Eco-efficiency of mealworms (*Tenebrio molitor)* protein extracts

Supporting information

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6 pages; 2 Tables; 6 Equations

Table S1. LCA input and output

Input to produce 1 kg mealworms (Mealworm rearing phase)

INPUT	PROCESS	QUANTITY	DATA SOURCE
STEEL FRAME (KG)	steel, low-alloyed | market for steel, low-alloyed	0.008136	33
STEEL (GALVANIZED) (KG)	sheet rolling, steel | market for sheet rolling, steel	0.001238	
POLYURETHANE FOAM (KG)	polystyrene foam slab | market for polystyrene foam slab	0.0008331	
SAWNWOOD (M^3)	sawnwood, softwood, dried (u=10%), planed | market for sawnwood, softwood, dried (u=10%), planed	1.433E-05	
CONCRETE (M^3)	concrete, sole plate and foundation | market for concrete, sole plate and foundation	3.508E-05	
GLASSWOOL (KG)	glass wool mat | market for glass wool mat	0.0003351	
PVC (KG)	polyvinylchloride, bulk polymerised | market for polyvinylchloride, bulk polymerised	2.526E-05	
WATER (KG)	tap water | market for tap water CA,Qc	2.536	34
ELECTRICITY (KWH)	electricity, medium voltage | electricity voltage transformation from high to medium voltage	2.286	Personnal communication with a local TM farmer
WHEAT BRAN (KG)	wheat bran	1.383	33 - 35
DDGS (KG)	Distiller's Dried Grains with Solubles | market for Distiller's Dried Grains with Solubles	1.106	
CARROT (KG)	carrot | carrot335 production	0.2766	
PET (KG)	polyethylene, high density, granulate | market for polyethylene, high density, granulate	0.0290	33
GLASS (KG)	glass tube, borosilicate | market for glass tube, borosilicate	8.927E-07	
STEEL (KG)	steel, low-alloyed | market for steel, low-alloyed	0.0003153	
POLYURETHANE (KG)	polyurethane, rigid foam | market for polyurethane, rigid foam	0.0003158	
POLYVINYLCHLORIDE (KG)	polyvinylchloride, bulk polymerised | market for polyvinylchloride, bulk polymerised	1.710E-05	
ALUMINIUM (KG)	aluminium alloy, AlMg3 | market for aluminium alloy, AlMg3	2.229E-07	
SODIUM HYDROXIDE (KG)	sodium hydroxide, without water, in 50% solution state | market for sodium hydroxide, without water, in 50% solution state	2.871E-06	
SODIUM HYPOCHLORITE (KG)	sodium hypochlorite, without water, in 15% solution state | market for sodium hypochlorite, without water, in 15% solution state	5.511E-05	
AMMONIUM CHLORIDE (KG)	ammonium chloride | market for ammonium chloride	2.5835E-05	
POLYPROPYLENE (KG)	polypropylene, granulate | market for polypropylene, granulate	8.1267E-07	

CO_2 (G)	Emission to atmosphere - Carbon dioxide	1134.1	12
CH_4 (G)	Emission to atmosphere - Methane	0.11	
N_2O (MG)	Emission to air - Dinitrogen monoxide	28.05	
NH_3 (MG)	Emission to air - Ammonia	100.1	

Processing phase

INPUT/OUTPUT		PROCESS	SCENARIO 1				SCENARIO 2				DATA SOURCE
			SP1	SP2	IP3	IP4	SP1	SP2	IP3	IP4	
INPUT	Mealworm (KG)	Mealworm rearing phase	2 181	2 006	2 120	2 042	3 701	5 489	7 589	7 477	From experiment
	Water (L)	tap water | tap water production, conventional treatment	12 871	23 512	57 379	73 801	20 871	31 043	10 2072	10 4671	From experiment
	Electricity (KWH)	electricity, medium voltage | electricity voltage transformation from high to medium voltage	8 759	9 315	11 074	11 765	11 235	10 779	18 044	16 167	1, 38, 40, 41
	Steam (KG)	steam, in chemical industry | market for steam, in chemical industry	6 866	9 443	-	-	6 866	9 443	-	-	39
	Hexane (KG)	hexane | market for hexane	1	1	2	2	2	2	5	3	36
	Ethanol (KG)	ethanol, without water, in 99.7% solution state, from ethylene | market for ethanol, without water, in 99.7% solution state, from ethylene	1	1	1	2	2	1	4	3	
	NaOH (KG)	sodium hydroxide, without water, in 50% solution state | market for sodium hydroxide,	326	599	442	995	552	813	1 133	1 639	From experiment

		without water, in 50% solution state									
	HCl (KG)	hydrochloric acid, without water, in 30% solution state | market for hydrochloric acid, without water, in 30% solution state	321	479	560	990	321	551	846	1 201	From experiment
OUTPUT	Emission - Hexane (KG)	Hexane	1	1	2	2	2	2	5	3	36
	Emission - EthanoL (KG)	Ethanol	1	1	1	2	2	1	4	3	36
	Wastewater (L)	wastewater, average | treatment of wastewater, average, capacity 1.1E10 L/year	10 903	10 032	30 395	34 417	18 504	13 610	11 0606	92 537	From experiment
	Waste (KG)	biowaste | treatment of biowaste, composting	-	-	-	-	626	325	1283	656	From experiment
	Lipid fraction (KG)	-	624	459	1279	925	624	459	1279	925	
	Chitin fraction (KG)	-	626	325	1283	656	-	-	-	-	From experiment
	Supernatant (L)	-	-	-	32726	47340	-	-	-	-	
	TM protein extract (Ton)	-	1	1	1	1	1	1	1	1	From experiment

Table S2. Data and references used in Figure 5.

Protein source	Protein (g) / product (kg)	GWP (kg CO_2 eq./kg)	Eco-efficiency score[1]	Reference
Scenario 1	547 – 800	3.5 - 5.5	14.5 - 156.3	Current study
Scenario 2	547 – 800	6.3 – 10.9	50.2 - 127.0	
Soy protein isolate	870	1 - 6	145 - 870	50
Whey protein concentrate	800	12 - 16	50 - 67	
Skim milk powder	350	7 - 9.1	38.5 – 50.0	
Sodium caseinate	910	17 - 27	33.7 – 53.5	
Microbial protein	650	1 - 8	81.25 - 650	51
Faba bean protein ingredients	900	3	300	52
Lupin seeds protein isolates	930	6	155	53
Egg protein concentrate	800	23.4	34	54

[1] Calculated using Equation 4 with GWP values above for each protein source.

General equations for energy consumption

Equation S1. Electricity for blanching [3]

$$\text{Electricity (kwh)} = \left(\frac{W\ .\ \Delta\text{T}\ .\ \text{SW}}{3\ 600\ 000}\right) + \left(\frac{TM\ .\ \Delta\text{T}\ .\ \text{STM}}{3\ 600\ 000}\right) \quad \text{(S1)}$$

W: Quantity of water (g)
ΔT: Temperature difference (°C)
SW: Specific heat of water (4.184 J / g / °C)
3 600 000: Conversion factor from J to kwh
STM [38]: Specific heat of TM (3320 J / kg / °C)
TM: Quantity of TM (kg)

Equation S2. Electricity for homogenisation [1]

$$\text{Electricity (kwh)} = \frac{EP\ .\ TM\ .\ V}{C} \quad \text{(S2)}$$

EP: Engine power (2.2 kW)

TM: Quantity of TM (kg)
V: Volume to homogenize (L/kg TM)
C: Capacity (500 L/h)

Equation S3. Electricity for centrifugation [41]

$$\text{Electricity (kwh)} = \frac{EP \,.\, TM \,.\, V}{C} \quad \text{(S3)}$$

EP: Engine power (19 kW)
TM: Quantity of TM (kg)
V: Volume to centrifuge (L/kg TM)
C: Capacity (20 000 L/h)

Equation S4. Electricity for agitation in protein solubilisation [42]

$$\text{Electricity (kwh)} = \frac{EP \,.\, TM \,.\, V \,.\, T}{C} \quad \text{(S4)}$$

EP: Engine power (24 kW)
TM: Quantity of TM (kg)
V: Volume to agitate (L/kg TM)
T: Time of agitation (h)
C: Capacity (4 000 L)

Equation S5. Electricity for heat during the protein solubilisation [39]

$$\text{Electricity (kwh)} = \frac{\left(\frac{N \,.\, \Delta\text{T} \,.\, \text{SN}}{3\,600\,000}\right) + \left(\frac{TM \,.\, \Delta\text{T} \,.\, \text{STM}}{3\,600\,000}\right)}{E} \quad \text{(S5)}$$

N: Quantity of NaOH (g)
ΔT: Temperature difference (°C)
SN: Specific heat of NaOH (3.98 J / g / °C)
3 600 000: Conversion factor from J to kwh
STM [38]: Specific heat of defatted TM (3405 J / kg / °C)
TM: Quantity of TM (kg)
E: Efficiency (0.75)

Equation S6. Steam for pre-concentration [40]

$$\text{Steam (kg)} = \text{SC} \,.\, \text{W} \quad \text{(S6)}$$

SC: Steam consumed by a three-effect evaporator (0.4 kg/kg water to evaporate)
W: Quantity of water to evaporate (kg)

Equation S7. Electricity for drying [36]

$$\text{Electricity (kwh)} = \frac{EC \,.\, W}{3\,600} \qquad (S7)$$

EC: Energy consumption of a single effect spray drying process (5000 kJ/kg of water to evaporate)
W: Quantity of water to evaporate (kg)
3 600: Conversion factor from kJ to kwh

Equation S8. Electricity for recuperating solvent and ethanol [37]

$$\text{Electricity (kwh)} = \left(\frac{\text{E} \,.\, \Delta\text{HE}}{3\,600}\right) + \left(\frac{\text{H} \,.\, \Delta\text{HH}}{3\,600}\right) \qquad (S8)$$

E: Quantity of ethanol to evaporate (kg)
ΔHE: Ethanol enthalpy (977 kJ/kg)
3 600: Conversion factor from kJ to kwh
H: Quantity of hexane to evaporate (kg)
ΔHH: Hexane enthalpy (335 kJ/kg)