg N-eq	0.0012	1.2x10 ⁻⁴	2.2x10 ⁻⁹	1.2x10 ⁻⁵	2.8x10 ⁻⁵	3.7x10 ⁻⁴	6.3x10 ⁻⁴
Terrestrial ecotoxicity	kg 1,4-DCB-eq	76.4	1.3	0.0047	2.21	13.6	0.58	31.7
Freshwater ecotoxicity	kg 1,4-DCB-eq	0.18	0.0060	4.1x10 ⁻⁶	0.016	0.011	0.0024	0.089
Marine ecotoxicity	kg 1,4-DCB-eq	0.31	0.0069	9.1x10 ⁻⁶	0.021	0.028	0.0037	0.15
Human carcinogenic toxicity	kg 1,4-DCB-eq	1.04	0.014	2.8x10 ⁻⁵	0.039	0.094	0.013	0.41
Human non-carcinogenic toxicity	kg 1,4-DCB-eq	6.03	0.16	1.3x10 ⁻⁴	0.24	0.38	0.21	3.63
Land use	m ² a crop-eq	4.65	0.05	1.2x10 ⁻⁵	0.033	0.019	7.81x10 ⁻⁴	0.039
Mineral resource scarcity	kg Cu-eq	0.013	0.00039	4.0x10 ⁻⁷	9.6x10 ⁻⁴	9.83x10 ⁻⁴	1.9x10 ⁻⁴	0.0054
Fossil resource scarcity	kg oil-eq	1.32	0.018	5.3x10 ⁻⁵	0.053	0.58	0.0050	0.27

5 Challenges and future outlook in commercial scaling

Prices and leather production cost figures used in comparing the spruce bark tannin product against other tannin options are listed in Table S14.

Table S14. Tanning agent economic comparison.

	Quebracho	Tara	Chestnut	Chromium sulphate
Consumption (kg/kg of hide)	0.27–0.285* [2, 9]	0.2 - 0.3 [10]	0.3 [10]	0.015 - 0.08 [9]
Price (€/kg)	2.27 [11]	1.62 [12]	1.71 [13]	0.75 - 0.85 [14]
Calculated production cost (€/kg of leather)	0.61 - 0.65	0.32 - 0.49	0.34	0.01 - 0.07

*Upper limit is a combination of *Xylocarpus Granatum*, Mimosa, and Quebracho tannins, limit assumed to be the same for Quebracho alone.

6 References

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