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Upgrading agrifood co-products via solid fermentation yields environmental benefits under specific conditions only

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Abstract

Transforming residual biomass into edible ingredients is increasingly promoted to alleviate environmental impacts of food systems. Yet, these approaches mostly rely on emerging technologies and constrained resources, and their environmental benefits remain unclear. By combining process-based consequential life cycle analysis, uncertainty assessment and biomass resource estimation, we quantified the impacts of deploying waste-to-nutrition pathways, here applied to agrifood co-products upgrading by solid-state fermentation (SSF). The benefits of reducing soybean meal's demand by enhancing feed's protein concentration through SSF do not compensate for the environmental burden induced by the process on climate change, water depletion and land use. Besides unlocking feed markets to low-feed-quality streams, SSF outperforms energy valorization for most environmental impacts, but is less competitive to mitigate climate change. Yet, SSF yields overall environmental benefits when unlocking food markets rather than supplying feed and energy services. Systematic methodological harmonization is required to assess the potential of novel ingredients, as outcomes vary according to the displaced food and feed baskets, and related land use changes accounting.

Main text

Introduction

To comply with future food demand while remaining within an environmentally safe zone¹, solutions that capitalize on locally available resources²⁻⁴ and enhance decoupling of food production from arable land (through the production of novel food and feed ingredients, for example) are increasingly promoted⁵. Indeed, multiple pathways to derive edible ingredients from underexploited locally available resources already exist, or are emerging⁶. Such resources, here encompassed under the generic term "residual biomass", include organic waste (e.g. manure), residues (e.g. primary crop and forestry residues) and agrifood co-products⁷. By presenting a relatively high local availability and nutritional quality, agrifood co-products are well positioned to provide not only novel food and feed, but also bio-based alternatives to molecules, materials and energy^{4,8}.

Agrifood co-products embrace a large variety of streams generated along the primary (e.g. pea pods) or secondary (e.g. bakery scraps) transformation of crops into food and beverage commodities. Although their generated volumes and current valorization strategies are context- and region-dependent, most agrifood co-products already support food systems through their integration into livestock diets^{9,10}. In France, for instance, around 60% of the agrifood co-products generated are already reused in livestock diets (**Fig.1**), including 85% of the food-grade streams (e.g. bran, offal)¹¹. Among the emerging valorization techniques, solid-state fermentation (SSF) proposes to nutritionally upgrade these agrifood co-products^{12,13}.

SSF is based on the colonization of a solid substrate by a biological agent which, in the case of feed applications, enhances or even unlocks the nutritional value of fibrous streams, mainly through

43 lignocellulose degradation, detoxification, protein concentration and digestibility enhancement^{14–17}.
44 Applied to streams already complying with food regulation (e.g. fruits peels and pomaces), SSF aims to
45 improve organoleptic properties and consumer attractiveness of the resulting output ingredients^{18,19}.
46 By unlocking or improving the nutritional services provided by local agrifood co-products, SSF could
47 reduce the production of resource-intensive commodities and therefore diminish global land pressure.
48 Yet, it remains unknown whether the implementation of SSF pathways to supply ingredients for the
49 food and feed markets can yield environmental benefits compared to other valorization pathways. In
50 fact, there is an acknowledged lack of environmental assessments for novel food and feed^{20,21}, which
51 is particularly true when it comes to low Technology Readiness Level SSF pathways. Even if upgrading
52 towards food and feed is in line with common valorization hierarchy guidelines^{4,22}, resource recovery
53 might also generate environmental impacts offsetting expected savings^{23,24}.

54 To assess the conditions under which SSF can sustainably be used as an alternative valorization option
55 for agrifood co-products, we performed a process-based life cycle assessments (LCA) of four
56 valorization pathways on a panel of six representative agrifood co-products streams. France was set
57 as the geographical scope, being the country that creates the highest agricultural throughput in the
58 EU²⁵, and is legally committed towards a circular economy²⁶. Due to market similarities the insights
59 drawn from this study are seen valid at the EU level.

60 Results

61 **Fig. 1 (Panel A)** presents the agrifood co-products resource potential for France. Streams are
62 currently mainly generated by the cereals, sugar and vegetable oil sectors (ca. 3-4 Mt_{DM}.y⁻¹ each) and
63 mostly supply feed markets. The potential of SSF to upgrade these streams was compared against
64 conventional valorization pathway supplying feed and energy markets in a unified LCA framework (**Fig.**
65 **1; Panel B**).

66 **Fig. 1 – Conventional and alternative management practices for agrifood co-products**

67 Net LCA results (**Fig. 2**) suggest that upgrading as food (SSF_{food} pathway), when possible, is the most
68 environmentally performant agrifood co-products management option for all assessed impacts except
69 for freshwater eutrophication, while energy and nutrients recovery (AD pathway) is the worst option.
70 When targeting feed markets, the nutritional enhancement of agrifood co-products (SSF_{feed} pathway)
71 does not yield any environmental benefits compared to direct feeding (CF pathway), except for
72 freshwater eutrophication, but to a minor extent. Yet, the key processes and parameters shaping the
73 results and the ranking of valorization scenarios differ among the case studies and impact categories.
74 These are further described.

75 **Fig.2 – Environmental impacts of four agrifood co-products management practices**

76 **SSF upgrading performance**

77 The main prospect of the SSF_{feed} pathways to increase environmental savings in comparison
78 to direct feeding (CF) was to modify the composition of avoided feed ingredients (**Fig. 3**). However,
79 avoided feed mix after SSF either (i) did not perform environmentally better than the originally avoided
80 feed mix or (ii) performed environmentally better but corresponding benefits were offset by the
81 additional SSF processes (mainly drying and sterilization; **Fig. 2**). Indeed, fungal consumption of fibers
82 and sugars systematically led to a net decrease in dry matter (DM) by ca. 18% (ranging 8-28%) of the
83 fermented substrate (**Fig. 3**). Although it increased the volumes of avoided protein feed by ca. 90%
84 (ranging 0-311%) compared to direct feeding (CF), SSF reduced the nutritional energy value of the
85 fermented stream by ca. 24% (ranging 0-47%; **Fig.3**). It means that the fermentation of agrifood co-

86 products, while allowing to avoid more soybean meal than CF pathways (in average $+49\text{kg.t}_{\text{ww}}^{-1}$, for the
87 six case studies), generated an additional demand of maize (i.e. less quantities are avoided; in average
88 $-58\text{kg.t}_{\text{ww}}^{-1}$). For most impacts assessed, avoiding more soybean than maize production is desirable;
89 marginal soybean meal is in fact over two-fold more impactful than maize on a weight basis (mainly
90 due to LUC and soybean processing operations, see **SI**). However, this does not apply for the water
91 depletion category, marginal soybean meal (mainly rainfed) being more efficient than maize by weight
92 for this impact (**SI**).

93 **Fig. 3 – Effects of SSF on ingredients avoided by agrifood co-products incorporation into feed**

94 As reflected in avoided and induced effects of **Fig. 2**, the benefits of avoiding more soybean meal did
95 not compensate the additional impacts generated by the SSF processes. For climate change, SSFfeed
96 achieved additional savings compared to CF of ca. $100\text{-}200\text{ kgCO}_{2\text{-eq.t}_{\text{ww}}^{-1}}$ over the six case studies by
97 avoiding more soybean meal, but generated an additional $150\text{-}550\text{ kgCO}_{2\text{-eq.t}_{\text{ww}}^{-1}}$ due to SSF energy
98 requirements and $50\text{-}150\text{ kgCO}_{2\text{-eq.t}_{\text{ww}}^{-1}}$ by inducing an additional maize demand compared to CF
99 valorization. For the land use impact category, the forecasted role of wood-based electricity
100 production in the marginal power mix canceled the land use benefits of avoiding additional soybean
101 production for SSFfeed pathway, despite its lower yield compared to maize. The presence of wood-
102 based electricity also lowered the net land use performance of CF compared to AD for low digestibility
103 and high moisture streams (here apple pomace). In a nutshell, SSFfeed achieved, over all case studies,
104 net lower environmental performances than CF for all assessed impacts but one, namely freshwater
105 eutrophication. This is due to the interrelation between soybean meal and palm oil, and the
106 phosphates emitted by the wastewater treatment of palm and soy oil refineries. In fact, avoiding
107 soybean meal induces palm oil production to compensate for the soybean oil co-product no longer
108 generated (see **SI**). When avoiding maize, these oil-refineries effects are not involved.

109 The relevance of the SSFfood pathway mainly depends on the quantity and composition of substituted
110 food preparations. Following current marketing strategies²⁷ and to provide a magnitude of the
111 achievable environmental benefits, fermented food ingredients (here flour co-products and apple
112 pomace) were assumed to displace marginal bakery flour (here wheat) on a weight basis. Except for
113 freshwater eutrophication, SSFfood pathways achieved environmental savings up to ten times greater
114 than CF. This reflects that it is preferable to avoid marginal wheat over the mix of marginal maize,
115 soybean meal and palm oil. This particularly applies for water depletion and land use, respectively
116 reflecting the intense irrigation requirements and lower yields of marginal wheat, in comparison to
117 marginal feed supplies. Benefits were reduced, but remain, for impacts where marginal wheat
118 displayed similar performances compared to marginal feed supplies (e.g. climate change). As
119 previously described, the freshwater eutrophication impacts of oilseed crops are greater than those of
120 carbohydrate ingredients, hence why SSFfood did not yield any benefits compared to CF for this
121 category.

122 The contribution analysis revealed that the processes which most influenced the LCA results were
123 related to (i) the performance of fungal fermentation (i.e. protein increase, fibers reduction,
124 digestibility enhancement, etc.), (ii) the impacts of avoided ingredients and (iii) energy requirements
125 (**Fig. 2**). Yet, their importance on the overall environmental performances were tightly related to key
126 parameters of the models, whose influence on the results (intensity, direction) differed from one
127 stream to another and among impacts. The robustness of the LCA results to these sensitive parameters
128 was assessed, and the system's uncertainty characterized (**Fig. 2 and S19**).

129 **Sensitivity analysis**

130 Overall, climate change was the impact that displayed the broadest uncertainty ranges while
131 freshwater eutrophication and land use impacts generally presented negligible ranges (**Fig. 2**). For
132 climate change, this is essentially shaped by the uncertainty related to LUC impacts, here addressed as
133 the share of expansion compared to intensification in response to an additional demand of arable land.
134 This share displays rather scattered values in the literature (calculated here to 55%, but potentially
135 ranging 25-85%; **see SI**). Moreover, the magnitude of LUC-related impacts of a specific food or feed
136 commodity is linked to the yield achieved within marginal supplying regions, which also presents
137 important variations depending on the time frame considered (here 2009-2019). Therefore, besides
138 being responsible for most of marginal ingredients' environmental impacts (particularly for climate
139 change and marine eutrophication, representing respectively 40-95% and 20-60% of total impacts; **SI**),
140 LUC-related parameters were also the ones contributing the most to the system's uncertainty. Initial
141 moisture content highly influenced the performances of wet streams ($>60\%_{\text{moisture}}$), for all pathways
142 and impact categories. In fact, this parameter determined the quantity of matter entering the
143 valorization chain, therefore fixing the magnitude of avoided services (e.g. in **Fig. 3**). The extent to
144 which SSFeed effectively enhances the organic matter (OM) digestibility of fermented substrates
145 (here taken as +15%) was highly variable in the studies reviewed and among streams (ranging from -
146 11% to +30%), hence shaping SSFeed result's uncertainty (**SI**).

147 ***Comparative performance of all assessed pathways***

148 Overlaps between variation ranges between SSFeed and CF pathways mostly occurred for
149 marine and freshwater eutrophication (**Fig. 2**). For the other impacts, results clearly show that SSFeed
150 pathways do not achieve benefits compared to CF, regardless of increased digestibility nor future
151 energy-efficient processes. Overlaps were also found for streams with low digestibility (e.g. apple
152 pomace) where future performances of AD (lower range in **Fig. 2**) might outperform CF and SSFeed
153 pathways for climate change. Yet for the other impact categories, unlocking feed markets to non-feed
154 quality streams through SSF (here olive press-cake) unambiguously yielded net benefits. AD was also
155 confirmed as the worst valorization option for feed-quality streams, regardless of future
156 improvements of this technology (**SI**). Indeed, CF pathways surpassed climate change benefits of AD
157 by ca. $200\text{-}300 \text{ kgCO}_{2\text{-eq}}\cdot\text{t}_{\text{ww}}^{-1}$ for wet feed-grade streams, and up to $600\text{-}1500 \text{ kgCO}_{2\text{-eq}}\cdot\text{t}_{\text{ww}}^{-1}$ for protein-
158 rich and dry streams. The limited climate change benefits of AD pathways for protein-rich streams are
159 partly explained by the trade-offs between the gains in avoided mineral fertilizer due to the N-rich
160 digestate and the resulting increased in N_2O emissions (**Fig. 2**). While AD future developments will
161 likely reduce methane leaks and heat requirements, the present analysis suggests that avoiding feed
162 ingredients would still remain more relevant than avoiding fossil energy. Finally, despite the
163 uncertainty ranges, SSFeed remained the most environmentally performant pathway, under the
164 condition that fermented ingredients do substitute their own weight of marginal flour in human diets.
165 This substitution rate was considered with an uncertainty between 50-100% per weight, but the lower
166 boundary was not enough for SSFeed to perform better than CF pathways in terms of GHG emissions
167 for quality feed streams (e.g. flour mill co-products; **Fig. 2**).

168 ***Implications on agrifood co-products management strategies***

169 The present analysis shows that SSF could improve environmental performances of agrifood
170 co-products management by either (i) unlocking feed markets to non-feed quality streams or (ii)
171 unlocking food markets to food-quality streams. The current widespread valorization of agrifood co-
172 products as feed ingredients in France and Europe²⁸ already generates net environmental benefits by
173 avoiding the production or importation of conventional ingredients. For example, for France, we
174 estimated that agrifood co-products suitable for SSF are currently replacing the equivalent production
175 of ca. $2.8 \text{ Mt}_{\text{ww}}\cdot\text{y}^{-1}$ soybean meal (almost equal to current French imports) and $4 \text{ Mt}_{\text{ww}}\cdot\text{y}^{-1}$ maize

176 (approximatively a third of France production). This represents an avoided annual budget of ca. 14.4
177 MtCO_{2-eq} while total French food system adds up to around 83 MtCO_{2-eq}²⁹. While the nutritional
178 enhancement of these streams through SSF could yield an extra 0.5 Mt_{ww}.y⁻¹ soybean meal avoided,
179 the additional maize demand (ca. +0.9 Mt_{ww}.y⁻¹) combined with SSF processes impacts would lead to a
180 net increase in GHG emissions of the food system ranging between 3-9 MtCO_{2-eq}. On the other hand,
181 a diversion towards energy recovery of feed-quality streams would also generate net GHG emissions.
182 For example, French sugar beet pulp alone (ca. 7 Mt_{ww}.y⁻¹) would yield a biogas production ranging
183 between 5-6 TWh.y⁻¹ (corresponding to 1.2% of current French gas demand³⁰), but diverting their use
184 from CF would induce a market demand for an additional 0.15 Mt_{ww}.y⁻¹ soybean meal and 1.30 Mt_{ww}.y⁻¹
185 maize, leading to a net overall increase of annual GHG emissions of 0.2-2.4 MtCO_{2-eq}. The upgrading
186 of French non-feed quality streams towards feed market would only avoid an additional 0.6 MtCO_{2-eq}
187 (compared to current uses) due to their limited volumes, and our results show that they probably
188 generate greater benefits in terms of climate change if diverted towards advanced AD platforms. For
189 regions with important volumes of non-feed quality streams (e.g. olive presscake in southern Europe),
190 SSF is a promising valorization option to decrease nutrients- and water-related impacts, but state-of-
191 the-art energy recovery likely remains the best strategy to adopt in a climate change mitigation
192 framework. Finally, the apple pomace and flour mill co-products cases showed that benefits of
193 upgrading current use from feed to food through SSF could likely achieve 0-800 kgCO_{2-eq}.t_{ww}⁻¹ net
194 savings. For flour mill co-products alone, SSF food upgrading would lead to annual GHG savings up to 1
195 MtCO_{2-eq} for France. As most agrifood co-product streams are already food-grade or could be food-
196 grade (mainly within cereals, sugar and fruits/vegetables sectors), SSF as a strategy to enhance the
197 attractiveness and organoleptic properties of such streams hosts potential to reduce the
198 environmental impacts of food systems.

199 Discussion

200 We propose a model to forecast future environmental performances of SSF nutritional
201 enhancement, but do not aim to provide an exhaustive picture of SSF potential, where the wide span
202 of enzymes and metabolic abilities of microorganisms can be synergistically combined in co- and/or
203 sequential cultures towards different objectives. For example, as avoiding vegetable oil generates
204 more environmental benefits than avoiding protein feed on a weight basis (**see SI**), SSF nutritional
205 enhancement strategies relying on lipids-producing strains (e.g. yeast *Yarrowia Lipolytica*) could also
206 boost SSF potential. Moreover, SSF techniques are adaptable to a wider span of residual biomasses,
207 such as crop residues^{15,31}. Combining important availability and low-value current uses³², crop residues
208 upgrading towards ruminant feed through SSF is also a key area of research¹⁴. Our transparent and
209 replicable evaluation method systematically estimates environmental performances and key
210 parameters of novel food and feed pathways, here illustrated with SSF of agrifood co-products. Yet, in
211 the light of the multi-dimensional aspect of nutrition and sustainability³³, a next version of this analysis
212 could account for all the constraints of feed formulations (e.g. specific amino acids, animal species,
213 stage of life, etc.) to model the exact displaced feed basket³⁴⁻³⁶, here simplified with the ruminant-
214 focused Scandinavian feed unit (SFU) proxy. Similarly, a validation of the forecasted SSF performances
215 with experimental evidences (particularly the *in-vivo* digestibility) could be performed. Downstream
216 effects such as eventual changes in quantity and quality of manure or human excreta were not included
217 in this work. These are not likely to change conclusions regarding SSF feed pathways, but might
218 decrease some benefits of SSF food³⁷. Likewise, substituting another protein feed than soybean meal
219 would not modify the main trends observed (**SI**).

220 As illustrated here for SSF valorization of agrifood co-products, respecting the principles of valorization
221 hierarchy^{22,38} and circular bioeconomy⁴ is a prerequisite to guide towards overall sustainability, but is

222 not enough to support decision for resource allocation. Cradle-to-grave LCA remains required to reveal
223 trade-offs, providing a comparison framework to arbitrate among different value chains. Yet available
224 LCA of novel food and feed still lack harmonization, beginning with their scattered use of system
225 expansion, LUC impacts accounting³⁹, and context-deployment choices (e.g. selected energy mix). A
226 standardized LCA framework tailored to novel food and feed pathways (e.g. building upon the PEFCR
227 guidance in the EU⁴⁰) could further lead to its integration in the broader decision toolbox of funding
228 partners and regulatory agencies. It would represent a step towards concrete implementation of the
229 “one health” approach⁴¹, where subsidies and authorizations are granted to projects not only
230 complying with food safety standards (as for current Novel Food regulation in the EU⁴²), but also with
231 demonstrated ecosystems benefits. Indeed, unraveling the interplays of novel food and feed pathways
232 with the other demand- and supply-side solutions is key to design coherent roadmaps towards
233 sustainable and bioeconomy-integrated food systems. It likely requires the comprehensive integration
234 of process-based LCA, biophysical system modeling² and socio-cultural empirical evidence⁴³. While a
235 tailored assessment framework is built, policies should be framed to ensure that novel food initiatives
236 (e.g. here SSFfood) support consumers in their transition towards healthy and sustainable diets²⁰,
237 provide enabling conditions for joint collaborations between project promoters and civil society, and
238 stimulate understanding of food and bioeconomy challenges. Moreover, in front of the lack of
239 unconstrained alternatives to plant-based proteins to sustainably supply a growing livestock demand
240 (**SI**), long-term policies should guide efforts towards downscaling and retailing livestock systems to
241 make the most of locally-available constrained resources (e.g. non-food-grade co-products)⁴⁴.
242 Downscaling meat consumption will synergistically reduce land usage conflicts, liberating space to fuel
243 the transition towards low-fossil carbon sourcing of other sectors (e.g. energy, materials).

244 This study proposed the basis for standardized modelling of novel food and feed pathways,
245 applied to the nutritional enhancement of agrifood co-products through SSF. We showed that SSF is a
246 promising agrifood co-product valorization option when allowing increased marketability and
247 consumer’s desirability of food-grade streams. Yet, when not food-grade and as far as climate change
248 mitigation remains a top priority, direct inclusion of agrifood co-products within livestock diets (CF)
249 remains the most suitable option or, for low-feed-quality streams, their energy valorization (AD). Next
250 step should expand this analysis to a wider span of low- and mid-TRL competing waste-to-nutrition
251 solutions (e.g. insect farming, single cell proteins, etc.) to highlight how and under which conditions
252 such emerging value chains can help the food system meeting its sustainability goals.

253 **Methods**

254 **Modeling of SSF performance**

255 SSF as a valorization option for agrifood co-products is of low-TRL, with scattered available
256 experimental data (see **SI**). To explore the potential of nutritional SSF pathways, a simplified fungal
257 growth model was established with the ideal assumption that (i) increase in protein content, (ii) lignin
258 and fibers degradation and (iii) increase in digestibility can be achieved simultaneously while usually
259 trade-offs between these effects are reported¹⁵. This choice was made to reflect an optimistic range
260 of SSF techniques future improvements (best case), and is seen valid as the predicted results followed
261 the trend of experimental values (**SI**). Key performances indicators of fungal growth (energy
262 coefficient, degradation indexes, change in organic matter digestibility, etc.) were derived from a
263 literature benchmark of the strain *Pleurotus Ostreatus*. Only the degradation of cellulose,
264 hemicellulose and free sugars were considered to be effectively used for the fungal growth⁴⁵.
265 Substrate-dependent fungal development was modeled through the use of stoichiometric
266 heterotrophic cell growth equations combined with mass balance, in a parametrical modular fashion
267 allowing to flexibly vary the key parameters (**SI**). The N required for fungal growth was assumed to be

268 supplied through the addition of ammonium sulphate, a food-grade mineral N salt⁴⁶. To
269 homogeneously model fungal protein enrichment among all the co-products, the fungus was
270 considered to metabolize the mineral N supplied only, without using the proteins originally present in
271 the substrate. While this assumption appears valid for low-protein co-products (**SI**), it represents an
272 ideal behavior regarding protein-rich co-products, see **SI**. The estimation of all the energy and material
273 flows required for SSF process covers the whole value chain, including the standardization of moisture
274 and nitrogen content, the fungal seed preparation, the anoxic fermentation after sterilization, and
275 finally the drying and feed pelletizing stages.

276 Selection of the case studies

277 Quantities, composition and current uses of French agrifood co-products were gathered by
278 cross-checking and harmonizing data of several French as well as international specialized institutions
279 and biomass composition data catalogues (details in **SI**). Over the 93 different agrifood co-products
280 identified nation-wide, only streams (i) complying with EU feed legislation, (ii) considered as
281 unavoidable²² and (iii) hosting a lignocellulosic matrix (required for *Pleurotus spp.*) were initially
282 considered. The biological efficiency (BE; proxy of feedstock' suitability for fungal growth, expressed
283 in $\text{kgDM}_{\text{fungi}} \cdot \text{kgDM}_{\text{feedstock}}^{-1}$) was calculated for each agrifood co-product, and only streams yielding a BE
284 higher than 2% qualified. Case studies were further defined to encompass the three upgrading
285 possibilities of SSF: (i) give low feed-quality streams access to feed markets, (ii) enhance the nutritional
286 value of streams currently used as feed ingredients and (iii) unlock food markets to current feed-grade
287 streams. For case (i) and (ii), the selection criterion was based on the potential of SSF to substitute
288 soybean meal. Indeed, soybean meal is the feed ingredients whose substitution is the most prioritized
289 in Europe (and France), as being associated with deforestation^{2,47,48}. Avoided soybean meal was
290 estimated based on the Scandinavian Feed Unit (SFU) proxy⁴⁹. Similarly used in e.g. Tonini et al (2016)⁵⁰
291 and Vural Gursel et al (2021)⁵¹, the inclusion of agrifood co-products (as generated or after SSF) in
292 animal diets was assumed to displace a mix of three ingredients: (i) soybean meal, (ii) palm oil, (iii)
293 maize. These ingredients are respectively the fastest growing (i.e. marginal) source of (i) feed proteins,
294 (ii) feed lipids and (iii) feed carbohydrates, based on last 10 years trend of available global production
295 data⁵² (details in **SI**). The soybean meal substitution potential was calculated for each agrifood co-
296 product and compared with the annual French imports (reference value of $3 \text{ Mt}_{\text{ww}} \cdot \text{y}^{-1}$). Streams
297 qualified for being considered for full LCA if yielding a net potential (SSF minus current use) for avoiding
298 the equivalent of at least 1% of current soybean meal yearly imports. Resulting streams included flour
299 mill co-products, distiller' spent grains (here chosen as corn), sugar beet pulp and canola press-cake.
300 Also qualified, sunflower press-cake was not selected as a case study in its own right because of its
301 similarities to canola press-cake. No streams with current "low value" use (energy and agronomic
302 recovery) were found in significant volumes in France (**Fig. 1**). Indeed, these represent only around
303 19% of generated agrifood co-products (wet basis), and no individual streams yield over $0.2 \text{ Mt}_{\text{ww}} \cdot \text{y}^{-1}$;
304 see **SI**. Yet, to illustrate this possibility, olive press-cake, widely available in e.g. Spain and mostly
305 undergoing bioenergy or biofertilizer valorization⁵³, was added as a case. No specific criterion was
306 defined for the SSF valorization towards food markets. Flour mill co-products (mostly wheat bran) was
307 the only selected stream being currently food-grade, therefore its upgrading as food through SSF was
308 considered. Indeed, SSF of wheat bran is reported to enhance its organoleptic and functional
309 properties, leading to an improvement of its attractiveness as a food ingredient^{54,55}. Additionally,
310 considering the recent advances on fruit and vegetable co-products SSF valorization towards food
311 markets^{27,46,56}, apple pomace was chosen as the last case study (apple being the main fruit produced
312 in France).

313 Life cycle assessment implementation

314 LCA standards (ISO 14040/44:2006)⁵⁷ were followed, applying a consequential modeling
315 approach⁵⁸, recommended to assess feed services impacts⁵⁹. Indeed, the main goal of the study was
316 to capture the long-term induced effects of implementing novel valorization strategies, which is the
317 purpose of consequential LCA methodology⁶⁰. Background LCI data was derived from the ecoinvent
318 v3.7.1. consequential database⁶¹, and only unconstrained resources supplies were considered. The
319 geographical scope was set to France (in line with the case studies definition), which mostly
320 determined the electricity mix, and supplied the legal context with regards to the use of co-products
321 as food and feed. However, most required inputs are internationally traded (e.g. crops, chemicals,
322 fertilizers)⁶². Therefore, these were modeled using ecoinvent's "Global", "Rest of the world" or
323 "Europe" in terms of transportation to France, as well as electricity and production processes used in
324 these locations. The temporal scope was set to reflect current and medium-term conditions for
325 technical performances. Environmental impacts were calculated using the ILCD 2.0 2018 midpoint
326 assessment method, with the open-access LCA software Brightway 2.0 (through the Activity Browser
327 interface)⁶³. The common functional unit to compare all cases was set to: "the management of one
328 tonne of a given agrifood co-product stream per year, delivered at the production site".

329 The deterministic LUC approach established by Tonini et al (2016)⁵⁰ was adapted and updated with
330 latest data on emission factors and deforestation trends. The additional land required per kilogram of
331 crops was estimated based on the weighted average yield of corresponding marginal suppliers from a
332 variety of countries (last 10 years trends from the FAO). Therefore, in this model, differences in LUC
333 impacts between crops are essentially driven by their different marginal yields. To avoid double
334 counting, original LUC impacts were systematically removed (when existing) from the ecoinvent
335 background database, and replaced with deterministic LUC impacts as calculated herein⁶⁴. More
336 detailed explanations on LUC accounting are provided in the **SI**.

337 The LCI of AD pathways (i.e. feedstock-dependent estimation of biogas and digestate production with
338 related emissions) were mainly based on similar works from Hamelin et al (2014)⁶⁵, Bareha et al
339 (2021)⁶⁶ and INRAE Transfert⁶⁷. For digestate's return to soils, nitrogen's mineral fertilizer equivalent
340 (MFE) and related emissions were estimated following the method of Brockmann et al (2018)⁶⁸. MFE
341 for phosphorus was derived from literature^{69,70}, and similar values were assumed for potassium's MFE
342 as a proxy, due to the lack of available data. Land- and storage-related emissions induced by the
343 management of digestate were calculated following IPCC guidelines (2019)^{71,72}.

344 **Global sensitivity analysis (GSA)**

345 The sensitivity analysis consists in steps zero, one and two of the Global Sensitivity Analysis
346 (GSA) method described in Bisinella et al (2016)⁷³; these are (0) contribution analysis, (1) one-at-a-time
347 parameter analysis and (2) uncertainty propagation. The choice of this method is further detailed in
348 the **SI**. As a result of step (0), sixteen process-based parameters were selected and assessed in step (1).
349 Only parameters yielding an average absolute result change of 3% for an initial 10% variation (SSF
350 pathway) were selected for step (2). After setting a probability distribution for each selected parameter
351 (**SI**), sensitivity coefficients, sensitivity indexes and analytical uncertainties were calculated for each
352 set of (parameter; pathway; case study) combinations to derive coefficients of variations of the results
353 (i.e. range of uncertainty). A process-based global sensitivity analysis for the AD pathway was out of
354 the scope of this work as the focus was rather given to nutritional services. However, for the robustness
355 of the comparison, ranges for AD pathways were quantified based on the higher and lower values of
356 four simulations (two different biogas valorization scenarios, each developed within two contexts). The
357 reference scenario (in **Fig. 2**) consists in valorizing the biogas through *in-situ* combined heat and power
358 generation (CHP) while the alternative scenario considers biogas upgrading and grid injection for
359 transport services. These two scenarios were simulated using (i) currently reported performance

360 parameters and (ii) optimistic (forecasted) performance parameters likely to represent future AD's
361 efficiency. Finally, the sensitivity of the results to feedstock's initial biochemical composition was also
362 estimated, but not displayed in the main manuscript as not yielding any additional relevant
363 information.

364 The full methodological details as well as background data and references are available in **the**
365 **supporting information (SI)**.

366 **Data availability statement**

367 The datasets generated during and/or analyzed during the current study are available in the dataverse
368 repository, <https://doi.org/10.48531/JBRU.CALMIP/C2X512>

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377 **Author contributions statement**

378 U. Javourez: Conceptualization, Data curation, Formal analysis, Investigation, Methodology,
379 Visualization, Writing – Original Draft.

380 E.A. Rosero Delgado: Conceptualization, Data curation, Formal analysis, Investigation, Methodology,
381 Writing – Review & Editing.

382 L. Hamelin: Conceptualization, Methodology, Funding acquisition, Resources, Supervision, Validation,
383 Writing – Review & Editing.

384 **Competing interests statement**

385 The authors declare no conflict of interest.

386 **Tables**

387 **Figure legends / captions**

388 ***Fig.1 legend***

389 *Panel A: Agrifood co-products resource potential for France were compiled by regionally relevant*
390 *agrifood sectors (individual streams detailed in SI). High value current uses include reuse as food,*
391 *petfood, within cosmetics or pharmaceutical sectors, while low value current uses mostly include*
392 *energy and agronomic recovery. Streams from the meat sector are not reused as animal feed in France*
393 *due to current low acceptance and the Animal By-products EU legislation¹⁰. Panel B: Four valorization*
394 *pathways for agrifood co-products streams: SSF pathways supplying human food (1) and animal feed*
395 *(2), direct inclusion in livestock compound feed (CF; 3) and anaerobic digestion (AD; 4). CF is*
396 *representative of current agrifood co-products valorization pathways, while AD was selected to*
397 *represent near-future low-value uses (energy) due to its forecasted role to supply renewable gas in*
398 *France and Europe^{26,27}. Pathways 1-3 introduce ingredients to food and feed markets, therefore*
399 *avoiding the production of conventional commodities and related land use changes (LUC). Similarly,*
400 *AD's digestate and biogas avoid respectively fertilizer and energy services. All models were built on a*

401 literature benchmark, and were flexibly designed to be process parameter- and feedstock composition-
402 dependent. The functional unit for all case studies was defined as “the management of one wet tonne
403 of a given agrifood co-product stream per year, delivered at the production site”. Detailed unit
404 operations and process flow diagrams are available in the SI. Dotted lines illustrate avoided products
405 or services, while full lines illustrate induced ones.

406 **Fig.2 legend**

407 LCA results for the four valorization pathways were calculated considering as an input one tonne (wet
408 basis) of a given agrifood co-product stream. The 16 International Life Cycle Data system (ILCD) 2.0
409 2018 midpoint indicators were assessed (available in the SI), but only the five tightly related with food
410 systems^{28,29} and most contributing to the single normalized and weighted score are detailed here (see
411 methods). The process contribution breakdown highlights the effects of unit operations on the overall
412 performance of the valorization chain pathway. Impacts above zero are induced, while those below
413 zero are avoided (savings); the red diamonds represent the net impacts. For each stream and impact
414 category, the best performing valorization pathway is the one displaying the lower net environmental
415 impact (i.e. lower red diamond). However, when net results display overlapping variation ranges
416 (calculation detailed in the methods section and SI), no conclusions can be drawn. The reference
417 scenario for AD (i.e. red diamonds and process contribution) was modeled considering current reported
418 performances of biogas valorization through in-situ combined heat and power (CHP) production
419 (details in SI). The six streams were selected based on their importance in terms of resource potential
420 for France and to have a representative panel of initial composition, digestibility, moisture and current
421 use (top; see methods). Being already food-grade, only apple pomace and flour mill co-products (mainly
422 bran) were considered for the SSF food pathway. As olive press-cake does not currently supply animal
423 feed markets, the CF pathway was not simulated for this stream.

424 **Fig.3 legend**

425 For each stream, the biochemical composition “as generated” was derived from the literature. The
426 effects of SSF on substrate’s composition “after SSF” were simulated based on a simplified model
427 combining fungal growth and mass balance. The food-grade white-rot fungi *Pleurotus ostreatus* was
428 selected as the biological agent, for its established abilities to degrade lignocellulose^{30–32} and its
429 nutritional safety^{33,34}. The N used for fungal growth was considered to be supplied with ammonium
430 sulphate. Detailed in the SI, the model predicts rather optimistic performances when compared to
431 current experimental data (SI; Table S1), but can be seen as representative of future improvements.
432 Then, the compositions of both fermented and unfermented streams were translated in terms of
433 nutritional value (for livestock) based on the Scandinavian Feed Unit proxy (SFU; see SI). The relative
434 importance of proteins, carbohydrates and palm oil (modulated by the digestibility and fibers content)
435 in the calculated SFU allowed to derive equivalents in terms of avoided soybean meal, maize and palm
436 oil for each stream (with and without SSF). These are respectively the marginal supply of feed proteins,
437 energy and lipids (SI). As SSF not only modifies the relative distribution of macronutrients, but also the
438 digestibility and fibers content of biomass streams, not only is their SFU net value after SSF modified
439 compared to their SFU before SSF, but also the relative contribution of proteins, lipids and
440 carbohydrates to determine the SFU value is modified. The functional unit (FU) being defined per wet
441 weight of generated agrifood co-product stream, the initial moisture content strongly shapes the
442 magnitude of avoided feed services.

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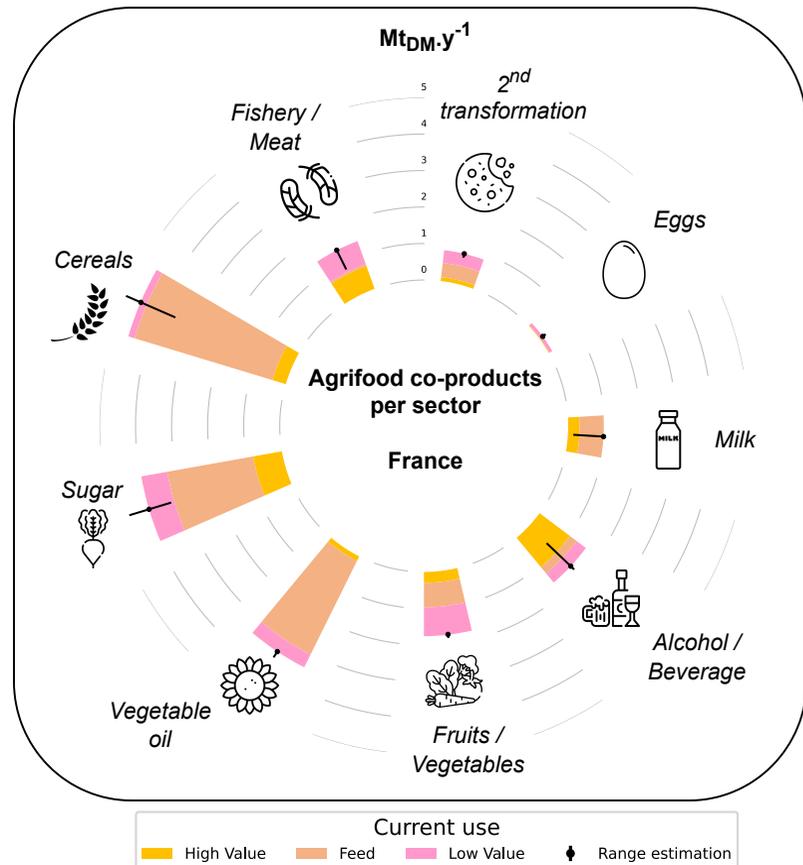
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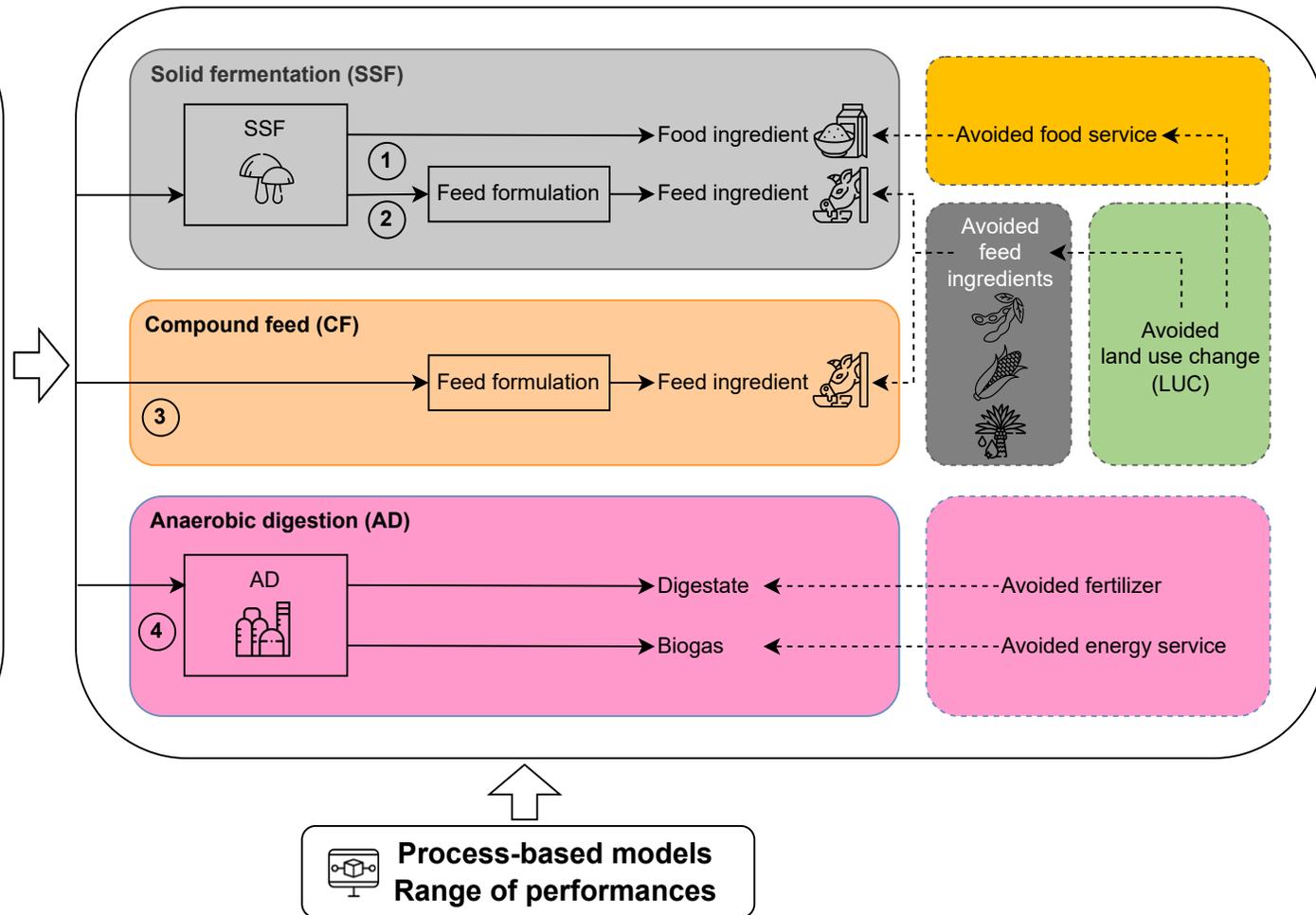
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- 612

A. Resource potential estimation



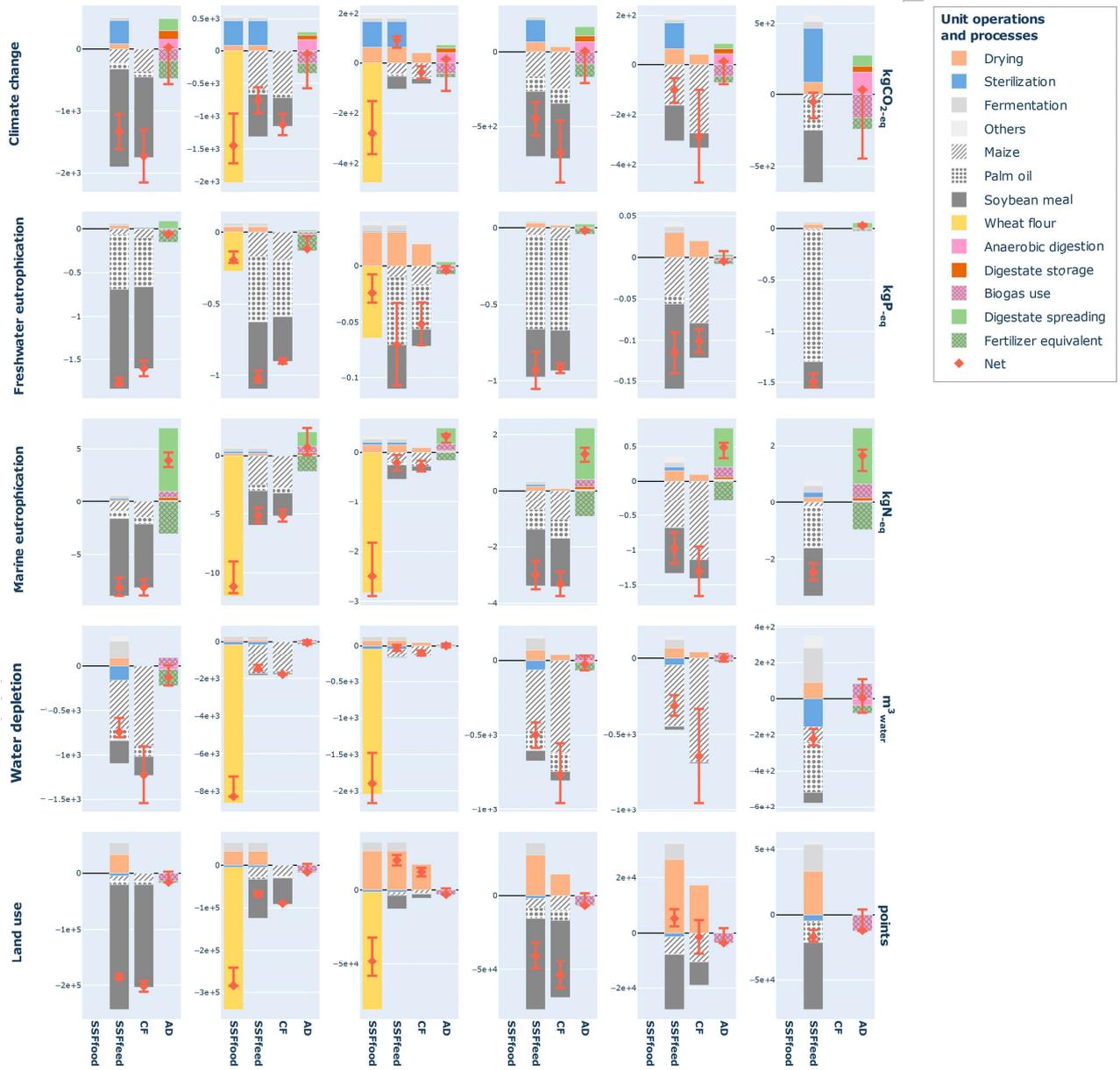
B. Life cycle assessment (LCA) and Global sensitivity analysis (GSA)

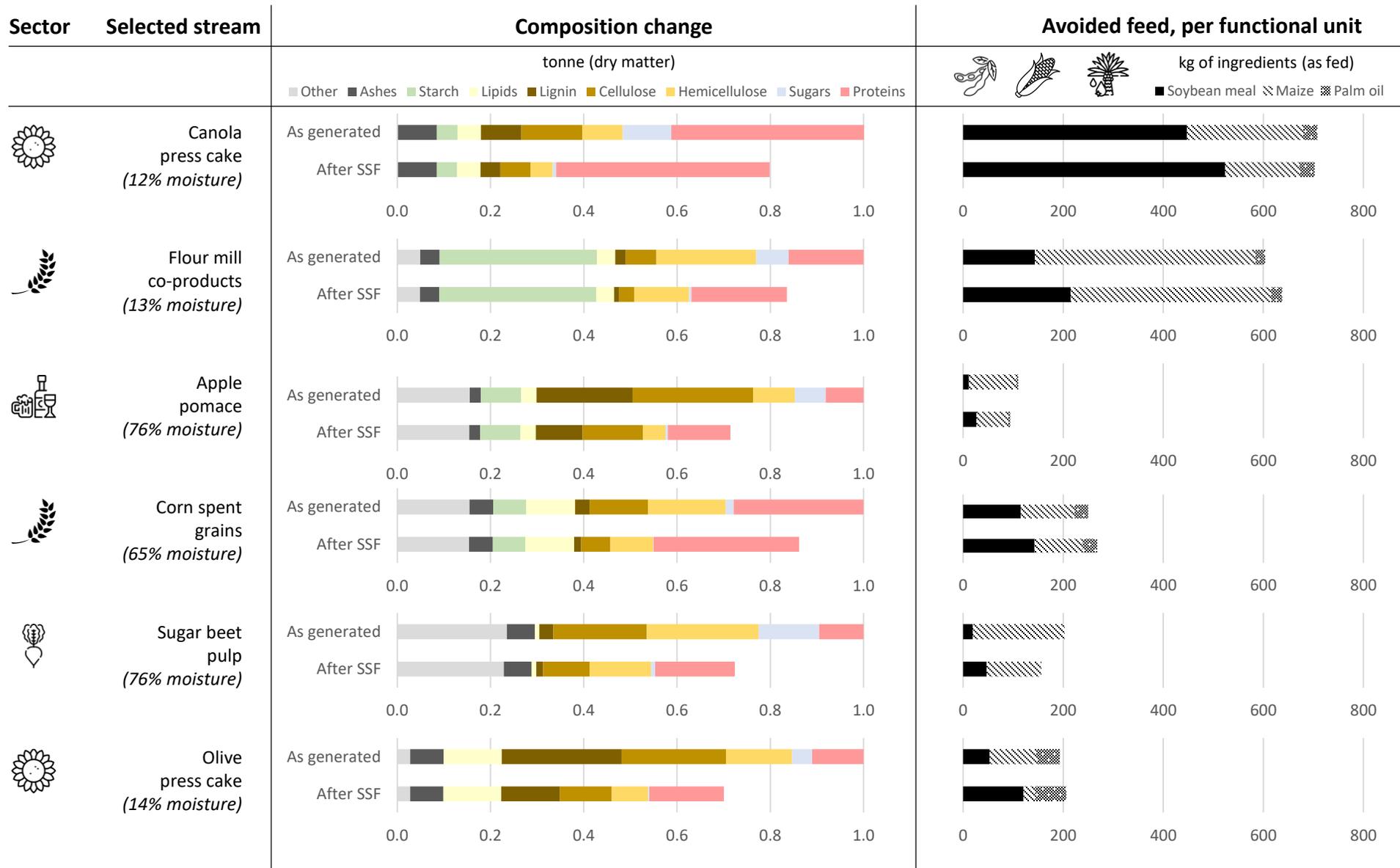


Canola presscake 88 %_{DM} Flour mill co-products 87 %_{DM} Apple pomace 24 %_{DM} Corn spent grains 35 %_{DM} Sugarbeet pulp 24 %_{DM} Olive presscake 86 %_{DM}

Protein content
Digestibility
Moisture

| | | | | | | |
|-----------------|----|---|---|----|---|---|
| Protein content | ++ | + | - | ++ | - | - |
| Digestibility | + | + | - | + | + | - |
| Moisture | - | - | + | + | + | - |





“Other” mainly composed by pectin and non-starch polysaccharides