Supporting Information

for

Life cycle assessment of zein, ethyl lactate and derivative nanofiltration membranes

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1. Life Cycle Inventory

This section is divided in de different scenarios proposed including the processes and the values used in each of them.

1.1. Life Cycle Inventory for the extraction of 1 kg of zein (Scenario Z1–Z10)

The processes were modeled using the data reported by Anderson based in Carter et al. Method as shown in Figure 1. Zein was extracted either from corn gluten meal [1] or distillers dried grains with solubles [2] using different solvents.

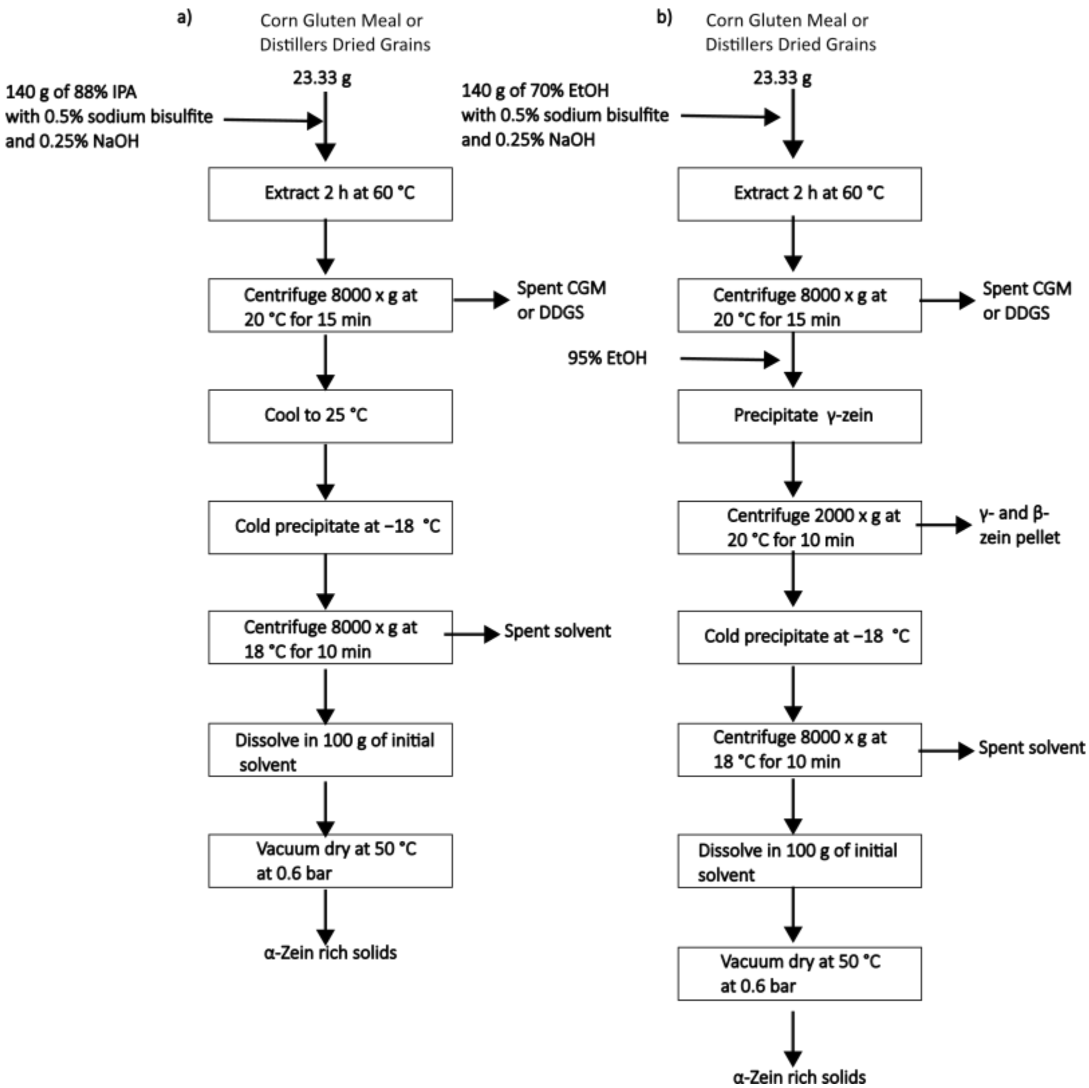

Figure S1. Schematic description of zein extraction from corn by a) Carter and Reck and b) Anderson methods.

Table S1. Life Cycle Inventory for Scenario Z1.

Material or energy	Quantity	Database	Process Name	Comments
Output				
Zein Sc Z1	5.4 g			
Spent solvent	240 g	Ecoinvent v3	Spent solvent mixture {RoW}|treatment of spent solvent mixture, hazardous waste incineration, with energy recovery, in the waste flows	
Input				
Corn Gluten Meal	23.3 g	Agri-footprint	Maize Gluten Meal dried at processing {US} Economic, S	
Isopropanol	211.2 g	Ecoinvent v3	Isopropanol {RoW}| market for isopropanol | Cut-off, S	
Water	28.8 g	Ecoinvent v3	Tap water {CA-QC}| market group for tap water | Cut-off, S	
Sodium hydroxide	0.35 g	Ecoinvent v3	Neutralising agent, sodium hydroxide-equivalent {GLO}| soda ash, dense, to generic market for neutralising agent | Cut-off, S	
Disodium bisulfite	0.7 g	Ecoinvent v3	Disodium disulphite {GLO}|market for disodium disulphite | Cut-off, S	Proxy for sodium disulfite
Electricity	209 kJ	Ecoinvent v3	Electricity, medium voltage {US} | market group for electricity, medium voltage, Cut-off, S	

Table S2. Life Cycle Inventory for Scenario Z2.

Material or energy	Quantity	Database	Process Name	Comments
Output				
Zein Sc Z2	7.99 g			
Spent solvent	240 g	Ecoinvent v3	Spent solvent mixture {RoW}|treatment of spent solvent mixture, hazardous waste incineration, with energy recovery, in the waste flows	
Input				
Corn Gluten Meal	23.3 g	Agri-footprint	Maize Gluten Meal dried at processing {US} Economic, S	
Ethanol	176.84 g	Ecoinvent v3	Ethanol without water in 95% solution state, from fermentation {US} l ethanol production from maize | Cut-off, S	
Water	63.16 g	Ecoinvent v3	Tap water {CA-QC}| market group for tap water | Cut-off, S	
Sodium hydroxide	0.35 g	Ecoinvent v3	Neutralising agent, sodium hydroxide-equivalent {GLO}| soda ash, dense, to generic market for neutralising agent | Cut-off, S	
Disodium bisulfite	0.7 g	Ecoinvent v3	Disodium disulphite {GLO}|market for disodium disulphite | Cut-off, S	Proxy for sodium disulfite
Electricity	275 kJ	Ecoinvent v3	Electricity, medium voltage {US} | market group for electricity, medium voltage, Cut-off, S	

Table S3. Life Cycle Inventory for Scenario Z3.

Material or energy	Quantity	Database	Process Name	Comments
Output				
Zein Sc Z3	0.233 g			
Spent solvent	240 g	Ecoinvent v3	Spent solvent mixture {RoW}|treatment of spent solvent mixture, hazardous waste incineration, with energy recovery, in the waste flows	
Input				
Distillers Dried Grains with Solubles (DDGS)	23.3 g	Ecoinvent v3	Distillers Dried Grains with Solubles {US}| ethanol production from maize | Cut-off, S	
Isopropanol	211.2 g	Ecoinvent v3	Isopropanol {RoW}| market for isopropanol | Cut-off, S	
Water	28.8 g	Ecoinvent v3	Tap water {CA-QC}| market group for tap water | Cut-off, S	
Sodium hydroxide	0.35 g	Ecoinvent v3	Neutralising agent, sodium hydroxide-equivalent {GLO}| soda ash, dense, to generic market for neutralising agent | Cut-off, S	
Disodium bisulfite	0.7 g	Ecoinvent v3	Disodium disulphite {GLO}|market for disodium disulphite | Cut-off, S	Proxy for sodium disulfite
Electricity	209 kJ	Ecoinvent v3	Electricity, medium voltage {US} | market group for electricity, medium voltage, Cut-off, S	

Table S4. Life Cycle Inventory for Scenario Z4.

Material or energy	Quantity	Database	Process Name	Comments
Output				
Zein Sc Z4	1.0951 g			
Spent solvent	240 g	Ecoinvent v3	Spent solvent mixture {RoW}|treatment of spent solvent mixture, hazardous waste incineration, with energy recovery, in the waste flows	
Input				
Distillers Dried Grains with Solubles (DDGS)	23.3 g	Ecoinvent v3	Distillers Dried Grains with Solubles {US}| ethanol production from maize | Cut-off, S	
Ethanol	176.84 g	Ecoinvent v3	Ethanol without water in 95% solution state, from fermentation {US} l ethanol production from maize | Cut-off, S	
Water	63.16 g	Ecoinvent v3	Tap water {GLO}| market group for tap water | Cut-off, S	
Sodium hydroxide	0.35 g	Ecoinvent v3	Neutralising agent, sodium hydroxide-equivalent {GLO}| soda ash, dense, to generic market for neutralising agent | Cut-off, S	
Disodium bisulfite	0.7 g	Ecoinvent v3	Disodium disulphite {GLO}|market for disodium disulphite | Cut-off, S	Proxy for sodium disulfite
Electricity	275 kJ	Ecoinvent v3	Electricity, medium voltage {US} | market group for electricity, medium voltage, Cut-off, S	

In the method described by Cheryan [3] the extraction of zein is from Distillers Dried Grains (DDGS) in US. It was assumed that 1 kg of corn produces 0.33 kg of DDGS [4]. It is mentioned that for 1 g of corn, 4 mL of solvent is added. It was considered the water required to precipitate the zein. The densities considered were for water 1 g mL^{-1} and ethanol 0.78 g mL^{-1}.

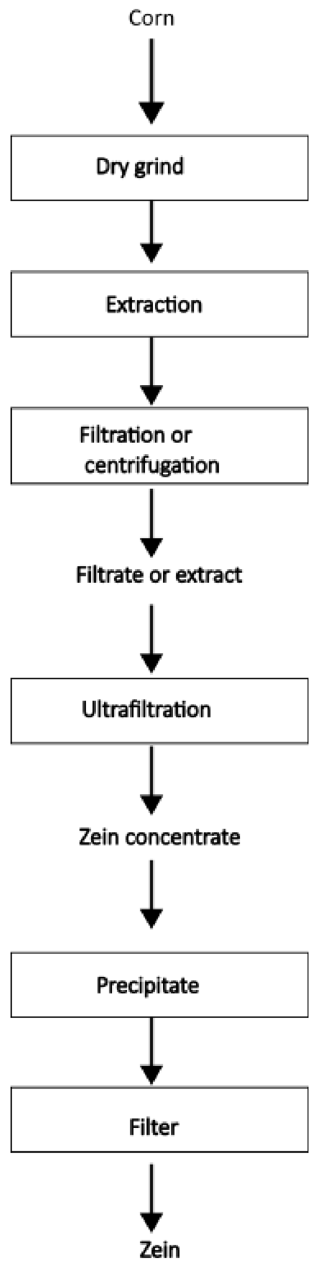

Figure S2. Schematic description of zein extraction from corn based on Cheryan method.

Table S5. Life Cycle Inventory for Scenario Z5.

Material or energy	Quantity	Database	Process Name
Output			
Zein Sc Z5	0.03438 kg		
Spent solvent	6.351 kg	Ecoinvent v3	Spent solvent mixture {RoW}|treatment of spent solvent mixture, hazardous waste incineration, with energy recovery, in the waste flows
Input			
Distillers Dried Grains with Solubles (DDGS)	0.333 kg	Ecoinvent v3	Distillers Dried Grains with Solubles {US}| ethanol production from maize | Cut-off, S
Ethanol	2.301 kg	Ecoinvent v3	Ethanol without water in 95% solution state, from fermentation {US} l ethanol production from maize | Cut-off, S
Water	4.05 kg	Ecoinvent v3	Tap water {GLO}| market group for tap water | Cut-off, S
Electricity	10591 kJ	Ecoinvent v3	Electricity, medium voltage {US} | market group for electricity, medium voltage, Cut-off, S

Table S6. Life Cycle Inventory for Scenario Z6.

Material or energy	Quantity	Database	Process Name
Output			
Zein Sc Z6	0.0224 kg		
Spent solvent	8.223 kg	Ecoinvent v3	Spent solvent mixture {RoW}|treatment of spent solvent mixture, hazardous waste incineration, with energy recovery, in the waste flows
Input			
Distillers Dried Grains with Solubles (DDGS)	0.333 kg	Ecoinvent v3	Distillers Dried Grains with Solubles {US}| ethanol production from maize | Cut-off, S
Ethanol	4.173 kg	Ecoinvent v3	Ethanol without water in 95% solution state, from fermentation {US} l ethanol production from maize | Cut-off, S
Water	4.05 kg	Ecoinvent v3	Tap water {GLO}| market group for tap water | Cut-off, S
Electricity	12744 kJ	Ecoinvent v3	Electricity, medium voltage {US} | market group for electricity, medium voltage, Cut-off, S

Table S7. Life Cycle Inventory for Scenario Z7.

Material or energy	Quantity	Database	Process Name	Comments
Output				
Zein Sc Z7	0.233 g			
Spent solvent	80 g	Ecoinvent v3	Spent solvent mixture {RoW}|treatment of spent solvent mixture, hazardous waste incineration, with energy recovery, in the waste flows	
Input				
Distillers Dried Grains with Solubles (DDGS)	23.3 g	Ecoinvent v3	Distillers Dried Grains with Solubles {US}| ethanol production from maize | Cut-off, S	
Isopropanol	70.4 g	Ecoinvent v3	Isopropanol {RoW}| market for isopropanol | Cut-off, S	
Water	9.6 g	Ecoinvent v3	Tap water {CA-QC}| market group for tap water | Cut-off, S	
Sodium hydroxide	0.35 g	Ecoinvent v3	Neutralising agent, sodium hydroxide-equivalent {GLO}| soda ash, dense, to generic market for neutralising agent | Cut-off, S	
Disodium bisulfite	0.7 g	Ecoinvent v3	Disodium disulphite {GLO}|market for disodium disulphite | Cut-off, S	Proxy for sodium disulfite
Electricity	136.4 kJ	Ecoinvent v3	Electricity, medium voltage {US} | market group for electricity, medium voltage, Cut-off, S	

Table S8. Life Cycle Inventory for Scenario Z8.

Material or energy	Quantity	Database	Process Name	Comments
Output				
Zein Sc Z8	0.233 g			
Spent solvent	24 g	Ecoinvent v3	Spent solvent mixture {RoW}|treatment of spent solvent mixture, hazardous waste incineration, with energy recovery, in the waste flows	
Input				
Distillers Dried Grains with Solubles (DDGS)	23.3 g	Ecoinvent v3	Distillers Dried Grains with Solubles {US}| ethanol production from maize | Cut-off, S	
Isopropanol	21.12 g	Ecoinvent v3	Isopropanol {RoW}| market for isopropanol | Cut-off, S	
Water	2.88 g	Ecoinvent v3	Tap water {CA-QC}| market group for tap water | Cut-off, S	
Sodium hydroxide	0.35 g	Ecoinvent v3	Neutralising agent, sodium hydroxide-equivalent {GLO}| soda ash, dense, to generic market for neutralising agent | Cut-off, S	
Disodium bisulfite	0.7 g	Ecoinvent v3	Disodium disulphite {GLO}|market for disodium disulphite | Cut-off, S	Proxy for sodium disulfite
Electricity	209 kJ	Ecoinvent v3	Electricity, medium voltage {US} | market group for electricity, medium voltage, Cut-off, S	

Table S9. Life Cycle Inventory for Scenario Z9.

Material or energy	Quantity	Database	Process Name
Output			
Zein Sc Z9	0.0224kg		
Spent solvent	0.822 kg	Ecoinvent v3	Spent solvent mixture {RoW}|treatment of spent solvent mixture, hazardous waste incineration, with energy recovery, in the waste flows
Input			
Distillers Dried Grains with Solubles (DDGS)	0.333 kg	Ecoinvent v3	Distillers Dried Grains with Solubles {US}| ethanol production from maize | Cut-off, S
Ethanol	0.417 kg	Ecoinvent v3	Ethanol without water in 95% solution state, from fermentation {US} l ethanol production from maize | Cut-off, S
Water	0.405 kg	Ecoinvent v3	Tap water {GLO}| market group for tap water | Cut-off, S
Electricity	14896 kJ	Ecoinvent v3	Electricity, medium voltage {US} | market group for electricity, medium voltage, Cut-off, S

1.2. Life Cycle Inventory for the fabrication of 1 kg of ethyl lactate (Scenario E1-E4)

The production of ethyl lactate was modeled as described by Argonne National Laboratory [5]. Since it is a document from USA tons were adjusted to USA ton to european tons to be used in SimaPro Software. The four scenarios considered were based in this process. The difference among them is the origin of lactic acid and ethanol. In Scenario **E1**, we consider both of them come from synthesis, Scenario **E2**, we consider ethanol and lactic acid come from corn grain, Scenario **E3**, ethanol comes from corn grain and lactic acid from the corn stover, and Scenario **E4**, both of them come from stalk.

Energy Input	*MMbtu/ton*
Natural gas[a]	8.2
Electricity[a]	0.051
Material Inputs	*ton/ ton*
L-lactic acid	0.81
Ethanol	0.42

Figure S3. Material and energy intensities for ethyl lactate by Argonne National Laboratory.

Table S10. Life Cycle Inventory for Scenario E1.

Material or energy	Quantity	Database	Process Name
Output			
Ethyl lactate Sc E1	1 ton		
Input			
Lactic acid synthetic	0.81 ton	Ecoinvent v3	Lactic acid {GLO}| market for lactic acid | Cut-off, S
Ethanol synthetic	0.421 ton	Ecoinvent v3	Ethanol without water in 99.7% solution state, from ethylene {RoW} l ethanol production, ethylene hydration | Cut-off, S
Heat	8200000 Btu	Ecoinvent v3	Heat, central or small-scale, natural gas {RoW} | market for heat, central or small-scale, natural gas | Cut-off, S
Electricity	51000 Btu	Ecoinvent v3	Electricity, medium voltage {US} | market group for electricity, medium voltage, Cut-off, S

Table S11. Life Cycle Inventory for Scenario E2.

Material or energy	Quantity	Database	Process Name
Output			
Ethyl lactate Sc E2	1 ton		
Input			
Lactic acid corn grain (Manandhar)	0.81 ton		
Ethanol	0.442 ton	Ecoinvent v3	Ethanol without water in 95% solution state, from fermentation {US} l ethanol production from maize | Cut-off, S
Heat	8200000 Btu	Ecoinvent v3	Heat, central or small-scale, natural gas {RoW} | market for heat, central or small-scale, natural gas | Cut-off, S
Electricity	51000 Btu	Ecoinvent v3	Electricity, medium voltage {US} | market group for electricity, medium voltage, Cut-off, S

Table S12. Inventory for the production of lactic acid from corn flour in US, based on Manandhar et al process.[6]

Material or energy	Quantity	Database	Process Name
Output			
Lactic acid Manandhar et al process	12.6 ton		
Input			
Corn flour	19.6 ton	Agri-footprint	Maize flour, at processing {US}Economic, S
Water	36.6 ton	Ecoinvent v3	Tap water {GLO}| market group for tap water | Cut-off, S
Alpha amylase	0.004 ton	USLCI	Enzyme, Alpha-amylase, Novozyme Liquozyme/kg/RER
Glucoamylase	0.016 ton	USLCI	Enzyme, Glucoamylase, Novozyme Spirizyme/kg/RER
Methanol	0.1 ton	Ecoinvent v3	Methanol {US} | market for methanol | Cut-off, S
Corn steep liquor	0.3 ton	USLCI	Corn steep liquor/kg/RNA
Diammonium phosphate	0.03 ton	Ecoinvent v3	Diammonium phosphate {CN} market for diammonium phosphate| Cut-off, S
Steam	256 ton	Ecoinvent v3	Steam in chemical industry {RoW} | market for steam, in chemical industry | Cut-off, S
Electricity	4806 kWh	Ecoinvent v3	Electricity, medium voltage {US} | market group for electricity, medium voltage, Cut-off, S

Table S13. Life Cycle Inventory for Scenario E3.

Material or energy	Quantity	Database	Process Name
Output			
Ethyl lactate Sc E3	1 ton		
Input			
Lactic acid corn stalk (Wang)	0.81 ton		
Ethanol	0.442 ton	Ecoinvent v3	Ethanol without water in 95% solution state, from fermentation {US} l ethanol production from maize | Cut-off, S
Heat	8200000 Btu	Ecoinvent v3	Heat, central or small-scale, natural gas {RoW} | market for heat, central or small-scale, natural gas | Cut-off, S
Electricity	51000 Btu	Ecoinvent v3	Electricity, medium voltage {US} | market group for electricity, medium voltage, Cut-off, S

Table S14. Life Cycle Inventory for Scenario E4.

Material or energy	Quantity	Database	Process Name
Output			
Ethyl lactate Sc E4	1 ton		
Input			
Lactic acid corn stalk (Wang)	0.81 ton		
Ethanol corn stalk (Wang)	0.421 ton		
Heat	8200000 Btu	Ecoinvent v3	Heat, central or small-scale, natural gas {RoW} | market for heat, central or small-scale, natural gas | Cut-off, S
Electricity	51000 Btu	Ecoinvent v3	Electricity, medium voltage {US} | market group for electricity, medium voltage, Cut-off, S

Table S15. Inventory for the production of lactic acid from corn stover in US, based on Wang et al. Process [7].

Assumption: Corn stover was a substitute for corn stalk due to the availability in the software.

Material or energy	Quantity	Database	Process Name
Output			
Lactic acid Wang et al. Process.	70.61 g		
Ethanol Wang et al. Process.	135.56 g		
Input			
Corn stover	1 kg	USLCI	Corn stover, production, average, US, 2022/kg/RNA
Sodium hydroxide	0.1853 kg	Ecoinvent v3	Neutralising agent, sodium hydroxide-equivalent {GLO}| soda ash, dense, to generic market for neutralising agent | Cut-off, S
Water	19 kg	Ecoinvent v3	Tap water {CA-QB}| market group for tap water | Cut-off, S
Enzyme	0.236 kg	USLCI	Enzyme, cellulase, Novozyme Celluclast/kg/RER
Corn steep liquor	0.147kg	USLCI	Corn steep liquor/kg/RNA
Electricity	1.45 MJ	Ecoinvent v3	Electricity, medium voltage {US} | market group for electricity, medium voltage, Cut-off, S

1.3. Life Cycle Inventory for the fabrication of 1 m^2 zein membrane (Scenario M1-M3)

The membrane fabrication process was based on our previous paper [8] and the energy was previously reported [9] .

Table S16. Life Cycle Inventory for Scenario M1.

Material or energy	Quantity
Output	
Zein membrane Sc M1	1 m^2
Input	
Ethyl lactate Sc E3	122.74 g
Zein Sc Z2	37.26 g
Electricity	0.0124 kWh

Table S17. Life Cycle Inventory for Scenario M2.

Material or energy	Quantity
Output	
Zein membrane Sc M2	1 m^2
Input	
Ethyl lactate Sc E3	122.74 g
Zein Sc Z4	37.26 g
Electricity	0.0124 kWh

Table S18. Life Cycle Inventory for Scenario M3.

Material or energy	Quantity
Output	
Zein membrane Sc M3	1 m^2
Input	
Ethyl lactate Sc E3	122.74 g
Zein Sc Z9	37.26 g
Electricity	0.0124 kWh

2. Life cycle Impact Assessment (LCIA)

2.1. Life Cycle Impact Assessment for the extraction of 1 kg of zein (Scenario Z1-Z9)

Table S19. Global warming potential in kg CO_2 eq.

Scenario	Feedstock	Solvent	Tap water	Neutralizing agent	Reductant	Electricity	Spent solvent mixture
Sc Z1	3.5501	135.9675	0.00114	0.1132	0.19208	3.3471	89.0072
Sc Z2	2.3992	41.4813	0.00169	0.0765	0.12981	2.2621	60.1551
Sc Z3	2.1113	3151.1802	0.02646	2.6235	4.45154	77.5730	2062.8295
Sc Z4	0.4492	302.6538	0.01234	0.5582	0.94714	16.5048	438.8999
Sc Z5	0.2045	125.4383	0.10613			40.8209	369.9511
Sc Z6	0.3138	349.1560	0.16289			75.3893	735.1743
Sc Z7	2.1113	1050.3934	0.00882	2.6235	4.45154	77.573	687.6098
Sc Z8	2.1113	315.1180	0.00265	2.6235	4.45154	77.573	206.2829
Sc Z9	0.3138	26.7660	0.01628			88.119	73.4906

Table S20. Land use in m^2a crop eq.

Scenario	Feedstock	Solvent	Tap water	Neutralizing agent	Reductant	Electricity	Spent solvent mixture
Sc Z1	4.5997	2.7107	1.78E-04	0.00284	0.00588	0.0787	0.1818
Sc Z2	3.1087	62.7537	2.63E-04	0.00192	0.00397	0.0532	0.1228
Sc Z3	3.1941	62.8247	0.00411	0.06583	0.1362	1.8246	4.2136
Sc Z4	0.6796	457.8596	0.00192	0.01401	0.02898	0.3882	0.8965
Sc Z5	0.3093	189.7651	0.00244			0.9601	0.7556
Sc Z6	0.4748	528.2093	0.003748			1.7732	1.5017
Sc Z7	3.1941	20.9415	0.00137	0.06583	0.1362	1.8246	1.4045
Sc Z8	3.1941	6.2824	4.11E-04	0.06583	0.1362	1.8246	0.4213
Sc Z9	0.4748	40.2290	0.00374			2.0726	0.1501

Table S21. Water consumption in m^3.

Scenario	Feedstock	Solvent	Tap water	Neutralizing agent	Reductant	Electricity	Spent solvent mixture
Sc Z1	0.22011	0.7305	5.40E-03	0.0012	0.00209	0.0221	0.0859
Sc Z2	0.14876	1.4660	8.00E-03	8.14E-04	0.00141	0.0149	0.0580
Sc Z3	0.07462	16.9304	0.12506	0.0279	0.04838	0.5131	1.9919
Sc Z4	0.01588	10.6962	0.05835	0.00594	0.01029	0.1091	0.4238
Sc Z5	0.00722	4.4331	0.11775			0.2701	0.3572
Sc Z6	0.01193	12.3397	0.18074			0.49866	0.7099
Sc Z7	0.07462	5.6434	0.04169	0.0279	0.04838	0.5131	0.6639
Sc Z8	0.07462	1.6930	1.25E-02	0.0279	0.04838	0.5131	0.1991
Sc Z9	0.01109	1.7323	0.01807			0.5828	0.0709

Table S22. Global warming potential in kg CO_2 eq.

Scenario	Feedstock	Solvent	Tap water	Neutralizing agent	Reductant	Electricity	Spent solvent mixture
Sc Z3	2.11138	3151.18025	0.02646	2.62355	4.45154	77.573	2062.8295
Sc Z7	2.11138	1050.39342	0.00882	2.62355	4.45154	77.573	687.6098
Sc Z8	2.11138	315.11803	0.00265	2.62355	4.45154	77.573	206.2829
Sc Z6	0.31388	349.1562	0.1628			75.38933	735.1743
Sc Z9	0.3138	26.7668	0.01628			88.1198	73.4906

2.2. Life cycle Impact Assessment (LCIA) for the fabrication of 1 kg of ethyl lactate (Scenario E1-E4)

Table S23. Global warming potential in kg CO_2 eq.

Scenario	Ethanol	Lactic acid	Heat	Electricity
Sc E1	0.8	4.32	0.72	0.07
Sc E2	0.83	6.7	0.72	0.07
Sc E3	0.83	5.97	0.72	0.07
Sc E4	2.99	5.97	0.72	0.07

Table S24. Land use in m^2a crop eq.

Scenario	Ethanol	Lactic acid	Heat	Electricity
Sc E1	0.0208	0.07841	0.00329	0.000168
Sc E2	1.25322	1.43583	0.00329	0.000168
Sc E3	1.25322	2.61828	0.00329	0.000168
Sc E4	1.31329	2.61828	0.00329	0.000168

Table S25. Water consumption in m^3.

Scenario	Ethanol	Lactic acid	Heat	Electricity
Sc E1	0.00377	0.03966	5.51E-04	4.72E-04
Sc E2	0.02928	0.06774	5.51E-04	4.72E-04
Sc E3	0.02928	0.11736	5.51E-04	4.72E-04
Sc E4	0.05887	0.11736	5.51E-04	4.72E-04

2.3. Life Cycle Impact Assessment for the fabrication of 1 m^2 of zein membrane (Scenario M1-M3)

Table S26. Global warming potential in kg CO_2 eq.

Scenario	Zein	Ethyl lactate	Electricity
Sc M1	3.96841	0.92295	0.00592
Sc M2	28.31036	0.92295	0.00592
Sc M3	7.03124	0.92295	0.00592

Table S27. Land use in m^2a crop eq.

Scenario	Zein	Ethyl lactate	Electricity
Sc M1	2.46	0.47561	1.39134E-4
Sc M2	17.15	0.47561	1.39134E-4
Sc M3	1.59	0.47561	1.39134E-4

Table S28. Water consumption in m^3.

Scenario	Zein	Ethyl lactate	Electricity
Sc M1	0.063	0.01807	3.91265E-5
Sc M2	0.425	0.01807	3.91265E-5
Sc M3	0.089	0.01807	3.91265E-5

3. References

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