Can agrifood co-products do better? Life cycle platform for solid fermentation

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Article

Keywords: Bioeconomy, LCA, Fungi, Novel food, Alternative feed, Agro-industrial biomass, Circular economy

Posted Date: March 10th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1373820/v1

Version of Record: A version of this preprint was published at Nature Food on October 31st, 2022. See the published version at https://doi.org/10.1038/s43016-022-00621-9.

Abstract

Solutions towards decoupling food production from arable land are increasingly promoted to alleviate food system's environmental impacts. It includes solid substrate fermentation (SSF), allowing to nutritionally enhance fibrous co-products. Yet, it remains unclear whether and to which extent SSF valorization pathways really improve environmental performances of agrifood co-products in comparison to current practices. Using a framework which combines process-based consequential life cycle analysis, uncertainty assessment and biomass resource potential estimation, we quantify and qualify implications of SSF nutritional enhancement through six selected case studies. When used to unlock food markets, SSF yields environmental benefits for all impact categories. When used to unlock feed markets (low-value streams), SSF pathways are preferable options compared to energy valorization for most impacts except climate change. We show that the environmental impacts of novel food and feed are principally dependent on avoided crops and land use change accounting methods, these requiring further and systematic harmonization.

Full Text

Achieving generalized and significant changes of current food system is essential, not only to meet environmental targets, but also to comply with future food demand[1,2]. Therefore, reducing the dependence on crop importations by developing locally sourced commodities and enhancing the decoupling of food production from land are levers to mitigate food system's environmental impacts[3,4]. Among these solutions, "waste-to-nutrition" pathways, transforming organic wastes, residues and co-products into edible ingredients, are increasingly promoted[5]. In this study, we assess the conditions under which fungal solid substrate fermentation (SSF) can sustainably be used as an alternative valorization option for agrifood co-products.

SSF is based on the colonization of a solid substrate by a biological agent which, in the case of feed applications, allows to enhance or even unlock the nutritional value of fibrous feedstocks, mainly through lignocellulose degradation, proteins concentration and digestibility enhancement[6–9]. Applied to feedstocks already complying with food regulation (e.g. fruits peels), SSF are reported to improve organoleptic properties and consumer attractiveness of the resulting output ingredients[5,10]. Agrifood co-products include a large variety of streams generated along the transformation of crops into food and beverage commodities traded by agrifood industries (e.g. vegetable oil, sugar facilities, etc.). On one hand, these streams already sustain the food system through their integration in livestock[11,12] and human diets albeit only 15% of food-grade co-products (e.g. bran, offals, etc.) are estimated to effectively be reintroduced in food markets[13]. On the other hand, these organic streams are also considered to represent an underexploited quality feedstock to support the shift towards low-fossil carbon economies (e.g. bioeconomy)[14,15] by providing biomolecules, biomaterials or bioenergy[13,16]. Accordingly, there are three ways SSF could improve environmental performances of agrifood co-products management: (i) by unlocking feed markets to (currently) non-feed-related streams, (ii) by enhancing the nutritional value of streams already used as feed ingredients and (iii) by upgrading feed-grade biomasses towards food markets.

Life cycle assessment (LCA) is a leading tool to analyze the environmental performances of emerging technologies and anticipate potential trade-offs[17,18]. This is particularly important for resource recycling or reuse pathways as the processes involved might generate impacts offsetting expected savings[18]. Nevertheless, except one study using LCA methodology to eco-design a SSF nutritional enhancement process for a specific case (surplus bread)[19], identified food- and feed-related SSF valorization LCAs rather focus on mushroom production[20–22]. Therefore, it remains unclear whether and to which extent SSF-driven nutritional upgrading really yields environmental benefits in comparison to current practices.

Accordingly, this study proposes a five-steps framework and parametric tool to quantify and characterize the environmental relevance of SSF for six case studies (**Fig. 1 and Fig.S2-S6)** selected among over 90 different agrifood co-products. The food-grade white-rot fungi *Pleurotus ostreatus* was selected as the biological agent, for its established abilities to degrade lignocellulose[23–25] and its nutritional safety[26,27]. Applied to the scale and context of France in terms of feedstock potential (quantity, composition, current use), the framework, coupling an SSF parametric model to an LCA combined with global sensitivity analysis (GSA) is further detailed in the **methods section and in the supporting information (SI)**. The 16 ILCD 2.0 2018 midpoint indicators were assessed **(SI)**, but only climate change, freshwater and marine eutrophication, dissipated water and land use impacts are presented herein, these being tightly related with food systems[28,29].

Results

SSF upgrading potential

The selection criteria **(methods)** screened (i) flour mill co-products, (ii) distiller's spent grains, (iii) sugar beet pulp and (iv) canola press-cake, for their potential to yield beneficial impacts if nutritionally enhanced by SSF (**Fig. 2**). Also highlighted, sunflower press-cake was not retained as a case in its own right for its similarities with canola. No streams with current energy or agronomic valorization were found in significant volumes in France. Yet, to illustrate this possibility, olive pomace (v) widely available in e.g. Spain and mostly undergoing bioenergy or biofertilizer valorization[32], was added as a case. Wheat bran, the major component of flour mill co-products (i) is already food-grade. Nevertheless, to complete the upcycling possibilities offered by SSF, apple pomace (vi) was included as the last case, illustrating fruits and vegetables co-products valorization towards food markets[33,34].

SSF induces major changes in composition characterized by an overall decrease of lignin, cellulose, hemicellulose and sugars at the profit of a net increase in protein (**Fig. 3**). As fibers and sugars are consumed, there is systematically a net decrease in dry matter (DM) by ca. 18% [8–28] between the fermented and unfermented substrates. Moreover, the higher the initial share of fibers and sugars, the higher the protein increase but the larger the net decrease in DM (**Fig.S8**). For example, flour mill co-products (37% of the DM being fibers and sugars) have an increase of their protein content by 52% and a net decrease in DM by 16%, while these are respectively 128% and 28% for apple pomace (55% of the DM being fibers and sugars). Streams currently used as feed already avoid the use of conventional ingredients (e.g. Figure 1). Yet, as average over all feed-grade co-product streams, 92% [0-311] of additional soybean meal is avoided by using SSF, while avoided maize decreases by 24% [0–47] as a result of fungi's organic matter consumption. A high initial fibers content leads to high increases in avoided soybean meal due to the combination of fiber consumption and protein enrichment: 50% more soybean meal but 9% less maize is avoided after SSF of flour mill co-products (30% fibers), while these are respectively 140% and 42% for sugar beet pulp (47% fibers, **Fig.S10**). By share, the change in avoided soybean meal appears important for protein-poor co-products (e.g. apple pomace) in comparison to protein-rich ones (e.g. canola press-cake, **Fig.S11**), but both translate to a similar quantity of avoided soybean meal post-SSF (overall, ca. 70kg [35–105] per tDM of input). Palm oil substitution is rather low due to reduced lipid content within identified agrifood co-products, and SSF do not significantly change this trend (ca. 4kg [0–10] of additional palm oil avoided per tDM only due to lipids concentration).

Environmental hotspots

Avoided crops induced by the food and feed services provided by agrifood co-products play a major role for almost all the environmental impacts assessed (direct use as compound feed; CF and SSF pathways; **Fig. 4; SI**). For CF pathways, avoided crops impacts represent 90–100% of pathway's total absolute impacts, or 60–70% for high water content streams (e.g. apple pomace, **Table S10**). For SSF pathways, despite the additional processes involved, avoided crops still represent 50–80% of absolute environmental impacts (30–50% for high water content streams). It should also be highlighted that for some impact categories, particularly climate change and marine eutrophication, most of the impact related to crops is associated to land use changes (LUC; respectively 40–95% and 20–60%; **Fig. 4-left, Table S4**). Therefore, the net differences in environmental impacts between CF and SSF pathways are directly related to the extent to which benefits resulting from the increase in avoided soybean meal are compensated by the additional impacts associated to the loss in avoided maize. To render SSF environmentally performant, this difference should at least compensate the intrinsic impacts of SSF processes (mainly drying and sterilization; **Fig. 4-right**). An immediate minimum requirement lies in the necessity for soybean meal to host worse environmental impacts than maize, per kilogram. This is mostly the case, except for dissipated water, as marginal soybean is mainly rainfed (**Fig. 4-left**). Nevertheless, regarding climate change, SSF processes' impacts are shown to offset benefits of displacing avoided feed crops mix (150–550 $kgCO_2$-eq.tww^{-1} generated by SSF processes vs 50–100 $kgCO_2$-eq.tww^{-1} savings due to avoided crops). Generalizable net effects are not clear for marine and freshwater eutrophication. Marginal French electricity production partly relies on wood-based combined heat and power production (CHP) which requires land (consequential background data). Accordingly, SSF's electricity-demanding processes (here drying stage) are shown to totally offset land use benefits of substituting low yield soybean production. Similarly, SSF upgrading towards food market is mainly shaped by avoided impacts of wheat flour production. Marginal wheat flour hosts an impact generally comparable to soybean meal and much higher than all crops for the case of dissipated water (**Fig. 4-left**), reflecting the environmental relevance of its substitution.

Environmental impacts of anaerobic digestion (AD) pathways are a balance between the benefits brought by avoided services (i.e. fertilizers and energy) and leaks. Biogas use (*in-situ* CHP in **Fig. 4**) is generally the most impactful stage with ca. 30–50% average share in total environmental impacts (except for marine eutrophication). The mineral fertilizers avoided through digestate application represent ca. 10–20% of total impacts for nutrients-poor co-products (e.g. olive pomace) while it rises to 30–40% for nutrient-rich co-products (e.g. canola press-cake). Nevertheless, for the latter, gains are partly offset by increased impacts of digestate spreading stage (N- and P- flows to the environment). Regarding climate change, impacts of N_2O emissions during both digestate storage and spreading represent 30% of impacts for protein-rich co-products while these fall to 15% for protein-poor ones. For the former, gains in CO_2-eq emissions due to avoided mineral fertilizer represent up to 20–30% of total absolute emissions. Leaks and heat requirements during anaerobic digestion stage (ca. 20–30% of climate change impacts) partly offset benefits brought by biogas valorization. Using AD mainly saves land use through electricity mix substitution (13% wood-based). Marine and Freshwater eutrophication are principally driven by the mineral fertilizer equivalent of digestate and the difference in emission factors between mineral and organic fertilizers (**SI**).

Uncertainty assessment

Processes impacting LCA results the most are related to (i) the performance of fungal fermentation, (ii) avoided crops impacts and (iii) energy requirements (**Fig. 4**). Sixteen parameters related to these three hotspots were screened in the one-at-the-time parameter analysis of the SSF pathways (**Fig. 5; top-right; SI**). Marginal crop yields (P2-P5; in particular soybean), share of expansion vs intensification (P1) in the LUC response and sterilization energy requirements (P13) were the parameters displaying the highest sensitivity ratio (i.e. whose change most influence the LCA results), followed by feedstock's moisture (P15) and drying energy (P14). This sensitiveness differs in intensity and direction from a stream to another, and among impacts. On the other hand, SSF's performance-related parameters have a rather limited influence on the results, with the notable exception of SSF-induced change in digestibility (P16). Indeed, P16 yields the higher sensitivity ratio for SSF pathways, for all co-products and environmental impacts, highlighting the need to build more systematic data collection on this aspect. Overall, climate change is the impact most sensitive to selected parameters while freshwater eutrophication is not significantly affected. This is because flows related to climate change (e.g. CO_2, CH_4, N_2O) are prominent in LUC impacts while flows related to freshwater eutrophication (P) are limited to 1% of applied phosphorus fertilizer.

These sensitive parameters are also associated to a relatively high uncertainty range; for instance, a range of 375–1300 $MJ.tww^{-1}$ is considered for sterilization (P13) and of 25–85% for the future share of expansion vs intensification (P1) (**Table S6**). Marginal yields also display a 30–50% uncertainty mainly depending on future responding producers, except soybean where marginal production is concentrated in few countries (e.g. Brazil) achieving better yields than world's average. Replacement ratio of common wheat flour by upcycled co-product in human diets (either included in ready-to-eat products or as raw material for consumer) is rather uncertain: it is estimated to range from 1 (baseline) to 0.5, with the hypothesis that a lower substitution rate would be limited by economic considerations. Accordingly, uncertainty regarding food-oriented SSF pathways is mainly driven by the uncertainty on flour substitution ratio (measured by sensitivity indexes in **Fig. 5, bottom-right**). Moreover, the important contribution of initial moisture's uncertainty to the overall results' uncertainty for wet co-products (apple pomace, sugar beet pulp and corn spent grains) can be highlighted. For the other co-products, the LCA uncertainty of CF pathways display the widest ranges, mostly resulting from the share of expansion (P1) and marginal maize yield (P4) uncertainties. Regarding feed-oriented SSF pathways, the uncertainty of digestibility (P16) has in most cases, a higher contribution to the LCA uncertainty than the ones related to crop yields (P2-P5). Sterilization (P13) is the parameter which most influence uncertainty on climate change while the share of expansion (P1) mainly influences marine eutrophication variability. The share of expansion's uncertainty does not induce large variability for climate change impacts because of the trade-offs between CO_2 and CH_4 emissions brought by expansion and N_2O emissions brought by intensification, inherent to the way LUC emissions are modeled in this study. Regarding water dissipation, the uncertainty of initial moisture (P15) and post-SSF digestibility (P16) are shown to shape the overall system uncertainty.

Ranking agrifood co-products management options

Within the 18 cases (3 impacts x 6 co-product) presented in **Fig. 5-left**, eight host overlaps between two or more pathways, which mostly occur for marine eutrophication between feed-oriented SSF and CF. Overlaps (i.e. impossibility to rank pathways) were also found for streams with low digestibility (i.e. apple pomace and olive press cake) where it is not clear if AD performs better than CF and feed-oriented SSF regarding climate change. Apart from these, there is no doubts that AD is always the worst valorization option for most impacts categories (**SI**). Moreover, it is also clear that enhancing the feed qualities of an already edible co-products (CF towards SSF pathway) worsen climate change and dissipated water impact categories, and it is inconclusive whether any benefits are yielded regarding marine eutrophication. This is true regardless of future improvements in sterilization technologies. Nevertheless, SSF as a biotechnology to upgrade feed ingredients towards food markets can generate net environmental benefits for all the impact categories assessed, except freshwater eutrophication. Finally, unlocking feed markets for low quality streams (here olive press cake) yield net benefits regarding marine eutrophication and dissipated water impacts (AD towards SSF pathway). This does not apply for climate change, especially for high moisture and low digestible streams, in front of AD's forecasted performances.

Among the key insights which can be derived from this study, we highlight that the current use of France's lignocellulosic agrifood co-products as animal feed is estimated to replace the equivalent of ca. 2.8 $Mtww.y^{-1}$ soybean meal and 4 $Mtww.y^{-1}$ maize (**SI**). This is close to France's annual importations for soybean meal, and equivalent to slightly less than one third of total France's maize production in 2019

(12.9 Mtww). Cereals and oilseeds co-products are those contributing the most to avoid soybean meal imports (ca. 92% of total co-products). Nevertheless, as showed here, upgrading edible co-products towards food markets instead of feed yield net environmental benefits: the use of fermented flour mill co-products as alternative to wheat flour could save up to 1 $MtCO_2$-eq annually in France (current French food system: 83 $MtCO_2$-eq).

Discussions

Accounting for avoided crops is key to assess environmental performance of novel food and feed, but systematic estimation methodologies are still missing at the light of the multi-dimensional aspect of nutrition and the complex dimensions of sustainability[35]. The estimation used in this study could be complemented by accounting for specific amino acids content and targeting specific animal species and stage of life[36–38] and through its corroboration with feed industry experimental data (e.g. regarding digestibility[39] and palatability[6]) combined with techno-economic assessments. Other important aspects such as downstream effects (e.g. induced change in quantity and quality of manure)[40] were not included. These are not likely to change conclusions regarding the use of SSF for feed, but might decrease benefits of SSF regarding food uses. Albeit key to crop production environmental assessment, LUC-related impacts are still not consistently and widely accounted in LCAs[41] (e.g. **Table S1**). Here we show that LUC strongly influences the environmental gap between crop ingredients. As the magnitude and direction of this gap is the basis on which current strategies to mitigate feed ingredients impacts are based, we call for a better understanding and harmonization of LUC impacts accounting and implications.

Albeit the study focuses on white rot fungus SSF, the use of other microorganisms could yield different results in front of the wide span of enzymes arsenals and metabolic abilities. Particularly, as avoiding palm oil generates more benefits than avoiding soybean meal, nutritional enrichment of agrifood co-products with lipids-producing strains (e.g. yeast *Yarrowia Lipolytica*) is another possibility to assess. Moreover, SSF can upcycle a wider span of residual biomasses, in particular crop residues (e.g. straws)[42]. In this regard, SSF towards ruminant feed is a key area of research as such residues are not as constrained in quantities and are often valorized through low value end-of-life pathways (animal bedding, burning or on-site ploughing).

To conclude, co-products already used as quality feed ingredients achieve net environmental savings compared to energy valorization. In this case, nutritional enhancement through SSF does not allow any additional benefits in front of the net decrease in DM. On the other hand, the entry of low-quality co-products in feed markets through SSF yields positive results for some impact categories, but not climate change. Particularly at stakes are the real effects of SSF on the digestibility of the substrate and the energetic context of the target region/country. Therefore, environmental assessments of agrifood co-products management should include pathways towards food and feed instead of only comparing agronomic and energy valorization pathways. The most promising option (environmentally) to use SSF is to increase marketability and consumer’s desirability of human edible co-products. Nevertheless, further studies should cover dynamics and consequences of both (i) novel food inclusion in human diets and (ii) novel feed inclusions in animal diets to faithfully quantify their environmental relevance. Our results are an additional confirmation to the environmental relevance of common biowaste[43] and biomass[44] management hierarchy guidelines which first promotes prevention and reuse for human consumption, followed by reuse as animal feed before the recovery of other services. Additionally, this work provides a systematic framework to assess the relevance of waste-to-nutrition pathways and highlight its limits in the case of SSF. Further research could integrate a wider span of competing waste-to-nutrition solutions (e.g. insects, single cell proteins) to the framework provided herein, in order to consistently rank their environmental performances and assess their potential in helping the food sector to meet its sustainability goals towards planet-boundaries compliant economies.

Methods

Agrifood co-products resource potential

Quantities, compositions and current uses of French agrifood co-products were gathered by cross-checking and harmonizing data of several French as well as international specialized institutions and biomass composition data catalogues (detailed in the **SI**). The diversity of current uses was captured within three umbrella categories derived from biowaste management hierarchy[45]: (i) high value uses (incl. reuse as food, petfood, within cosmetic sector, etc.), (ii) reuses as animal feed and (iii) low value uses (incl. energy and nutrient recovery).

SSF upgrading potential: model platform

SSF performances estimation for *Pleurotus ostreatus* strain were compiled from a literature benchmark (incl. energy coefficient, degradation indexes, induced change in digestibility; **SI**). Fungal growth was modeled through the use of stoichiometric heterotrophic cell growth equations combined with mass balance, in a parametrical modular fashion allowing to flexibly vary key parameters. The nitrogen initially present in the feedstock is mainly bounded to proteins, which were assumed untouched by the fungus. Yet, the adequate C:N ratio for mycelia growth is met by supplying food-grade ammonium sulphate as nitrogen source to the substrate[46].

Case studies selection criteria

Only streams complying with EU feed legislation were initially considered. Fungal bioconversion efficiency (BE) indicator was calculated with two sets of degradation indexes (min; max) and streams qualified if yielding an average BE value of minimum 2%. Avoided feed crops were estimated following the Scandinavian Feed Unit (SFU) proxy[47]. Similarly used in e.g. Tonini et al (2016)[48] and Vural Gursel et al (2021)[49], the inclusion of agrifood co-products in animal diets was assumed to displace a mix of three ingredients: (i) soybean meal, (ii) palm oil, (iii) maize. These ingredients are respectively the most competitive (i.e. marginal) source of (i) feed proteins, (ii) feed carbohydrates and (iii) feed lipids. For the selection criteria 3 (**Fig. 2**), only soybean meal substitution potential was considered regarding its relevance for France[50], and calculated based on average SFU value of fermented feedstock (min and max degradation indexes).

Life cycle assessment implementation

LCA standards (ISO 14040/44:2006)[51] were followed, applying a consequential modeling[52], recommended to assess feed services impacts[53]. Background LCI data was derived from ECOINVENT 3.7.1. consequential database[54]. The geographical scope is France, and the temporal scope was set to reflect current and medium-term conditions for technical performance (**SI**). Environmental impacts were calculated with the open-access LCA software Brightway 2.0 (through the Activity Browser interface)[55]. The common functional unit to all cases is: "the management of one tonne of a given agrifood co-product stream per year, *ex-works*".

The deterministic LUC approach established by Tonini et al (2016)[48] was adapted and updated with latest data on emission factors and deforestation trends. The additional land required per kilograms of crops was estimated based on the weighted average yield of corresponding marginal suppliers from a variety of countries (last 10 years trend). Therefore, in this model, differences in LUC impacts between crops are essentially driven by their different marginal yields. More detailed explanation on LUC accounting status is provided in the **SI**. To avoid double counting, original LUC impacts were systematically removed (when existing) from ECOINVENT background database, and replaced with deterministic LUC impacts as calculated herein[56].

Life cycle inventories of AD pathways (i.e. feedstock-dependent estimation of biogas and digestate production) were mainly based on similar works from Hamelin et al (2014)[57], Bareha et al (2021)[58] and INRAE Transfert[59]. For digestate's return to soils, nitrogen's mineral fertilizer equivalent (MFE) and related emissions were estimated following the method of Brockmann et al (2018)[60]. MFE for phosphorus was derived from literature[61,62], and similar values were assumed for potassium's MFE in front of the lack of available data. Land- and storage-related emissions induced by the management of digestate were calculated following IPPC guidelines (2019)[63,64].

Global sensitivity analysis (GSA)

The sensitivity analysis consists in steps zero, one and two of the Global Sensitivity Analysis (GSA) method described in Bisinella et al (2016)[65], respectively (0) contribution analysis, (1) one-at-the-time parameter analysis and (2) uncertainty propagation. The choice for this method is further detailed in the **SI**. As a result of step (0), 16 parameters were selected and assessed in step (1). Only parameters yielding an average absolute result change of 3% for an initial 10% variation (SSF pathway) were selected for step (2). After labelling a probability distribution for each selected parameter (**SI**), sensitivity coefficients, indexes and analytical uncertainties were calculated for each (parameter x scenario) combinations to derive coefficients of variations of the results (i.e. range of uncertainty). A process-based sensitivity analysis for the AD pathway is out of the scope of this work as the focus is rather given to nutritional services. However, for the robustness of the comparison, LCA uncertainty ranges of AD pathways were based on the higher and lower values of four scenarios: biogas use in *in-situ* CHP vs gas upgrading and injection in grid for transport services, both modeled with base (current) and optimistic performance parameters likely to represent future AD's efficiency. Finally, sensitivity of the results to the initial biocomposition distribution of feedstocks was also estimated, but not display in the main manuscript as not yielding any additional relevant information.

The full methodological details of this five-steps assessment frameworks as well as background data and references are available in **the supporting information (SI).**

Declarations

Credit authorship contribution statement

U. Javourez: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – Original Draft.
E.A. Rosero Delgado: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – Review & Editing.
L. Hamelin: Conceptualization, Methodology, Funding acquisition, Resources, Supervision, Validation, Writing – Review & Editing.

Competing interests' statement

The authors declare no conflict of interest.

Data availability statement

The datasets generated during and/or analysed during the current study are available in the dataverse repositery, https://doi.org/10.48531/JBRU.CALMIP/C2X5I2

Acknowledgement

This work was carried out within the framework of the research project Cambioscop (https://cambioscop.cnrs.fr), partly financed by the French National Research Agency, Programme d'Investissement d'Avenir (ANR-17-MGPA-0006) and Region Occitanie (18015981). U. Javourez was additionally funded by the Metaprogram GLOFOODS (INRAE-CIRAD) and received financial assistance by Programme d'Investissements d'Avenir (ANR-18-EURE-0021). Dr. Rosero Delgado was funded by the France-Ecuador FSPI program.

Credits

Figures of the present manuscript have been designed using free icons resources from Flaticon.com (authors: Freepik, Eucalyp, Fliqqer, Surang, max.icons, Good Ware, Icongek26).

Abbreviations

AD, Anaerobic digestion; CF, Compound feed; CHP, Combined Heat and Power; DM, Dry matter; GHG, Greenhouse gases; GSA, Global sensitivity analysis; LCA, Life cycle assessment; LCI, Life cycle inventory; LUC, Land use changes; SSF, Solid substrate fermentation.

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Figures

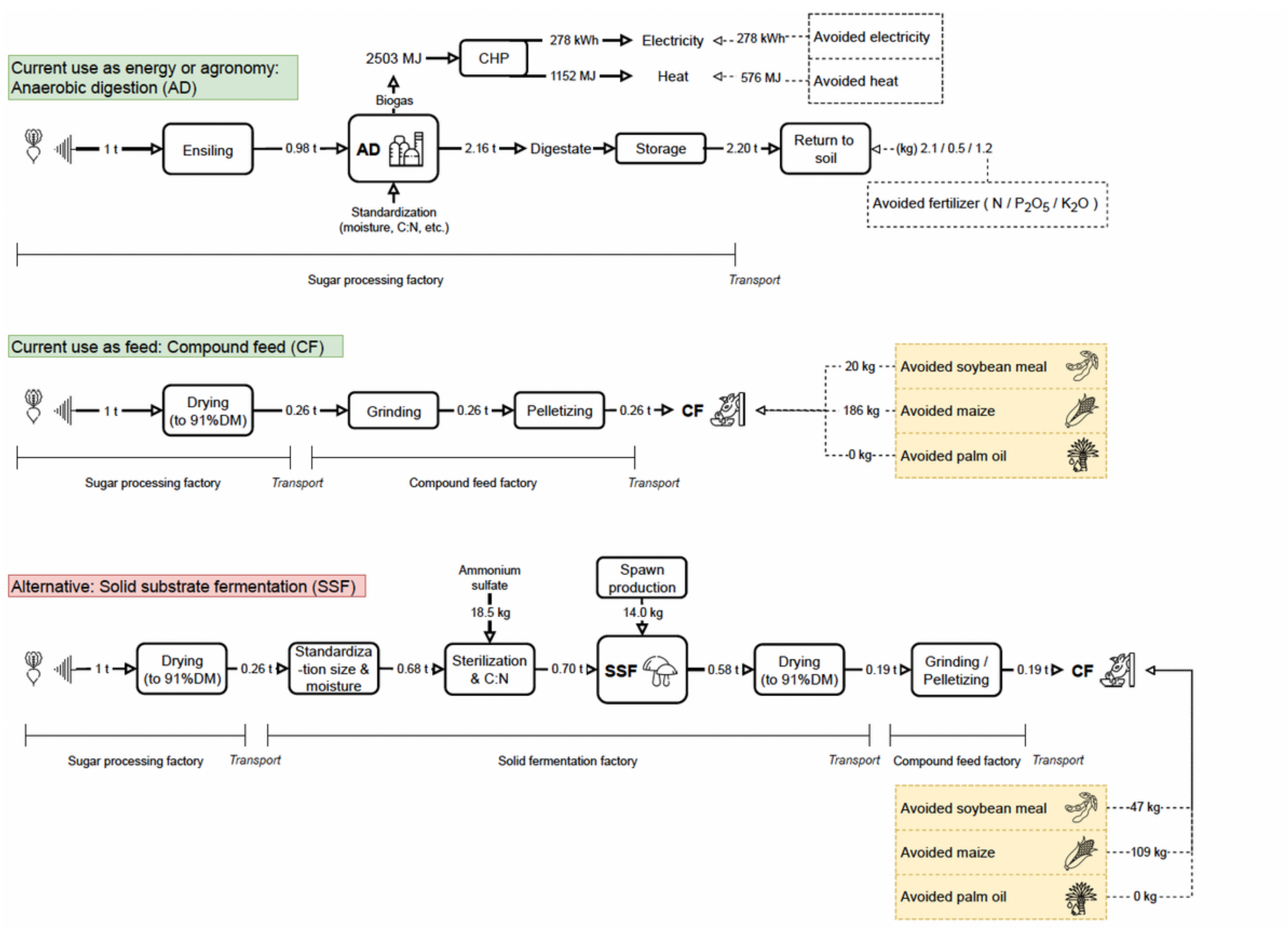

Figure 1

Process flow diagrams: alternative management practices for sugar beet pulp

Baseline modelling of three management options for one tonne of sugar beet pulp (24%DM). The functional unit for all case studies is defined as “the management of one tonne of a given agrifood co-product stream per year, ex-works”. Compound feed (CF) i.e. direct animal feeding and (ii) anaerobic digestion (AD) represents both current and near-future competitive pathways. Indeed, feed markets are already the major destination of France's agrifood co-products (ca. 60%, by wet weight; ***SI****), while AD is part of the global strategy to decarbonize the energy sector in France*[30,31]*.*

Sector	Streams (examples)	Quantity ($MtDM.y^{-1}$)	Current use: high value	Current use: feed	Current use: energy or agronomy	Composition	Criteria 1 (lignocellulosic & unavoidable)	Criteria 2[1] (biological efficiency, %)	Criteria 3[1] (Additional soybean meal avoided, %imports)
Fishery/meat	*Canning co-products, feather, bristle, etc.*		50%	3%[2]	47%	Non-lignocellulosic, mainly proteins and fats (>60%DM)			
Cereals	*Bran, germ cake, distiller's grain, etc.*		9%	88%	3%	Lignocellulosic, with low lignin content (<8%DM)	✓	5.5% [4.0 – 7.1] *Gluten feed is discarded*	**Flour mill co-products** 1.5% [0.3 – 2.8] **Distiller's grains** 1.0% [0.1 – 2.4]
Sugar	*Sugar beet pulp, molasses, etc.*		20%	61%	19%	Lignocellulosic, with low lignin content (<4%DM)	✓	8.5% *Only sugar beet pulp remaining*	**Sugar beet pulp** 3.5% [0.6 – 6.4]
Vegetable oil	*Oilseeds press-cake*		4%	84%	12%	Lignocellulosic, with high protein content (>35%DM)	✓	4.6% [3.0 – 5.5]	**Canola press cake** 4.1% [0.3 – 8.0] **Sunflower press cake** 1.2% [0.1 – 2.2]
Fruits/Veget.	*Pead pods, tomato pulp, starch pulp, etc.*		17%	38%	45%	Diverse, high content of starch or sugars (>40%DM)	✓	6.0% [2.4 – 11.5] *Carrots and potatoes discarded*	
Alcohol/Bev.	*Brewer's grain, grape and apple pomace, etc.*		66%	14%	20%	Lignocellulosic, protein-rich (beer) and lignin-rich (wine)	✓	4.9% [3.2 – 7.6] *Yeast and vinasses are discarded*	
Dairy	*Whey, buttermilk, etc.*		32%	68%	low	Liquid, mainly proteins, and sugars (>80%DM)			
Eggs	*Shell juice, etc.*		16%	20%	64%	High share non-organic (shells)			
Pre-consum.	*Bakery, ready-to-eat and other agroindustries*		13%	46%	41%	Mainly macronutrients (proteins, fats, starch and sugars, >80%DM)			

[1]: here, average value / [2]: low due to Animal By-Products Regulation (EU)

Figure 2

France agrifood co-products resource potential: suitability for SSF valorization towards feed

Background data available in the ***SI****. “High value” current uses include reuse as food, petfood or within sectors such as cosmetics, pharmaceutics. Biological efficiency is a proxy of feedstock's suitability for fungal growth expressed in % ($kgDM_{fungi}.kgDM_{feedstock}^{-1}$). Reference value for French soybean meal imports is 3 $Mtww.y^{-1}$, streams qualify if their upgrading potential exceeds 1% of yearly importations avoidance.*

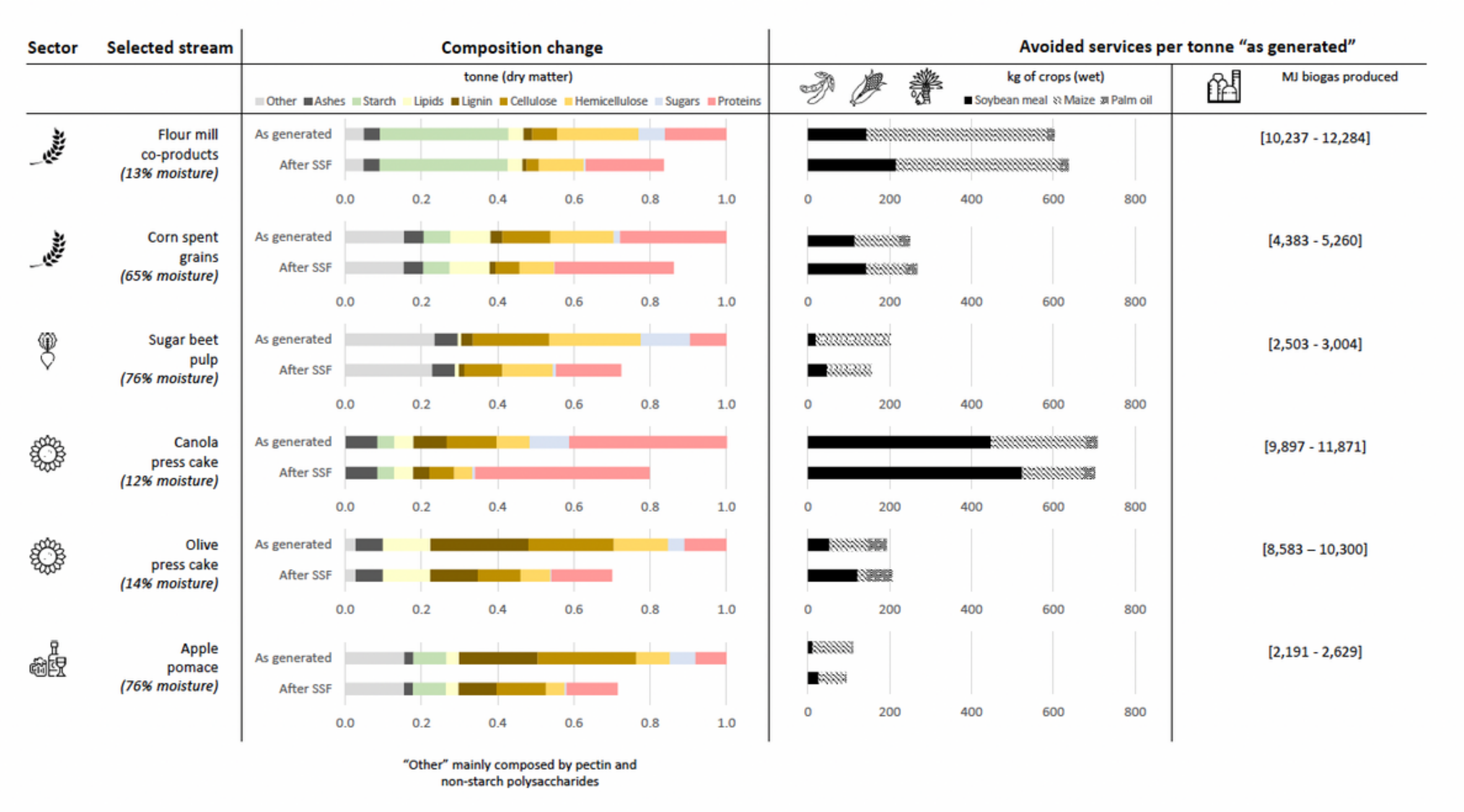

Figure 3

Quantification of avoided services by agrifood co-products

Background data available in the ***SI****. Icons are as defined in* ***Fig.1*** *and* ***Fig.2****. Initial moisture strongly determines magnitude of avoided services. Ranges of biogas potential are estimated by using both current and forecasted performances of anaerobic digestion. Fibers refer to lignin, cellulose and hemicellulose. Avoided crops estimations are based on the Scandinavian Feed Unit (SFU) approach, detailed in* ***SI****.*

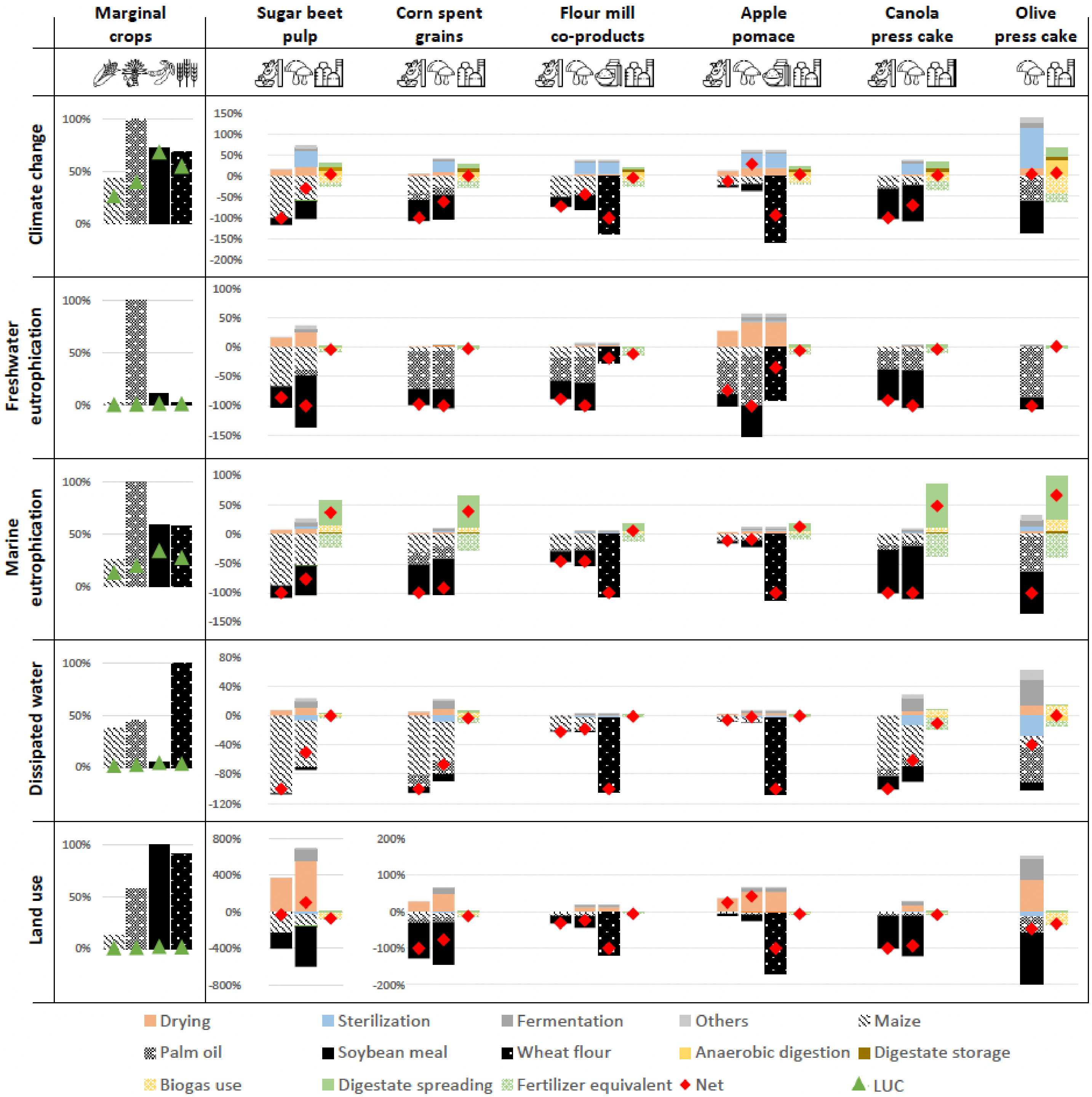

Figure 4

LCA process contribution analysis

*Background data available in the **SI** and icons are as defined in **Fig.1**. In the left-hand side, individual crops impacts are compared (maize, refined palm oil, soybean meal, wheat flour). "LUC" represents the share of the deterministic land use change impacts estimation in total marginal crop impacts. In the right-*

hand side, baseline modeling LCA results of valorization options (CF, SSF towards feed, SSF towards food and AD, depending on specific stream) are normalized and compared.

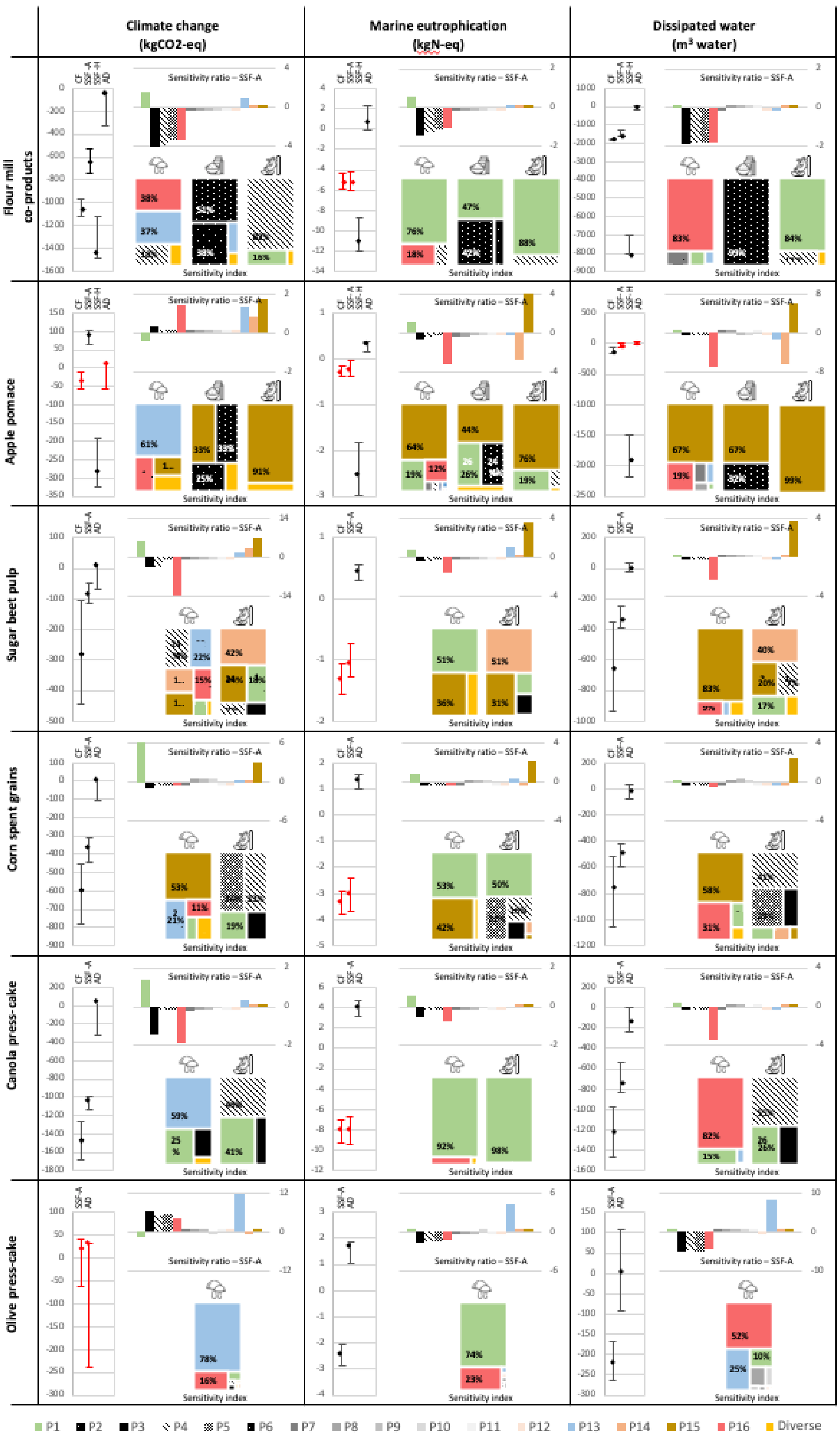

Figure 5

LCA global sensitivity analysis

The four valorization pathways are represented by icons (defined in Fig. 1) and abbreviated as follow: compound feed (CF), animal-oriented SSF (SSF-A), human-oriented SSF (SSF-H) and anaerobic digestion (AD). Sensitivity indexes (i.e. contribution of parameters to overall uncertainty) are displayed for CF, SSF-A and SSF-H pathways. Sensitivity ratios (i.e. sensibility of the results to a given parameter) are only displayed for SSF-A pathways but contemplates the sixteen identified parameters. LCA uncertainty ranges displayed in red are overlapping, therefore no preference between corresponding pathways can be established. See ***method section and SI*** *for details on uncertainty metrics and ranges calculation.*

Parameters for SSF and CF pathways are defined as follows: P1, share of expansion vs intensification response to meet demand of additional arable land; P2-P5, land required to produce one kilo of respectively wheat flour, soybean meal, maize grain and refined palm oil; P6, substitution ratio of wheat flour; P7, fungal energy coefficient; P8-P12, fungal degradation indexes of respectively cellulose, hemicellulose, lignin, sugars and crude fibers; P13-14, energy requirements of respectively sterilization and drying processes; P15, input moisture content and P16, digestibility after SSF treatment.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- 4.Supportinginformation.pdf