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Life Cycle Assessment of an Innovative Microalgae Cultivation System in the Baltic region: Results from SMORP Project

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ANNEX

CONTENT

ANNEX A. DATA ANALYSIS FOR SMORP

The total area of microalgae cultivation is calculated using Eq. (1):

$$\text{Total area} = \text{Single pond surface} \cdot \text{Number of ponds}. \tag{1}$$

The total volume of microalgae culture using Eq. (2):

$$\text{Total volume} = \text{Total area} \cdot \text{water depth} \tag{2}$$

The total energy needed for microalgae growth is calculated using Eq. (3):

$$\text{Total energy} = \frac{PAR\,requested \cdot \text{Total area}}{2.1}. \tag{3}$$

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The factor for downtime by crash (F_{crash}) is calculated using Eq. (4):

$$F_{crash} = \frac{365 - (number\ of\ crashes \cdot prod\ downtime\ per\ crash)}{365}, \quad (4)$$

where *number of crashes* is the crash occurrence per year, and *prod downtime per crash* is the estimated mean time necessary to empty, clean, inoculate a new strain, and to be able to restart the harvest in the pond.

The optimal temperature for microalgae growth is species-dependent and decreases according to specific law, moving away from this optimal value. This law calculates a temperature factor (*Tf*) as an exponential limitation caused by sub-optimal temperatures, based on James and Boriah law [1] as described in Eq. (5):

$$T_f = e^{-K(T - T_{opt})2}, \quad (5)$$

where the difference between actual (T) and optimal temperature (T_{opt}) is used to calculate the production limitation through an empirical constant (K=0.004).

The evaporation rate is expressed in kg $(m^2\ h)^{-1}$ and calculated in Eq. (6):

$$M_{ev} = \text{Total area} \cdot \frac{(30.6 + 32.1 \cdot V_{wind}) \cdot (P_w - P_a)}{DH_v}, \quad (6)$$

where (P_w) is the saturation of vapor pressure at water temperature, (*Pa*) is the saturation vapor pressure at air dew point, and (*DHv*) is the latent heat of water at the pond temperature, multiplied by the surface area of the ponds (*Total area*). (*Vwind*) is assumed to be equal to 0, values of 30,6 and 32,1 are two empirical constants. The water flow inevitably influences the evaporation rate. Thus, the calculated evaporation rate is considered indicative. (P_a) is expressed in kPa and calculated using equation (11):

$$P_a = 0.6108 \cdot \frac{17.27 \cdot T_{air}}{e^{273.15 + T_{air}}}, \quad (7)$$

where (T_{air}) represents the air dew point temperature. The same equation can be used to calculate (P_w) while substituting (T_{air}) by (T_w) representing the average water temperature. The latent heat of water at pond temperature (DH_v, expressed in kJ kg^{-1}) is calculated as showed in Eq. (8) [2]:

$$DH_v = 2500.8 - 2.36 \cdot T_w + 0.0016 \cdot T_w^2 - 0.00006 \cdot T_w^3. \quad (8)$$

After converting evaporation rate in $m^3\ month^{-1}$ (E_r) for the total pond surface, is therefore possible to calculate heat loss in kWh $month^{-1}$ through evaporation rate using Eq. (9):

$$\text{Heat loss evaporation} = \text{DHv} \cdot \text{Er} \cdot 1000 \cdot 0.000278, \quad (9)$$

where 0.000278 is the conversion factor from kJ to kWh.

A simplified heat loss calculation for crashes was made through the number of crashes multiplied for the total water volume and the water-specific heat capacity assuming 10 °C difference from the tap water and the pond temperature calculated by Eq. (10):

$$R_h = \frac{(Er + H_2O\ \text{overflow} \cdot \frac{\text{day}}{\text{month}}) \cdot 10 \cdot 4180}{0.001}, \quad (10)$$

where (Rh) represents the heat required to warm up the refill water lost for evaporation and the recirculation water that cools down outside the heated pond, (H2O overflow) represents the daily recirculation water that goes into the settling tank and returns into the pond, and 4180 J (kg °C)–1 is the water-specific heat capacity.

Heat loss for convection (Hlc) is calculated according to Stefan-Boltzmann's fourth power law using alpha parameter (α=1.146240), ponds total area, and the difference between pond and air temperature, as shown in Eq. (11):

$$H_{lc} = \frac{a \cdot (pond\,temp - air\,temp) \cdot \text{Total area} \cdot \frac{h}{gg} \cdot \frac{gg}{m}}{1000}. \quad (11)$$

Assumption for wall dispersion represents the quantity of heat which, through the walls of the pond, is dispersed in the surrounding environment (D_{tw}). The material chosen for its good optical and mechanical characteristics for the construction of the SMORP pilot is the PMMA, which has a thermal transmission coefficient (k), expressed in W (m^2 °C)$^{-1}$ equal to 5.80. For the calculation of total heat losses through ponds walls in kWh month^{-1} Eq. (12) has been used:

$$D_{tw} = \frac{\Delta T \cdot k \cdot (Ba + Wa) \cdot \frac{h}{gg} \cdot \frac{gg}{m}}{1000}, \quad (12)$$

where (ΔT) represents the difference between air temperature inside the greenhouse and water temperature, (Ba) is the total base area of the ponds and (Wa) the total area of the ponds walls.

Solar radiation represents the sun's thermal energy in the infrared area, which contributes to pond heating. It was calculated first by converting the global radiation expressed in J (m^2 month)$^{-1}$ to kWh (m^2 month)$^{-1}$ using Eq. (13):

$$Grad(\text{kWh}) = \frac{Grad(J)}{1000} \cdot 0.000278, \quad (13)$$

where 0.000278 is the conversion factor from kJ to kWh. The heat input is expressed in kWh month^{-1} calculated using Eq. (14):

$$H_{in} = \text{Total area} \cdot (1 - Pe) \cdot Grad(\text{kWh}), \quad (14)$$

where (H_{in}) is the heat input from solar radiation, *Total area* the total area of the ponds, and (Pe) the photosynthetic efficiency, the part of the radiation that is absorbed by microalgae and does not contribute to the medium heating.

The power requirement for each hydraulic pump in J s^{-1} is dependent on the gravitational acceleration g, total lift expressed in m, flow rate in m^3 s^{-1}, the density of fluid in kg (m^3)$^{-1}$, hydraulic (η_{hydr}), organic (η_{org}), and electric (η_{el}) efficiency of the electric motor as summarized in Eq. (15):

$$Power = \frac{g \cdot Tot\,lift \cdot Flowrate \cdot Fluid\,density}{\eta_{hydr} \cdot \eta_{org} \cdot \eta_{el}}, \quad (15)$$

where *Tot lift* in metres is the sum of static lift and pipe head loss. Pipe head losses are calculated with the Darcy–Weisbach equation and is presented in Eq. (16):

$$hf = \frac{f \cdot L \cdot V^2}{2 \cdot g \cdot D}, \quad (16)$$

where hf is head loss due to friction expressed in (m), L is the length of the pipe (m), V is the mean velocity of the flow (m s^{-1}), g is the acceleration of gravity (m/s^2), D is the pipe diameter (m), and f is the friction factor. The Swamee–Jain equation is used to solve for the Darcy-Weisbach friction factor f, and is presented in Eq. (17):

$$f = \frac{0.25}{[\log_{10}(\frac{\varepsilon}{3.7 \cdot D} + \frac{5.74}{\mathrm{Re}^{0.9}})]^2}, \quad (17)$$

where ε is the pipeline roughness (m), and Re is the Reynolds number for fluid flow in a pipe (unitless). The Reynolds number is calculated with Eq. (18):

$$\mathrm{Re} = \frac{Q \cdot D_H}{A \cdot v}, \quad (18)$$

where Q is the volumetric flowrate (m^3 s^{-1}), D_H is the hydraulic diameter of the pipe (m), A is the pipe cross sectional area (m^2), and v is the water kinematic viscosity in (m^2 s^{-1}). The mean velocity of the flow in (m s^{-1}) is expressed in Eq. (19):

$$V = \frac{Q}{A}, \quad (19)$$

where A is the pipe cross sectional area (m^2), and Q is the volumetric flow rate (m^3 s^{-1}). The cross-sectional area of a circular pipe is expressed in Eq. (20):

$$A = \pi \cdot (\frac{D}{2})^2, \quad (20)$$

where D is the diameter of the pipe (m). For each pump 2 meters of pipe with concentrated losses at the inlet and outlet are considered. Each pump has a daily working time of 30 minutes, composed of 3 sessions of 10 minutes, each to respect the microalgae growth rate assuming an 8 hours retention period. Flowrate is calculated scaling data related to another study. [3] According to estimate, the hydraulic pumps have a lower consumption compared, for instance, to mixing or artificial lighting.

Electricity consumption for spraying flue gas inside the pond has been taken from literature. [63] As this value is expressed in kWh kg^{-1} of flue gases. The algal biomass quantity is related to CO_2 consumption [4] according to Eq. (21):

$$\mathrm{CO_2\ flue\ gas{=}kg\ biomass\ DW}\,realised \cdot \frac{\mathrm{kgCO_2}}{kg\,biomass\,DW}. \quad (21)$$

Consequently, the quantity of flue gases in kg that is sprayed into the pond to ensure the correct amount of CO_2 needed for algal growth is expressed as given in Eq. (22):

$$\text{Flue gas spraying} = \frac{\mathrm{CO_2\ from\ flue\ gas}}{\mathrm{CO_2\ uptake\ eff} \cdot \mathrm{\%CO_2\ in\ flue\ gas}}. \quad (22)$$

The actual average pond temperature is equal to set desired average temperature when the heat system is activated and equal to the air temperature when higher than the set temperature, calculated with Eq. (23):

$$\text{Actual pond temp} = \text{MAX}[\mathit{TairGH}; \mathit{setTemp}], \tag{23}$$

where *TairGH* represent the average air temperature inside the greenhouse and *setTemp* is the desired set pond temperature. Factor for sub-optimal pond temperature, as seen in the Temperature-Growth curve, represents the limiting growth factor for the particular microalgae species when the medium temperature is not optimal.

Biomass potential production is the quantity of biomass that SMORP pilot can theoretically produce if no culture crashes occur during the production. The monthly values are obtained with Eq. (24):

$$pot\,biom.prod = biomass\,prod \cdot Total\,area \cdot Tf \cdot Pf\ , \tag{24}$$

where *biomass prod* is the biomass daily production and *Pf* the production factor considering that the plant is not operative 365 days per year, due to holidays and festivities, and in these days the harvest stops. It is assumed that this factor limits only the algae production but not the energy consumptions. *Pf* value is calculated according to Eq. (25):

$$Pf = \text{days of the month} - \frac{365 - \text{total working days}}{12} \tag{25}$$

Biomass realized production represents a hypothetical actual biomass production. It is calculated multiplying the potential biomass production with the crash production factor, *Fcrash*. Lost biomass by crashes is the difference between theoretical and actual production. Wasted water by crashes (*Wwcrashes*) represents the amount of water (m^3 $year^{-1}$), which is wasted based on the number of annual crashes, considering that in each subsequent washing it is necessary to fill the tank twice to clean it from any contamination that could compromise the restart of the culture, as shown in Eq. (26):

$$\text{Wwcrashes} = \text{Number of crashes} \cdot \text{Tot vol} \cdot 2 \tag{26}$$

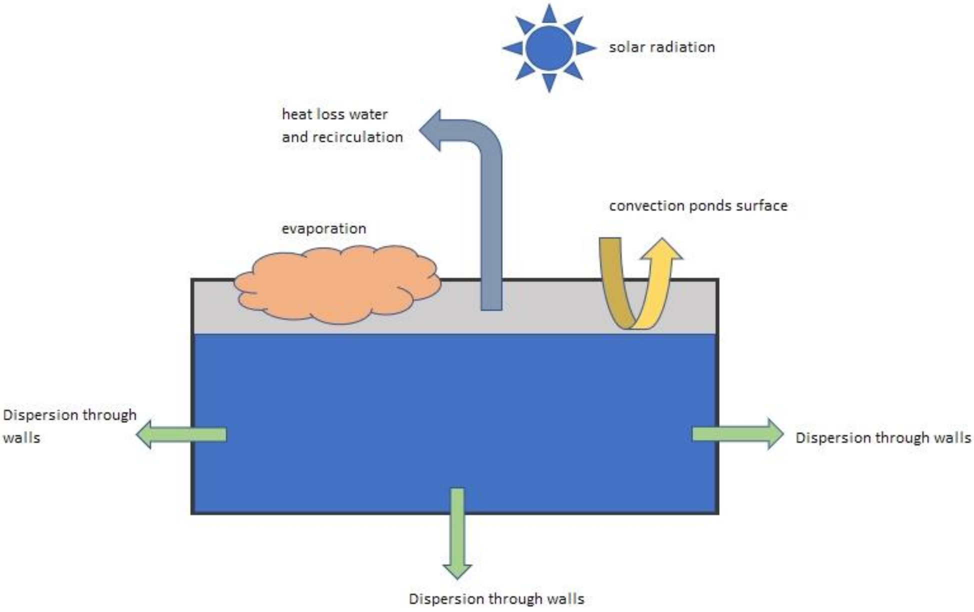
Evaporation value is taken from the heat parameters and useful for the total water calculation, represents the quantity of water (m^3 $month^{-1}$) that evaporate from the pond surface.

Biomass to centrifuge is the amount of biomass expressed in kg, extracted after the centrifugation system. Biomass losses due to centrifuge inefficiency or due to recirculation to the pond are not considered.

To calculate electricity consumption in centrifuge, the specific centrifugation consumption per m^3 of water treated is multiplied by the volume of treated water (see Eq. (27)), calculated by scaling down a larger pond system [5]:

$$\text{Elec. centrif.} = \frac{\text{days}}{months} \cdot \frac{\frac{l\,treated}{day}}{1000} \cdot specific\,consumption \tag{27}$$

ANNEX B. HEAT BALANCE IN SMORP


solar radiation
heat loss water
and recirculation
convection ponds surface
evaporation
Dispersion through
walls
Dispersion through walls
Dispersion through walls

ANNEX C. SMORP PILOT PARAMETERS

TABLE 2. SUMMARY OF SMORP PILOT PARAMETERS

Parameter	Unit	Value	Source
Single pond surface	m^2	3.6	[6]
Single pond water depth	m	0.4	[6]
Number of ponds	number of units	3	[6]
Photosynthetic efficiency	%	1.5	[1]
Biomass concentration	kg DW/m^3	0.3	[1]
Biomass daily production	g (m2 day)$^{-1}$	20	[7]
Digestate needed	kg/kg DW	6	[1]
Total working days	days year^{-1}	300	Estimation
Culture crashes	crash year^{-1}	3	Estimation
Culture downtime per crash	days	7	[1]
Production downtime per crash	days	14	[1]
Electricity for CO_2 spraying	kWh/kg flue gas	0.0222	[8]
Electricity for mixing	kWh/kg DW	8,9	[9]
Electricity for centrifuge	kWh/m^3	8	[8]
CO_2 uptake efficiency	%	30	[10]
CO_2 required	g/g DW	1.8	[11]
% CO_2 in flue gas	%	7	[1]
PAR requested	μmol phot (m^2 s)$^{-1}$	50	Estimation

ANNEX D. LIFE CYCLE INVENTORY OF SMORP PILOT

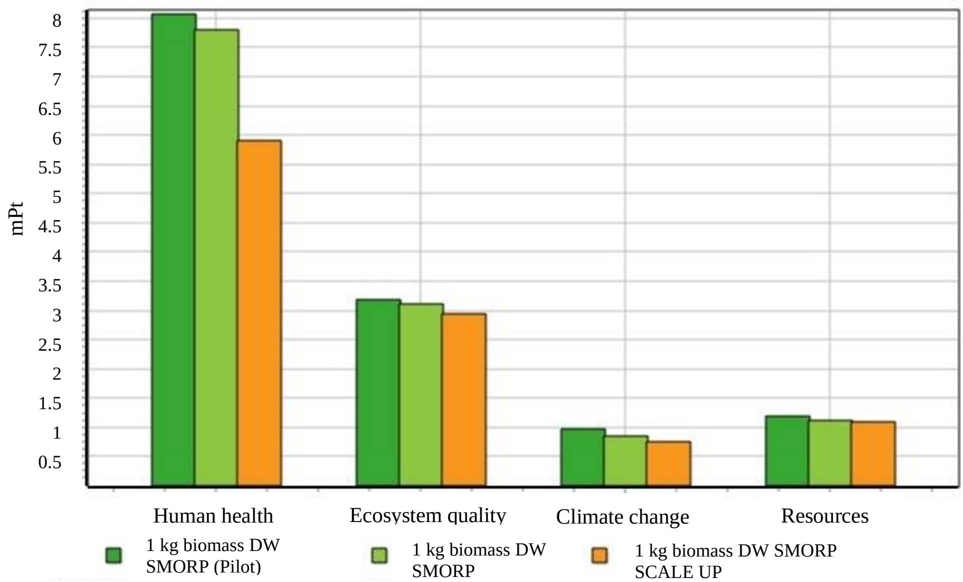
TABLE 1. SUMMARY OF INPUTS FOR SMORP PILOT OPERATION

Process inputs	Value	Unit
Cultivation inputs		
Electricity for CO_2 spraying	2640	kWh
Electricity for mixing	28620	kWh
Heat	60455	MJ
Tap water	774	m^3
Electricity for lighting	7500	kWh
Cultivation avoided products		
Carbon dioxide biogenic	1958.19	kg
Nitrogen fertiliser	29,64	kg
Harvesting inputs		
Electricity for inflow to settler	5840	kWh
Electricity for outflow to pond	5610	kWh
Electricity for centrifuge	1260	kWh
Harvesting outputs		
DW algae biomass	1025.4	kg

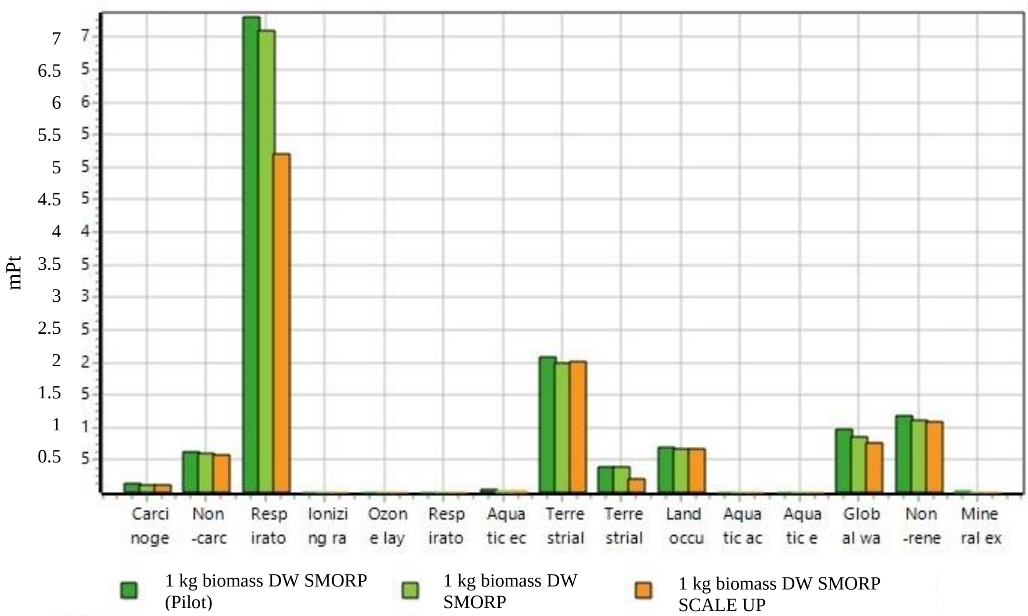
Annex E. SMORP Pilot Energy Consumptions and Biomass Production

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	units		total	unit
Calculation of production																
In operation?	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes				
monthly daylight mean energy	0,26	0,67	1,51	2,74	4,02	4,18	4,12	3,09	1,83	0,96	0,31	0,16	GJ/month		23,85	GJ/year
desired average temperature ponds	20	20	20	20	20	20	20	20	20	20	20	20	°C			
actual average temperature ponds	20,0	20,0	20,0	20,0	21,4	25,5	26,9	26,2	22,0	20,0	20,0	20,0				
Factor for non optimal pond temp	0,90	0,90	0,90	0,90	0,94	1,00	0,98	1,00	0,96	0,90	0,90	0,90				
biomass production potential (dry weight; kg)	5,00	4,41	5,00	4,80	5,18	5,29	5,44	5,50	5,12	5,00	4,80	5,00	kg dry biomass/month		60,56	kg dw biomass/year
biomass production realised (dry weight)	4,42	3,91	4,42	4,25	4,59	4,68	4,81	4,87	4,53	4,42	4,25	4,42	kg dry biomass/month		53,59	kg dw biomass/year
lost biomass by crashes (dry weight)	0,58	0,51	0,58	0,55	0,60	0,61	0,63	0,63	0,59	0,58	0,55	0,58	kg dry biomass/month		6,97	kg dw biomass/year
waste water by crashes															25,92	m3 water/year
evaporation (volume on total ponds surface)	0,3	0,3	0,4	0,4	0,3	0,4	0,3	0,3	0,2	0,2	0,2	0,2	m3 water/month		4,16	m3 water/year
rainfall (volume on total ponds surface)	0,36	0,27	0,33	0,42	0,46	0,66	0,85	0,85	0,82	0,65	0,66	0,53	m3 water/month		6,87	m3 water/year
heat use	2501	2082	1588	399	0	0	0	0	0	500	1434	2177	kWh/month		10832,00	kWh/year
electricity flue gas sparging	5	5	5	5	5	5	5	5	5	5	5	5	kWh/month		63,64	kWh/year
electricity paddle wheel	40	40	40	40	40	40	40	40	40	40	40	40	kWh/month		477,00	kWh/year
digestate needed															387,90	kg/year
Centrifuge																
biomass to centrifuge (dry weight)	4,42	3,91	4,42	4,25	4,59	4,68	4,81	4,87	4,53	4,42	4,25	4,42	kg dry biomass/month		53,59	kg dw biomass/year
algae DW concentration kg/m3	20	20	20	20	20	20	20	20	20	20	20	20				
m3 harvested each month	0,2221	0,1953	0,2212	0,2126	0,2293	0,2340	0,2406	0,2435	0,2266	0,2212	0,2126	0,2021	m3/month		2,68	m3/year
electricty centrifuge	5,36	4,84	5,36	5,18	5,36	5,18	5,36	5,36	5,18	5,36	5,18	5,36	kWh/month		63,00	kWh/year
Flue gas uptake																
kg CO2/ kg DW															2,50	kg co2/kg dw
CO2 uptake from flue gas	11,06	9,76	11,06	10,63	11,47	11,70	12,03	12,18	11,33	11,06	10,63	11,06	kg CO2/month		134,00	kg CO2/year
Flue gas flow through pond	527	465	527	506	546	557	573	580	540	527	506	527	kg flue gass/month		6380,00	kg flue gas/year
water use																
total water use															30,10	m3/year
Pumps																
elec. overflow pump 1 (after tanker)	12,81	21,50	23,81	23,04	23,81	23,04	23,81	23,81	23,04	23,81	23,04	23,81	kWh/month		280,30	kWh/year
elec. overflow pump 2 (after centrifuge)	-	-	-	-	-	-	-	-	-	-	-	-	kWh/month		-	kWh/year
elec. inflow pump to settler	24,8	22,4	24,8	24,0	24,8	24,0	24,8	24,8	24,0	24,8	24,0	24,8	kWh/month		292,00	kWh/year
elec. inflow pump to centrifuge	-	-	-	-	-	-	-	-	-	-	-	-	kWh/month		-	kWh/year
elec. inflow digestate	-	-	-	-	-	-	-	-	-	-	-	-	kWh/month		-	kWh/year
elec. Flue gas sparging	11,7	10,6	11,7	11,4	11,7	11,4	11,7	11,7	11,4	11,7	11,4	11,7	kWh/month		138,00	kWh/year
elec. inflow H2O	-	-	-	-	-	-	-	-	-	-	-	-	m3/month		-	m3/year
LED light supply																
elec. LED lightning	51,88	36,30	25,82	10,31	0,00	0,00	0,00	5,12	19,27	35,01	46,97	55,84			286,51	kWh/year

Annex F. Comparative LCIA, weighting at midpoint



Method: IMPACT 2022+ V2.14/IMPACT 2002+/Weighting
Comparing 1 p '1 kg Biomass DW SMORP (pilot)', 1 p '1 kg Biomass DW SMORP' and 1 p '1 kg Biomass DW SMORP SCALE UP'



Method: IMPACT 2022+ V2.14/IMPACT 2002+/Weighting
Comparing 1 p '1 kg Biomass DW SMORP (pilot)', 1 p '1 kg Biomass DW SMORP' and 1 p '1 kg Biomass DW SMORP SCALE UP'

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