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**Supporting information (SI) for:**

## **Inclusion of multiple climate tipping as a new impact category in life cycle assessment of polyhydroxyalkanoate (PHA)-based plastics**

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## S1. Details of literature review

Recall, that a literature review was conducted specifying type of feedstock, microorganism used in the fermentation, scale of production, capacity of production and polymer yield, to support collection of data relevant for the LCA. Studies were identified in the search engine Scopus in March 2020 in two steps:

1. Limiting the search to review articles published after 2017 (assuming that these recently published review articles refer to relevant, older studies) and applying key words related to PHA and its synonyms and plant scale (pha OR polyhydroxyalkanoate\* OR \*polyhydroxybutyrate\* OR phb OR hbv AND "large scale" OR "industrial plant" OR pilot OR "large-scale" OR "large scale" OR "scale-up")
2. Applying key words related to PHA and to LCA to identify studies related to environmental assessment of PHA production were identified (lca AND pha OR polyhydroxyalkanoate\* OR \*polyhydroxybutyrate\* OR phb OR phbv). An additional search for studies producing PHA by fermenting molasses by *R. eutropha* (i.e. not limited to review articles) was conducted to ensure that recent studies similar to the large scale plant, not captured in the reviews, were identified (key words: pha OR polyhydroxyalkanoate\* OR \*polyhydroxybutyrate\* OR phb OR phbv AND molasses AND *ralstonia* OR *necator* OR "*R.eutropha*" AND fermentation).

Cited and citing studies that were found to contain relevant data were consulted to complement the search, and this process was iterated until no new study was found. In total, 25 studies were included in the review (see [Table S1](#) for an overview).

**Table S1.** Overview of studies identified in the literature analysis conducted to support the inventory data collection.

Study	Type of study	Feedstock (substrate)	Microorganism	Production scale <sup>a</sup>	Capacity	Polymer yield
(Valappil et al., 2007)	Fermentation technology	Sterilized glucose and soybean dialysate	<i>Bacillus cereus</i> SPV	Pilot*	20 L	0.114 g/g substrate
(Koller et al., 2015)	Fermentation technology	Glucose	<i>Haloferax mediterranei</i> DSM 1411	Pilot*	10 L	0.23 g/g substrate
(Koller et al., 2007a)	Fermentation technology	Hydrolyzed whey permeate	<i>Haloferax mediterranei</i> DSM 1411	Pilot*	42 L	0.29 g/g substrate
(Koller et al., 2007b)*	Fermentation technology	Hydrolyzed whey permeate	<i>Haloferax mediterranei</i> DSM 1411	Pilot*	10 L	0.2 g/g substrate
(Bengsston et al., 2017; Werker et al., 2018)	Fermentation technology	Wastewater from candy factory (Volatile fatty acids (VFA))	Mixed microbial cultures	Pilot	1200 L	0.4 g/g substrate
(Larriba et al., 2020)	Fermentation technology	Wastewater sludge (VFA)	Nitrite oxidizing bacteria	Pilot	2500 L	0.05 g/g COD
(Moretto et al., 2020)	Fermentation technology	from AD of biowaste (VFA)	Mixed microbial cultures	Pilot	100-380 L	3.86 g/L OFMSW
(Ntaikou et al., 2014)	Fermentation technology	Olive-mill wastewater (VFA)	Enriched culture of <i>Pseudomonas sp</i>	Pilot	50 L	7.58 ± 0.06 g/L
(Tamis et al., 2014)	Fermentation technology	Waste water from Mars candy bar factory (VFA)	<i>P. acidivorans</i>	Pilot	200 L	0.37 g/g substrate
(Amulya et al., 2015)	Fermentation technology	Waste water from acidogenic fermentation of municipal solid waste (VFA)	Anaerobic consortia (mixed culture) procured	Pilot	34 L	0.17 g/g substrate
(Morgan-Sagastume et al., 2015)	Fermentation technology	Activated wastewater sludge (VFA)	Mixed culture: active sludge	Pilot	400 L	0.38 g/g substrate
(Jia et al., 2014)	Fermentation technology	Activated wastewater sludge (VFA)	Mixed culture: active sludge	Pilot	70 L	0.17 g/g substrate
(Valentino)	Fermentation	Organic fraction of MSW	Mixed microbial culture	Pilot	140 L	0.39-0.47 g/g VSS

et al., 2018)	technology	(VFA)				
(Elbahloul and Steinbüchel, 2009)	Fermentation technology	Octanoate	<i>P. putida</i> GPo1	Pilot*	650 L	0.41 g/g substrate
(Kshirsagar et al., 2013)	Fermentation technology	Maltose	<i>Halomonas campisalis</i>	Pilot*	14 L	0.09 g/g substrate
(Wang and Lee, 1997)	Fermentation technology	Glucose	Recombinant <i>Escherichia coli</i> ( <i>A. eutrophus</i> PHA biosynthesis genes)	Pilot*	50 L	0.27-0.28 g/g substrate
(Mohammad and Steinbüchel, 2009)	Fermentation technology	Glycerol	<i>Zorbellella denitrifican</i>	Pilot*	42 L	0.25 g/g substrate
(Kellerhals et al., 2000)	Fermentation technology	Octanoic acid	<i>P. putida</i> KT2442	Pilot*	30 L	0.22 g/g substrate
(Kellerhals et al., 2000)	Fermentation technology	Oleic acid	<i>P. putida</i> KT2442	Pilot*	30 L	0.56 g/g substrate
(Nath et al., 2008)	Fermentation technology	Cheese whey (lactose)	<i>Methylobacterium sp.</i> ZP24	Pilot*	30 L	0.315 g/g substrate
(Harding et al., 2007)	LCA	Sugar cane (sucrose)	<i>Cupriavidus necator</i>	Pilot (upscaled)	1 L	0.36 g/g substrate
(Leong et al., 2017)	Environmental and economic assessment	Glycerol	<i>Cupriavidus necator</i>	Large scale (simulated)	9000 t polymer/year	0.36 g/g substrate
(Kookos et al., 2019)	LCA	Seed oil and sucrose	<i>Ralstonia eutropha</i>	Large (upscaled)	10000 t polymer/year	0.17 g/g substrate
(Pavan et al., 2019)	Economic analysis	Citric molasses	<i>Cupriavidus necator</i>	Large (upscaled)	2000 t polymer/year	0.28 g/g substrate
(Koller et al., 2013)	Environmental assessment	Whey	<i>Haloferax mediterranei</i> DSM 1411	Pilot	300 L	0.188 g/g substrate

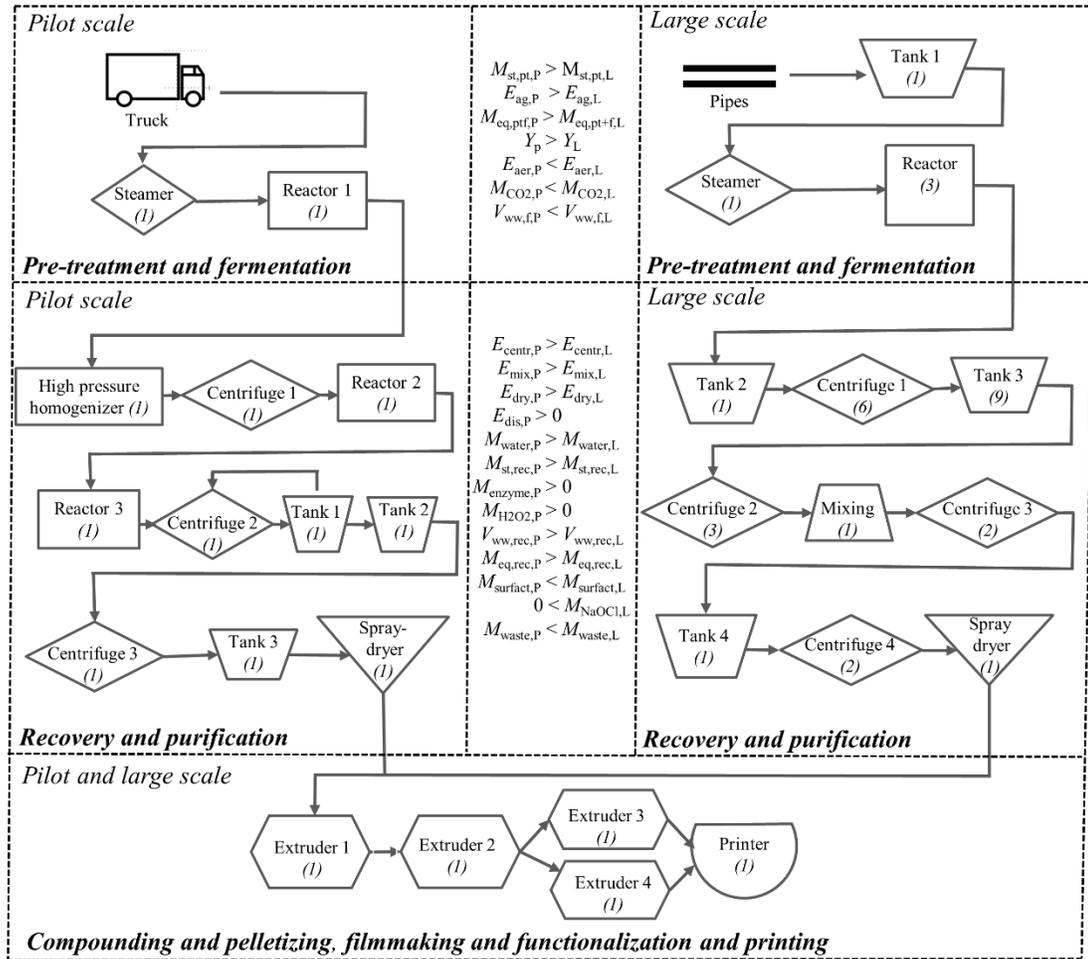
<sup>a</sup> Scale as defined by the study itself or between 10-1000L (indicated with "\*\*")

**Table S2.** Overview of studies used as data sources in this LCA study for parameters related to fermentation, recovery and purification installations at pilot and large scale.

<b>Study</b>	<b>Details</b>	<b>Scale</b>	<b>Parameters used in LCA modelling</b>
(Harding <i>et al.</i> 2007)	LCA study on a PHA pilot production facility (1 t PHA/year) fermenting sucrose from sugar cane by <i>R. eutropha</i> . The data are obtained combining data scaled up from lab-scale study and process flowsheet from a pilot plant.	Pilot	Steam for sterilization and spray drying, yield of fermented PHA, wastewater, consumptions of water, surfactant, enzyme and hydrogen peroxide and bill of materials.
(Leong <i>et al.</i> 2017)	Economic and environmental assessment on a PHA large scale facility (9000 t PHA/year) fermenting glycerol by <i>R. eutropha</i> . The large scale facility is simulated based on heuristics and experience.	Large scale	Yield of fermented and recovered PHA, waste and wastewater, consumption of water and surfactant and NaOCl and bill of materials.
(Kookos <i>et al.</i> 2019)	LCA study on a PHA large scale facility (10000 t PHA/year) fermenting sucrose by <i>R. eutropha</i> . The large scale facility is simulated based on lab-scale PHA production study.	Large scale	Steam for sterilization and spray drying, yield of fermented and recovered PHA, consumptions of electricity, ammonia and surfactant and NaOCl, CO <sub>2</sub> emissions.
(Pavan <i>et al.</i> 2019)	Economic analysis of a PHA large scale facility (2000 t PHA/year) fermenting sucrose from citric molasses by <i>R. eutropha</i> . The large scale facility is simulated based on lab-scale PHA production study.	Large scale	Yield of fermented PHA and consumptions of ammonia.

## S2. Data underlying LCA model

**Figure S1.** Process set-up for PHA-film packaging production at two scales  $s$  (where  $s=P$  and  $s=L$  for pilot and large scale, respectively). The numbers in italics in parenthesis indicate the number of installations. Collection of feedstock, pre-treatment, fermentation, and recovery and extraction are modelled differently at pilot and large scale, the following parameters are distinct: steam applied for sterilizing feedstock during pre-treatment ( $M_{st,pt,s}$  in kWh/kg<sub>feedstock</sub>), electricity used for agitation and aeration during fermentation ( $E_{ag,s}$  and  $E_{aer,s}$  in kWh/kg<sub>PHA</sub>), mass of equipment applied during pre-treatment and fermentation ( $M_{eq,ptf,s}$  in kg material/kg<sub>PHA</sub>), yield of raw PHA ( $Y_s$  in kg<sub>PHA</sub>/kg<sub>substrate</sub>), mass of CO<sub>2</sub> emitted during fermentation ( $M_{CO_2,s}$  in kg/kg<sub>PHA</sub>), volume of wastewater during fermentation ( $V_{ww,f,s}$  in m<sup>3</sup>/kg<sub>PHA</sub>), mass of equipment applied during recovery and purification  $M_{eq,rec,s}$  in kg material/kg<sub>PHA</sub>, electricity used for centrifugation, mixing, spray drying and cell disruption during recovery and purification ( $E_{centri,s}$ ,  $E_{mix,s}$ ,  $E_{dry,s}$  and  $E_{dis,s}$  in kg/kg<sub>PHA, recovered</sub>), water and steam consumed during recovery ( $M_{water,s}$  and  $M_{steam,rec,s}$  in kg/kg<sub>PHA, recovered</sub>), mass of enzyme and chemicals applied for recovery and purification ( $M_{enzyme,s}$ ,  $M_{H_2O_2,s}$ ,  $M_{NaOCl,s}$  and  $M_{surfact,s}$  in kg/kg<sub>PHA, recovered</sub>) and volume and mass of wastewater and waste effluent recovery ( $V_{ww,rec,s}$  in m<sup>3</sup>/kg<sub>PHA</sub> and  $M_{waste,s}$  in kg/kg<sub>PHA, recovered</sub>).



**Table S3.** Overview of scenarios for sensitivity analysis and perturbed parameter values assessed for PHA-based plastic value chain. All scenarios apply to the PHA-based bioplastic, except scenarios 9-12 which apply to PLA, PP and PE only.

# scenario	Sensitivity parameter	Plant scale <sup>a</sup>	Geographic location <sup>b</sup>	Conventional use of molasses	Material and surface treatment	Thickness of layers (μm) <sup>c</sup>	Yield (kg PHA <sub>raw</sub> /kg molasses) <sup>d</sup>	Landfilling degradation kinetics <sup>e</sup>
1	Baseline	Pilot	IT	Used as animal feed	PHA+PLA	76.5+20	0.176	Fast
2	Plant scale	Large scale	IT	Used as animal feed	PHA+PLA	76.5+20	0.131	Fast
3-4	Geographic location	Pilot, Large scale	DE	Used as animal feed	PHA+PLA	76.5+20	0.131	Fast
5-6	Avoided treatment of molasses	Large scale	IT, DE	Used for ethanol production	PHA+PLA	76.5+20	0.131	Fast
7-12	Material and surface treatment	Large scale	IT	Used as animal feed	PHA+Al, PHA+AlOx, PLA(91), PLA(50), PP, PE	76.5+0.01, 76.5+0.01, 91, 50, 31, 31	0.131	Fast
13-18	Yield	Large scale	IT	Used as animal feed	PHA+PLA	76.5+20	0.083, 0.110, 0.150, 0.176, 0.210, 0.245	Fast
19-48	Thickness of PHA film	Large scale	IT	Used as animal feed	PHA+PLA	15.5+15.5, 20+20, 40+20, 60+20, 100+20	0.083, 0.110, 0.150, 0.176, 0.210, 0.245	Fast
49-53	End of life degradation	Large scale	IT	Used as animal feed	PHA+PLA	76.5+20	0.131	Medium, Slow, Very slow, Delayed (20), Delayed (40)

<sup>a</sup>details on the difference between pilot and large scales are presented in [Section 2.3](#)

<sup>b</sup>IT: Italy, DE: Germany. The following parameters are updated according to the geographic location: electricity grid mix and conventional waste management technologies.

<sup>c</sup>Thicknesses are within range of relisting values and were chosen based on ongoing experimental trials (BioBarr 2019) for the PHA-based plastics with improved barrier properties, or based on current practice for the PLA, PP and PE.

<sup>d</sup>Yields for baseline pilot and large scale plants are based on literature data (see details in [Table S4](#)). Yields for scenarios 13-18 are based on minimum PHA fermentation from molasses yield in literature (Kookos *et al.* 2019) and an estimated maximum theoretical yield (based on a theoretical yield from Yamane (1993) and assuming that 95% of the accumulated biomass is PHA) and yields in between this range.

<sup>e</sup>Fast kinetics: 90% degradation in 2 years (100% degraded in 100 years), medium kinetics: 90% degradation in 31 years (99.9% degraded in 100 years), slow kinetics: 90% degradation in 105 years (89 % degraded in 100 years), very slow kinetics: 90% degraded in 22798 years (1% degraded in 100 years), delayed (20): degradation delayed by 20 years, fast kinetics, delayed (40): degradation delayed by 40 years, fast kinetics

**Table S4.** Overview of parameters and data sources for feedstock collection, pre-treatment, fermentation and PHA recovery at pilot and large scales.

Parameter	Pilot scale Average (min-max)	Large scale Average (min-max)	Unit	Note	Main data source
<b>Feedstock and collection</b>					
Electricity (pumping)	Not relevant	50	kWh/t <sub>feedstock</sub> , dw	Electricity use for pumping of feedstock into the reactor. <ul style="list-style-type: none"> <li><i>Pilot scale:</i> The feedstock is transported to the plant by truck. Hence, electricity for pumping is not relevant.</li> <li><i>Large scale:</i> Electricity consumed to pump the feedstock is assumed similar to the electricity reported in Owsianiak <i>et al.</i> (2016) for pumping of wet biowaste at full scale.</li> </ul>	L: Assumed based on Owsianiak <i>et al.</i> (2016)
Transportation distance	50	Not relevant	km	Transportation distance from biomass collect point to the fermentation plant <ul style="list-style-type: none"> <li><i>Pilot scale:</i> The feedstock is transported to the plant by lorry (Ecoinvent process; “Transport, freight, lorry 16-32 metric ton, EURO4 {RoW}  transport, freight, lorry 16-32 metric ton, EURO4   Conseq, U”). It is assumed that its transportation distance is 50 km.</li> <li><i>Large scale:</i> The feedstock is transported in pipeline system from a neighboring provider (sugar production plant). Hence, transportation by truck is not relevant.</li> </ul>	P: Assumed L: not relevant
Substrate content	49 (46-52)	49 (46-52)	% ww	Content of substrate (sucrose) in sugar beet molasses. <ul style="list-style-type: none"> <li><i>Pilot scale:</i> The sucrose content is calculated based on 8 data points from literature (ÇALIK <i>et al.</i>, 1939; El-Geddawy <i>et al.</i>, 2012; Šarić <i>et al.</i>, 2016)</li> <li><i>Large scale:</i> Assumed the same as for the pilot scale</li> </ul>	P and L: (ÇALIK <i>et al.</i> , 1939; El-Geddawy <i>et al.</i> , 2012; Šarić <i>et al.</i> , 2016)
Water content	18 (16-25)	18 (16-25)	% ww	Content of water in sugar beet molasses. <ul style="list-style-type: none"> <li><i>Pilot scale:</i> The water content is calculated based on 8 data points from literature (ÇALIK <i>et al.</i>, 1939; El-Geddawy <i>et al.</i>, 2012; Šarić <i>et al.</i>, 2016)</li> <li><i>Large scale:</i> Assumed the same as for the pilot scale</li> </ul>	P and L: (ÇALIK <i>et al.</i> , 1939; El-Geddawy <i>et al.</i> , 2012; Šarić <i>et al.</i> , 2016)
<b>Pre-treatment and media preparation</b>					

Steam (sterilization)	0.15	0.04	$\text{kg}_{\text{steam}}/\text{kg}_{\text{feedstock}}$	<p>Steam use for sterilizing the feedstock by steam.</p> <ul style="list-style-type: none"> <li><i>Pilot scale:</i> The steam consumed is assumed same as Harding <i>et al.</i> (2007) (converted from 1.06 kg/ <math>\text{kg}_{\text{PHA, recovered}}</math>) considering yield of raw PHA and recovered PHA). The electricity consumed to heat the stream is 0.1016 kWh/kg feedstock (as the Ecoinvent process “Steam, in chemical industry {RER}  market for steam, in chemical industry   Conseq, U”).</li> <li><i>Large scale:</i> The steam consumed is assumed same as in Kookos <i>et al.</i> (2019) (converted from 0.347 kg/ <math>\text{kg}_{\text{PHA, recovered}}</math>) considering yield of raw PHA and recovered PHA). The electricity consumed to heat the stream is 0.1016 kWh/kg feedstock (as the Ecoinvent process “Steam, in chemical industry {RER}  market for steam, in chemical industry   Conseq, U”).</li> </ul>	P: (Harding <i>et al.</i> , 2007) L: Kookos <i>et al.</i> (2019)
Ammonia (NH <sub>3</sub> )	0.27 (0.13 – 0.41)	0.27 (0.13 – 0.41)	$\text{kg}/\text{kg}_{\text{PHA, raw}}$	<p>Ammonia is added as source of nitrogen for fermenting bacteria.</p> <ul style="list-style-type: none"> <li><i>Pilot scale:</i> Nitrogen consumed is assumed to be the same as in the large scale facility.</li> <li><i>Large scale:</i> Minimum and maximum mass of ammonia added is based on Kookos <i>et al.</i>, (2019) and Pavan <i>et al.</i>, (2019), respectively.</li> </ul>	P: Assumed L: (Kookos <i>et al.</i> , 2019; Pavan <i>et al.</i> , 2019)
<b>Fermentation</b>					
Yield (raw PHA)	0.360	0.268 (0.170 – 0.360)	$\text{kg}_{\text{PHA, raw}}/\text{kg}_{\text{substrate}}$	<p>Mass of raw PHA produced per mass of substrate in feedstock. Raw PHA refers to the PHA product effluent fermentation that has not yet undergone a recovery and extraction process.</p> <ul style="list-style-type: none"> <li><i>Pilot scale:</i> The yield of raw PHA per mass of substrate is equal to the one reported in Harding <i>et al.</i>, (2007). The yield per mass of molasses feedstock is 0.176 considering a substrate content of 49% in molasses.</li> <li><i>Large scale:</i> The average, minimum and maximum yield is based on the yield of (Kookos <i>et al.</i>, 2019; Leong <i>et al.</i>, 2017; Pavan <i>et al.</i>, 2019). The yield per mass of molasses feedstock is 0.131 (0.083 – 0.176), considering a substrate content of 49% in molasses.</li> </ul>	P: (Harding <i>et al.</i> , 2007) L: (Kookos <i>et al.</i> , 2019; Leong <i>et al.</i> , 2017; Pavan <i>et al.</i> , 2019)
Electricity (agitation)	0.31	0.25	$\text{kWh}/\text{kg}_{\text{PHA, raw}}$	<p>During the fermentation process, electricity is needed to agitate the feedstock in the fermenter.</p> <ul style="list-style-type: none"> <li><i>Pilot scale:</i> Assumed equal to the electricity for agitation as of Harding <i>et al.</i> (2007) (converted from 1.36 MJ/<math>\text{kg}_{\text{PHA, recovered}}</math> considering the recovery yield of 0.81 <math>\text{kg}_{\text{PHA, recovered}}/\text{kg}_{\text{PHA, raw}}</math>).</li> <li><i>Large scale:</i> Electricity consumed for agitation is assumed equal to the one of Kookos <i>et al.</i> (2019).</li> </ul>	P: (Harding <i>et al.</i> , 2007) L: (Kookos <i>et al.</i> , 2019)
Electricity	0.12	0.5	$\text{kWh}/\text{kg}_{\text{PHA, raw}}$	During fermentation, electricity is needed for aeration, which is necessary to	P: (Harding <i>et al.</i> ,

(aeration)				<p>supply oxygen and to remove carbon dioxide from microbial cells suspended in the culture broth.</p> <ul style="list-style-type: none"> <li><i>Pilot scale:</i> Assumed similar to the electricity for aeration as of Harding et al. (2007) (converted from 0.512 MJ/kg<sub>PHA, recovered</sub> considering the recovery yield of 0.81 kg<sub>PHA, recovered</sub>/kg <sub>PHA, raw</sub>).</li> <li><i>Large scale:</i> Electricity consumed for aeration is assumed equal to the one of Kookos et al. (2019).</li> </ul>	2007) L: (Kookos et al., 2019)
Carbon emitted as CO <sub>2</sub>	0.37	0.37	kg <sub>carbon</sub> /kg <sub>carbon, feed stock</sub>	<p>Carbon emitted as CO<sub>2</sub> during fermentation as a portion of incoming carbon in feedstock.</p> <ul style="list-style-type: none"> <li><i>Pilot scale:</i> Calculated as for to large scale facility</li> <li><i>Large scale:</i> Mass of CO<sub>2</sub> emissions is calculated assuming that the same portion of carbon present in the feedstock is emitted as CO<sub>2</sub> as in Kookos et al., (2019) (0.884 kg CO<sub>2</sub>/kg sucrose). This is calculated based on the total CO<sub>2</sub> emissions (6.5 kg CO<sub>2</sub>/kg <sub>PHA, recovered</sub>), recovery yield (0.8 kg <sub>PHA, recovered</sub>/kg, and <sub>PHA</sub> yield (0.17 kg <sub>PHA, raw</sub>/kg sucrose). Combined with carbon content of sucrose (0.42kg C/kg sucrose, calculated considering sucrose's chemical structure), the amount of carbon emitted as CO<sub>2</sub> is calculated.</li> </ul> <p>Even though this parameter is equal for the pilot and large scale system, overall, more CO<sub>2</sub> is emitted in the large scale system, as this system has a higher amount of incoming carbon due to the lower yield (i.e., a higher consumption of feedstock).</p>	P and L: Calculated and assumed based on Kookos et al., (2019)
Wastewater	0.0006	0.0006	m <sup>3</sup> /kg <sub>feedstock</sub>	<p>Liquid waste from fermentation</p> <ul style="list-style-type: none"> <li><i>Pilot scale:</i> Volume of wastewater is calculated considering water content of feedstock and the part of the feedstock that is not turned into PHA-biomass is considered (calculated based on yield of raw PHA).</li> <li><i>Large scale:</i> Calculated as for the pilot scale facility.</li> </ul> <p>Even though this parameter is equal for the pilot and large scale system, overall, more wastewater is emitted in the large scale system, as this system has a lower yield hence a higher consumption of feedstock.</p>	P and L: Calculated
<b>PHA recovery and purification</b>					
Yield (recovered PHA)	0.81 (0.80 – 0.82)	0.81 (0.80 – 0.82)	kg <sub>PHA, recovered</sub> /kg <sub>PHA, raw</sub>	<p>The proportion of raw PHA recovered as PHA powder after the recovery and extraction process.</p> <ul style="list-style-type: none"> <li><i>Pilot scale:</i> Assumed same as large scale</li> <li><i>Large scale:</i> Minimum and maximum values from Leong et al., (2017) and Kookos et al., (2019), respectively.</li> </ul>	P and L: (Kookos et al., 2019; Leong et al., 2017)
Electricity	0.073	0.062	kWh/kg <sub>PHA, recovered</sub>	Electricity consumed by centrifuges.	P: (Harding et al.,

(centrifuges)				<ul style="list-style-type: none"> <li>• <i>Pilot scale</i>: Electricity consumption is assumed equal to as reported in Harding et al. (2007).</li> <li>• <i>Large scale</i>: Electricity consumption is assumed equal to as reported in Kookos et al. (2019).</li> </ul>	2007) L: (Kookos et al., 2019)
Electricity (agitation and mixing)	0.010	0.016	kWh/kg <sub>PHA, recovered</sub>	Electricity needed to agitate the fermented broth and mix it with water during the recovery process and electricity consumed by centrifuges. <ul style="list-style-type: none"> <li>• <i>Pilot scale</i>: Electricity consumption is assumed equal to as reported in Harding et al. (2007).</li> <li>• <i>Large scale</i>: Electricity consumption is assumed equal to as reported in Kookos et al. (2019).</li> </ul>	P: (Harding et al., 2007) L: (Kookos et al., 2019)
Electricity (spray dryer)	0.590	0.260	kWh/kg <sub>PHA, recovered</sub>	Electricity needed to for spray drying. <ul style="list-style-type: none"> <li>• <i>Pilot scale</i>: Electricity consumption is assumed equal to as reported in Harding et al. (2007).</li> <li>• <i>Large scale</i>: Electricity consumption is assumed equal to as reported in Kookos et al. (2019).</li> </ul>	P: (Harding et al., 2007) L: (Kookos et al., 2019)
Electricity (cell disruption)	0.502	Not relevant	kWh/kg <sub>PHA, recovered</sub>	Biomass cells are disrupted in a high pressure homogenizer at pilot scale. <ul style="list-style-type: none"> <li>• <i>Pilot scale</i>: Electricity consumption is assumed equal to as reported in Harding et al. (2007)</li> <li>• <i>Large scale</i>: No high pressure homogenizer is applied at large scale</li> </ul>	P: (Harding et al., 2007) L: not relevant
Tap water	65.2	8.81	kg/kg <sub>PHA, recovered</sub>	Process water used for blending and washing during extraction and purification <ul style="list-style-type: none"> <li>• <i>Pilot scale</i>: Water consumption is assumed equal to as reported in Harding et al. (2007).</li> <li>• <i>Large scale</i>: Water consumption is assumed equal to as reported in Leong et al., (2017).</li> </ul>	P and L: Leong <i>et al.</i> (2017)
Steam	3.819	0.603	kg/kg <sub>PHA, recovered</sub>	Steam fed to the spray drier. <ul style="list-style-type: none"> <li>• <i>Pilot scale</i>: Steam consumption is assumed equal to as reported in Harding et al. (2007).</li> <li>• <i>Large scale</i>: Electricity consumption is assumed equal to as reported in Kookos et al. (2019).</li> </ul>	P: (Harding et al., 2007) L: (Kookos et al., 2019)
Surfactant	0.034	0.535 (0.247-0.822)	kg/kg <sub>PHA, recovered</sub>	Surfactant added to lower the surface tension during PHA recovery. It is assumed that type of surfactant used is a non-ionic surfactant in both the pilot and large-scale model. <ul style="list-style-type: none"> <li>• <i>Pilot scale</i>: Amount of surfactant applied is assumed equal to as reported in Harding et al. (2007) (converted from 0.000033 m<sup>3</sup>/kg considering a density of 1.02 kg/L for Synperonic, which is the surfactant applied in Harding et al. (2007)).</li> <li>• <i>Large scale</i>: Surfactant consumption is assumed equal to minimum and maximum values Kookos et al., (2019) and Leong et al.,</li> </ul>	P: (Harding et al., 2007) L: (Kookos et al., 2019; Leong et al., 2017)

				(2017), respectively.	
NaOCl	Not relevant	0.19 (0.17 – 0.22)	kg/kg <sub>PHA, recovered</sub>	NaOCl added to extract PHA from biomass at large scale. <ul style="list-style-type: none"> <li>• <i>Pilot scale</i>: NaOCl is not applied in pilot scale system</li> <li>• <i>Large scale</i>: Minimum and maximum values from Leong et al., (2017) and Kookos et al., (2019), respectively.</li> </ul>	P: not relevant L: (Kookos et al., 2019; Leong et al., 2017)
H <sub>2</sub> O <sub>2</sub>	0.053	Not relevant	kg/kg <sub>PHA, recovered</sub>	Hydrogen peroxide (H <sub>2</sub> O <sub>2</sub> ) is added for purification at pilot scale. <ul style="list-style-type: none"> <li>• <i>Pilot scale</i>: The amount applied is assumed equal to as reported in Harding et al. (2007).</li> <li>• <i>Large scale</i>: Hydrogen peroxide is not applied in large scale system</li> </ul>	P: (Harding et al., 2007) L: not relevant
Enzyme	0.0024	Not relevant	kg/kg <sub>PHA, recovered</sub>	Enzyme applied during recovery and extraction at pilot scale. <ul style="list-style-type: none"> <li>• <i>Pilot scale</i>: It is assumed that enzyme (optimase) is applied during recovery and extraction at pilot scale as reported in Harding et al. (2007)</li> <li>• <i>Large scale</i>: Enzyme is not applied in large scale system</li> </ul>	P: (Harding et al., 2007) L: not relevant
Wastewater	65.2	8.81	kg/kg <sub>PHA, recovered</sub>	Wastewater from recovery and extraction. <ul style="list-style-type: none"> <li>• <i>Pilot scale</i>: Amount of wastewater is assumed equal to as reported in Harding et al. (2007). The major part of the wastewater is from washing reactors between batches.</li> <li>• <i>Large scale</i>: Amount of wastewater is assumed equal to Leong et al., (2017)</li> </ul>	P: (Harding et al., 2007) L: (Leong et al., 2017)
Waste	0.24	1.23	kg/kg <sub>PHA, recovered</sub>	Solid biowaste from recovery and extraction. <ul style="list-style-type: none"> <li>• <i>Pilot scale</i>: Amount of biowaste is assumed equal to as reported in Harding et al. (2007).</li> <li>• <i>Large scale</i>: Amount of biowaste is assumed equal to Leong et al., (2017)</li> </ul>	P: (Harding et al., 2007) L: (Leong et al., 2017)
<b>Equipment</b>					
Capacity (PHA output)	99	9000	t <sub>PHA, recovered</sub> /year	Capacity in mass of recovered PHA produced per year. <ul style="list-style-type: none"> <li>• <i>Pilot scale</i>: The capacity is calculated based on capacity of each batch (1 t<sub>PHA, recovered</sub>/batch), time of fermentation (80 h/batch) as of Harding et al. (2007) and assuming same yearly operating hours as at large scale (7920 h/year) (Leong et al., (2017).</li> <li>• <i>Large scale</i>: The capacity is assumed to be equal as for the PHA production plant of Leong et al., (2017) with time of fermentation of 54 hours (including turnaround time required for cleaning and recharging).</li> </ul>	P: Calculated L: (Leong et al., 2017)
Life time of equipment	20	20	Year	Life time of fermenter and other equipment is assumed the same for pilot and large scale	P: Assumed L: Assumed
Number of pumps	Not relevant	1	piece	Pump for pumping of feedstock into the reactor. <ul style="list-style-type: none"> <li>• <i>Pilot scale</i>: The feedstock is transported to the plant by truck.</li> </ul>	P: not relevant L: Assumed

				<p>Hence, pump is not relevant.</p> <ul style="list-style-type: none"> <li>• <i>Large scale:</i> It is assumed that one pump is used to pump the feedstock into the reactor. The material for the pump is assumed same as in the the Ecoinvent process “Pump station {RoW}  construction   Conseq, U” with a capacity of 644546 m<sup>3</sup> and a lifetime of 70 years.</li> </ul>	
Mass, steel	7025	111659	kg	<p>Mass of steel in the equipment applied during pre-treatment, fermentation, and recovery and extraction. It is assumed that the steel type is chromium steel.</p> <ul style="list-style-type: none"> <li>• <i>Pilot scale:</i> The mass is calculated based on the process set-up by Harding et al., (2007). See Table S3 for details. Considering a life time of the equipment of 20 years and yearly capacity, the mass of steel per mass of recovered PHA is 3.5E-03 kg/kg<sub>PHA, recovered</sub>.</li> <li>• <i>Large scale:</i> The mass is calculated based on the process set-up by Leong et al. (2017). See Table S4 for details. Considering a life time of the equipment of 20 years and yearly capacity, the mass of steel per mass of recovered PHA is 6.2E-04 kg/kg<sub>PHA, recovered</sub>.</li> </ul>	<p>P: Calculated based on Harding et al., (2007) L: Calculated based on Leong et al. (2017)</p>
Mass, plastic	54	811	kg	<p>Mass of plastic in the equipment applied during pre-treatment, fermentation, and recovery and extraction. It is assumed that the plastic type is polypropylene.</p> <ul style="list-style-type: none"> <li>• <i>Pilot scale:</i> The mass is calculated based on the process set-up by Harding et al., (2007). See Table S3 for details. Considering a life time of the equipment of 20 years and yearly capacity, the mass of plastic per mass of recovered PHA is 2.7E-05 kg/kg<sub>PHA, recovered</sub>.</li> <li>• <i>Large scale:</i> The mass is calculated based on the process set-up by Leong et al. (2017). See Table S4 for details Considering a life time of the equipment of 20 years and yearly capacity, the mass of plastic per mass of recovered PHA is 6.2E-04 kg/kg<sub>PHA, recovered</sub>.</li> </ul>	<p>P: Calculated based on Harding et al., (2007) L: Calculated based on Leong et al. (2017)</p>

**Table S5.** Bill of materials for equipment used during pre-treatment, fermentation, and recovery and extraction at pilot scale based on installations described in Harding et al., (2007). It is assumed that the steel type is chromium steel and plastic type is polypropylene.

Equipment	Mass, steel (kg)	Mass, plastic (kg)	Note
<b><i>Pre-treatment and fermentation</i></b>			
Heat sterilizer (pre-treatment)	218	1	The number of sterilizers (1) is assumed equal as in Harding et al., (2007). The weight is estimated by matching it to a pilot scale heat sterilizer from a commercial supplier with the volume of 0.55 m <sup>3</sup> and assuming a cylindrical shape for this equipment with a height of 2 m, a wall thickness of 0.005 m (Chandrashekar and Rao, 2010) and that it consists of 100% steel with a density of 7850 kg/m <sup>3</sup> . Moreover, additional parts are considered (e.g. motors, control panels etc.), by assuming that the additional parts add 33% to the total weight (as in (Alfalava, n.d.)). It is assumed that these additional parts consist of 98% steel and 2% plastic.
Fermenter reactor	1323	7	The volume (10 m <sup>3</sup> ) and number reactors (1) is assumed equal as in Harding et al., (2007). The weight is calculated assuming a cylindrical shape for this equipment with a height of 2 m, a wall thickness of 0.005 m and that it consists of 100% steel with a density of 7850 kg/m <sup>3</sup> . Moreover, additional parts are considered (e.g. motors, control panels etc.), by assuming that the additional parts add 33% to the total weight (as in (Alfalava, n.d.)). It is assumed that these additional parts consist of 98% steel and 2% plastic.
<b><i>Recovery and purification</i></b>			
High pressure homogenizer	218	1	The number homogenizer (1) is assumed equal as in Harding et al., (2007) and the weight is assumed same as the heat sterilizer.
Centrifuges	1147	23	The number of centrifuges (3) is assumed equal as in Harding et al., (2007). The weight per centrifuge is assumed to be equal to the small centrifuge from Flottweg, (n.d.) (390 kg/centrifuge) and assumed to consist of 100% steel and 2% plastic.
Reactor tanks	2645	13	The number of reactor tanks (2) is assumed equal as in Harding et al., (2007). The weight is assumed the same as the fermenter reactor.
Mixing tanks	1395	7	The number of reactor tanks (3) is assumed equal as in Harding et al., (2007). The volume of each tank is assumed to be half the volume of fermenter reactor (5 m <sup>3</sup> ). The weight is calculated assuming a cylindrical shape for this equipment with a height of 2 m, a wall thickness of 0.005 m and that it consists of 100% steel with a density of 7850 kg/m <sup>3</sup> . Moreover, additional parts are considered (e.g. motors, control panels etc.), by assuming that the additional parts add 33% to the total weight (as in (Alfalava, n.d.)). It is assumed that these additional parts consist of 98% steel and 2% plastic.
Spray dryer	78	2	The number of spray dryer (1) was assumed equal as in Harding et al., (2007). The weight is assumed to be equal the gross weight of the small spray dryer from commercial supplier (Yamato, 2017) (80kg/spray dryer) and assumed to consist of 98% steel and 2% plastic.

**Table S6.** Bill of materials for equipment used during pre-treatment, fermentation, and recovery and extraction at large scale based on installations described in Leong et al. (2017). It is assumed that the steel type is chromium steel and plastic type is polypropylene.

Equipment	Mass, steel (kg)	Mass, plastic (kg)	Notes
<b>Pre-treatment and fermentation</b>			
Blending tank (Tank 1 in Figure 2)	7163	36	The volume (76.6 m <sup>3</sup> ) and number tanks (1) is assumed equal as in Leong <i>et al.</i> (2017). The weight was calculated assuming a cylindrical shape for this equipment with a height of 5 m, a wall thickness of 0.007 m (Chandrashekhara and Rao, 2010) and that it consists of 100% steel with a density of 7850 kg/m <sup>3</sup> . Moreover, additional parts are considered (e.g. motors, control panels etc.), by assuming that the additional parts add 33% to the total weight (as in (Alfalava, n.d.)). It is assumed that these additional parts consist of 98% steel and 2% plastic.
Heat sterilizer (pre-treatment)	1814	9	The dimensions (diameter=0.8m and length=15.6 m) and number of sterilizers (1) is assumed equal as in Leong <i>et al.</i> (2017). The weight was calculated assuming a cylindrical shape for this equipment with a height of 5 m, a wall thickness of 0.007 m (Chandrashekhara and Rao, 2010) and that it consists of 100% steel with a density of 7850 kg/m <sup>3</sup> . Moreover, additional parts are considered (e.g. motors, control panels etc.), by assuming that the additional parts add 33% to the total weight (as in (Alfalava, n.d.)). It is assumed that these additional parts consist of 98% steel and 2% plastic.
Fermenter reactor	25928	131	The volume (102 m <sup>3</sup> ) and number reactors (3) is assumed equal as in Leong <i>et al.</i> (2017). The weight is calculated assuming a cylindrical shape for this equipment with a height of 5 m, a wall thickness of 0.007 m (Chandrashekhara and Rao, 2010) and that it consists of 100% steel with a density of 7850 kg/m <sup>3</sup> . Moreover, additional parts are considered (e.g. motors, control panels etc.), by assuming that the additional parts add 33% to the total weight (as in (Alfalava, n.d.)). It is assumed that these additional parts consist of 98% steel and 2% plastic.
Piping	12750	-	The length of the piping (300) is assumed and its weight was estimated by matching it to commercial pipes (The process piping, n.d.), assuming an inner diameter of 200 mm and a standard wall thickness (8.2 mm).
<b>Recovery and purification</b>			
Flat-bottom tank (Tank 2 in Figure 2)	9189	47	The volume (112 m <sup>3</sup> ) and number tanks (1) is assumed equal as in Leong et al. (2017). The weight is calculated assuming a cylindrical shape for this equipment with a height of 5 m, a wall thickness of 0.007 m (Chandrashekhara and Rao, 2010) and that it consists of 100% steel with a density of 7850 kg/m <sup>3</sup> . Moreover, additional parts were considered (e.g. motors, control panels etc.), by assuming that the additional parts add 33% to the total weight (as in (Alfalava, n.d.)). It is assumed that these additional parts consist of 98% steel and 2% plastic.
Disk-stack centrifuges (Centrifuge 1 in Figure 2)	12627	258	The number of centrifuges (6) is assumed equal as in Leong et al. (2017). The weight per centrifuge is assumed to be the average gross weight of industrial scale centrifuges from Flottweg, (n.d.) (2148 kg /centrifuge) and assumed to consist of 100% steel and 2% plastic.
Blending tank (Tank 3 in Figure 2)	16707	85	The volume (8.17 m <sup>3</sup> ) and number tanks (9) is assumed equal as in Leong et al. (2017). The weight is calculated by assuming a cylindrical shape for this equipment with a height of 5 m, a wall thickness of 0.007 m

			(Chandrashekhara and Rao, 2010) and that it consists of 100% steel with a density of 7850 kg/m <sup>3</sup> . Moreover, additional parts are considered (e.g. motors, control panels etc.), by assuming that the additional parts add 33% to the total weight (as in (Alfalava, n.d.)). It is assumed that these additional parts consist of 98% steel and 2% plastic.
Disk-stack centrifuge (Centrifuge 2 in Figure 2)	10523	215	The number of centrifuges (5) was assumed equal as in Leong et al. (2017). The weight per centrifuge is assumed to be the average gross weight of industrial scale centrifuges from Flottweg, (n.d.) (2148 kg /centrifuge) and assumed to consist of 100% steel and 2% plastic.
Disk-stack centrifuge (Centrifuge 3 in Figure 2)	4209	86	The number of centrifuges (2) was assumed equal as in Leong et al. (2017). The weight per centrifuge is assumed to be the average gross weight of industrial scale centrifuges from Flottweg, (n.d.) (2148 kg /centrifuge) and assumed to consist of 100% steel and 2% plastic.
Blending tank (Tank 4 in Figure 2)	6362	32	The volume (38.8 m <sup>3</sup> ) and number tanks (1) was assumed equal as in Leong et al. (2017). The weight is calculated by assuming a cylindrical shape for this equipment with a height of 5 m, a wall thickness of 0.007 m (Chandrashekhara and Rao, 2010) and that it consists of 100% steel with a density of 7850 kg/m <sup>3</sup> . Moreover, additional parts are considered (e.g. motors, control panels etc.), by assuming that the additional parts add 33% to the total weight (as in (Alfalava, n.d.)). It is assumed that these additional parts consist of 98% steel and 2% plastic.
Disk-stack centrifuge (Centrifuge 4 in Figure 2)	4209	86	The number of centrifuges (2) was assumed equal as in Leong et al. (2017). The weight per centrifuge is assumed to be the average gross weight of industrial scale centrifuges from Flottweg, (n.d.) (2148 kg /centrifuge) and assumed to consist of 100% steel and 2% plastic.
Spray dryer	176	4	The number of spray dryer (1) was assumed equal as in Leong et al. (2017). The weight is assumed to be equal the gross weight of industrial scale spray dryer from (Yamato Scientific, 2017) (180kg/spray dryer) and assumed to consist of 100% steel and 2% plastic.

**Table S7.** Overview of parameters and data sources for production on PHA biofilm, lamination and coating, printing, use and disposal of packing. Parameters are for large scale production, and assumed applicable at pilot scale.

Parameter	Large scale Average (min-max)	Unit	Note	Main data source
<b>Compounding and pelletizing</b>				
Pellets yield	0.826 (0.785 – 0.867)	kg powder/kg <sub>pellet</sub>	Mass of recovered PHA pellets converted from PHA powder (measured). Perturbation values are assumed 5% increase/decrease.	Assumed
Amount of additive	0.174 (0.154 – 0.170)	kg/kg <sub>pellets</sub>	Additives such as plasticizer, nucleating agents, stabilizers are needed to tune properties of the material (such as barrier and mechanical properties). The applied additives are selected considering preservation of the intrinsic biodegradability of PHA. It is assumed that the additive used is a plasticizer based on sulfonated melamine formaldehyde and the amount is assumed to be in a realistic range of values. Additives such as reinforcing fillers are added to biopolymers as a nucleating	Assumed

			agent to enhance the crystallization and as a thermal barrier, improving the thermal stability of the biopolymer (Bugnicourt et al., 2014). It is assumed that acrylic filler is used as filler in this study and the amount is assumed to be in a realistic range of values. Perturbation values as assumed 5% increase/decrease.	
Electricity for extrusion	4.27 (3.50 – 5.00)	kWh/kg <sub>pellets</sub>	Electricity used for corotating twin screw extruder to melt the compound and for cooling, drying, pelletizing, dehumidifying (assumed to be in a realistic range of values).	Assumed
Tap water	0.040 (0.038 – 0.042)	l/ kg <sub>pellets</sub>	Cooling water for the extrusion. The volume of water applied is assumed to be in realistic range of values.	Assumed
Number of extruders	1	piece	Material for equipment (one extruder) is assumed equal to the equipment in the Ecoinvent process for plastic sheet extrusion (“Extrusion, co-extrusion {FR}  of plastic sheets   Conseq, U”).	Assumed based on Ecoinvent
<b><i>PHA filmmaking</i></b>				
Yield of biofilm	0.925	kg <sub>biofilm</sub> /kg <sub>pellets</sub>	Mass of biofilm produced per mass of PHA pellet (measured by Tampere University of Technology (TUT), Finland).	Measured
Amount of biowaste	0.075	kg <sub>biofilm</sub> /kg <sub>pellets</sub>	Mass of biowaste generated during the production of PHA film calculated considering the biofilm yield (1 – biofilm yield).	Calculated
Electricity use	0.1	kWh/kg <sub>pellets</sub>	Electricity consumed for heating, melting, and pumping (measured by TUT).	Measured
Amount of auxiliaries and water	See Ecoinvent process	-	Auxiliaries (detergents and solvents) and water consumed for PHA filmmaking is assumed equal to what is used in the Ecoinvent process for plastic sheet extrusion (“Extrusion, co-extrusion {FR}  of plastic sheets   Conseq, U”).	Assumed based on Ecoinvent
Number of extruders	4	piece	The extrusion of biofilm is done at a plant with four extruders with different outputs with the possibility for (co)extrusion coating and lamination, casting, dispersion coating and various surface treatments (including corona, flame, plasma, UV, IR, LFS). Bill of material for each extruder is assumed equal to the material in the Ecoinvent process “Extrusion, co-extrusion {FR}  of plastic sheets   Conseq, U”.	Assumed based on Ecoinvent
<b><i>Ink (varnish and pigment)</i></b>				
Content of acrylic resin	0.224	kg/kg <sub>ink</sub>	Acrylic resin used as solvent for the varnish (measured by KAO Chimigraf).	Measured
Content of silicone defoamer	0.0056	kg/kg <sub>ink</sub>	Silicone used as defoamer (measured by KAO Chimigraf).	Measured
Content of wetting agent (ethoxylate alcohol)	0.012	kg/kg <sub>ink</sub>	Ethoxylate alcohol used as wetting agent in the ink mix (measured by KAO Chimigraf).	Measured
Content of biocide	0.0017	kg/kg <sub>ink</sub>	It is assumed that the biocide used is Benzimidazole-compound (BIT) (measured by KAO Chimigraf).	Measured
Content of wax (polyethylene)	0.003	kg/kg <sub>ink</sub>	Polyethylene applied as wax (measured by KAO Chimigraf).	Measured
Content of retardant	0.03	kg/kg <sub>ink</sub>	Glycerin used as solvent in the ink mix (measured by KAO Chimigraf).	Measured

accelerator solvent (glycerin)				
Content of water	0.5637	kg/kg <sub>ink</sub>	Water mixed in the ink (measured by KAO Chimigraf).	Measured
Content of pigment (carbon)	0.16	kg/kg <sub>ink</sub>	It is assumed that carbon is used as organic pigment (measured by KAO Chimigraf).	Measured
Use of electricity	0.11	kWh/kg <sub>ink</sub>	Electricity consumed to produce the ink (measured by KAO Chimigraf).	Measured
<b>PHA packaging production (PHA film functionalization and printing)</b>				
Weight of PHA layer	88	g/m <sup>2</sup> <sub>packaging</sub>	Weight of PHA biofilm measured by Icimendue. This corresponds to a thickness of 76.5 micro m when applying a density of 1.15 g/cm <sup>3</sup> (BioBarr, 2019).	Measured
Weight of PLA layer	24.8	g/m <sup>2</sup> <sub>packaging</sub>	Weight of the PLA layer laminated with the PHA biofilm (measured). This corresponds to a thickness of 20 micro m when applying a density of 1.24 g/cm <sup>3</sup> (Sousa et al., 2019).	Measured
Yield of PLA biofilm	0.925	kg <sub>biofilm</sub> /kg <sub>pellets</sub>	Mass of biofilm produced per mass of PLA pellet assumed equal to as for the PHA biofilm.	Assumed
Weight of Aluminum fiber coil	0.027	g/m <sup>2</sup> <sub>packaging</sub>	Weight of the aluminum consumed as surface treatment of the PHA biofilm (i.e. metallization). The treatment is based on deposition under vacuum of a thin aluminum layer on the biofilm. The weight is calculated based on aluminum layer thickness of 10 nm (measured by Icimendue) and a density of 2.710 g/cm <sup>3</sup> for aluminum. It is assumed that aluminum ingot is representative as aluminum fiber coil, as the majority of the energy consumed during production of both aluminum ingot and coil is for melting the aluminum. Hence, the production step from aluminum ingot to coil is not considered.	Measured and calculated
Weight of AlOx	0.039	g/m <sup>2</sup> <sub>packaging</sub>	Weight of AlOx layer as surface treatment of the PHA biofilm. As for the aluminum layer, the AlOx treatment is a based on the deposition under vacuum of a thin aluminum layer on the biofilm. In addition, in the case of AlOx treatment, oxygen is introduced in the vacuum chamber oxidizing the aluminum before deposition. The AlOx layer therefore appears transparent. The weight is calculated based on AlOx layer thickness of 10 nm (measured by Icimendue) and a density of 3.95 g/cm <sup>3</sup> for AlOx. Al <sub>2</sub> O <sub>3</sub> constitutes of 47 % O <sub>2</sub> and 53 % Al (weight based).	Measured and calculated
Amount of adhesive	2.2	g/m <sup>2</sup> <sub>packaging</sub>	Amount of adhesive applied to glue to PHA film with a PLA layer (only relevant in the scenarios where PLA is used for surface functionalization). Measured by Icimendue.	Measured
Amount of ink	19	cm <sup>3</sup> /m <sup>2</sup> <sub>packaging</sub>	Amount of ink printed on the packaging. Measured by Icimendue.	
Use of electricity, lamination and printing	0.208	kWh/kg <sub>packaging</sub>	Electricity consumed when laminating the PHA + PLA film layer and printing (only relevant in the scenarios where PLA is used for surface functionalization). Assumed to be the same as the electricity consumed for printing and laminating without corona treatment measured by Icimendue.	Measured and assumed
Use of electricity, surface treatment and printing	0.432	kWh/kg <sub>packaging</sub>	Electricity consumed to vaporize the aluminum coil and AlOx during metallization surface treatment and printing (relevant for scenario 7 and 8). Assumed to be the same as the electricity consumed for printing and laminating with corona treatment	Assumed based on measurements

			measured by Icimendue	
<b>Use</b>				
Transport	442	Km	Transport distance from the food manufacturer where the packaging is enwrapped the croissants (at Corsini biscotti, Via delle Cellane, 9, 58033 Castel del Piano GR, Italy) to where the croissant are sold for consumption (Milan). The transport distance is assumed the same in the scenario where Germany is the geographic location.	Calculated
<b>Packaging use and disposal</b>				
Rates for recycling, incineration and landfill	See Table S9	See Table S9	See Table S9	See Table S9
Waste treatment processes	See Table S7	See Table S7	Based on an existing Ecoinvent processes. See Table S6.	See Table S7

**Table S8.** Overview of parameters and data sources for packaging based on polypropylene, polyethylene and PLA

Parameter	Large scale Average (min-max)	Unit	Note	Main data source
Polypropylene, weight	29.6	$\text{g/m}^2_{\text{packaging}}$	Mass of polypropylene film with properties similar to the one for the PHA-based packaging film, which corresponds to a thickness of 31 micro m. Currently used by Corsini biscotti.	Measured by Corsini biscotti
Polyethylene, weight	29.6	$\text{g/m}^2_{\text{packaging}}$	Mass of polyethylene film with properties similar to the one for the PHA-based packaging film, which corresponds to a thickness of 31 micro m. Currently used by Corsini biscotti.	Measured by Corsini biscotti
PLA, weight	112.8 and 62	$\text{g/m}^2_{\text{packaging}}$	Mass of polypropylene film with properties similar to the one for the PHA-based packaging. Two scenarios for PLA weight were tested; 1) weight of PLA film was assumed to be equal to the weight of PHA + PLA in the PHA-based packaging film ( $112.8 \text{ g/m}^2$ ) corresponding to a thickness of 91 micro m (applying a density $1.24 \text{ g/cm}^3$ ) and 2) weight corresponds to 50 micro m thickness assumed by Icimendue.	Assumed
Amount of ink	19	$\text{cm}^3/\text{m}^2_{\text{packaging}}$	Amount of ink printed on the packaging. Assumed to be equal to the amount of ink applied for PHA packaging (Table S5).	Assumed
Electricity for printing	0.0208	$\text{kWh/kg}_{\text{packaging}}$	Electricity consumed for printing on the polypropylene, polyethylene and PLA packaging. Assumed to be 10% of the electricity consumed for printing and laminating as of the PHA packaging (Table S5).	Assumed

Transportation	442	km	Transport distance from manufacturer to the location where the product is sold, is assumed equal to the amount of ink applied for PHA packaging (Table S5).	Calculated
Rates for recycling, incineration and landfill and waste treatment processes	See <a href="#">Table S11</a>	See <a href="#">Table S11</a>	The waste management rates of PLA, PP and PHA packaging is assumed equal as for PHA packaging (Table S5). Landfill and incineration processes for PLA is modelled equal as to PHA. Landfill and incineration processes for PP and PE are modelled according to existing Ecoinvent processes (“plastic, mixture {CH}  treatment of, sanitary landfill   Conseq, U”, “Waste polyethylene {CH}  treatment of, municipal incineration with fly ash extraction   Conseq, U”, “Waste polypropylene {CH}  treatment of, municipal incineration with fly ash extraction   Conseq, U”), however, updating the substituted electricity and heat processes to processes representing Italy as geographical location.	See <a href="#">Table S11</a>

**Table S9.** Adaptation of existing Ecoinvent processes applied as background processes

Existing process	New process	Modifications
Electricity, high voltage {IT}  market for   Conseq, U	Electricity, high voltage {IT}  market for   Average mix, U_2018_EBV	Modified according to average Italian electricity grid mix considering electricity generation by source (2018) from IEA World Energy Balances 2019 and proportion of imported energy based on “Electricity, high voltage {IT}  market for   APOS, U”. See Table S8 for details. The electricity grid mix of countries from which Italy import more than 1% from was also updated (France and Switzerland). This update was done by using the APOS electricity process, representing the 2017 grid mix (e.g. “Electricity, high voltage {FR}  market for   APOS, U”), and substituting the individual electricity production processes with consequential versions (to handle multifunctionality with system expansion instead of allocation). See Table S8 for an overview of the resulting average electricity grid mix process.
Electricity, high voltage {DE}  market for   Conseq, U	Electricity, high voltage {DE}  market for   Average mix, U_2018_EBV	Modified according to average German electricity grid mix considering electricity generation by source (2018) from IEA World Energy Balances 2019 and proportion of imported energy based on “Electricity, high voltage {DE}  market for   APOS, U”. See Table S8 for details. The electricity grid mix of countries from which Germany import more than 1% from was also updated (France). This update was done by using the APOS electricity process, representing the 2017 grid mix (e.g. “Electricity, high voltage {FR}  market for   APOS, U”), and substituting the individual electricity production processes with consequential versions (to handle multifunctionality with system expansion instead of allocation).
Electricity, low voltage {IT}  market for   Conseq, U	Electricity, low voltage {IT}  market for   Average mix, U_2018_EBV	Links from the market for low voltage electricity were updated to the average mix for high voltage electricity through transformation processes and medium voltage (Electricity, low voltage {IT}  electricity voltage transformation from medium to low voltage   Average mix, U_2018_EBV, Electricity, medium voltage {IT}  market for   Average mix, U_2018_EBV, Electricity, medium voltage {IT}  electricity voltage transformation from high to medium voltage   Average mix U_2018_EBV).
Electricity, low voltage {DE}  market for   Conseq, U	Electricity, low voltage {DE}  market for   Average mix, U_2018_EBV	Links from the market for low voltage electricity were updated to the average mix for high voltage electricity through transformation processes and medium voltage (Electricity, low voltage {DE}  electricity voltage transformation from medium to low voltage   Average mix, U_2018_EBV, Electricity, medium voltage {DE}  market for   Average mix, U_2018_EBV, and Electricity, medium voltage {DE}  electricity voltage transformation from high to medium voltage   Average mix U_2018_EBV).
Electricity, high voltage {IT}  heat and power co-generation, biogas, gas engine   Conseq, U	Electricity, high voltage {IT or DE}  heat and power co-generation, biogas, gas engine   Conseq, U_EBV	Biogas input to the heat and power co-generation was updated from marginal biogas mix for the rest of the world region (“Biogas {RoW}  market for biogas   Conseq, U”) (100% biogas from manure) to average biogas mix, according to the APOS process (representing average biogas mix in the rest of the world region) (“Biogas {IT or DE}  market for biogas   Average mix, U”). The average mix consist of 33% biogas from manure, 30% from biowaste, 37% from sewage sludge and 0.31% from vegetable cooking oil by anaerobic digestion. APOS processes were substituted with Conseq, where applicable (for the biogas production from the waste materials, there is not consequential version). Furthermore, biogas from manure was updated from "Biogas {CH}  anaerobic digestion of manure   Conseq, U" to “Biogas {IT or DE}  anaerobic digestion of manure   Conseq, U” by updating the geography of the electricity consumed during the anaerobic digestion of manure and substituted when incinerating the digester sludge to Italy or Germany.
Biowaste {CH}  treatment of,	Biowaste {IT or DE}  treatment of,	It was assumed that metals are not present in the biowaste derived from PHA production. Emissions of metals (aluminium, arsenic, cadmium, chromium,

municipal incineration with fly ash extraction   Conseq, U	municipal incineration with fly ash extraction   Conseq, U_EBV	cobalt, copper, iron, lead, mercury, nickel, tin, zinc) to air and water were therefore removed. Waste treatment of “Spent activated carbon with mercury {GLO}  market for   Conseq, U” was removed. Heat and electricity for reuse in municipal waste incineration processes was updated to represent those for Italy or Germany.
Biowaste {CH}  treatment of biowaste, industrial composting   Conseq, U	Biowaste {IT or DE}  treatment of biowaste, industrial composting   Conseq, U_EBV	Electricity and waste treatments was updated to represent electricity grid mix of Italy or Germany.
Biowaste {CH}  treatment of biowaste by anaerobic digestion   Conseq, U	Biowaste {IT or DE}  treatment of biowaste by anaerobic digestion   Conseq, U_EBV	Electricity was updated to represent electricity grid mix of Italy Germany and tap water and wastewater treatment to Europe without Switzerland.
Waste plastic, mixture {CH}  treatment of, municipal incineration with fly ash extraction   Conseq, U	Bioplastic {IT or DE}  treatment of, municipal incineration with fly ash extraction   Conseq, U_EBV	It was assumed that metals are not present in the bioplastic packaging, except aluminum. Emissions of metals (aluminium, arsenic, cadmium, chromium, cobalt, copper, iron, lead, mercury, nickel, tin, zinc) to air and water were therefore removed. Waste treatment of "Spent activated carbon with mercury {GLO}  market for   Conseq, U" was removed. Geography of electricity and heat for reuse in municipal waste incineration processes was updated to Italy or Germany. Emission of fossil CO <sub>2</sub> was replaced by biogenic CO <sub>2</sub> and the mass of CO <sub>2</sub> emitted from incineration is calculated, considering the initial content of C in the packaging and assuming that 100% is emitted as CO <sub>2</sub> (Rossi et al., 2015). Hence, emissions of CH <sub>4</sub> were also removed.
Wastewater, average {Europe without Switzerland}  treatment of wastewater, average, capacity 1E9l/year   Conseq, U	Wastewater, average {Europe without Switzerland}  treatment of wastewater, average, capacity 1E9l/year   Conseq, U_EBV	Carbon-related emissions adapted to carbon content of PHA-fermentation effluent wastewater (parameterized considering yield of raw PHA and associated mass of feedstock). Metal-related emissions are removed, except aluminum, chromium, iron and titanium, as it is assumed that these are related to the input chemicals of the wastewater treatment.
Waste plastic, mixture {CH}  treatment of, sanitary landfill   Conseq, U	Bioplastic, mixture {IT or DE}  treatment of, sanitary landfill   Conseq, U_EBV	It was assumed that metals are not present in the bioplastic packaging, except aluminum. Emissions of metals (aluminium, arsenic, cadmium, chromium, cobalt, copper, iron, lead, mercury, nickel, tin, zinc) to air and water were therefore removed. Geography of heat and electricity consumption was updated. Emission of fossil CO <sub>2</sub> was replaced by biogenic CO <sub>2</sub> and the mass of CO <sub>2</sub> emitted from incineration is calculated considering the initial content of C in the packaging, a degradation fraction (i.e. how much is degraded after 100 years, depending on the degradation scenarios) and assuming that 29% is emitted as CO <sub>2</sub> and 71% as CH <sub>4</sub> (Rossi et al., 2015).
Extrusion, co-extrusion {FR}  of plastic sheets   Conseq, U	Extrusion, co-extrusion {IT or DE}  of PHA plastic sheets   Conseq, U_EBV	Paper for labelling sheets considered in the original process are not relevant and were removed. Geography of electricity was update to Italian or German average grid mix and mass as measured in project. Plastic waste was removed, as waste from the PHA bioplastic film extrusion is already considered (see Table S4). Material for equipment was removed as this was considered separately in the modelling.
Packaging film, low density polypropylene {RER}	Packaging film, low density polypropylene {IT}  production	Electricity applied for extrusion is updated to represent the electricity grid mix of Italy.

production   Conseq, U	Conseq, U_EBV	
Packaging film, low density polyethylene {RER}  production   Conseq, U	Packaging film, low density polyethylene {IT}  production   Conseq, U_EBV	Electricity applied for extrusion is updated to represent the electricity grid mix of Italy.

**Table S10.** Electricity generation by source in Italy and Germany, 2018 (IEA, 2018).

Source	Italy (GWh)	Italy (fraction)	Germany (GWh)	Germany (fraction)
Coal	30542	0.125	241479	0.421
Natural gas	129743	0.530	85043	0.148
Hydro	5925	0.024	1548	0.003
Wind	17492	0.071	111590	0.195
Biofuels	16858	0.069	45101	0.079
Waste	4806	0.020	13244	0.023
Solar	22653	0.093	46164	0.080
Oil	10762	0.044	5231	0.009
Nuclear	0	-	24170	0.042
Geothermal	6080	0.025	0	0

**Table S11.** Rates of recycling, incineration, and landfilling in Italy and Germany for the major materials in the PHA production plant

Waste	Landfilling (%)		Incineration (%)		Incineration with energy recovery		Recovery other than energy recovery (%)		Source
	Italy	Germany	Italy	Germany	Italy	Germany	Italy	Germany	
Metal waste, ferrous	0.05%	0.26%	0%	0%	0%	0.89%	99.95%	98.85%	Eurostat (2016 data)
Plastic waste	35%	0%	0%	0%	35%	62%	30%	38%	(Plastics Europe, 2019)
Biowaste	2.6%	0.7%	2.5%	1.9%	8.3%	44.9%	86.6% <sup>a</sup>	52.5% <sup>a</sup>	Eurostat (2017 data)
Plastic packaging waste	18.17%	0.21%	0%	0%	40.01%	50.06%	41.82% <sup>b</sup>	49.73% <sup>b</sup>	Eurostat (2017 data)

<sup>a</sup>In Italy, 52% of the recovered biowaste is treated by composting and 48% by anaerobic digestion (AD) (ENC, 2019) (2017 data), and in Germany, 36% by composting and 64% by AD (Bundesgütegemeinschaft, 2014) (2013 data).

<sup>b</sup>It is assumed that the bioplastic packaging waste that is “recovered other than energy recovery”, cannot be recycled, but it treated proportionally to the treatment of non-recovered plastic waste (50% and 0% landfilled and 50% and 100% incinerated with energy recovery for Italy and Germany respectively).

### S3. Details of life cycle impact assessment

Table S12. Overview of equations used for calculation of impact scores (*IS*) with the three-climate-related metrics.

	Impact score calculation	Symbols
GWP100 <sub>ILCD</sub> [kg CO <sub>2</sub> eq/functional unit]	$IS_{GWP100_{ILCD}} = \sum_i M_i \cdot GWP100_i - Credit_i$ $Credit_i = \sum_{T=2}^{100} m_i(T) \cdot T \cdot EQ_i$	<p><math>M_i</math> = total mass of gas <math>i</math> emitted in 100 years [kg]; <math>GWP100_i</math> = GWP100 of gas <math>i</math> [kg CO<sub>2</sub>eq · kg<sup>-1</sup>]<sup>a</sup>; <math>Credit_i</math> = ILCD credit for carbon storage; <math>m_i(T)</math> = mass of gas <math>i</math> emitted at (relative) time <math>T</math>; <math>EQ_i</math> = equivalency factor for gas <math>i</math> (0.01 and 0.34 [kg CO<sub>2</sub>eq · kg<sup>-1</sup> · yr<sup>-1</sup>] for CO<sub>2</sub> and CH<sub>4</sub> respectively)(EC-JRC, 2010)</p>
MCTP [ppt <sub>rc</sub> /functional unit]	$IS_{MCTP} = \sum_i \sum_{T_{emission}=2021}^{T_{tipping,j_{last}}} m_i(T_{emission}) \cdot MCTP_i(T_{emission})$	<p><math>T_{tipping,j_{last}}</math> = year of last tipping point; <math>m_i(T_{emission})</math> = mass of gas <math>i</math> emitted at year <math>T_{emission}</math> [kg]; <math>MCTP_i(T_{emission})</math> = MCTP for gas <math>i</math> and emission year <math>T_{emission}</math> [ppt<sub>rc</sub> · kg<sup>-1</sup>]</p>
GTP100 [kg CO <sub>2</sub> eq/functional unit]	$IS_{GTP100} = \sum_i M_i \cdot GTP100_i$	<p><math>M_i</math> = total mass of gas <math>i</math> emitted over 100 years [kg]; <math>GTP100_i</math> = GTP100 of gas <math>i</math> [kg CO<sub>2</sub>eq · kg<sup>-1</sup>]</p>

<sup>a</sup> GWP100 for biogenic and fossil methane used are 34 and 36 kg CO<sub>2</sub>eq/kg CH<sub>4</sub>, respectively from IPCC (2014)

## S4. Additional results

**Table S13.** Characterized impacts, expressed in category-specific units per functional unit for the pilot scale (scenario 1) and large scale PHA value chains (scenario 2). Results for all scenarios are documented in [Table SI4](#).

Impact category	Unit	Impact score	
		Scenario 1 (Pilot)	Scenario 2 (Large)
Climate change (GWP100)	kg CO2 eq	5.5E-02	5.2E-02
Global temperature change (GTP100)	kg CO2 eq	8.5E-02	1.0E-01
Multiple climate tipping (MCTP <sub>RCP6, 2020</sub> )	ppt <sub>re</sub>	1.0E-03	1.2E-03
Stratospheric ozone depletion	kg CFC11 eq	5.2E-07	6.8E-07
Ionizing radiation	kBq Co-60 eq	2.3E-04	2.7E-04
Ozone formation, Human health	kg NOx eq	1.5E-04	2.0E-04
Fine particulate matter formation	kg PM2.5 eq	6.6E-05	8.9E-05
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.6E-04	2.1E-04
Terrestrial acidification	kg SO2 eq	2.1E-04	2.6E-04
Freshwater eutrophication	kg P eq	5.0E-06	4.4E-06
Marine eutrophication	kg N eq	1.1E-04	1.6E-04
Terrestrial ecotoxicity	kg 1,4-DCB	2.9E-01	3.7E-01
Freshwater ecotoxicity	kg 1,4-DCB	1.7E-04	4.0E-04
Marine ecotoxicity	kg 1,4-DCB	3.1E-04	4.1E-04
Human carcinogenic toxicity	kg 1,4-DCB	4.6E-04	5.3E-04
Human non-carcinogenic toxicity	kg 1,4-DCB	2.1E-02	2.8E-02
Land use	m <sup>2</sup> a crop eq	7.7E-02	1.1E-01
Mineral resource scarcity	kg Cu eq	3.3E-04	4.5E-04
Fossil resource scarcity	kg oil eq	1.8E-02	2.2E-02
Water consumption	m <sup>3</sup>	7.4E-03	1.0E-02

**Table S14.** Characterized impact scores in category-specific units excluding long-term emissions for sensitivity scenarios 3-53

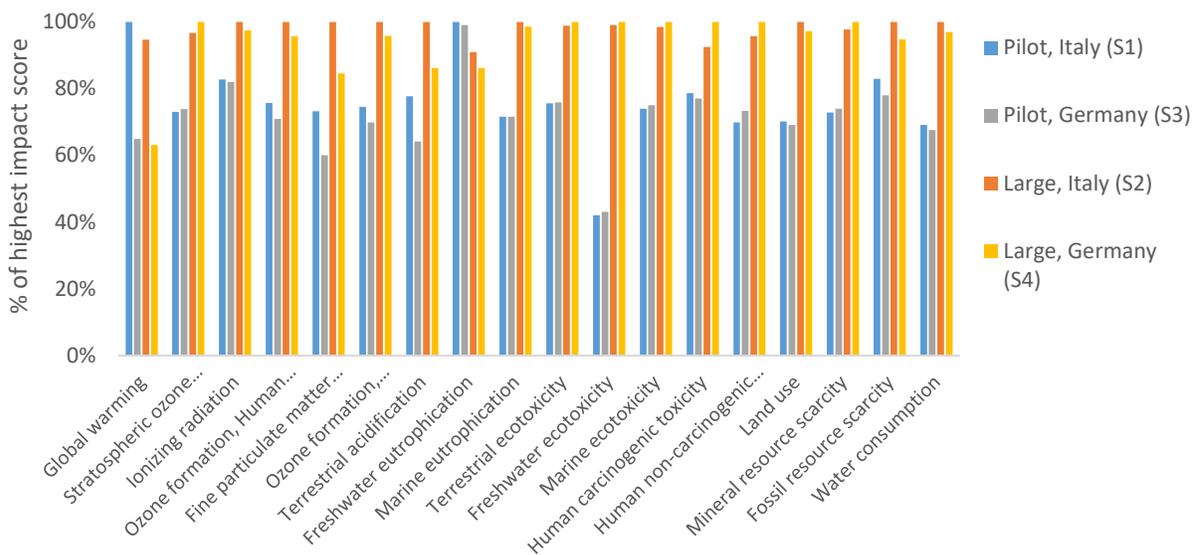
	Unit	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14
Climate change	kg CO2 eq	3.6E-02	3.5E-02	4.7E-02	3.1E-02	4.9E-02	4.9E-02	4.4E-02	2.5E-02	5.9E-03	6.4E-03	5.2E-02	5.2E-02
Stratospheric ozone depletion	kg CFC11 eq	5.3E-07	7.1E-07	7.4E-07	7.7E-07	6.5E-07	6.5E-07	1.3E-07	7.3E-08	2.2E-09	2.4E-09	1.1E-06	8.1E-07
Ionizing radiation	kBq Co-60 eq	2.2E-04	2.7E-04	2.3E-04	2.3E-04	2.8E-04	2.8E-04	-4.6E-05	-2.6E-05	7.0E-06	1.2E-05	3.2E-04	2.9E-04
Ozone formation, Human health	kg NOx eq	1.4E-04	1.9E-04	2.2E-04	2.2E-04	1.9E-04	1.9E-04	5.0E-05	2.8E-05	5.3E-06	7.0E-06	2.7E-04	2.2E-04
Fine particulate matter formation	kg PM2.5 eq	5.4E-05	7.6E-05	9.9E-05	8.6E-05	8.6E-05	8.6E-05	1.7E-05	9.8E-06	1.5E-06	3.0E-06	1.2E-04	9.8E-05
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.5E-04	2.0E-04	2.3E-04	2.3E-04	1.9E-04	1.9E-04	5.3E-05	3.0E-05	6.1E-06	8.4E-06	2.8E-04	2.3E-04
Terrestrial acidification	kg SO2 eq	1.7E-04	2.3E-04	2.9E-04	2.5E-04	2.6E-04	2.6E-04	4.4E-05	2.6E-05	2.5E-06	1.3E-06	3.7E-04	3.0E-04
Freshwater eutrophication	kg P eq	4.9E-06	4.3E-06	-1.6E-05	-1.6E-05	4.0E-06	4.0E-06	5.9E-07	-1.9E-07	-1.4E-06	-1.4E-06	8.6E-06	5.8E-06
Marine eutrophication	kg N eq	1.1E-04	1.6E-04	1.1E-05	1.0E-05	1.6E-04	1.6E-04	1.1E-05	6.1E-06	7.8E-07	7.9E-07	2.4E-04	1.9E-04
Terrestrial ecotoxicity	kg 1,4-DCB	2.9E-01	3.8E-01	4.9E-01	5.0E-01	3.5E-01	3.5E-01	8.9E-02	5.2E-02	2.4E-02	2.7E-02	4.9E-01	4.1E-01
Freshwater ecotoxicity	kg 1,4-DCB	1.7E-04	4.1E-04	4.9E-04	5.0E-04	3.8E-04	3.8E-04	9.9E-05	5.5E-05	3.4E-06	4.1E-06	4.8E-04	4.3E-04
Marine ecotoxicity	kg 1,4-DCB	3.2E-04	4.2E-04	4.4E-04	4.5E-04	3.9E-04	3.9E-04	1.1E-04	6.3E-05	1.8E-05	2.1E-05	5.5E-04	4.6E-04
Human carcinogenic toxicity	kg 1,4-DCB	4.5E-04	5.8E-04	6.3E-04	6.8E-04	5.1E-04	5.1E-04	1.1E-04	6.8E-05	2.6E-05	2.6E-05	6.7E-04	5.8E-04
Human non-carcinogenic toxicity	kg 1,4-DCB	2.2E-02	3.0E-02	3.8E-02	4.0E-02	2.7E-02	2.7E-02	2.8E-03	1.7E-03	2.5E-04	2.2E-04	3.9E-02	3.2E-02
Land use	m2a crop eq	7.6E-02	1.1E-01	-4.0E-02	-4.1E-02	1.1E-01	1.1E-01	1.9E-03	1.2E-03	-1.4E-04	-2.8E-04	1.7E-01	1.3E-01
Mineral resource scarcity	kg Cu eq	3.4E-04	4.6E-04	7.6E-04	7.7E-04	4.3E-04	4.3E-04	9.1E-05	5.2E-05	1.7E-05	1.7E-05	6.1E-04	5.0E-04
Fossil resource scarcity	kg oil eq	1.7E-02	2.1E-02	2.6E-02	2.5E-02	2.0E-02	2.0E-02	9.8E-03	5.6E-03	3.2E-03	3.2E-03	2.6E-02	2.3E-02
Water consumption	m3	7.2E-03	1.0E-02	5.1E-03	4.9E-03	1.0E-02	1.0E-02	7.7E-04	4.3E-04	-1.1E-05	-8.5E-06	1.6E-02	1.2E-02
GTP100	kg CO2 eq	7.7E-02	9.5E-02	1.3E-01	1.2E-01	9.8E-02	9.8E-02	3.7E-02	2.1E-02	4.5E-03	4.7E-03	1.4E-01	1.2E-01
MCTPs	ppt	7.4E-04	9.5E-04	1.1E-03	8.9E-04	1.2E-03	1.2E-03	5.2E-04	3.0E-04	4.7E-05	4.8E-05	1.6E-03	1.3E-03

		S15	S16	S17	S18	S19	S20	S21	S22	S23	S24	S25	S26
Climate change	kg CO2 eq	5.3E-02	5.3E-02	5.3E-02	5.3E-02	1.7E-02	1.7E-02	1.7E-02	1.7E-02	1.7E-02	1.7E-02	1.7E-02	2.1E-02
Stratospheric ozone depletion	kg CFC11 eq	6.0E-07	5.2E-07	4.4E-07	3.9E-07	2.3E-07	1.8E-07	1.6E-07	1.4E-07	1.2E-07	1.1E-07	9.6E-08	3.0E-07
Ionizing radiation	kBq Co-60 eq	2.6E-04	2.5E-04	2.4E-04	2.3E-04	6.1E-05	5.4E-05	5.1E-05	4.9E-05	4.6E-05	4.4E-05	4.3E-05	7.9E-05
Ozone formation, Human health	kg NOx eq	1.8E-04	1.7E-04	1.5E-04	1.4E-04	6.3E-05	5.3E-05	4.8E-05	4.5E-05	4.2E-05	3.9E-05	3.6E-05	8.0E-05
Fine particulate matter formation	kg PM2.5 eq	8.4E-05	7.8E-05	7.3E-05	6.9E-05	2.7E-05	2.3E-05	2.1E-05	2.0E-05	1.9E-05	1.8E-05	1.7E-05	3.4E-05
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.9E-04	1.7E-04	1.6E-04	1.5E-04	6.6E-05	5.6E-05	5.1E-05	4.7E-05	4.4E-05	4.1E-05	3.9E-05	8.4E-05
Terrestrial acidification	kg SO2 eq	2.5E-04	2.2E-04	2.0E-04	1.9E-04	8.2E-05	6.9E-05	6.2E-05	5.8E-05	5.3E-05	4.9E-05	4.6E-05	1.0E-04
Freshwater eutrophication	kg P eq	3.6E-06	2.6E-06	1.8E-06	1.2E-06	1.0E-06	4.8E-07	1.9E-07	1.9E-08	-1.7E-07	-3.4E-07	-4.7E-07	1.7E-06
Marine eutrophication	kg N eq	1.4E-04	1.2E-04	1.0E-04	9.2E-05	5.1E-05	3.9E-05	3.4E-05	3.0E-05	2.6E-05	2.3E-05	2.0E-05	6.5E-05
Terrestrial ecotoxicity	kg 1,4-DCB	3.5E-01	3.2E-01	3.0E-01	2.8E-01	1.2E-01	1.0E-01	9.2E-02	8.7E-02	8.2E-02	7.7E-02	7.4E-02	1.5E-01
Freshwater ecotoxicity	kg 1,4-DCB	3.8E-04	3.6E-04	3.5E-04	3.3E-04	1.1E-04	1.0E-04	9.4E-05	9.0E-05	8.7E-05	8.3E-05	8.1E-05	1.4E-04
Marine ecotoxicity	kg 1,4-DCB	3.9E-04	3.6E-04	3.3E-04	3.1E-04	1.3E-04	1.1E-04	1.0E-04	9.5E-05	8.9E-05	8.4E-05	8.0E-05	1.6E-04
Human carcinogenic toxicity	kg 1,4-DCB	5.1E-04	4.8E-04	4.5E-04	4.4E-04	1.6E-04	1.4E-04	1.3E-04	1.3E-04	1.2E-04	1.2E-04	1.1E-04	2.0E-04
Human non-carcinogenic toxicity	kg 1,4-DCB	2.6E-02	2.3E-02	2.1E-02	1.9E-02	8.5E-03	7.0E-03	6.3E-03	5.8E-03	5.3E-03	4.8E-03	4.5E-03	1.1E-02
Land use	m2a crop eq	9.6E-02	8.3E-02	7.0E-02	6.1E-02	3.5E-02	2.7E-02	2.2E-02	2.0E-02	1.7E-02	1.5E-02	1.3E-02	4.5E-02
Mineral resource scarcity	kg Cu eq	4.1E-04	3.8E-04	3.4E-04	3.2E-04	1.4E-04	1.2E-04	1.0E-04	9.8E-05	9.0E-05	8.4E-05	7.9E-05	1.8E-04
Fossil resource scarcity	kg oil eq	2.1E-02	2.0E-02	2.0E-02	1.9E-02	6.9E-03	6.4E-03	6.1E-03	6.0E-03	5.8E-03	5.7E-03	5.6E-03	8.7E-03
Water consumption	m3	9.4E-03	8.1E-03	7.0E-03	6.1E-03	3.4E-03	2.6E-03	2.2E-03	2.0E-03	1.8E-03	1.5E-03	1.4E-03	4.3E-03
GTP100	kg CO2 eq	9.5E-02	8.7E-02	8.0E-02	7.4E-02	3.4E-02	2.9E-02	2.6E-02	2.5E-02	2.3E-02	2.2E-02	2.0E-02	4.3E-02
MCTPs	ppt	1.1E-03	1.0E-03	9.7E-04	9.1E-04	3.9E-04	3.4E-04	3.2E-04	3.0E-04	2.8E-04	2.7E-04	2.6E-04	7.2E-05

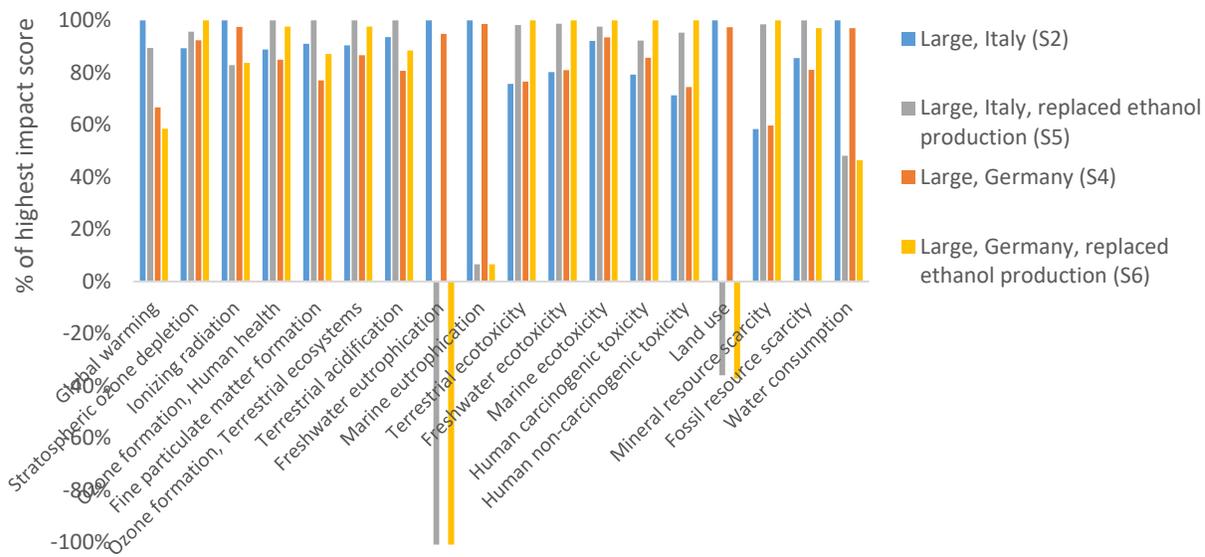
		S27	S28	S29	S30	S31	S32	S33	S34	S35	S36	S37	S38
Climate change	kg CO2 eq	2.1E-02	2.1E-02	2.1E-02	2.1E-02	2.1E-02	2.1E-02	3.2E-02	3.2E-02	3.2E-02	3.2E-02	3.2E-02	3.2E-02
Stratospheric ozone depletion	kg CFC11 eq	2.3E-07	2.0E-07	1.8E-07	1.6E-07	1.4E-07	1.2E-07	5.7E-07	4.4E-07	3.8E-07	3.3E-07	2.9E-07	2.5E-07
Ionizing radiation	kBq Co-60 eq	7.0E-05	6.6E-05	6.2E-05	5.9E-05	5.7E-05	5.5E-05	1.7E-04	1.5E-04	1.4E-04	1.3E-04	1.3E-04	1.2E-04
Ozone formation, Human health	kg NOx eq	6.8E-05	6.2E-05	5.7E-05	5.3E-05	4.9E-05	4.6E-05	1.5E-04	1.2E-04	1.1E-04	1.0E-04	9.3E-05	8.5E-05
Fine particulate matter formation	kg PM2.5 eq	2.9E-05	2.7E-05	2.6E-05	2.4E-05	2.3E-05	2.2E-05	6.3E-05	5.4E-05	4.9E-05	4.6E-05	4.3E-05	4.0E-05
Ozone formation, Terrestrial ecosystems	kg NOx eq	7.1E-05	6.5E-05	6.0E-05	5.6E-05	5.2E-05	4.9E-05	1.5E-04	1.3E-04	1.2E-04	1.1E-04	9.8E-05	9.0E-05
Terrestrial acidification	kg SO2 eq	8.8E-05	7.9E-05	7.4E-05	6.8E-05	6.2E-05	5.8E-05	2.0E-04	1.6E-04	1.5E-04	1.3E-04	1.2E-04	1.1E-04
Freshwater eutrophication	kg P eq	9.5E-07	6.1E-07	3.6E-07	1.2E-07	-1.0E-07	-2.7E-07	4.1E-06	2.7E-06	2.0E-06	1.5E-06	1.0E-06	5.7E-07
Marine eutrophication	kg N eq	5.1E-05	4.4E-05	3.9E-05	3.4E-05	3.0E-05	2.6E-05	1.3E-04	9.9E-05	8.5E-05	7.5E-05	6.5E-05	5.6E-05
Terrestrial ecotoxicity	kg 1,4-DCB	1.3E-01	1.2E-01	1.1E-01	1.0E-01	9.8E-02	9.3E-02	2.7E-01	2.3E-01	2.1E-01	2.0E-01	1.8E-01	1.7E-01
Freshwater ecotoxicity	kg 1,4-DCB	1.3E-04	1.2E-04	1.2E-04	1.1E-04	1.1E-04	1.0E-04	2.6E-04	2.3E-04	2.2E-04	2.1E-04	2.0E-04	1.9E-04
Marine ecotoxicity	kg 1,4-DCB	1.4E-04	1.3E-04	1.2E-04	1.1E-04	1.1E-04	1.0E-04	3.0E-04	2.5E-04	2.3E-04	2.2E-04	2.0E-04	1.9E-04
Human carcinogenic toxicity	kg 1,4-DCB	1.8E-04	1.7E-04	1.6E-04	1.5E-04	1.5E-04	1.4E-04	3.7E-04	3.2E-04	3.0E-04	2.8E-04	2.7E-04	2.6E-04
Human non-carcinogenic toxicity	kg 1,4-DCB	9.0E-03	8.1E-03	7.4E-03	6.7E-03	6.2E-03	5.7E-03	2.1E-02	1.7E-02	1.5E-02	1.4E-02	1.3E-02	1.1E-02
Land use	m2a crop eq	3.4E-02	2.9E-02	2.6E-02	2.2E-02	1.9E-02	1.6E-02	8.9E-02	6.8E-02	5.8E-02	5.1E-02	4.4E-02	3.7E-02
Mineral resource scarcity	kg Cu eq	1.5E-04	1.3E-04	1.2E-04	1.2E-04	1.1E-04	1.0E-04	3.3E-04	2.7E-04	2.5E-04	2.3E-04	2.1E-04	1.9E-04
Fossil resource scarcity	kg oil eq	8.1E-03	7.8E-03	7.6E-03	7.3E-03	7.1E-03	7.0E-03	1.5E-02	1.3E-02	1.3E-02	1.2E-02	1.2E-02	1.2E-02
Water consumption	m3	3.4E-03	2.9E-03	2.6E-03	2.3E-03	2.0E-03	1.7E-03	8.5E-03	6.6E-03	5.6E-03	5.0E-03	4.3E-03	3.7E-03
GTP100	kg CO2 eq	3.7E-02	3.4E-02	3.1E-02	2.9E-02	2.7E-02	2.6E-02	7.7E-02	6.5E-02	5.9E-02	5.4E-02	5.0E-02	4.6E-02
MCTPs	ppt	5.9E-05	4.1E-04	3.8E-04	3.6E-04	3.4E-04	3.3E-04	8.8E-04	7.5E-04	6.9E-04	6.5E-04	6.0E-04	5.6E-04

		S39	S40	S41	S42	S43	S44	S45	S46	S47	S48	S49	S50
Climate change	kg CO2 eq	3.2E-02	4.3E-02	4.3E-02	4.3E-02	4.3E-02	4.3E-02	4.4E-02	4.4E-02	6.5E-02	6.5E-02	6.5E-02	6.6E-02
Stratospheric ozone depletion	kg CFC11 eq	2.2E-07	8.3E-07	6.4E-07	5.5E-07	4.8E-07	4.2E-07	3.6E-07	3.1E-07	1.4E-06	1.0E-06	8.9E-07	7.8E-07
Ionizing radiation	kBq Co-60 eq	1.2E-04	2.5E-04	2.3E-04	2.1E-04	2.0E-04	1.9E-04	1.9E-04	1.8E-04	4.3E-04	3.8E-04	3.6E-04	3.4E-04
Ozone formation, Human health	kg NOx eq	7.9E-05	2.1E-04	1.8E-04	1.6E-04	1.5E-04	1.3E-04	1.2E-04	1.1E-04	3.5E-04	2.9E-04	2.6E-04	2.3E-04
Fine particulate matter formation	kg PM2.5 eq	3.8E-05	9.2E-05	7.8E-05	7.2E-05	6.7E-05	6.2E-05	5.8E-05	5.5E-05	1.5E-04	1.3E-04	1.2E-04	1.1E-04
Ozone formation, Terrestrial ecosystems	kg NOx eq	8.4E-05	2.2E-04	1.8E-04	1.7E-04	1.5E-04	1.4E-04	1.3E-04	1.2E-04	3.6E-04	3.0E-04	2.7E-04	2.5E-04
Terrestrial acidification	kg SO2 eq	1.0E-04	2.9E-04	2.4E-04	2.1E-04	2.0E-04	1.8E-04	1.6E-04	1.5E-04	4.7E-04	3.9E-04	3.5E-04	3.2E-04
Freshwater eutrophication	kg P eq	2.3E-07	6.6E-06	4.4E-06	3.4E-06	2.6E-06	1.9E-06	1.2E-06	7.4E-07	1.1E-05	7.9E-06	6.2E-06	4.9E-06
Marine eutrophication	kg N eq	5.0E-05	1.9E-04	1.5E-04	1.3E-04	1.1E-04	9.6E-05	8.3E-05	7.3E-05	3.1E-04	2.4E-04	2.1E-04	1.8E-04
Terrestrial ecotoxicity	kg 1,4-DCB	1.6E-01	3.9E-01	3.3E-01	3.0E-01	2.8E-01	2.6E-01	2.4E-01	2.3E-01	6.3E-01	5.3E-01	4.8E-01	4.5E-01
Freshwater ecotoxicity	kg 1,4-DCB	1.9E-04	3.8E-04	3.4E-04	3.2E-04	3.0E-04	2.9E-04	2.8E-04	2.7E-04	6.2E-04	5.5E-04	5.2E-04	4.9E-04
Marine ecotoxicity	kg 1,4-DCB	1.8E-04	4.3E-04	3.7E-04	3.3E-04	3.1E-04	2.9E-04	2.6E-04	2.5E-04	7.0E-04	5.9E-04	5.4E-04	5.0E-04
Human carcinogenic toxicity	kg 1,4-DCB	2.4E-04	5.3E-04	4.6E-04	4.3E-04	4.1E-04	3.9E-04	3.6E-04	3.5E-04	8.6E-04	7.5E-04	6.9E-04	6.6E-04
Human non-carcinogenic toxicity	kg 1,4-DCB	1.1E-02	3.1E-02	2.5E-02	2.2E-02	2.0E-02	1.8E-02	1.7E-02	1.5E-02	5.1E-02	4.1E-02	3.7E-02	3.3E-02
Land use	m2a crop eq	3.2E-02	1.3E-01	1.0E-01	8.6E-02	7.5E-02	6.5E-02	5.5E-02	4.8E-02	2.2E-01	1.7E-01	1.4E-01	1.3E-01
Mineral resource scarcity	kg Cu eq	1.8E-04	4.8E-04	4.0E-04	3.6E-04	3.3E-04	3.0E-04	2.7E-04	2.5E-04	7.9E-04	6.5E-04	5.8E-04	5.3E-04
Fossil resource scarcity	kg oil eq	1.1E-02	2.1E-02	1.9E-02	1.8E-02	1.7E-02	1.7E-02	1.6E-02	1.6E-02	3.3E-02	3.0E-02	2.8E-02	2.7E-02
Water consumption	m3	3.3E-03	1.3E-02	9.7E-03	8.4E-03	7.4E-03	6.4E-03	5.5E-03	4.9E-03	2.1E-02	1.6E-02	1.4E-02	1.2E-02
GTP100	kg CO2 eq	4.3E-02	1.1E-01	9.2E-02	8.3E-02	7.7E-02	7.0E-02	6.4E-02	6.0E-02	1.8E-01	1.5E-01	1.3E-01	1.2E-01
MCTPs	ppt	5.3E-04	1.3E-03	1.1E-03	9.7E-04	9.1E-04	8.4E-04	7.8E-04	7.4E-04	2.0E-03	1.7E-03	1.5E-03	1.4E-03

		S51	S52	S53
Climate change	kg CO2 eq	6.6E-02	6.6E-02	6.6E-02
Stratospheric ozone depletion	kg CFC11 eq	6.7E-07	5.7E-07	5.0E-07
Ionizing radiation	kBq Co-60 eq	3.3E-04	3.2E-04	3.1E-04
Ozone formation, Human health	kg NOx eq	2.1E-04	1.9E-04	1.8E-04
Fine particulate matter formation	kg PM2.5 eq	1.0E-04	9.4E-05	8.9E-05
Ozone formation, Terrestrial ecosystems	kg NOx eq	2.2E-04	2.0E-04	1.9E-04
Terrestrial acidification	kg SO2 eq	2.9E-04	2.6E-04	2.4E-04
Freshwater eutrophication	kg P eq	3.7E-06	2.6E-06	1.7E-06
Marine eutrophication	kg N eq	1.6E-04	1.4E-04	1.2E-04
Terrestrial ecotoxicity	kg 1,4-DCB	4.2E-01	3.8E-01	3.6E-01
Freshwater ecotoxicity	kg 1,4-DCB	4.7E-04	4.5E-04	4.3E-04
Marine ecotoxicity	kg 1,4-DCB	4.6E-04	4.2E-04	4.0E-04
Human carcinogenic toxicity	kg 1,4-DCB	6.2E-04	5.8E-04	5.6E-04
Human non-carcinogenic toxicity	kg 1,4-DCB	3.0E-02	2.7E-02	2.5E-02
Land use	m2a crop eq	1.1E-01	9.2E-02	7.9E-02
Mineral resource scarcity	kg Cu eq	4.8E-04	4.4E-04	4.1E-04
Fossil resource scarcity	kg oil eq	2.6E-02	2.5E-02	2.4E-02
Water consumption	m3	1.1E-02	9.1E-03	8.0E-03
GTP100	kg CO2 eq	1.1E-01	1.0E-01	9.4E-02
MCTPs	ppt	1.3E-03	1.2E-03	1.2E-03



**Figure S2.** Comparison of impact scores when testing the influence of geographic location at pilot and large scale (S1, S2, S3 and S4). The impact scores are normalized to the highest score in each impact category.



**Figure S3.** Comparison of impact scores when testing the influence of avoided treatment of molasses waste at large scale in Italy and Germany (S2, S4, S5 and S6). Impact scores are normalized to the highest score in each impact category. Bars for freshwater eutrophication for S5 and S6 are cut off to fit the figure (their values are -358 and -359%, respectively)

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