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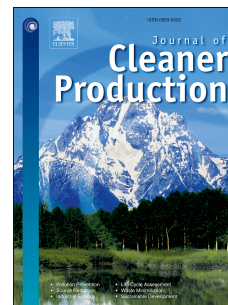
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3 **The impact of palm oil feedstock within the LCA of a bio-sourced cosmetic** 4 **cream**

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13 Keywords: Life cycle assessment, Cosmetic, Palm oil, Peat soil, Deforestation, Land Use

14 Abstract

15 We performed a cradle-to-grave life cycle assessment (LCA) of a bio-based cosmetic cream
16 containing Refined Palm Kernel Oil (RPKO). The objective was to investigate the importance of the
17 RPKO production within the environmental impact of the cosmetic cream. We assumed a baseline
18 scenario with best oil palm agricultural practices in Malaysia, and then tested different parameters,
19 i.e. deforestation, peat soil drainage and improved effluent treatment, in order to check their
20 influences.

21 In the baseline scenario, transport of the cosmetic cream was the main contributing process (largest
22 contribution for 11 out of 15 impact indicators). Contribution of the packaging of the cosmetic cream
23 was also significant (largest for 2 out of 15). RPKO had a low impact contribution in the baseline
24 scenario, albeit a much more critical one in the alternative scenarios. Deforestation and peat soil
25 drainage (i.e. transformation and occupation) influenced two environmental indicators: Climate
26 Change and Land Use. On Climate change indicator, deforestation caused an increase of about 9% of

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27 the cosmetic cream impacts and peat soil occupation an increase of 16%. On Land Use indicator,
28 deforestation caused an increase of 3%, peat soil transformation and occupation caused increases of
29 938% and 41%, respectively. Methane capture from palm oil mill effluent treatment and conversion
30 to electricity represented a low decrease of environmental impact of cosmetic cream (from – 0.1% to
31 – 2.8%). This paper showed that the palm oil agricultural phase could have a non-negligible impact
32 over the life-cycle of a cosmetic cream in case of deforestation and peat cultivation, despite its small
33 contribution in both mass and economic terms.

34 1 Introduction

35 Assessing environmental impacts has become mainstream when designing new or improved
36 production systems. It is particularly crucial when promoting new bio-based products that are meant
37 to displace their fossil equivalents in order to reduce the overall environmental impact. Arguments
38 put forward are the renewable aspect and the independence from oil or mineral, implicitly promising
39 low environmental impacts. However, several studies have shown that net environmental benefits
40 from bio-sourced products are not automatic and depend on the studied commodity chain and the
41 way it is assessed (Fargione et al., 2008; Farrel et al., 2006; Gibbs et al., 2008; Gnansounou et al.,
42 2009).

43 Life Cycle Assessment (LCA) has been widely applied to assess the impact of bio-sourced product
44 (ADEME and BIO Intelligence Service, 2010; JRC et al., 2008; Secchi et al., 2016). LCA holistic
45 approach allows for comparing commodity chains while avoiding hidden problem shifting between
46 stages or environmental impacts. It can integrate the whole life cycle of the product (from cradle to
47 grave), i.e. starting with extraction of raw materials until the end of life of the used product, and
48 assesses a wide range of potential environmental impacts.

49 The aim of this study is to assess the environmental impacts of a bio-sourced moisturizing cream
50 applying LCA. This cream contains an alkyl polyglucoside (APG) surfactant based on palm oil. Palm oil
51 is nowadays the most used vegetable oil worldwide, accounting in 2015 for 28.3% of the global oils
52 and fats production (European Palm Oil Alliance, 2015). About 19% of total palm oil production is
53 used as oleo-chemicals, especially palm kernel oil (Rival and Levang, 2014). Various LCA on palm oil
54 and palm oil-based products have shown that the feedstock production at the farm stage is a major
55 contributor to most of potential environmental impacts (Boonrod et al., 2016; Chavalparit et al.,
56 2006; Choo et al., 2011; Chuchuoy et al., 2009; Nilsson et al., 2010; Schmidt, 2007; Yusoff and
57 Hansen, 2007). This large contribution of the farm stage, due to combined high input levels in the
58 field and low input levels at the mill and refinery stages, remains a key issue when including further

59 processing stages to convert palm oil into biodiesel (Achten et al., 2010; Angarita et al., 2009;
60 Arvidsson et al., 2011; Choo et al., 2011; Harsono et al., 2012; Papong et al., 2010; Pleanjai et al.,
61 2009). Focusing on global warming impact, main contributors are GHG emissions during the farm
62 stage and methane emissions from palm oil mill effluent treatment (POME). Whereas the impact
63 from POME can be drastically reduced if the biogas is captured (Choo et al., 2011; Chuchuy et al.,
64 2009) and further used at the mill stage (Chavalparit et al., 2006), the impact from the farm stage
65 becomes overwhelming when forests or peat soil areas are converted to palm plantations (Reijnders
66 and Huijbregts, 2008; Schmidt, 2007; Wicke et al., 2008; Zulkifli et al., 2009)

67 In this paper, we investigated the relative contributions of the various production phases of the
68 moisturizing cream over its life cycle from cradle to grave, i.e. from the palm oil production up to the
69 cream use. The first objective was to appraise the impact of the palm oil derivative within the whole
70 supply chain of the moisturizing cream. Then, we focused on exploring how various palm oil
71 production alternatives may critically influence the final LCA results of the bio-based used cream. We
72 first described the implementation of the LCA following ISO norms and International Life Cycle Data
73 (ILCD) guidelines. We then analysed and discussed the influence of the palm oil production scenarios
74 in light of the overall environmental impacts of the studied moisturizing cream.

75 2 Material and methods

76 2.1 LCA goal and scope

77 We implemented LCA according to ISO norms 14040 series and following recommendations from the
78 ILCD (EC-JRC, 2011). We used primary data, where available, and we used Simapro v.8 software with
79 Ecoinvent v.3 database for background inventories. For palm oil feedstock, we used mixed primary
80 and secondary data from the literature to model the plantation management and the industrial
81 plant. Field emission models are detailed in sub-section 2.2.1.3. For the other biomass feedstock, we
82 relied on Ecoinvent processes. Finally, for the industrial processing of the cosmetic cream, we used
83 primary data from a site-specific industry (Guilbot et al., 2013) and secondary data for the
84 background processes, e.g. electricity production and related emissions. ILCD guidelines define a set
85 of 16 recommended impacts categories, which were applied in this study, except for Water Depletion
86 due to some inconsistencies between the water impact assessment method and Ecoinvent v.3
87 database.

88 The studied functional unit was the preparation and use of one 30 g jar of cosmetic cream (Guilbot et
89 al., 2013). The production system consisted of 8 main stages (Fig. 1). We first considered an average
90 palm plantation located in Malaysia (stages 1-2), including all transports from the manufacture sites

91 to the field for field inputs and from the plantation gate to the mill for the fruits. Malaysia is the
92 second world producer of palm oil and the most described system in life cycle inventory studies. The
93 palm oil transformation into cetearyl alcohol (Transesterification & Hydrogenation) was assumed to
94 take place in Germany (stage 3), including transport of palm kernel oil from Malaysia to Germany.
95 The wheat production providing the D-glucose was assumed to be located in Northern France (stages
96 4-5), as well as the final processing step including the production of alkyl polyglucoside (APG) and the
97 final cosmetic cream in accordance with primary data collected by the industry (stages 6-7). We
98 added transport of D-glucose from the Northern (wheat production site) to the Southern part of
99 France, where the final cream production occurred. We finally considered that the cosmetic cream
100 was sold and use in Europe (stage 8), hence accounting for average European market conditions and
101 adding transportation of cosmetic cream from manufacturer to retailer, from retailer to consumer,
102 and of packaging residues from consumer to end of life treatment plant. All capital goods were
103 included, except for the supermarket infrastructure.

104 To allocate co-product burdens, we reasoned with economic values in accordance with Ecoinvent v3
105 database guidelines, i.e. using 5 economic allocations:

- 106 - Kernel (18.7%) and Crude Palm Oil (81.3%) (Jungbluth et al., 2007)
- 107 - Crude Palm Kernel Oil (92.5%) and Palm Kernel Cake (7.5%) (Jungbluth et al., 2007) Palm oil
108 prices may be quite volatile, however the ratios between palm oil and palm kernel oil or
109 kernel meal are quite constant; hence price ratios from 2007 are still relevant for the study.
- 110 - Refined Palm Kernel Oil (99.22%) and Free Fatty Acid (0.78%) (Blonk Agri-footprint, 2014)
- 111 - Cetearyl Alcohol (27.9%), Methyl Ester (62.38%) and Glycerol (9.68%) (unpublished industrial
112 data)
- 113 - The part of the cosmetic cream in transport during purchasing (the cosmetic cream price
114 represents 4.66% of an average shopping basket)¹

115 2.2 Production sub-systems and life cycle inventories

116 2.2.1 Palm oil production scenarios

117 In the current work, the baseline scenario was defined according to main standard industrial
118 practices and alternative scenarios were investigated to assess critical production parameters. These
119 scenarios are further detailed in the following sub-sections.

¹ http://www.famillesrurales.org/franche_comte/Upload/LienCMS/dp_obsvprix_janv2015_2_ljv_CMS314.pdf,
viewed 29/09/2016

120 2.2.1.1 Baseline scenario

121 We modeled the palm oil production system as a standard industrial production system in Malaysia
122 based on published data. We included all processes and flows from nursery production up to the
123 refined kernel palm oil (RKPO) including background processes. For the baseline scenario, we
124 considered a settled plantation (i.e. without Land Use change) on a mineral soil and conventional
125 industrial transformation processes up to palm oils, notably considering a conventional anaerobic
126 treatment of palm oil mill effluents (POME) in open ponds.

127 Our inventory data for the nursery stage were based on two studies. Data for water consumption,
128 electricity, diesel, plastic (production of polybags in Polyethylene, production of PVC irrigation pipes),
129 fertilizers, pesticides and road transport (seeds, fertilizers and pesticides transport between
130 Malaysian port and nursery) were taken from (Choo et al., 2011; Muhammad et al., 2010). Data for
131 sea transport of field inputs from manufacture site to Malaysian port were taken from Schmidt
132 (2007) (see Table S1, S2 and S3 in supplementary materials).

133 After the nursery, palm seedlings are transplanted in the oil palm plantation and cultivated for 25
134 years. The palms are planted at a density of 142 palms/ha (considering a 5% loss at replanting). Palm
135 Fresh Fruit Bunches (FFB) are harvested the whole year long starting after the third plantation year.
136 The composition of harvested FFB is: 20% oil, 25% nuts (5% kernels, 13% fibre and 7% shell) and 23%
137 of empty fruit bunches (EFB) that are brought back to the field as organic fertilizers. We considered a
138 standard management, including mineral and organic fertilizers, herbicides and field mechanization
139 (Table 1), and an average yearly yield over the whole cycle of 19.16 tFFB/ha.year as detailed in the
140 relevant background publications (Choo et al., 2011; Schmidt, 2007).

141 The collected FFB are directly sent to the palm oil mill and rapidly sterilized (within 24 hours) in order
142 to limit the formation of Free Fatty Acid (FFA) (Guilbot et al., 2013). Pulp from mesocarp and kernel
143 are then separated. Pulp is pressed with a screw press in order to obtain Crude Palm Oil (CPO).
144 Pressed mesocarp fibers and crushed kernel shells are burnt in the boiler to provide heat and power
145 leading to very limited amount of external energy input to the mill (Choo et al., 2011; Schmidt, 2007).
146 Pressing of kernel allows for the extraction of Crude Kernel Palm Oil (CPKO). Inventory data were
147 taken from various Malaysian studies (Choo et al., 2010; Vijaya et al., 2010). In the baseline scenario,
148 POME, which are composed of sterilization condensates and clarification waters (Parveen et al.,
149 2010), were conventionally treated in open anaerobic ponds that emit biogenic methane to the air
150 (Wicke et al., 2008).

151 After the mill stage, CPKO is chemically refined, implying degumming with acid then cleansing with
152 bleaching earth (Yew et al., 2010). Undesirable components such as FFA are stripped under vacuum
153 in the de-acidification and deodorization steps to finally produce refined palm kernel oil (RPKO)
154 (Guilbot et al., 2013). Energy for CPKO refining process is met by electricity from the grid (Malaysian
155 grid) and fossil-fuel fed boilers. Liquid wastes from the refinery include wastewater and free fatty
156 acid distillate (Table 1).

157 2.2.1.2 Alternative scenarios

158 Alternative scenarios were investigated from the farm stage up to the RPKO output, exploring (with
159 or without) 3 critical parameters: deforestation, peat soil oxidation, and methane capture and
160 electricity recovery from POME. Details on the calculation steps for the modified inventories are
161 provided in the following sub-sections.

162 Within LCA, the impact of deforestation can be included at both inventory and impact assessment
163 levels (the appraisal of the Land Use impact category is described in section 2.3.). In the inventory,
164 deforestation is translated into carbon losses from above and below-ground biomass emitted as CO₂.
165 We applied IPCC guidelines Tier1 (2006) to calculate these emissions, considering as previous Land
166 Use a primary forest in Asia (insular) with 350 x (1+0.37) t biomass/ha using a 37% ratio of below to
167 above-ground biomass. A palm plantation contains 136 x (1+0.28) t biomass/ha using a 28% ratio of
168 below to above-ground biomass (IPCC, 2006). Emissions from land use change were implemented in
169 both scenarios with deforestation on mineral and peat soils.

170 On top of deforestation, converting peat soil to cropland area requires a dense drainage that notably
171 leads to the oxidation of soil organic carbon and finally CO₂ emissions. In the inventory, we
172 accounted for annual CO₂ emissions due to the peat oxidation, which we further related to an
173 occupation impact (see section 2.3). We relied on the constant emission factor of 40 tCO₂/ha.year
174 (EPA, 2014). We did not account for a potential peak of emissions during the first 5-6 years right after
175 the peat drainage started due to a lack of available emission factor and data. We also accounted for
176 N₂O emissions from peat soil based on the IPCC emission factor (2013). According to IPCC (2013), we
177 did not account for any CH₄ emissions specific to changes in peat soil aeration status. No matter
178 whether the palm plantation on peat was established after forest or after replanting, the annual
179 emissions from peat oxidation were considered constant. We did not consider any fluctuations
180 depending on the initial thickness of the peat layer or the drainage depth. These assumptions were
181 further discussed (section 4).

182 Finally, POME can be treated in different ways. The conventional treatment implies to store POME in
183 open ponds, in which fermentation allows for the degradation of organic compounds in order to
184 reach legal critical levels of Chemical and Biological Oxygen Demands before releasing or spreading
185 of treated effluents. The anaerobic transformation of organic compounds leads to methane
186 emissions, which contribute to global warming. Growing awareness on GHG issues has prompted the
187 industries to seek for new solutions. The development of EFB composting allows for the recycling of
188 raw POME. Moreover, a growing numbers of mills are combined with bioreactors that capture and
189 flare methane from POME treatment with or without energy recovery (EPA, 2012). In our baseline
190 scenario, we considered the conventional treatment and included pond methane emissions
191 (Schmidt, 2007), as well as field emissions after treated POME field application based on IPCC
192 emission factors for organic fertilizers (De Klein et al., 2006). In the alternative scenario, we
193 considered the most interesting treatment alternative up to electricity recovery and substitution of
194 grid electricity.

195 2.2.1.3 Field emission models

196 We took into account the emissions related to the use of fertilizers and pesticides. We followed IPCC
197 guidelines (De Klein et al., 2006) in order to calculate the fractions of mineral and organic N-fertilizers
198 emitted to the water (NO_3^-) and the air (NH_3 , direct and indirect N_2O). NO_x emissions were
199 determined according to EMEP/EEA guidelines (EMEP and EEA, 2013). At the nursery stage, it was
200 considered that no leaching could occur through the polybags. We also calculated P-fertilizer losses
201 to the environment based on SALCA-P model (Prasuhn, 2006). For pesticides, we considered that the
202 full rates of pesticides applied ended up in the soil. Fertilizers also contain heavy metals that we
203 considered as stored in the soil (Brockmann et al., 2014).

204 2.2.2 Palm-based surfactant production

205 2.2.2.1 Production of the palm-based cetearyl alcohol

206 The processing of RPKO into a palm-based surfactant takes place in Europe. RPKO is transported from
207 Malaysia to France (Marseille) by transoceanic freight ship, then to Germany by train (Guilbot et al.,
208 2013). We considered a transesterification of RPKO with methanol in the presence of sodium
209 hydroxide given the low cost, good yield and easiness to process (Zah and Hischer, 2007). The
210 recovered methanol is recycled in the process. The C-8/14 methyl ester is slit from the C-16/18
211 methyl ester by distillation separation. The last step is a continuous catalysed hydrogenation of the
212 C-16/18 methyl ester under high temperature (250–300 °C) and high hydrogen pressure (25–35 MPa)

213 in a fixed bed trickle flow process. The targeted C-16/18 alcohol is finally distilled to reach a purity of
214 more than 95% (Giraldo et al., 2010) (see Table S4 in supplementary material).

215 2.2.2.2 Production of the complementary wheat-based crystallized D-glucose

216 Crystallized D-glucose is needed to produce the palm-based surfactant (128 g per kilogram of APG).
217 The used crystallized D-glucose is derived from wheat starch (Guilbot et al., 2013). For our study, we
218 used an Ecoinvent wheat inventory ("wheat grain {FR}, wheat production, alloc def") to represent a
219 proxy for the culture of wheat in France. After harvesting, the wheat grains are washed and ground
220 into flour and mixed up with water. The starch and gluten are then separated, and the resulting
221 starch milk is totally hydrolyzed.. The final processing steps involve demineralization, discoloration,
222 concentration by evaporation and crystallization to obtain anhydrous D-glucose (Gerngross, 1999).
223 An amount of 5.6 g of cultivated wheat provides 3.7 g of D-glucose, with a transformation energy
224 cost of 1.6×10^{-2} MJ of energy (heat). The output crystallized D-glucose undergoes a Fischer
225 Glucosylation, with sodium hydroxide as neutralization agent. Un-reacted glucose is removed by
226 decantation and centrifugation (Guilbot et al., 2013).

227 2.2.2.3 Final production of the palm-based surfactant

228 The last step is the shaping of alkyl polyglucoside (APG) by pearlizing, which was assumed in this
229 study to take place in France (Castres city). We assumed a standard batch of 10.9 t of APG (Guilbot et
230 al., 2013), using 10.5 t of cetearyl alcohol and 1.4 t of crystallized D-glucose (Fig. 1). The supplying of
231 these raw materials is done by lorry (~1200 km for the cetearyl alcohol coming from Germany to
232 Castres and ~ 900 km for the glucose coming from the North of France to Castres). APG is stored in
233 plastic bags, themselves stored in packaging board of 25 kg. We considered the following packaging:
234 5.44×10^{-2} g packaging board and 6.68×10^{-3} g of plastic film for 1.50 g of APG. This packaging was
235 recovered in the cosmetic cream plant. We considered a recycling rate of 89% for packaging board
236 and 20% for plastic film, the remaining being incinerated (Badey and Lahitte, 2013).

237 As the APG is solid at room temperature (melting point ~65 °C), the entire process is carried out by
238 heating with steam produced by a gas boiler (104 kg of steam per t of APG) (Guilbot et al., 2013).
239 Water input in the whole pearlizing process amounts 1.4 m³ per t of APG including the used cooling
240 water use that is recycled in a closed circuit system. The final input is dinitrogen, 2.2 m³ per t of APG,
241 which is used during the entire process in order to prevent coloration with oxygen from the air. Apart
242 from APG, final co-products are: i) glucose muds from the decantation and centrifugation steps
243 (~76 kg per t of APG), which are incinerated in a specific treatment plant (at ~ 160 km from the
244 production site); and ii) liquid aqueous effluents (~14 l per t of APG containing 3000 mg per l of

245 COD), which are transferred to a wastewater treatment plant (see Table S5 in supplementary
246 materials).

247 2.2.3 Moisturizing cream production and use

248 2.2.3.1 Production of the cosmetic cream

249 The studied cosmetic cream contains 75% of water, 20% of an Argan oil phase (not available and
250 hence replaced by “global market for vegetable oil, refined ”fromecoinvent”), and 5% of APG
251 (Guilbot et al., 2013). The emulsification process consists in mixing the three components for about
252 2 h at 70°C under vigorous agitation, which requires 85 kg steam and 6 kWh electricity per tonne of
253 cream. Waste are mud (70 kg per t of cream) and liquid wastewater (10 l per t of cream with
254 3,000 mg COD per l). The final cream is bottled in a 30 g jar made of 7 g of HDPE and a tight fitting lid
255 made of 1.79 g of HDPE. Each jar is packaged in a small cardboard box (5 × 5 × 5 cm) wrapped in a
256 very thin HDPE film (100 µm). Our functional unit is the study of 1 jar (Table 2).

257 2.2.3.2 Use and end of life stage

258 The final use of the cream is its application on the skin of a consumer. The penetration (dose
259 absorbed through the skin) depends on skin permeability and properties of the cream as saturation
260 solubility. Some authors (Kroes et al., 2007; Williams et al., 2016) defined maximum flux (J_{max}) to deal
261 with aspect and classified the dose absorbed during 24h according to it. A cosmetic cream with
262 surfactants, which was the case the present work, enhances skin penetration and promotes dermal
263 absorption of cosmetic ingredients (Williams et al., 2016). Jolliet (Jolliet et al., 2015) considered that
264 after 12h, 96% of the cream was absorbed. Consequently, in the present work, we assumed that the
265 cream was absorbed for the most part and the quantity of the cream streamed to the wastewater
266 treatment was negligible. This is in accordance with the Sustainability consortium (2013) guidelines
267 where wastewater treatment after the use of a cosmetic product is excluded of the system.

268 In our study, we did not consider any direct leakage after skin application (Guilbot et al., 2013).
269 However, we considered other potential impacts before and after the cream use, notably the
270 transport steps between production plant and storage (1,000 km by lorry), storage and retailer store
271 (100 km by lorry), from the store up to the consumer house. We also considered the recovery of
272 the jar.

273 We considered four types of transport in order to buy the cosmetic cream according to the European
274 average: personal car (57%), walk (24%), public transport (11%), and bicycle (8%) (De La Fuente
275 Layos, 2005).

276 The “public transport” category could be separated into 2 sub categories with the following
277 percentages (European Commission, 2014):

- 278 - Subway: 18% (i.e. 2% from the 11% public transport)
- 279 - Bus: 82% (i.e. 9% from the 11% public transport)

280 The assumed average roundtrip distance between the customer house and the store was 10 km (De
281 La Fuente Layos, 2005). We carried out an economic allocation in order to calculate the ratio of the
282 cosmetic cream over the total shopped basket during the purchasing transport.

283 Wastes were collected to be treated. The cosmetic cream jar with associated packaging consists of
284 8.79 g of HDPE, 3.75 g of cardboard and 1.41 g of plastic film. If recycling rate for HDPE is very high
285 like for bottles at consumer level, small dirty HDPE containers are commonly not separately collected
286 and can be assimilated to undifferentiated small packaging with a recycled rate of 3% (BIO
287 Intelligence Service, 2013). In the European context, 65%² of cardboard and 10% of plastic film are
288 recycled (BIO Intelligence Service, 2013). The non-recycled parts (97%, 35% and 90% respectively),
289 are incinerated and landfilled according European waste management practices³, (49% and 51 %
290 respectively). These assumptions are further discussed (section 4).

291 2.3 Impact characterisation and selected indicators

292 We applied ILCD (2011 V1.06) (European Commission, 2012) recommendations regarding the
293 selection of impact characterisation methods. We hence assessed 12 potential midpoint impacts (see
294 Table S6 in supplementary material).

295 Concerning the Land Use impact, following ILCD, we applied the “Land Use” indicator (Brandão and
296 Milà i Canals, 2013; Koellner et al., 2013; Milà i Canals et al., 2007). This indicator measures the
297 change in the amount of organic matter in soil (30 cm deep) as a proxy to quantify how the use of a
298 land area may impact the soil properties and functions. This indicator is expressed in kg C deficit. It
299 integrates the impact due to land transformation and land occupation relatively to a reference state

² <http://ec.europa.eu/eurostat/web/waste/key-waste-streams/packaging> viewed 29/09/2016

³ <http://ec.europa.eu/eurostat/tgm/refreshTableAction.do?tab=table&plugin=1&pcode=tsdpc240&language=en> viewed 29/09/2016

300 (without considering any irreversible process). The occupation indicator theoretically includes two
 301 compounds. The first one refers to the impact of delaying the restoration of the potential SOC due to
 302 land occupation, the second refers to a further actual degradation or improvement in the SOC due to
 303 the land occupation. The latter, further referred to as “occupational change”, is not yet implemented
 304 in ILCD (EC-JRC, 2011). We further refer to “occupational delay” for the currently implemented
 305 occupation impact in Land Use indicator. Characterisation factors are calculated based on SOC
 306 database from IPCC (2006).

307 For transformation, the gain or loss of SOC is calculated according to the following formula (Brandão
 308 and Milà i Canals, 2013; Milà i Canals et al., 2007):

309 Eq.1

$$\Delta SOC \left(\frac{kg_C}{m^2} \right) = \frac{\frac{1}{2} (t_{relax} - t_{ini}) * (SOC_{ini} - SOC_{end})}{(t_{end} - t_{ini})}$$

310 Where:

311 SOC_{ini} = Soil Organic Carbon at the initial state

312 SOC_{end} = Soil Organic Carbon at the final state

313 t_{ini} = Initial time

314 t_{end} = Final time

315 t_{relax} = Relaxation time (at t_{relax} SOC has reverted to the level in the reference state)

316 In the baseline scenario, there is no transformation ($SOC_{ini} = SOC_{end}$ = palm plantation). In the
 317 alternative scenarios, we first calculated the Land Use transformation impact linked to deforestation
 318 (i.e. SOC_{ini} = primary forest on mineral soil; SOC_{end} = palm plantation on mineral soil). We then also
 319 calculated the Land Use impact linked to peat soil cultivation with Land Use change (i.e. SOC_{ini} =
 320 primary forest on peat soil; SOC_{fin} = palm plantation on peat soil).

321 For peat soil in Asia, there was no characterisation factor in the Land Use indicator of ILCD
 322 methodology. We hence needed to create this soil category in order to take into account the original
 323 high carbon stocks in peat soils and potential subsequent effects from the draining and oxidation of
 324 peat soil. According to Page et al. (2011), the soil carbon content of a peat soil in Southeast Asia is
 325 55.3 kg C/m² (considering the stock over the first 30 cm depth with a homogeneous distribution over

326 the first 150 cm). We considered this stock to be the potential initial carbon stock (SOC_{ini}) and used
 327 the soil carbon content of 8.6 kg C/m² as a final stock (SOC_{end}). The latter is the one given for
 328 tropical wetland under natural vegetation. We chose this stock as the final one considering that it
 329 was too low to refer to a natural undisturbed peat soil under forest.

330 In our study, we considered a regeneration or relaxation time, t_{relax} , for a used peat soil to recover
 331 its initial soil carbon stock, of 1,000 years. This time period corresponded to the highest relaxation
 332 time available (i.e. the one considered for sealed land)(Milà I Canals et al., 2007), considering that all
 333 potential changes are reversible. According to Milà I Canals (2007), we assumed an initial
 334 instantaneous transformation over one year, i.e. $t_{end} - t_{ini} = 1$.

335 The calculated characterisation factor for peat soil transformation was finally: $\Delta SOC =$
 336 23,350 kg C/m²

337 For occupation, the impact on soil is calculated according to the following formula:

$$\Delta SOC \left(\frac{kgC}{m^2} \right) = \frac{(SOC_{pot} - SOC_{ini}) * (t_{relax} - t_{ini})}{(t_{end} - t_{ini})}$$

338 Where:

339 SOC_{ini} = Soil Organic Carbon at the initial state

340 SOC_{pot} = Soil Organic Carbon potential (at the native state)

341 t_{ini} = Initial time

342 t_{end} = Final time

343 t_{relax} = Relaxation time (at t_{relax} SOC has reverted to the level in the reference state)

344 In this formula, according to Milà I Canals (2007), we considered that $t_{relax} = t_{end}$

345 The occupational delay impact is a constant annual carbon deficit due to the lack in carbon stock
 346 compared to potential natural state. Result is valid for each year without specification on the soil
 347 type. For occupation of peat soil in Asia, we took $SOC_{pot} = 55.3$ kgC/m², and $SOC_{ini} = 8.6$ kgC/m², i.e.
 348 $\Delta SOC = 46.7$ kg C/m².year. For occupation of mineral soil, we use the ILCD default characterisation
 349 factor for “permanent crop Land Use occupation”, without specification on the soil type, i.e. $\Delta SOC =$
 350 4 kg C/m².year.

351 In addition to this occupational delay impact factor, we also added an actual annual degradation, i.e.
352 occupational change, in soil carbon content due to the draining and oxidation of peat soil. The
353 oxidation of peat soil causes high CO₂ emissions, which we have included in the life cycle inventory in
354 terms of greenhouse gas emissions contributing to the Climate Change impact (see section 2.2.1.2).
355 In order to be consistent and to take into account this soil organic carbon loss for the Land Use, we
356 converted this CO₂ inventory flow into an annual carbon stock change for Land Use impact category
357 (was converted into 1.1 kg C/m².year) (section 2.2.1.2).

358

359 3 Results

360 3.1. Baseline scenario: continuous palm plantation on mineral soil

361 We performed a contribution analysis of the various production stages including the refined palm
362 kernel oil (RKPO), the rest of the cosmetic cream compound production and processing, the
363 production of the packaging, the transport to retailer and consumer, and the consumer waste
364 management (Fig.2). We notably wanted to assess the relative contributions of agricultural stage
365 (with a focus on palm oil production) and other industrial and logistical stages.

366 The contribution of each stage group to the total impacts varied with the impact category. Most
367 impacting stages were transport to retailer and consumer, packaging and cosmetic cream. Transport
368 to retailer and consumer was the main contributing process (largest for 11 out of 15 impacts
369 indicators, min = 12% for Ionising Radiation Human Health, max = 82% for Mineral, Fossil and
370 Renewable Resources Depletion). The high impact in terms of Mineral, Fossil and Renewable
371 Resource Depletion was due to fossil fuel use in engines. Packaging production was also a significant
372 contributing process (largest for 2 out of 15 impacts indicators, min = 4% for Mineral, Fossil and
373 Renewable Resource Depletion, max = 82% for Ionising Radiation Human Health). The high impacts
374 were notably related to the energy input, especially the electricity use from the French mix that
375 relies greatly on nuclear electricity leading to a high contribution on Ionising Radiation Human
376 Health. The total contribution of the production of the cosmetic cream itself, i.e. the production of
377 refined palm kernel oil and other compounds and further transformations and assemblages up to the
378 cream without its packaging, represented a high impact (min = 6% for Ionising Radiation Human
379 Health, max = 58% for Land Use) of the impacts. Main contributing stages in the cosmetic cream
380 production were the industrial transformation processes and the production of other vegetable oil,
381 followed by RPKO and the wheat derivative. Cosmetic cream production, RPKO apart, had a non-
382 negligible impact (min = 6% for Ionising Radiation Human Health, max = 54% for Land Use). The high

383 impact for Land Use was related to the use other vegetable oil besides RPKO. The RPKO production in
384 the baseline scenario, which represented a non-negligible agricultural input on a feedstock mass
385 basis (1.9 g RPKO for 0.3 g wheat and 6 g of other oils, i.e. 20% of the 30 g cream), only had limited
386 impacts (min = 0.3% for Ionising Radiation Human Health, max = 12% for Marine Eutrophication). The
387 consumer waste management had a non-negligible impact in terms of avoided impact due to
388 material recycling notably regarding Ionizing Radiation Ecosystems, where it led to a 32% reduction
389 of the global impact.

390 We further investigated the process contributions within the RPKO production stage (Fig. 3). In the
391 baseline scenario, the impacts of RPKO production were driven by the fresh fruit bunch (FFB)
392 production in the field and the palm oil processing. The palm oil mill effluent (POME) treatment
393 essentially contributed to the Climate Change impact (53%) due to the release of methane during
394 anaerobic treatment in open ponds. FFB production had the largest impact overall (min = 34% for
395 Climate Change, max = 96% for Marine Eutrophication). This high impact was notably due to the use
396 of synthetic mineral fertilizers greatly contributing to Climate Change, Photochemical Ozone
397 Formation, Acidification and Eutrophication impact categories. Crude palm oil (CPO) extraction, i.e.
398 fruit production apart, also had a high impact (min = 1% for Land Use, max = 60% for Climate
399 Change). CPO has a high impact for Particulate Matter mostly came from power central (boiler) and
400 to a lesser extent from the plant construction. Further contributions from other energy and chemical
401 uses (refinery step), as well as input and fruit transport to the mill, had low impacts.

402 3.2. Influences of deforestation, peat soil oxidation, and POME treatment

403 We investigated deeper the influence on the overall cosmetic cream impacts of the palm plantation
404 establishment and the palm oil mill effluent treatment. The parameters tested in the alternative
405 scenarios (see section 2.2.1.2) were the following:

- 406 - The previous Land Use: primary forest, i.e. deforestation, or palm cultivation, i.e. continuous
407 agricultural land use
- 408 - Soil type: mineral or peat soils
- 409 - The treatment of POME: conventional treatment or methane capture and electricity recovery.

410 Deforestation and peat soil transformation and occupation were translated i) in the life cycle
411 inventory as GHG emissions, and ii) in soil organic carbon changes embedded in the Land Use impact.
412 Hence, these two parameters only influenced two impact categories, i.e. Climate Change and Land

413 Use (Fig. 4). On Climate Change indicator, deforestation caused an increase of about 9% in the
414 cosmetic cream final impact (i.e. +282% in the RPKO impact), peat soil occupational change (i.e.
415 annual degradation of carbon stock and related CO₂ emissions) caused an even greater increase of
416 16% over the whole cosmetic cream life cycle (i.e. +46% for the RPKO). On Land Use indicator,
417 deforestation caused an increase of 3%, peat soil occupational delay (i.e. both the annual
418 degradation and the annual cost for delaying the relaxation to natural stock) and transformation
419 caused impact increases of 41% and 938%, respectively. The influence of peat soil transformation
420 and occupational delay was tremendous and in particular even much higher than that of
421 deforestation. These high increases corresponded to a variation of +917% for peat soil occupational
422 delay and +20,904% for peat soil transformation when focusing on the RPKO impacts.

423 Methane capture and conversion to electricity represented a low decrease in environmental impact
424 (min = -0.1% for Ionizing Radiation Human Health, max = -3% for Marine Eutrophication). The gain
425 provided by the improved treatment of POME was very low but consistent across all impact
426 categories. Focusing on RPKO production stage, POME improved treatment allowed a low decrease.
427 So, at the agricultural scale, POME improved treatment in order to produce electricity remained
428 interesting. At the cream final product scale, the gain provided remained negligible. However,
429 compared to deforestation and peat soil transformation and occupation, improved POME treatment
430 had a general, albeit small, positive influence on all impact categories.

431 4 Discussion

432 In the baseline scenario, which corresponded to a standard industrial palm production system in
433 Malaysia with no land use change, we could observe an impact of the palm kernel oil production and
434 refinery on the overall life cycle impact of the cosmetic cream. In this context, the contribution of
435 refined palm kernel oil was not critical with regard to the other process stages along the whole life-
436 cycle of the cosmetic cream. Moreover, palm kernel oil extraction and refinery processes were less
437 energy intensive (particularly in terms of fossil energy use) than most of the other up- and
438 downstream processes.

439 In comparison with the baseline economic allocation approach, using mass allocation ratios (except
440 at purchase stage due to lack of data for mass of shopping basket), environmental impacts would
441 have been lower (min=-0.4% for Ionizing Radiation; max=-15% for Marine Eutrophication). Mass
442 allocation ratios lowered RPKO impacts given the higher price per mass unit compared to refined
443 palm oil. The contribution of RPKO production to the final cream impact was very low. Besides

444 reduction in RPKO impacts with mass allocation ratio, the contributions of other cream life cycle
445 stages were not influenced by the change in allocation ratios.

446 Within the whole life-cycle of the cosmetic cream, the more impacting stages were packaging and
447 transport. The primary data from the industrial partner allowed for a refined site-specific modelling
448 of the industrial phase. However, some assumptions were still needed as well as the use of some
449 secondary data from Ecoinvent v.3 database for some upstream background processes. We also
450 modelled average current practices in term of transportation means and distances. More specific
451 transport strategies might be explored to reduce the overall impacts but would need to be assessed
452 on a case-by-case basis. Transport apart, the main remaining problem is the packaging which
453 influenced significantly the final cream impacts, we looked at alternative scenarios for the end of life
454 of the packaging (see Fig S1 in supplementary materials). When the HDPE packaging was entirely
455 recycled, the total cream impacts were reduced (min=0% for Ozone Depletion; max=-25% for Ionizing
456 Radiation), with a packaging impact (production + end of life management) contribution slightly
457 decreased. Further complementary investigations might also be needed to check whether the
458 assumption of the cream absorption with negligible washing out (Guilbot et al., 2013) may have an
459 influence on the final results.

460 In the alternative scenarios, the RPKO contribution became much more critical for two impact
461 categories, i.e. Climate Change and Land Use. The annual CO₂ emissions and the cumulated soil
462 organic carbon depletion due to the draining and oxidation of the peat soil were the most influential
463 parameters over all. Impact of peat soil drainage and oxidation would be even higher considering the
464 former IPCC coefficient for wetland N₂O emissions (2006), i.e. +10% in the RPKO Climate Change
465 impact, or lower with another reference for CO₂ emissions (Hooijer et al., 2010), i.e. -18% in the
466 RPKO Climate Change impact. This emphasises the need for further research work and consensus
467 finding on guidelines and coefficients to assess the environmental impact of peat soil conversion. We
468 adapted some coefficients and stocks found in the literature and proposed to include some part of
469 the occupation impact, which is usually considered as negligible. However, more needs to be done.
470 Concerning peat soil conversion, several factors in particular would need to be further addressed,
471 e.g. the flush emissions right after opening and drainage start, the irreversible impact due to acute
472 subsidence, the methane emissions from the drains or the indirect impacts at the watershed level,
473 etc. From an environmental point of view, though, these estimate on Climate Change and Land Use
474 impacts, albeit incomplete and perfectible, already highlight the prohibitive impact of peat soil
475 conversion to agricultural uses where dense drainage is mandatory.

476 Our study aimed at providing a comprehensive LCA of a bio-sourced product, while focusing on the
477 relative importance of the agricultural stage and production conditions over the whole supply chain.
478 Further investigations would be necessary in order to better model potential discrepancies in
479 agroecological performances between oil palm productions on mineral or peat soils, e.g. potential
480 variations in crop cycle length, yields, disease pressure, and pesticide or fertilizer managements.

481 5 Conclusion

482 This study dealt with environmental impacts of a cosmetic cream, which contained palm kernel oil-
483 based as surfactant, from feedstock production to end of life management. It gave a precise picture
484 of main impact contributors over the whole life-cycle of a bio-based cosmetic cream. It turned out
485 that the transport from the retailer to the customer had the highest impact (highest for 11 out of 15
486 impacts indicators, min = 12% for Ionising Radiation Human Health, max = 82% for Mineral, Fossil and
487 Renewable Resource Depletion). It was mainly caused by the use of petrol. The packaging had also a
488 high impact (2 out of 15, min = 4% for Mineral, Fossil and Renewable Resource Depletion, max = 82%
489 for Ionising Radiation Human Health). Agricultural phase in order to obtain RPKO had a small impact
490 contribution (min = 0.3% for Ionising Radiation Human Health, max = 12% for Marine
491 Eutrophication). The rests of the impacts were due to chemical step (min = 6% for Ionising Radiation
492 Human Health, max = 54% for Land Use) and end of life management (min = -32%, max = 11%).

493 Many parameters could influence the palm oil production (i.e. RPKO impact contribution) and we
494 investigated three of them: the previous land use, soil type and POME management. Mainly two
495 impacts indicators were concerned in the alternative scenarios: Climate Change and Land Use with
496 an increase of 25% and 1,528%, respectively, compared to the baseline scenario. On Climate Change,
497 9% were caused by deforestation and 16% by peat soil transformation and use. On Land Use, 938%
498 were caused by peat soil transformation, 41% by peat soil use and occupational delay, and 3% by
499 deforestation. Within the complete cream life-cycle, peat soil transformation and cultivation had the
500 highest impact, while POME management was negligible.

501 An eco-design of the cosmetic cream could reduce its environmental impact considering some
502 improvements at several stages. One of the key aspects was the packaging, where lower mass could
503 reduce production and transportation impacts. Ecodesign would also require the integration of good
504 farming practices, mainly concerning the previous land use and the type of soil, avoiding peat soil
505 use. Through the example of a palm oil based cosmetic cream, this study showed the interest of a
506 whole approach to bring face-to-face agricultural productions, transformations and use of products.

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Table 1: Life Cycle Inventory for the production of 23.57kg of RPKO (from 1000kg of FFB)

	Unit	FFB	Kernels	CPKO	RPKO
Output products					
FFB	kg	1,000 ^b			
Kernels	kg		53.2 ^b		
CPKO	kg			23.88 ^b	
RPKO	kg				23.57 ^b
CPO	kg		199.8 ^b		
EFB	kg		225 ^b		
POME			672.5 ^b		
Palm kernel cake	kg			27.72 ^b	
Free Fatty Acid	kg				0.24 ^b
Input					
Soil transformation	m ²	20.9 ^h			
Soil occupation	m ² year	521.9 ^h			
Energy use					
Diesel : agriculture machinery	L	2.37 ^a	0.57 ^b		
Electricity from the grid	MJ		0.8 ^b	10.03 ^b	2.99 ^b
Electricity produced	MJ		31 ^b		
Heat (steam)	MJ				7.73 ^b
Material use					
Water	L		1,300 ^b	9.55 ^b	16.5 ^b
Oil palm seedling	Transplant	0.33 ^a			
Amonium sulfate	kg	8.05 ^a			
Urea	kg	0.41 ^a			
Ammonium nitrate	kg	0.76 ^a			
Ammonium chloride	kg	0.72 ^a			
Nitrogen fertiliser, as N	kg	3.49 ^a			
Potassium chloride, as K ₂ O	kg	11.60 ^a			
Potassium fertiliser, as K ₂ O	kg	4.50 ^a			
Phosphate rock, as P ₂ O ₅	kg	6.55 ^a			
Phosphate fertiliser, as P ₂ O ₅	kg	0.64 ^a			
Glyphosate	kg	0.34 ^a			
[Sufonyl]urea compounds	kg	0.15 ^a			
Bipyridylum compounds	kg	0.10 ^a			
Pyretroid compounds	kg	2.15x10 ^{-2a}			
Organophosphorus compounds	kg	6.40x10 ^{-2a}			
Dimethylamine	kg	3.10x10 ^{-2a}			
Pesticide unspecified	kg	2.13 ^a			
Phosphoric acid	kg				5.89x10 ^{-3b}

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NaOH	kg				6.83×10^{-2b}
Bleaching earth	kg				1.06×10^{-1b}
Transport					
FFB to mill, lorry	tkm	50			
Fertilizer from plant to port, ship	tkm	171.95^b			
Pesticides from plant to port, ship	tkm	14.14^b			
Fertilizer from port to plantation, lorry	tkm	5.10^a			
Pesticides from port to plantation, lorry	tkm	0.15^a			
Raw material and ancillaries, lorry	tkm		0.1^b		
Kernel, lorry	tkm			4.2^b	
Palm kernel cake, lorry	tkm			1.1^b	
Phosphoric acid	tkm				5.89×10^{-3b}
NaOH	tkm				6.84×10^{-2b}
Bleaching earth	tkm				1.06×10^{-1b}
Diesel	tkm				3.77×10^{-2b}
Fodder fat	tkm				4.71×10^{-2b}
Emissions to air					
CO ₂	kg	0			
CO ₂ land transformation	kg	0			
NH ₃	kg	4.50×10^{-1c}	4.24×10^{-2b}		
N ₂ O	kg	$7.57 \times 10^{-2b,c}$	6.81×10^{-3b}		
NOx	kg	9.35×10^{-2e}	2.72×10^{-1b}		
CH ₄	Kg		8.74^b		
H ₂ S	kg		5.79×10^{-2b}		
SO ₂	kg		2.4×10^{-3b}		
CO	kg		6.71×10^{-1b}		
Particulates, < 2.5 um	kg		1.51×10^{-1b}		
Acetaldehyde	kg		1.2×10^{-4b}		
Arsenic	kg		1.9×10^{-6b}		
Benzene	kg		1.73×10^{-3b}		
Benzene, ethyl-	kg		5.72×10^{-5b}		
Benzene, hexachloro-	kg		1.37×10^{-11b}		
Benzo(a)pyrene	kg		9.52×10^{-7b}		
Cadmium	kg		1.33×10^{-6b}		
Chlorine	kg		3.42×10^{-4b}		
Chromium	kg		7.54×10^{-6b}		
Chromium VI	kg		7.62×10^{-8b}		
Copper	kg		4.20×10^{-5b}		
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	kg		5.90×10^{-11b}		
Formaldehyde	kg		2.48×10^{-4b}		
Hydrocarbons, aliphatic, alkanes, C10,	kg		1.73×10^{-3b}		

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Hydrocarbons, aliphatic, unsaturated	kg		6×10^{-3b}		
Lead	kg		4.76×10^{-5b}		
m-Xylene	kg		2.28×10^{-4b}		
Manganese	kg		3.24×10^{-4b}		
Mercury	kg		5.72×10^{-7b}		
Nickel	kg		1.14×10^{-5b}		
NM VOC, non-methane volatile organic compounds	kg		1.71×10^{-3b}		
PAH, polycyclic aromatic hydrocarbons	kg		2.12×10^{-5b}		
Phenol, pentachloro-	kg		1.54×10^{-8b}		
Phosphorus	kg		5.72×10^{-4b}		
Toluene	kg		5.72×10^{-4b}		
Zinc	kg		5.72×10^{-4b}		
Emissions to water					
NO ³⁻	kg	4.78 ^c		7.16×10^{-5b}	
PO ₄ ³⁻	kg	3.94×10^{-2f}			
P	kg				1.88×10^{-3b}
Emissions to soil					
Lead	mg	51.9 ^{a,g}			
Cadmium	mg	140 ^{a,g}			
Chromium	mg	1,480 ^{a,g}			
Nickel	mg	265 ^{a,g}			
Copper	mg	292 ^{a,g}			
Zinc	mg	2,460 ^{a,g}			
Mercury	mg	0.682 ^{a,g}			
Arsenic	mg	73.8 ^{a,g}			
Thallium	mg	3.93 ^{a,g}			
Glyphosate	kg	0.338 ^{a,g}			
Metsulfuron-methyl	kg	0.148 ^{a,g}			
Paraquat	kg	0.104 ^{a,g}			
Cypermethrin	kg	$2.15 \times 10^{-2 a,g}$			
Glufosinate ammonium	kg	$3.20 \times 10^{-2 a,g}$			
Methamidophos	kg	$3.20 \times 10^{-2 a,g}$			
Carbofuran	kg	$3.50 \times 10^{-2 a,g}$			
Dimethylamine	kg	$3.10 \times 10^{-2 a,g}$			
Waste to treatment					
Waste water	kg				16.5 ^b
Bleaching earth to landfill	kg				1.51×10^{-1b}

^a (Choo et al., 2011)

^b (Schmidt, 2007)

^c (De Klein et al., 2006)

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^g (Brockmann et al., 2014)^h (faostat.fao.org/)

Table n°2: LCI of the production of 30 g of cosmetic cream (primary data from the industrial partner)

	Unit	Quantity
Inputs		
APG	g	1.5
Vegetable oil	g	6.0
Nitrogen	g	12.2
Tap water	g	24.7
Energy		
Electricity	kWh	2.1×10^{-2}
Steam	g	2.5×10^{-3}
Transport lorry	kgkm	6.3
Output		
Wastewater	ml	3.0×10^{-1}
Mud to incineration	g	2.1

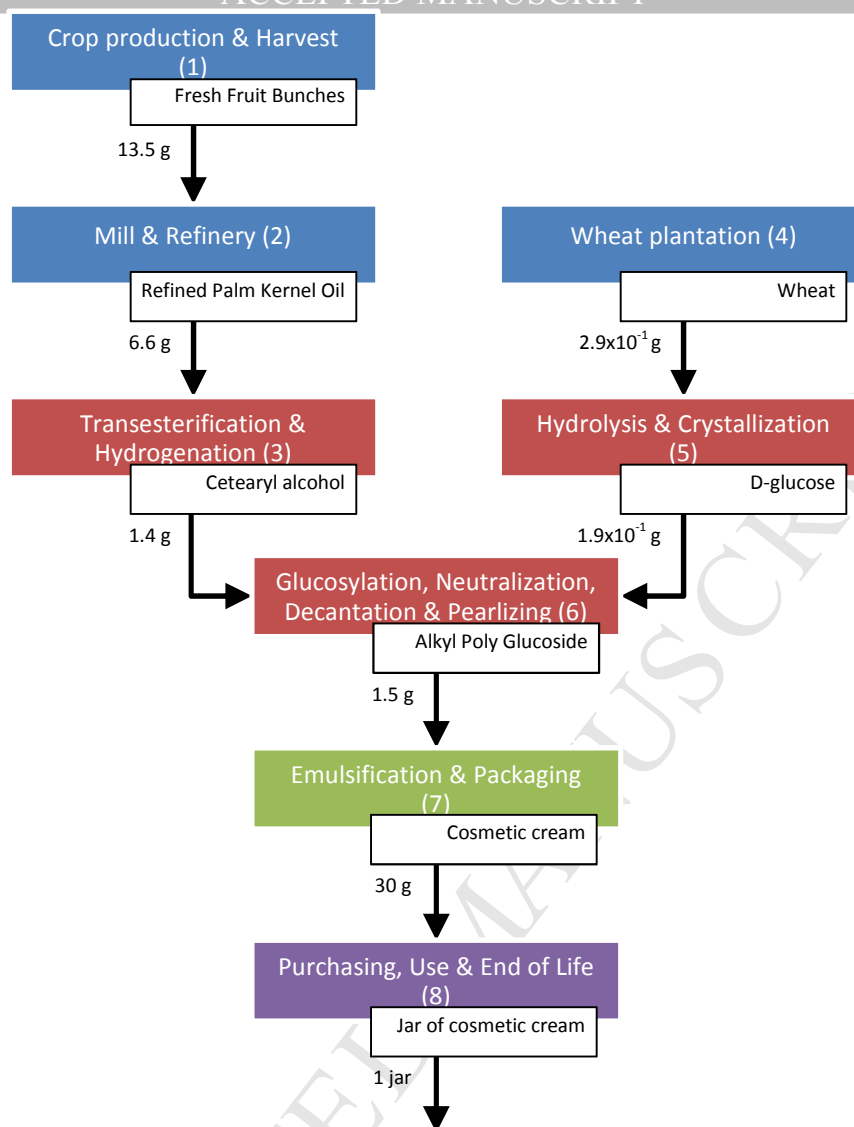


Fig 1: Overview of the global system for 1 jar of cosmetic cream.

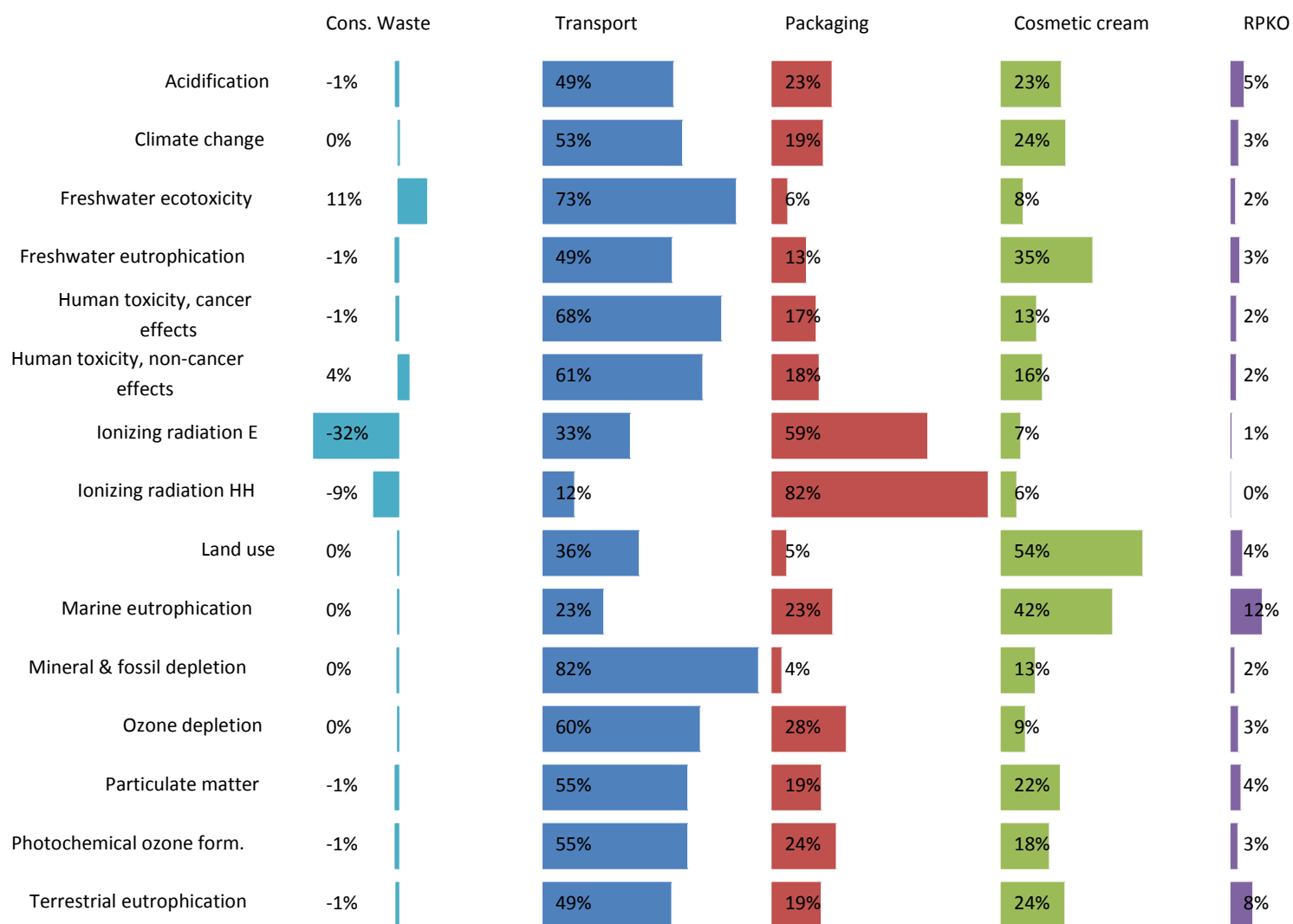


Fig 2: LCA results of the continuous palm plantation on mineral soil (baseline scenario)

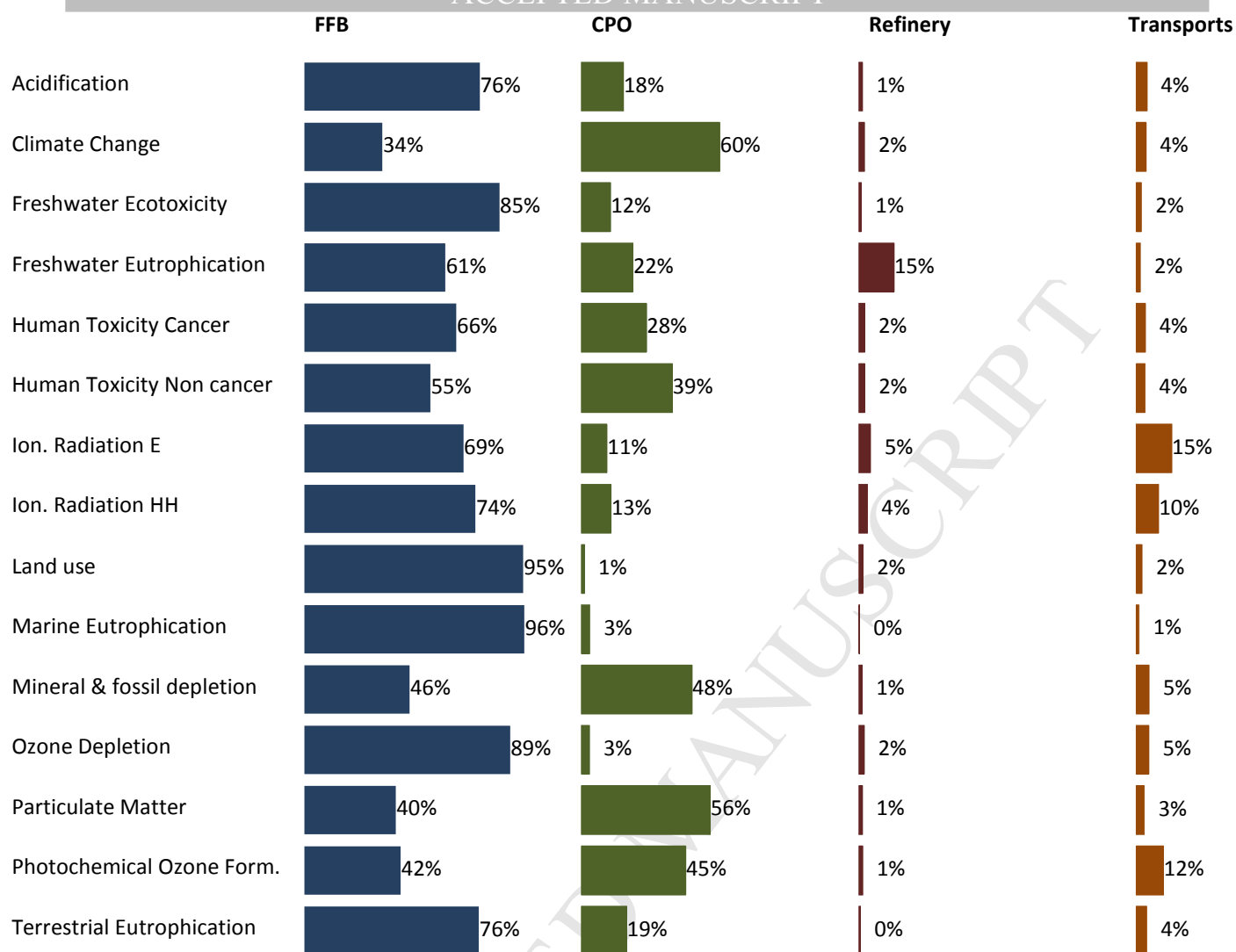


Fig 3: LCA results of RPKO in baseline scenario

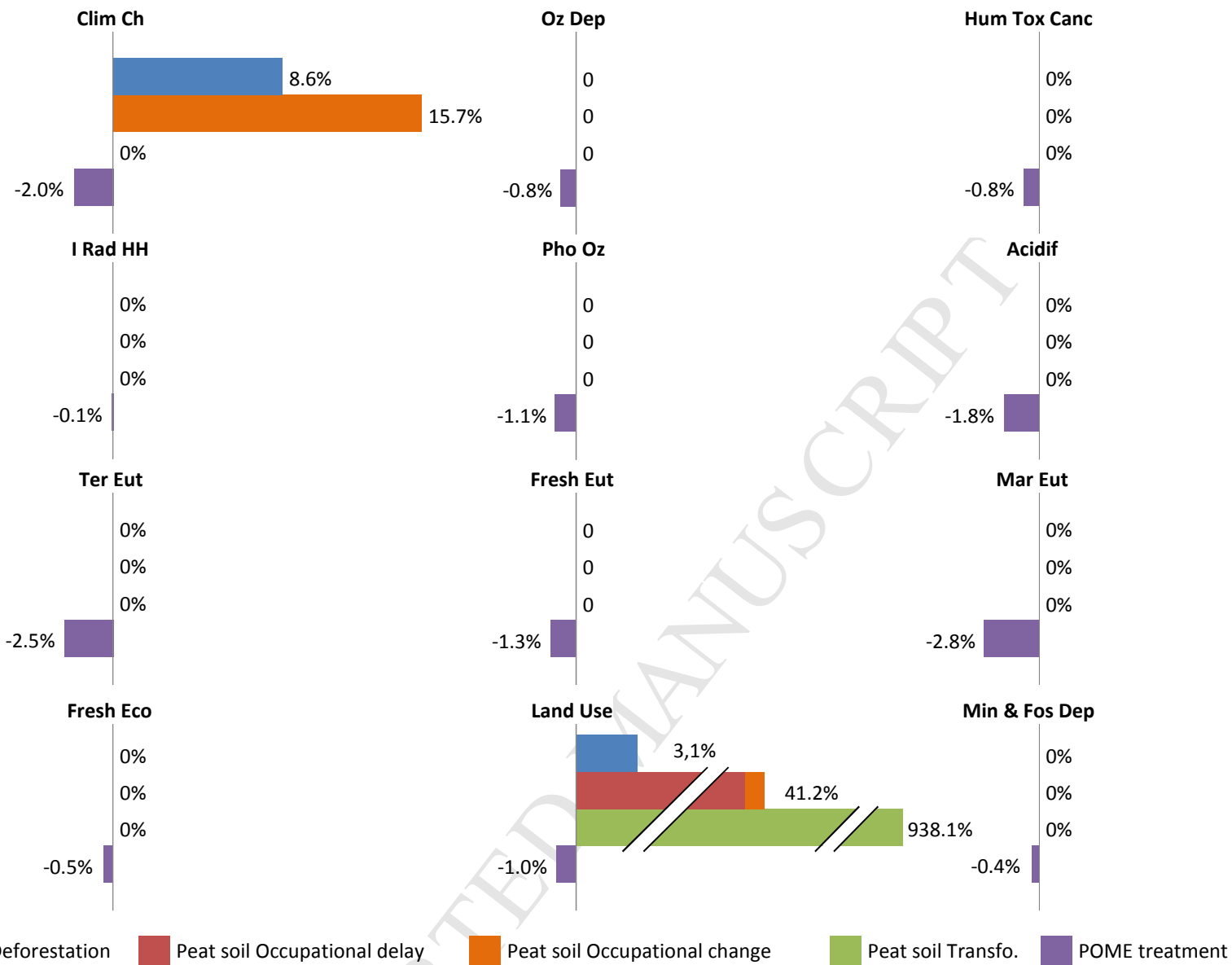


Fig 4: Influence of deforestation, peat soil transformation, peat soil occupation, POME treatment

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Highlights

- Transport and packaging contribute the most to all impacts over the cream life cycle
- Refined Palm Kernel Oil represents on average 20% of this total impact
- Deforestation increases Climate Change by 12% and Land Use impact by 6%
- Peat soil occupation increases Climate Change by 22% and Land Use impact by 84%
- Improving palm oil mill effluent treatment reduces impacts by 1.49% on average

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