The environmental impact and economic feasibility assessment of composite calcium alginate bioplastics derived from S*argassum*

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Appendix A- Supplementary data

1. Economic assessment

1.1 Total capital expenditure (CAPEX)

The allocation of the costing factors for the estimation of the FCI are given in **Table S1**. The fixed capital cost of the plant as a function of the total purchased equipment was estimated using the following Factorial Method of Cost Estimation[1] in equation (S1);

$$C = \sum_{i=1}^{i=M} C_e\left[(1 + f_p) + (f_{er} + f_{el} + f_i + f_c + f_s + f_l)/f_m\right] \quad \text{Equation S1}$$

Where C is the total plant cost, C_e is the total delivered cost of the major equipment items, f is an installation factor and M is the total number of pieces of equipment.

.**Table S1** Installation factors for process plant equipment

Item	Costing Factor
f_{er}, Equipment erection	0.5
f_p, Piping	0.6
f_i, Instrumentation and control	0.3
f_{el}, Electrical	0.2
f_c, Civil	0.3
f_s, Structures and building	0.2
f_l, Lagging and paint	0.1
$f_{m,ss}$, stainless steel	1.3
$f_{m,cs}$, carbon steel	1
Offsites (OS)	0.4
Design and Eng (D&E)	0.25
Contingency (X)	0.1

FCI was then calculated using the summation of the equipment cost, offsites, design and engineering and contingency[1] given in equation (S2).

$$FCI = C(1 + OS)(1 + DE + X) \quad \text{Equation S2}$$

Purchased equipment costs were determined using equipment costs for existing plant equipment, adjusted to the present value and capacity using the six-tenths rule and Chemical Engineering Plant Cost Indices (CEPCI) as well as the correlations given in equation (S3).[1]

$$C_e = a + bS^n \qquad \text{Equation S3}$$

Where C_e = purchased equipment cost, January 2006 (CE index = 478.6), a and b are cost constants, S is the sizing parameter and n is the exponent for that type of equipment. The six-tenths rule is given in equation (S4) followed by the CEPCI method to scale prices to the cost year 2019 given in equation (S5).

$$C_2 = C_1\left(\frac{S_2}{S_1}\right)^n \qquad \text{Equation S4}$$

Where C_2 is the capital cost of the equipment with capacity S_2 and C_1 is the capital cost of the equipment with capacity S_1. For the six-tenths rule, n is taken as 0.6 where data is not available.

$$Cost\ in\ 2019 = Cost\ in\ year\ X \times \frac{Cost\ index\ in\ 2019\ (619.2)}{Cost\ index\ in\ Year\ X} \qquad \text{Equation S5}$$

Table S2 gives information as to the sizing parameters used for the different pieces of equipment. S refers to the equipment specific sizing parameter needed to determine the cost.[2-5]

Table S2. Design parameters for process equipment.

Equipment	S		Unit	a	b	n
[a]Washing/ holding tanks	Volume	88-1170	m^3	-	-	0.58
Grinders	Grinding rate	3571-1000	kg/h	3000	390	0.5
[a]Hoppers	Volume	473-688	m^3	-	-	0.65
[b]Rotary dryer	Water removal rate	28571	kg/h	-	-	0.6
Exchangers	Surface area	0.5- 184	m^2	10000	88	1

[b]Reactors	Volume	10- 351	m^3	-	-	0.6
[a]Centrifuges	Diameter	69-171	m^2	-	-	1
[a]Spray dryer	Water removal rate	2	kg/s	-	-	0.42
[a]Mixer	Volume	35	m^3	-	-	0.53
[a]Tape Caster	Area	20	m^2	-	-	1. 04

Note: [a]Cost were calculated using historic cost data with equipment specific n parameters, [b]Cost were calculated using the six-tenths rule.

1.2 Operating expenditure (OPEX)

Operating costs were calculated using the cost of operating labour, utility, waste treatment and raw material costs. Utility, waste treatment and raw material costs were calculated directly from the mass and energy balances used to design the process. The operating labor was derived from key unit operations according to equation (S6) and (S7):[6]

$$No\ of\ operators/shift = [6.29 + (No\ of\ key\ steps\ \times 0.23)]^{0.5} \qquad \text{Equation S6}$$

$$Labour\ costs, C_{OL} = (Approx\ \#\ of\ operators\ \times 4) \times 66910 \qquad \text{Equation S7}$$

The total operating cost was determined by equation (S8)[6] which took into consideration direct manufacturing costs, fixed manufacturing costs and general expenses.

$$OPEX\ =\ 0.280FCI + 2.73C_{OL} + 1.23(C_{UT} + C_{WT} + C_{RM}) \qquad \text{Equation S8}$$

Where C_{UT}, C_{WT} and C_{RM} are the cost of the utilities, waste materials and raw materials respectively.

1.3 Total annualized cost (TAC)

The TAC was calculated using equation (S9)[1] which considered both the annual capital and operating cost per kg of calcium alginate produced.

$$TAC = OPEX + \frac{[i(1+i)^n]}{[(1+i)^n - 1]} \times FCI$$ Equation S9

Where i is the calculated interest rate = 15%[7] and n is the estimated investment lifetime taken as 10 years.

2. Life cycle assessment

2.1 Functional unit derivation

In selecting a functional unit for our study, the most promising intrinsic property of the $Ca(Alg)_2$ bioplastic composite was selected- ultra low oxygen barrier. Oxygen barrier[8-11], a well-established terminology in plastics technology, is the ability to retard the movement of oxygen across a boundary layer when different oxygen partial pressures exist on either side of boundary layers. Good oxygen barriers[12] have values < 10$cm^3 \mu m\, m^{-2} d^{-1} kPa^{-1}$ while poor oxygen barriers >100 $cm^3 \mu m\, m^{-2} d^{-1} kPa^{-1}$.

The oxygen transfer rate, OTR_i, was calculated using equation (S10), in accordance with our previous work[13]:

$$OTR_i\left(\frac{cm^3}{m^2\, d\, hPa}\right) = \frac{P_{O_2} \times V_{cell}}{P_{standard} \times A \times \Delta P_{O_2}} \times \frac{T_{standard}}{T_{measurement}}$$ Equation S10

Where:

P_{O_2}- Increase in oxygen partial pressure in upper test chamber (hPa d^{-1})

V_{cell} – Volume of the upper test chamber (116 cm^3)

$P_{standard}$ – Standard pressure (1013 hPa)

A – Permeation area (0.0068 m^2)

It should be noted that testing conditions such as pressure, temperature and cross-sectional area were maintained throughout measuring the oxygen barrier for all materials. The measured thickness, l_i and oxygen transfer rate, OTR_i, of each material, i, was recorded and used to calculate the oxygen barrier, B_i,[8] according to equation (S11):

$$OTR_i l_i = B_i \quad \text{Equation S11}$$

For a given plastic barrier, $B_{plastic}$ the required thickness $l_{plastic}$ is calculated to maintain the same OTR as that of our $Ca(Alg)_2$ bioplastic composite, $OTR_{bioplastic}$, according to equation (S12):

$$l_{plastic} = \frac{B_{plastic}}{OTR_{bioplastic}} \quad \text{Equation S12}$$

Thus, the mass of plastic material required, $m_{plastic}$, is calculated for a given material density, $\rho_{plastic}$ and set film area, A, according to equation (S13):

$$m_{plastic} = l_{plastic}\rho_{plastic}A \quad \text{Equation S13}$$

Lastly, the normalized plastic material required to achieve the same oxygen barrier, for a set film area, is given according to Equation (S14):

$$\frac{m_{plastic}}{m_{bioplastic}} = \frac{l_{plastic}\rho_{plastic}A}{l_{bioplastic}\rho_{bioplastic}A} = \frac{B_{plastic}\rho_{plastic}}{B_{bioplastic}\rho_{bioplastic}} \quad \text{Equation S14}$$

2.2 Life cycle inventories (LCI)

The following inventories (Table S3) were retrieved from Ecoinvent and utilized in the life cycle impact assessment (LCIA) stage at the midpoint, using the ReCiPe (H) 2006 model within SimaPro. LCI for biomass-derived sorbitol was obtained accordingly[14] while E-MeOH was adapted accordingly.[15]

Table S3. Ecoinvent inventories used for each scenario-specific system boundary.

Flow	**System boundary**	**Ecoinvent Entries**
Formaldehyde	$Ca(Alg)_2$ Bioplastic	Formaldehyde, oxidation of methanol {RoW}

Na_2CO_3	$Ca(Alg)_2$ Bioplastic	Soda ash, dense {GLO} modified Solvay process, Hou's process
H_2SO_4	$Ca(Alg)_2$ Bioplastic	Sulfuric acid {RoW} market for sulfuric acid
NaClO	$Ca(Alg)_2$ Bioplastic	Sodium hypochlorite, without water, in 15% solution state {RoW}
Fossil based MeOH	$Ca(Alg)_2$ Bioplastic	Methanol {GLO}| production |APOS, U
Water	$Ca(Alg)_2$ Bioplastic	Tap water {RoW}| market for
Starch	$Ca(Alg)_2$ Bioplastic	Maize starch {GLO} market for
CMC	$Ca(Alg)_2$ Bioplastic	Carboxymethyl cellulose, powder {GLO}| market
PEG-200[a]	$Ca(Alg)_2$ Bioplastic	Ethylene glycol {GLO}| market
$CaCl_2$	$Ca(Alg)_2$ Bioplastic	Calcium chloride {RoW}| market for calcium chloride
Fossil-based heating	$Ca(Alg)_2$ Bioplastic	Heat, central or small-scale, natural gas {RoW} market for
Electricity	$Ca(Alg)_2$ Bioplastic	Electricity, high voltage {RoW} electricity production, natural gas, conventional power
Biomass by-product	$Ca(Alg)_2$ Bioplastic	Compost {GLO}| market for
Wastewater	$Ca(Alg)_2$ Bioplastic	Wastewater, average {RoW} market for wastewater
Bioenergy	$Ca(Alg)_2$ Bioplastic	Heat, district or industrial, other than natural gas {RoW} heat production, hardwood chips from forest, at furnace 1000kW
PET monomer	PET plastic	Polyethylene terephthalate, granulate, amorphous {GLO} market
PLA monomer	Bio-based PLA	Polylactide, granulate {GLO} production
PET, PLA Plastic film production	PET, PLA,	Extrusion, plastic film {GLO} market

2.3 LCIA

Tables S4-S8 gives an overview of the normalized impacts of the LCIA phase for each case-specific system boundary. Function unit = 1kg plastic/bioplastic produced.

Table S4. LCIA results for bio-based PLA films.

Impact category	**Unit**	**Total**	**Biogenic CO_2 removal**	**PLA monomer**	**Film Production**

Global warming	kg CO_2 eq	1.38E-00	-2.26E-00	3.07E-00	5.69E-01
Stratospheric ozone depletion	kg CFC11 eq	1.12E-05		1.10E-05	2.18E-07
Ionizing radiation	kBq Co-60 eq	2.95E-01		1.93E-01	1.02E-01
Ozone formation, Human health	kg NOx eq	8.87E-03		7.65E-03	1.23E-03
Fine particulate matter formation	kg PM2.5 eq	6.33E-03		5.23E-03	1.09E-03
Ozone formation, Terrestrial ecosystems	kg NOx eq	9.28E-03		8.03E-03	1.25E-03
Terrestrial acidification	kg SO2 eq	1.51E-02		1.32E-02	1.88E-03
Freshwater eutrophication	kg P eq	1.44E-03		1.17E-03	2.69E-04
Marine eutrophication	kg N eq	1.40E-03		1.35E-03	5.63E-05
Terrestrial ecotoxicity	kg 1,4-DCB	4.51E-00		3.81E-00	6.99E-01
Freshwater ecotoxicity	kg 1,4-DCB	1.67E-01		1.47E-01	1.99E-02
Marine ecotoxicity	kg 1,4-DCB	2.06E-01		1.79E-01	2.69E-02
Human carcinogenic toxicity	kg 1,4-DCB	2.08E-01		1.68E-01	3.96E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	2.86E-00		2.26E-00	6.06E-01
Land use	m^2a crop eq	9.02E-01		6.83E-01	2.20E-01
Mineral resource scarcity	kg Cu eq	9.05E-03		7.99E-03	1.05E-03
Fossil resource scarcity	kg oil eq	9.62E-01		8.14E-01	1.48E-01
Water consumption	m^3	1.52E-01		1.29E-01	2.31E-02

Table S5. LCIA results for plastic PET films.

Impact category	**Unit**	**Total**	**PET monomer**	**Film Production**
Global warming	kg CO_2 eq	3.77E-00	3.21E-00	5.69E-01
Stratospheric ozone depletion	kg CFC11 eq	2.02E-05	2.00E-05	2.18E-07
Ionizing radiation	kBq Co-60 eq	2.22E-01	1.20E-01	1.02E-01
Ozone formation, Human health	kg NOx eq	8.06E-03	6.83E-03	1.23E-03
Fine particulate matter formation	kg PM2.5 eq	5.01E-03	3.91E-03	1.09E-03
Ozone formation, Terrestrial ecosystems	kg NOx eq	8.40E-03	7.15E-03	1.25E-03
Terrestrial acidification	kg SO2 eq	1.08E-02	8.96E-03	1.88E-03
Freshwater eutrophication	kg P eq	9.19E-04	6.50E-04	2.69E-04
Marine eutrophication	kg N eq	1.44E-04	8.80E-05	5.63E-05
Terrestrial ecotoxicity	kg 1,4-DCB	8.94E-00	8.24E-00	6.99E-01
Freshwater ecotoxicity	kg 1,4-DCB	1.37E-01	1.17E-01	1.99E-02
Marine ecotoxicity	kg 1,4-DCB	1.81E-01	1.54E-01	2.69E-02
Human carcinogenic toxicity	kg 1,4-DCB	2.39E-01	1.99E-01	3.96E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	2.90E-00	2.29E-00	6.06E-01
Land use	m^2a crop eq	3.56E-01	1.36E-01	2.20E-01
Mineral resource scarcity	kg Cu eq	1.19E-02	1.08E-02	1.05E-03
Fossil resource scarcity	kg oil eq	1.75E-00	1.60E-00	1.48E-01
Water consumption	m^3	6.23E-02	3.92E-02	2.31E-02

Table S6. LCIA For $Ca(Alg)_2$ bioplastics with fossil-based MeOH and Energy.

Impact category	**Unit**	**Total**	**Process Emissions**	**Biogenic CO2**	**Formaldehyde**	**Na_2CO_3**	**H_2SO_4**	**NaClO**	**MeOH**	**Water**	**Starch**	**CMC**	**Sorbitol**	**PEG-200**	**$CaCl_2$**	**Heating**	**Electricity**	**Biomass by-product**	**Wastewater**
Global warming	kg CO2 eq	1.01E+01	3.86E-01	-3.31E+00	6.54E-01	1.63E+00	4.87E-01	1.83E+00	1.11E+00	3.11E-01	1.90E-02	1.18E-01	5.56E-02	2.69E-02	3.73E-01	6.21E+00	1.73E-01	-1.56E-01	1.58E-01
Stratospheric ozone depletion	kg CFC11 eq	5.39E-06			2.98E-07	4.09E-07	2.54E-07	1.81E-06	5.88E-07	2.68E-07	1.29E-07	5.74E-08	2.50E-07	5.52E-09	1.13E-07	1.73E-06	4.58E-08	-9.75E-07	4.05E-07
Ionizing radiation	kBq Co-60 eq	4.25E-01			1.76E-02	7.80E-02	3.49E-02	1.72E-01	1.76E-02	3.83E-02	8.32E-04	9.16E-03	1.68E-03	1.28E-03	1.35E-02	3.12E-02	2.56E-04	1.66E-03	7.01E-03
Ozone formation, Human health	kg NOx eq	2.00E-02			1.47E-03	2.75E-03	2.48E-03	4.64E-03	1.89E-03	6.94E-04	4.50E-05	2.88E-04	9.96E-05	5.80E-05	1.14E-03	4.04E-03	1.50E-04	-3.25E-04	5.83E-04
Fine particulate matter formation	kg PM2.5 eq	1.71E-02			7.22E-04	2.14E-03	5.40E-03	3.93E-03	9.51E-04	6.96E-04	4.47E-05	2.26E-04	9.10E-05	3.70E-05	9.45E-04	1.66E-03	2.62E-05	-2.03E-04	4.38E-04
Ozone formation, Terrestrial ecosystems	kg NOx eq	2.06E-02			1.54E-03	2.81E-03	2.53E-03	4.68E-03	2.05E-03	7.09E-04	4.58E-05	2.93E-04	1.02E-04	6.08E-05	1.15E-03	4.24E-03	1.53E-04	-3.35E-04	5.91E-04
Terrestrial acidification	kg SO2 eq	4.31E-02			1.73E-03	4.84E-03	1.75E-02	6.61E-03	2.60E-03	1.03E-03	2.18E-04	4.35E-04	4.31E-04	7.45E-05	3.03E-03	4.00E-03	6.80E-05	-4.78E-04	1.08E-03
Freshwater eutrophication	kg P eq	2.93E-03			1.16E-04	5.05E-04	5.00E-04	8.67E-04	9.77E-05	1.64E-04	5.93E-06	4.23E-05	1.16E-05	7.47E-06	1.63E-04	1.84E-04	1.95E-06	-4.36E-05	3.11E-04
Marine eutrophication	kg N eq	3.10E-03			8.89E-06	1.19E-03	1.99E-05	8.95E-05	9.52E-06	1.74E-05	2.99E-05	3.66E-06	5.70E-05	5.24E-07	1.21E-05	1.65E-05	2.56E-07	-7.33E-06	1.66E-03
Terrestrial ecotoxicity	kg 1,4-DCB	2.24E+01			6.98E-01	3.37E+00	1.18E+01	3.36E+00	3.36E-01	5.32E-01	5.81E-02	1.96E-01	1.14E-01	2.69E-02	1.21E+00	6.26E-01	1.06E-02	-4.29E-01	5.35E-01
Freshwater ecotoxicity	kg 1,4-DCB	7.18E-01			2.74E-02	9.59E-02	3.60E-01	1.12E-01	1.58E-02	1.38E-02	1.25E-03	4.35E-03	2.45E-03	1.04E-03	3.87E-02	3.64E-02	5.81E-04	-4.83E-03	1.34E-02
Marine ecotoxicity	kg 1,4-DCB	9.34E-01			3.55E-02	1.23E-01	4.63E-01	1.46E-01	2.14E-02	1.86E-02	1.47E-03	5.74E-03	2.89E-03	1.35E-03	5.01E-02	5.39E-02	7.61E-04	-6.37E-03	1.78E-02
Human carcinogenic toxicity	kg 1,4-DCB	8.77E-01			4.25E-02	1.29E-01	1.06E-01	1.64E-01	3.70E-02	1.55E-01	1.61E-03	7.31E-03	3.34E-03	1.59E-03	4.73E-02	1.18E-01	1.76E-03	-3.97E-03	6.68E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	1.34E+01			4.49E-01	1.69E+00	6.26E+00	2.26E+00	2.95E-01	3.15E-01	-1.20E-02	1.03E-01	-2.16E-02	2.02E-02	7.42E-01	5.36E-01	8.51E-03	-1.22E-01	8.49E-01
Land use	m2a crop eq	5.56E-01			2.25E-02	9.87E-02	6.55E-02	1.26E-01	9.79E-03	1.19E-02	1.72E-02	9.25E-02	3.28E-02	1.08E-03	5.00E-02	2.42E-02	3.84E-04	-7.86E-03	1.13E-02
Mineral resource scarcity	kg Cu eq	4.79E-02			2.12E-03	6.96E-03	2.13E-02	6.92E-03	1.39E-03	2.38E-03	1.06E-04	2.54E-04	2.08E-04	6.90E-05	2.82E-03	2.53E-03	5.53E-05	-1.75E-03	2.52E-03
Fossil resource scarcity	kg oil eq	5.45E+00			5.50E-01	4.02E-01	2.93E-01	4.53E-01	1.26E+00	7.98E-02	4.56E-03	3.48E-02	1.71E-02	1.42E-02	7.85E-02	2.19E+00	7.36E-02	-4.12E-02	3.45E-02
Water consumption	m3	1.82E-01			3.89E-03	3.05E-02	4.50E-02	4.38E-02	6.97E-03	2.88E-01	2.09E-04	1.67E-03	5.45E-04	3.49E-04	1.24E-02	3.43E-03	3.19E-04	-2.86E-03	-2.52E-01

Table S7. LCIA For $Ca(Alg)_2$ bioplastics with fossil-based MeOH and bioenergy.

Impact category	Unit	Total	Process Emissions	Biogenic CO2	Formaldehyde	Na_2CO_3	H_2SO_4	NaClO	MeOH	Water	Starch	CMC	Sorbitol	PEG-200	$CaCl_2$	Heating	Electricity	Biomass by-product	Wastewater
Global warming	kg CO2 eq	4.61E+00	3.86E-01	-3.31E+00	6.54E-01	1.63E+00	4.87E-01	1.83E+00	1.11E+00	3.11E-01	1.90E-02	1.18E-01	5.56E-02	2.69E-02	3.73E-01	7.37E-01	1.73E-01	-1.56E-01	1.58E-01
Stratospheric ozone depletion	kg CFC11 eq	6.63E-06			2.98E-07	4.09E-07	2.54E-07	1.81E-06	5.88E-07	2.68E-07	1.29E-07	5.74E-08	2.50E-07	5.52E-09	1.13E-07	2.97E-06	4.58E-08	-9.75E-07	4.05E-07
Ionizing radiation	kBq Co-60 eq	4.41E-01			1.76E-02	7.80E-02	3.49E-02	1.72E-01	1.76E-02	3.83E-02	8.32E-04	9.16E-03	1.68E-03	1.28E-03	1.35E-02	4.75E-02	2.56E-04	1.66E-03	7.01E-03
Ozone formation, Human health	kg NOx eq	3.75E-02			1.47E-03	2.75E-03	2.48E-03	4.64E-03	1.89E-03	6.94E-04	4.50E-05	2.88E-04	9.96E-05	5.80E-05	1.14E-03	2.15E-02	1.50E-04	-3.25E-04	5.83E-04
Fine particulate matter formation	kg PM2.5 eq	2.36E-02			7.22E-04	2.14E-03	5.40E-03	3.93E-03	9.51E-04	6.96E-04	4.47E-05	2.26E-04	9.10E-05	3.70E-05	9.45E-04	8.14E-03	2.62E-05	-2.03E-04	4.38E-04
Ozone formation, Terrestrial ecosystems	kg NOx eq	3.81E-02			1.54E-03	2.81E-03	2.53E-03	4.68E-03	2.05E-03	7.09E-04	4.58E-05	2.93E-04	1.02E-04	6.08E-05	1.15E-03	2.17E-02	1.53E-04	-3.35E-04	5.91E-04
Terrestrial acidification	kg SO2 eq	4.88E-02			1.73E-03	4.84E-03	1.75E-02	6.61E-03	2.60E-03	1.03E-03	2.18E-04	4.35E-04	4.31E-04	7.45E-05	3.03E-03	9.71E-03	6.80E-05	-4.78E-04	1.08E-03
Freshwater eutrophication	kg P eq	3.01E-03			1.16E-04	5.05E-04	5.00E-04	8.67E-04	9.77E-05	1.64E-04	5.93E-06	4.23E-05	1.16E-05	7.47E-06	1.63E-04	2.59E-04	1.95E-06	-4.36E-05	3.11E-04
Marine eutrophication	kg N eq	3.11E-03			8.89E-06	1.19E-03	1.99E-05	8.95E-05	9.52E-06	1.74E-05	2.99E-05	3.66E-06	5.70E-05	5.24E-07	1.21E-05	2.29E-05	2.56E-07	-7.33E-06	1.66E-03
Terrestrial ecotoxicity	kg 1,4-DCB	3.17E+01			6.98E-01	3.37E+00	1.18E+01	3.36E+00	3.36E-01	5.32E-01	5.81E-02	1.96E-01	1.14E-01	2.69E-02	1.21E+00	9.92E+00	1.06E-02	-4.29E-01	5.35E-01
Freshwater ecotoxicity	kg 1,4-DCB	7.23E-01			2.74E-02	9.59E-02	3.60E-01	1.12E-01	1.58E-02	1.38E-02	1.25E-03	4.35E-03	2.45E-03	1.04E-03	3.87E-02	4.15E-02	5.81E-04	-4.83E-03	1.34E-02
Marine ecotoxicity	kg 1,4-DCB	9.41E-01			3.55E-02	1.23E-01	4.63E-01	1.46E-01	2.14E-02	1.86E-02	1.47E-03	5.74E-03	2.89E-03	1.35E-03	5.01E-02	6.02E-02	7.61E-04	-6.37E-03	1.78E-02
Human carcinogenic toxicity	kg 1,4-DCB	9.05E-01			4.25E-02	1.29E-01	1.06E-01	1.64E-01	3.70E-02	1.55E-01	1.61E-03	7.31E-03	3.34E-03	1.59E-03	4.73E-02	1.47E-01	1.76E-03	-3.97E-03	6.68E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	1.54E+01			4.49E-01	1.69E+00	6.26E+00	2.26E+00	2.95E-01	3.15E-01	-1.20E-02	1.03E-01	-2.16E-02	2.02E-02	7.42E-01	2.53E+00	8.51E-03	-1.22E-01	8.49E-01
Land use	m^2a crop eq	5.45E+00			2.25E-02	9.87E-02	6.55E-02	1.26E-01	9.79E-03	1.19E-02	1.72E-02	9.25E-02	3.28E-02	1.08E-03	5.00E-02	4.92E+00	3.84E-04	-7.86E-03	1.13E-02
Mineral resource scarcity	kg Cu eq	4.75E-02			2.12E-03	6.96E-03	2.13E-02	6.92E-03	1.39E-03	2.38E-03	1.06E-04	2.54E-04	2.08E-04	6.90E-05	2.82E-03	2.09E-03	5.53E-05	-1.75E-03	2.52E-03
Fossil resource scarcity	kg oil eq	3.44E+00			5.50E-01	4.02E-01	2.93E-01	4.53E-01	1.26E+00	7.98E-02	4.56E-03	3.48E-02	1.71E-02	1.42E-02	7.85E-02	1.84E-01	7.36E-02	-4.12E-02	3.45E-02
Water consumption	m^3	1.83E-01			3.89E-03	3.05E-02	4.50E-02	4.38E-02	6.97E-03	2.88E-01	2.09E-04	1.67E-03	5.45E-04	3.49E-04	1.24E-02	4.07E-03	3.19E-04	-2.86E-03	-2.52E-01

Table S8. LCIA For $Ca(Alg)_2$ bioplastics with E-MeOH and bioenergy.

Impact category	Unit	Total	Process Emissions	Biogenic CO2	Formaldehyde	Na_2CO_3	H_2SO_4	NaClO	MeOH	Water	Starch	CMC	Sorbitol	PEG-200	$CaCl_2$	Heating	Electricity	Biomass by-product	Wastewater
Global warming	kg CO2 eq	2.12E+00	3.86E-01	-3.31E+00	-9.11E-02	1.63E+00	4.87E-01	1.83E+00	-6.40E-01	3.11E-01	1.90E-02	1.18E-01	5.56E-02	2.69E-02	3.73E-01	7.37E-01	1.73E-01	-1.56E-01	1.58E-01
Stratospheric ozone depletion	kg CFC11 eq	6.35E-06			2.08E-07	4.09E-07	2.54E-07	1.81E-06	4.00E-07	2.68E-07	1.29E-07	5.74E-08	2.50E-07	5.52E-09	1.13E-07	2.97E-06	4.58E-08	-9.75E-07	4.05E-07
Ionizing radiation	kBq Co-60 eq	4.44E-01			1.80E-02	7.80E-02	3.49E-02	1.72E-01	1.98E-02	3.83E-02	8.32E-04	9.16E-03	1.68E-03	1.28E-03	1.35E-02	4.75E-02	2.56E-04	1.66E-03	7.01E-03
Ozone formation, Human health	kg NOx eq	4.50E-02			3.51E-03	2.75E-03	2.48E-03	4.64E-03	7.34E-03	6.94E-04	4.50E-05	2.88E-04	9.96E-05	5.80E-05	1.14E-03	2.15E-02	1.50E-04	-3.25E-04	5.83E-04
Fine particulate matter formation	kg PM2.5 eq	2.56E-02			1.26E-03	2.14E-03	5.40E-03	3.93E-03	2.41E-03	6.96E-04	4.47E-05	2.26E-04	9.10E-05	3.70E-05	9.45E-04	8.14E-03	2.62E-05	-2.03E-04	4.38E-04
Ozone formation, Terrestrial ecosystems	kg NOx eq	4.58E-02			3.62E-03	2.81E-03	2.53E-03	4.68E-03	7.61E-03	7.09E-04	4.58E-05	2.93E-04	1.02E-04	6.08E-05	1.15E-03	2.17E-02	1.53E-04	-3.35E-04	5.91E-04
Terrestrial acidification	kg SO2 eq	5.53E-02			3.46E-03	4.84E-03	1.75E-02	6.61E-03	7.26E-03	1.03E-03	2.18E-04	4.35E-04	4.31E-04	7.45E-05	3.03E-03	9.71E-03	6.80E-05	-4.78E-04	1.08E-03
Freshwater eutrophication	kg P eq	3.06E-03			1.23E-04	5.05E-04	5.00E-04	8.67E-04	1.39E-04	1.64E-04	5.93E-06	4.23E-05	1.16E-05	7.47E-06	1.63E-04	2.59E-04	1.95E-06	-4.36E-05	3.11E-04
Marine eutrophication	kg N eq	3.26E-03			5.13E-05	1.19E-03	1.99E-05	8.95E-05	1.15E-04	1.74E-05	2.99E-05	3.66E-06	5.70E-05	5.24E-07	1.21E-05	2.29E-05	2.56E-07	-7.33E-06	1.66E-03
Terrestrial ecotoxicity	kg 1,4-DCB	3.37E+01			1.10E+00	3.37E+00	1.18E+01	3.36E+00	1.82E+00	5.32E-01	5.81E-02	1.96E-01	1.14E-01	2.69E-02	1.21E+00	9.92E+00	1.06E-02	-4.29E-01	5.35E-01
Freshwater ecotoxicity	kg 1,4-DCB	8.15E-01			5.34E-02	9.59E-02	3.60E-01	1.12E-01	8.08E-02	1.38E-02	1.25E-03	4.35E-03	2.45E-03	1.04E-03	3.87E-02	4.15E-02	5.81E-04	-4.83E-03	1.34E-02
Marine ecotoxicity	kg 1,4-DCB	1.05E+00			6.74E-02	1.23E-01	4.63E-01	1.46E-01	1.02E-01	1.86E-02	1.47E-03	5.74E-03	2.89E-03	1.35E-03	5.01E-02	6.02E-02	7.61E-04	-6.37E-03	1.78E-02
Human carcinogenic toxicity	kg 1,4-DCB	1.32E+00			1.60E-01	1.29E-01	1.06E-01	1.64E-01	3.30E-01	1.55E-01	1.61E-03	7.31E-03	3.34E-03	1.59E-03	4.73E-02	1.47E-01	1.76E-03	-3.97E-03	6.68E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	1.60E+01			6.06E-01	1.69E+00	6.26E+00	2.26E+00	7.35E-01	3.15E-01	-1.20E-02	1.03E-01	-2.16E-02	2.02E-02	7.42E-01	2.53E+00	8.51E-03	-1.22E-01	8.49E-01
Land use	m2a crop eq	5.47E+00			2.70E-02	9.87E-02	6.55E-02	1.26E-01	2.40E-02	1.19E-02	1.72E-02	9.25E-02	3.28E-02	1.08E-03	5.00E-02	4.92E+00	3.84E-04	-7.86E-03	1.13E-02
Mineral resource scarcity	kg Cu eq	5.79E-02			5.10E-03	6.96E-03	2.13E-02	6.92E-03	8.84E-03	2.38E-03	1.06E-04	2.54E-04	2.08E-04	6.90E-05	2.82E-03	2.09E-03	5.53E-05	-1.75E-03	2.52E-03
Fossil resource scarcity	kg oil eq	3.02E+00			4.24E-01	4.02E-01	2.93E-01	4.53E-01	9.70E-01	7.98E-02	4.56E-03	3.48E-02	1.71E-02	1.42E-02	7.85E-02	1.84E-01	7.36E-02	-4.12E-02	3.45E-02
Water consumption	m3	1.80E-01			2.95E-03	3.05E-02	4.50E-02	4.38E-02	4.84E-03	2.88E-01	2.09E-04	1.67E-03	5.45E-04	3.49E-04	1.24E-02	4.07E-03	3.19E-04	-2.86E-03	-2.52E-01

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