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Using olive and apple pomaces for fattening pig diets: Environmental impacts under an attributional and consequential perspective

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ABSTRACT

The livestock sector plays an essential role in anthropogenic greenhouse gas emissions, where fodder crop production has been largely identified as the main contributor to their environmental impact. This research evaluates the attributional environmental impacts of introducing food industry subproducts such as apple and olive pomaces to reduce the proportion of maize grain in the formulation of diets for fattening pigs, according to four alternatives, including the current diet with 69% maize. For this, the life cycle assessment (LCA) methodology has been used to determine the hotspots associated to these changes, considering a cradle-to-gate approach and two functional units: 1 kg of feed diet (FU1) and 1 kg of weight gain (FU2). Furthermore, the potential environmental consequences of using these subproducts for pig diet have also been considered with a consequential LCA methodology. The results show that the best diet was the one containing about 33% maize and 43% subproducts for all categories analysed. In addition, the allocation method used to assign subproduct loads, including mass, economic, and zero-burdens allocation, is crucial to validate the assumptions and recommendations for this strategy. The consequential LCA results suggest that this strategy could involve both positive and negative impacts (considered as environmental credits), depending on the substitutes for the avoided maize stover and the potential displaced bioproducts that could be obtained from these subproducts, mainly for bioenergy production.

1. Introduction

Livestock is one of the critical sectors related to anthropogenic greenhouse gas (GHG) emissions, occupying 75% of agricultural land and consuming 35% of the world grain (zu Ermgassen et al., 2016). Pork is the most widely produced meat in the world, with production increasing fourfold in the last five decades (Zira et al., 2021). China is the first producer with about 48% of its global production in 2022 and is forecast virtually unchanged yearly at 114.3 million tons in 2023 (USDA, 2023). In addition to climate change impacts, pig production drives deforestation in South America, as it relies on soy which accounts for 20% of Brazil's exports to

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the EU (Rajão et al., 2020).

Feed production is responsible for most of the environmental burdens of livestock production, especially in monogastric production systems (de Vries and de Boer, 2010; van Zanten et al., 2018). For instance, Reckmann et al. (2013) and González-García et al. (2015) reported that feeding stage comprised most of the environmental impacts related to the pork supply chain, mainly due to agricultural activities involved in the production of feed components. Four feed ingredients were found as the environmental hotspots: soybean (oil and meal), maize grain, wheat (silage and grain) and barley (grain) (González-García et al., 2015). In this regard, several studies have focused on replacing high environmental impact feed ingredients with lower environmental burdens alternatives, including, for instance, insects (Makkar et al., 2014), legumes (Jezierny et al., 2010), and algae (Holman and Malau-Aduli, 2013). Furthermore, the feeding of food waste to animals has become another relevant alternative in livestock production (Zentek et al., 2013) when it comes to reduce cost related to traditional feed ingredients (Joven et al., 2014). Since every year about 1.3 billion tonnes of edible food are wasted throughout global food supply chains (Alsaleh and Aleisa, 2023), their use as animal feed represents one of the easiest ways to exploit them. Particularly for pigs, food waste has historically been used as livestock feed (zu Ermgassen et al., 2016).

Traditionally, maize grain is the primary energy source in pig diets and its low price and nutritional characteristics encourage its use as feed (McGhee and Stein, 2023). For instance, 60% of maize production going to livestock and poultry in the 2000 s in the United States (Klopfenstein et al., 2013). In the last years, the global price of maize grain has experienced a significantly growth in the market. Its price rise from 165.6 to 318.4 $\$\cdot t^{-1}$ in the 2020–22 period on average (Federal Reserve Bank of St. Louis, 2023). This could be explained, firstly, by the Ukraine-Russia war, since Ukraine is one of the world's leading agricultural producers and the fourth largest exporter of maize (USDA, 2022); secondly, due to the price changes for key agricultural commodities such as fertilisers that doubled their values between June 2021 and July 2022 (Arndt et al., 2023).

The literature suggests that the use of apple pomace (AP), a by-product from the apple manufacturing sector, and olive cake (OC) from the olive oil sector, can be used in pig diets due to their higher content of soluble proteins (Ajila et al., 2015) and insoluble fibre (Ferrer et al., 2018). As remarkable examples, Egea et al. (2021) identified that using OC in up to 10% of the pig diet, increased the unsaturated fatty acid profile and water holding capacity of the meat and Steyn et al. (2018) evaluated replacing maize with dried apple pomace in cows feeding. Recently, Hernández et al. (2023) evaluated the joint use of AP and OC to replace maize grain in the diet of fattening pigs, obtaining acceptable values for growth factor and carcass quality, and providing a healthier lipid profile in fat tissues.

To evaluate the environmental implications of a new feeding strategy, the life cycle assessment (LCA) is a well-known methodology that allows to estimate the potential environmental burdens of products or services throughout their life cycle (ISO, 2006). This standardised tool has been used to determine the environmental impacts of feeding strategies such as replacing soybean meal with rapeseed meal in pig diets (Van Zanten et al., 2015); the use of local protein feed production compared imported protein feed for pig meat and dairy milk produced in Sweden (Sasu-Boakye et al., 2014); or determine the land use change emissions in the carbon footprints of fattening pig diets (Meul et al., 2012). These studies addressed an attributional LCA (A-LCA) approach, which aim is to determine the environmental loads attributed to the pig diet; however, this approach does not address in detail the consequences of implementing such strategies (van Zanten et al., 2018). For this purpose, the consequential LCA (C-LCA) approach can be used. The UNEP-SETAC Life Cycle Initiative, supported by the United Nations (UNEP-SETAC, 2011), establishes that "*the consequential approach attempts to provide information on the environmental burdens that occur, directly or indirectly, as a consequence of a decision*". Few studies evaluated the environmental consequences of changing livestock diets. Nguyen et al. (2013) evaluated switch maize silage-based to grass-based dairy systems. Van Zanten et al. (2014) assessed the GHG emissions and land use for increasing the use of wheat middling and beet tails in diets of dairy cattle and van Zanten et al. (2018) explored two cases of replacing soybean meal with rapeseed meal and with waste-fed larvae meal in diets of fattening pigs.

The aim of this research is to determine both the attributional and consequential environmental impacts of the use of olive and apple pomace as replacements of maize grain in the pig diets during the fattening stage. The focus on fattening pigs is motivated as they use about 60% of the total feed in the pig production chain (Van Zanten et al., 2015). To do this, three potential diets proposed by Hernández et al. (2023) are analysed, and compared with the current feed pig diet. In this regard, this work contributes to assessing the environmental viability and consequences of promoting the valorisation of agro-industrial subproducts in a circular economy framework to reduce dependence on maize grain in a context where food security is fundamental in the climate crisis.

2. Materials and methods

2.1. Scenario definition

A total of four scenarios were analysed based on a previous study of Hernández et al. (2023). The control diet (CD) is the conventional feed diet provided to fattening pigs in the meat company, and three alternative diets (D1, D2, D3) which consist of the combination of olive cake and apple pomace to reduce maize grain dependency. The composition of the four diets under study are presented in Table SM1 in the Supplementary Materials. According to the above mentioned research, the nutritional content of agro-industrial residues consists of a gross energy of 2232 and 3704 $kcal\cdot kg^{-1}$ in apple pomace and olive cake, respectively. In terms of dry mass, about 75% of crude fibre was observed in apple pomace, and about 74% in olive cake. In addition, the crude protein was nearly 1.4% and 10.7% in the apple pomace and olive cake, respectively.

Based on the analysis carried out in Hernández et al. (2023), the feed was supplied in a period of 63 days until pig reached the market weight (100 - 110 kg). The amount of feed intake was about 152, 185, 222, and 200 kg in the control, D1, D2, and D3 diets, respectively. Furthermore, the weight gain was 61.3, 54.8, 59.5, and 61.3 kg in the control, D1, D2, and D3 diets, respectively.

The three alternative diets were formulated making sure that they were iso-protein and iso-energetically balanced, maintaining the nutritional requirements for pigs (see Table SM2). Fresh feeds were prepared every two days to avoid putrefaction due to the high moisture content of these subproducts (about 87% in apple pomace and 56% in olive cake), whereas the control diet was prepared every seven days (Hernández et al., 2023). The apple and olive pomace are obtained from apple and olive oil processing plants, both in the region of Maule, Chile, respectively. Regarding the preparation of the feeding diet, a drying process was not required, and the ingredients were directly mixing in a blender equipment for 10 min.

2.2. *Attributional LCA*

To determine the potential environmental impacts of the feeding diets, the LCA methodology was used following the ISO 14040 principles (ISO, 2006).

2.2.1. *Aim and scope*

The first step is to define the objective and scope of the study. As mentioned previously, the aim is to determine the environmental burdens of a new alternative feeding diet that combines agro-industrial subproducts: apple pomace and olive cake, to replace maize grain. This research follows a cradle-to-gate approach (see Fig. SM1 in the Supplementary Materials); thus, it considers stages from the raw materials extraction, crop cultivation, food processing until feeding preparation. Furthermore, two functional units (FUs) were selected for reporting the environmental burdens of pig diets. The first one (FU1) was 1 kg of feed diet, and the second one (FU2) was 1 kg of weight gain.

2.2.2. *Life cycle inventory*

The transport of the subproducts was considered from the processing plants to the facility where diets were prepared, which was an agricultural company located at Molina, Maule Region, Chile (35°07′30.5" South latitude and 71°16′12.7" West longitude). The distance for the apple pomace, olive cake and the maize grain was 31.9, 14.2, and 21.1 km, respectively. The electricity production was modelled considering the mix generation of Chile during 2021, where sources were 33% coal, 14% solar, 13% hydraulic, 12% natural gas, and 9% eolic, among others (CNE, 2022).

The inventory of the apple juice production was taken from the research conducted by Cheng et al. (2022). The orchards and the apple processing plant are in Romeral, in the Central Valley of Chile. Similarly, the olives are located next to the processing plant. Thus, the transport of fresh apples and olives to the processing plant was discarded. In addition, an economic allocation method was used to distribute the loads in the processing stage between the apple juice product and the pomace. An average market price of 1.5 $\$\cdot kg^{-1}$ for the apple juice during the period 2018–2022 (ODEPA, 2023) and 0.01 $\$\cdot kg^{-1}$ for the pomace were considered according to the processing company reports. The annual production yield of the apple juice and pomace subproduct was 2.9 kt and 4.0 kt, respectively.

Regarding olive pomace, its inventory data was obtained from the work carried out by Rajaeifar et al. (2016), adapting background processes to the Chilean context (e.g., electricity generation mix). As with apple pomace, an economic allocation method should be used to distribute the loads between olive oil and pomace. As olive pomace is currently not sold but left in olive groves, no loads were attributed to this subproduct (in other words, all loads are allocated to olive oil). However, a mass allocation and a potential economic allocation (considering allocation factors of 5%, 10% and 20%) were also considered as sensitivity analyses.

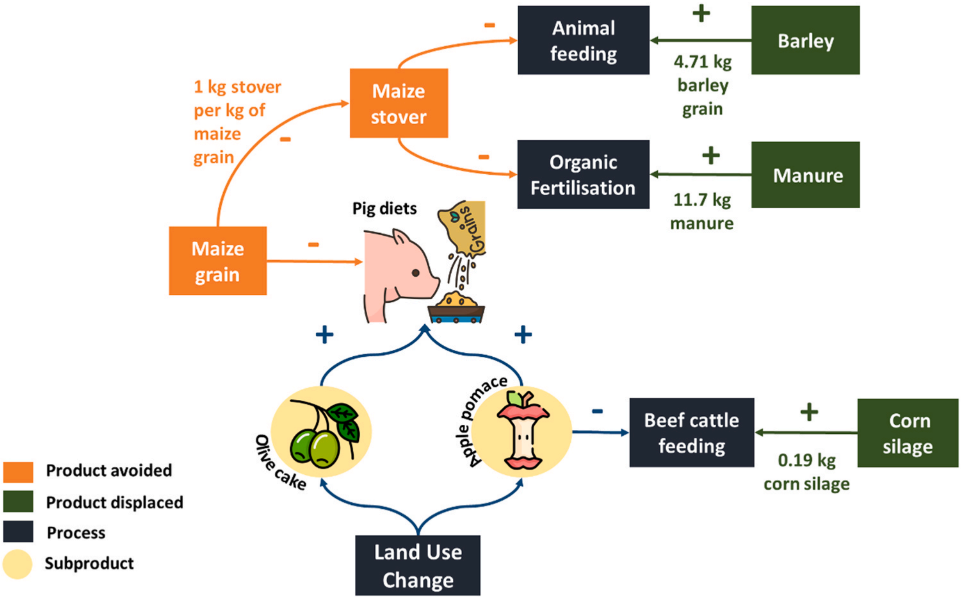
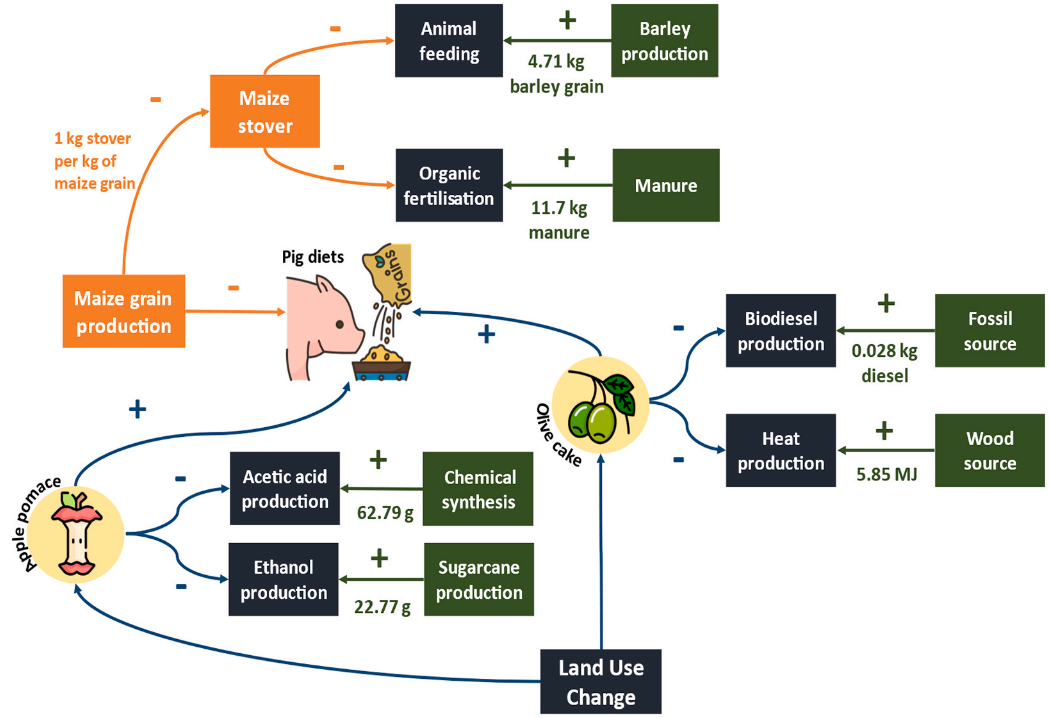


Fig. 1. System boundaries in the C-LCA approach for the baseline scenario.

The background processes were taken from the Ecoinvent® v3.8 (Wernet et al., 2016) and the Agri-footprint® v6 (2022) (Blonk Agri-footprint BV, 2015) databases. The latter was used particularly for obtaining the inventory data of the soybean bran subproduct (i.e., hulls), which correspond to one of the products (besides crude oil and meal) generated from the soybean processing sector. Furthermore, this inventory process assumes an economic distribution with an allocation factor of 2.9% for the bran. The dataset

a) Boundaries of C-LCA of potential displaced bioproducts



b) Boundaries of C-LCA using maize grain for PLA market

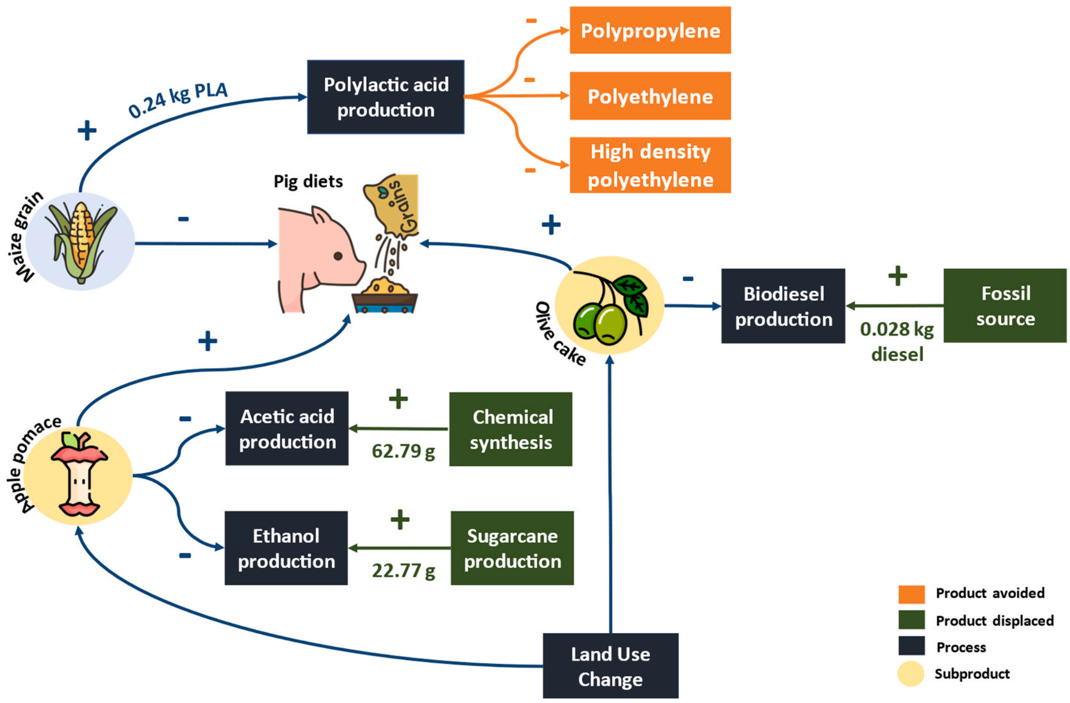


Fig. 2. Boundaries of C-LCA for potential displaced bioproducts.

corresponds to a manufacturing process from Argentina, but it was adapted to Chilean context (e.g., electricity generation mix).

From the composition diets in Table SM1, the ingredients such as antioxidant, furocycline 4.4%, Activate AD (protein), dicalcium phosphate and formicid® (preservative) were not available in the databases, so they were not considered. Nevertheless, their contribution is marginal as they represent (together) a share of less than 0.5% of the total diet.

2.3. Consequential LCA approach

Consequential approach also begins with the definition of the FU (i.e., 1 kg feed diet) and the system boundaries (cradle-to-gate). The latter includes the processes affected by a decision, mainly referring to changes in the product demand or supply (Schaubroeck et al., 2021). The aim is to determine which unit processes are affected by a change introduced through the functional unit and their causal relationships (Bello et al., 2022). As a consequential LCA only considers the changes, only the consequences related to those feeding ingredients of which the use changed were considered (van Zanten et al., 2018). Hence, the cause-effect events analysed were focus on the change of maize grain by apple and olive pomaces (see Fig. 1), considering only diet D1 since it presents the highest reduction of maize grain. The C-LCA approach was performed through the four-step procedure proposed by Bjørn et al. (2018), and it is described in the Supplementary Material.

2.3.1. Land-use change emissions

GHG emissions due to land use change (LUC) were also considered, which are those generated from transforming the original use of land into a different one. They are named as indirect (iLUC) and direct (dLUC). iLUC emissions occur when an occupation of land for food (or fodder) crops is converted to feedstock production (maintaining the demand of the previous land use), requiring offsetting this land capacity elsewhere. dLUC emissions are those generated when is modified the land use for a new one, leading to potential changes in carbon stocks (Cherubini, 2010). Here, iLUC emissions were estimated using the model proposed by Tonini et al. (2016), where two sources of additional land demand are considered: land expansion (i.e., deforestation) and intensification of land use. According to Tonini et al. (2016), the proportion of crop production change for the expansion of cultivated area and the intensification land use is 25% and 75%, respectively. The emissions related to the expansion land consider changes in carbon (C) and nitrogen (N) flows. In the case of intensification, it considers the growth use of N, phosphorus (P) and potassium (K) fertilisers, and their field emissions. For more details, please see Tonini et al. (2016). More details about iLUC emissions are available in the Supplementary Materials. Regarding the dLUC emissions, they were not accounted for since the production of apple and olives are traditional economic activities in the region analysed, so it was assumed that there was no change in land use in the last 20 years.

2.3.2. Sensitivity analysis: bioproducts and bioenergy displaced

The consequences of shifting products in the market are highly complex and dynamic. The interest of bio-based economy models has motivated the use of subproducts for elaborating value-added products (e.g., biochemicals) or producing bio-based energy. Consequently, the use of apple pomace and olive cake for pig diets could restrict the development of potential bio-based markets that depends on these feedstocks. The effects of these displacements were identified as follows (see Fig. 2**a**):

i) Olive cake: It can be pressed again for a second oil extraction (Joven et al., 2014) and can be valorised as biodiesel (Rajaeifar et al., 2016). Furthermore, olive cake can also be used as fuel for producing heating energy in a cogeneration system (Fernández-Puratich et al., 2021).
ii) Apple pomace: It can be used as feedstock for producing ethanol (Hernández et al., 2021; Parmar and Rupasinghe, 2013) or organic acids such as acetic acid (Vashisht et al., 2019).

In this regard, four sensitivity scenarios were analysed: i) maize stover substituted by barley with OC displaced in heat generation and AP for acetic acid, called MB-HA; ii) maize stover replaced by barley with OC displaced in diesel production and AP for ethanol production, called MB-DE; iii) maize stover as organic fertiliser (i.e., substituted by synthetic fertiliser) with OC displaced in heat generation and AP for acetic acid, called MF-HA; and iv) maize stover used as organic fertiliser with OC displaced in diesel production and AP for ethanol production, called MF-DE.

2.3.3. Shifting maize grain for bioeconomy models

Previously, the analysis was addressed considering the growing demand for subproducts and the assumption of a potential reduction in the maize grain production (i.e., avoided production). Here, we analysed the hypothesis of whether the remaining fraction of maize grain in pig diets can be used as a feedstock for other bio-products that are in high demand in the market. Accordingly, two scenarios were evaluated focusing on bioproducts and biofuel generation (see Fig. 2**b**):

i) Bioplastics: maize grain could serve as feedstock to produce polylactic acid (PLA), which avoid the production of fossil-based counterpart such as polypropylene (PP), polyethylene terephthalate (PET), and high-density polyethylene (HDPE) (Kim et al., 2022).
ii) Biofuel: The development of the fuel ethanol industry has motivated the use of maize grain as feedstock (Klopfenstein et al., 2013). This could avoid the production of ethanol, for instance, in Brazil which is the second producer of this fuel worldwide (RFA, 2023), and where ethanol is produced mainly from sugarcane, accounting for 99% of the national production (Palazzi et al., 2022).

2.4. *Life cycle impact assessment*

To estimate the potential environmental burdens of the feeding diets, the impact assessment method considered was the ReCiPe 2016 Midpoint (H) v1.07 / World (2010) to obtain the characterisation factors (Huijbregts et al., 2017). The selection of this method was motivated by the fact that it provides characterisation factors representative of the global scale, and it is one of the most widely used because it is frequently updated (Borghesi et al., 2022). The environmental impact categories evaluated were Global Warming - GW (CO_2 eq); Particulate Matter - PM (kg $PM_{2.5}$ eq); Terrestrial Acidification - TA (kg SO_2 eq); Freshwater Eutrophication - FE (kg P eq); Marine Eutrophication - ME (kg N eq); Terrestrial Ecotoxicity - TET (kg 1,4-DCB); Freshwater Ecotoxicity - FET (kg 1,4-DCB); Human Carcinogenic Toxicity - HT (kg 1,4-DCB); Land Use - LU (m^2a crop eq); Fossil Resource Scarcity - FRS (kg oil eq), and Water Consumption - WC (m^3).

3. Results and discussion

3.1. *Attributional LCA results*

Table 1 shows the attributional LCA results for the four diets analysed with both FUs. Concerning the FU1 (i.e., 1 kg feed diet), it is observed that all three diets proposed represent an environmental reduction with respect to the control diet. Furthermore, the diet D1 was the best alternative as it reached the lowest impacts in all categories evaluated. In the GW category, the D1 diet was about 32% lower than the control diet, while a significant decrease was observed in the HT, TA, and WC categories with 50% each, followed by PM and FE with 49%.

The contribution analysis of the pig diets is presented in Fig. SM2 in the Supplementary Materials. The critical contributor in the control diet was maize grain (see Fig. SM2a) which accounted for a range of 21% to 69% of the impacts in the categories analysed. Another relevant contributor was soybean bran in categories such as GW and LU, sharing about 44% and 51%, respectively. Furthermore, although the substitution of maize grain by olive and apple pomaces reduces the loads in the three proposed diets, maize crop is still the hotspot in categories such as PM, TA, and TET above 55%, and in WC category above 65% (see Fig. SM2b-d). The impacts reduction related to maize increase the share of soy bran in the three diets in GW (52 - 58%) and LU (59 - 66%) categories. In addition, the impacts related to apple pomace do not have a relevant contribution as most of the burdens were attributed to the juice product, as well as the transportation of the subproducts is not relevant either, since their origin is close to the farm.

The environmental profile of pig diets with FU2 (i.e., 1 kg weight gain) showed some changes with respect to FU1 (see Table 1), as the control diet was not the worst alternative in all impact categories. Again, diet D1 was the best alternative in all impact categories analysed. Furthermore, the D2 diet is not recommended considering categories such as GW and LU, where it was the alternative with the highest impact, or in the FET and FRS categories where it was close to the impacts of the control diet (around 1–3% lower). The changes in the diet preferences can be explained as the amount of feed intake with diet D2 was the highest of the sample (221.8 kg), but the weight gain did not rise in the same direction, as the ratio weight gain per kg of feed intake was 0.27 in diet D2 (the lowest) and 0.4 in control diet, while in diet D1 was 0.3.

3.1.1. *Sensitivity analysis of attributional LCA results*

To demonstrate the variations in the environmental profile of the feeding strategy due to the selected allocation method, the diet D1 was used here as an example since it was the best alternative previously identified. The profiles of the remaining diets are available in the supplementary materials (see Tables SM17-SM20). Table 2 shows the results of the sensitivity analysis performed based on the two functional units considered. From this, the assumption of a zero-loaded olive cake (ZB) represents the lowest environmental profile using both functional units, where the reductions compared to the control diet were around 32% and 7% with FU1 and FU2 in the GW category, respectively.

A mass allocation (MA) method implies a D1 diet with the highest impact profile (as olive pomace gets an allocation factor of 61%)

Table 1
Attributional environmental profiles of the analysed pig diets.

Impact category	Unit	FU1: 1 kg feed diet				FU2: 1 kg weight gain			
		Control diet	Diet D1	Diet D2	Diet D3	Control diet	Diet D1	Diet D2	Diet D3
GW	kg CO_2 eq	1.02	0.69	0.77	0.82	2.53	2.34	2.88	2.70
PM	g $PM_{2.5}$ eq	1.39	0.70	0.84	0.97	3.45	2.38	3.13	3.18
TA	g SO_2 eq	5.52	2.77	3.32	3.85	13.67	9.37	12.36	12.58
FE	g P eq	0.25	0.13	0.15	0.18	0.62	0.43	0.57	0.58
ME	g N eq	0.79	0.42	0.50	0.57	1.95	1.43	1.86	1.86
TET	kg 1,4-DCB	1.57	0.83	0.97	1.12	3.89	2.80	3.63	3.65
FET	g 1,4-DCB	26.92	15.23	17.69	19.87	66.73	51.53	65.93	64.98
HT	g 1,4-DCB	6.52	3.23	3.87	4.51	16.16	10.92	14.43	14.76
LU	m^2a crop eq	1.13	0.77	0.86	0.92	2.79	2.61	3.21	3.00
FRS	kg oil eq	0.13	0.07	0.08	0.09	0.32	0.24	0.31	0.31
WC	m^3	0.08	0.04	0.05	0.05	0.19	0.13	0.17	0.17

Table 2
Sensitivity results of the environmental profile of diet D1.

Impact category	Unit	FU1: 1 kg feed diet						FU2: 1 kg weight gain					
		Diet control	ZB	MA	EA-5%	EA-10%	EA-20%	Diet control	ZB	MA	EA-5%	EA-10%	EA-20%
GW	kg CO_2 eq	1.02	0.69	0.89	0.71	0.72	0.76	2.53	2.34	3.00	2.39	2.45	2.56
PM	g $PM_{2.5}$ eq	1.39	0.70	1.40	0.76	0.82	0.93	3.45	2.38	4.73	2.57	2.76	3.15
TA	g SO_2 eq	5.52	2.77	5.59	3.00	3.23	3.69	13.67	9.37	18.90	10.15	10.93	12.49
FE	g P eq	0.25	0.13	1.56	0.25	0.36	0.60	0.62	0.43	5.28	0.83	1.23	2.02
ME	g N eq	0.79	0.42	0.92	0.46	0.50	0.59	1.95	1.43	3.11	1.57	1.71	1.98
TET	kg 1,4-DCB	1.57	0.83	1.35	0.87	0.91	1.00	3.89	2.80	4.57	2.94	3.09	3.38
FET	g 1,4-DCB	26.92	15.23	20.64	15.68	16.12	17.01	66.73	51.53	69.84	53.03	54.53	57.54
HT	g 1,4-DCB	6.52	3.23	6.02	3.46	3.68	4.14	16.16	10.92	20.36	11.69	12.47	14.01
LU	m^2a crop eq	1.13	0.77	1.62	0.84	0.91	1.05	2.79	2.61	5.47	2.84	3.08	3.55
FRS	kg oil eq	0.13	0.07	0.10	0.07	0.08	0.08	0.32	0.24	0.35	0.25	0.26	0.28
WC	m^3	0.08	0.04	0.07	0.04	0.04	0.05	0.19	0.13	0.23	0.14	0.15	0.16

ZB: Zero burdens, MA: Mass allocation, EA-5%: Economic allocation factor of 5%, EA-10%: Economic allocation factor of 10%, EA-20%: Economic allocation factor of 20%.

in all categories with FU2, and in five out of 11 categories with FU1. Here the FE and LU categories were the most affected by the increased relevance of the olive subproduct due to upstream agricultural activities. Compared to the control diet, a mass allocation leads to an increase of about 19% in the GW category when FU2 is used, while a reduction of 13% (the lowest) was observed with FU1. In addition, increasing the economic value (and consequently the allocation factor) of olive pomace will raise the environmental profile of diet D1 even above that of the control diet using the functional unit FU2. Therefore, an economic allocation factor of about 10% could be the threshold in most impact categories (except FE and LU) to recommend diet D1 as a better environmental alternative.

3.2. Consequential LCA results

Table 3 presents the environmental impacts of the baseline scenario in the consequential perspective of shifting apple pomace and olive cake for pig diets. From this, changing maize grain by these subproducts does not represent environmental benefits in general (i.e., achieve negative values). The exception occurs only in three categories such as FE when maize stover can be used for feeding, as well as LU and WC categories when maize stover could be substituted with synthetic fertilisers. Overall, the impacts were higher when maize stover needs to be replaced by synthetic fertiliser, as manure is a restricted product.

Fig. 3 shows the contribution analysis of the consequential impacts of displacing demand for apple pomace and olive cake for pig diets. Accordingly, Fig. 3**a** indicates that indirect land use emissions and manure displacement were the main contributors in most of the categories evaluated. As for the former, they were mainly related to the land use for olive and the land expansion. Manure emissions correspond to the production of synthetic fertiliser as manure depends on main products such as meat or milk (i.e., restricted product). Furthermore, the greatest environmental benefits because of avoiding maize cultivation can be seen in categories such as LU and WC. On the other hand, Fig. 3**b** shows that the substitute product (i.e., barley) could represent the major impacts in categories such as ME, HT, LU and WC. In addition, iLUC emissions were the critical point in the GW category, particularly because of the olive crop. Besides, the potential increased demand for maize silage as a substitute for apple pomace in feeding activities does not represent a relevant contribution in both scenarios.

Table 3
Consequential LCA results in the baseline and bioproducts displaced scenarios.

Impact category	Unit	Baseline C-LCA approach		Heat and acetic acid production		Diesel and ethanol production	
		Maize stover for feeding	Maize stover for manure	MB-HA	MF-HA	MB-DE	MF-DE
GW	kg CO_2 eq	0.37	0.89	1.30	1.78	0.34	0.86
PM	g $PM_{2.5}$ eq	0.21	0.47	6.25	6.40	-0.12	0.13
TA	g SO_2 eq	1.95	1.69	7.62	7.21	2.20	1.94
FE	g P eq	-0.30	0.06	1.47	1.78	-0.46	-0.10
ME	g N eq	0.99	0.14	0.94	0.09	0.92	0.07
TET	kg 1,4-DCB	0.86	2.55	1.72	1.61	1.32	3.00
FET	g 1,4-DCB	1.96	10.70	43.77	42.12	0.37	9.11
HT	g 1,4-DCB	8.09	10.14	81.02	76.10	0.35	2.40
LU	m^2a crop eq	0.28	-0.06	0.43	0.08	0.16	-0.19
FRS	kg oil eq	0.03	0.10	0.27	0.32	0.06	0.13
WC	m^3	0.05	-0.02	0.04	-0.02	0.01	-0.06

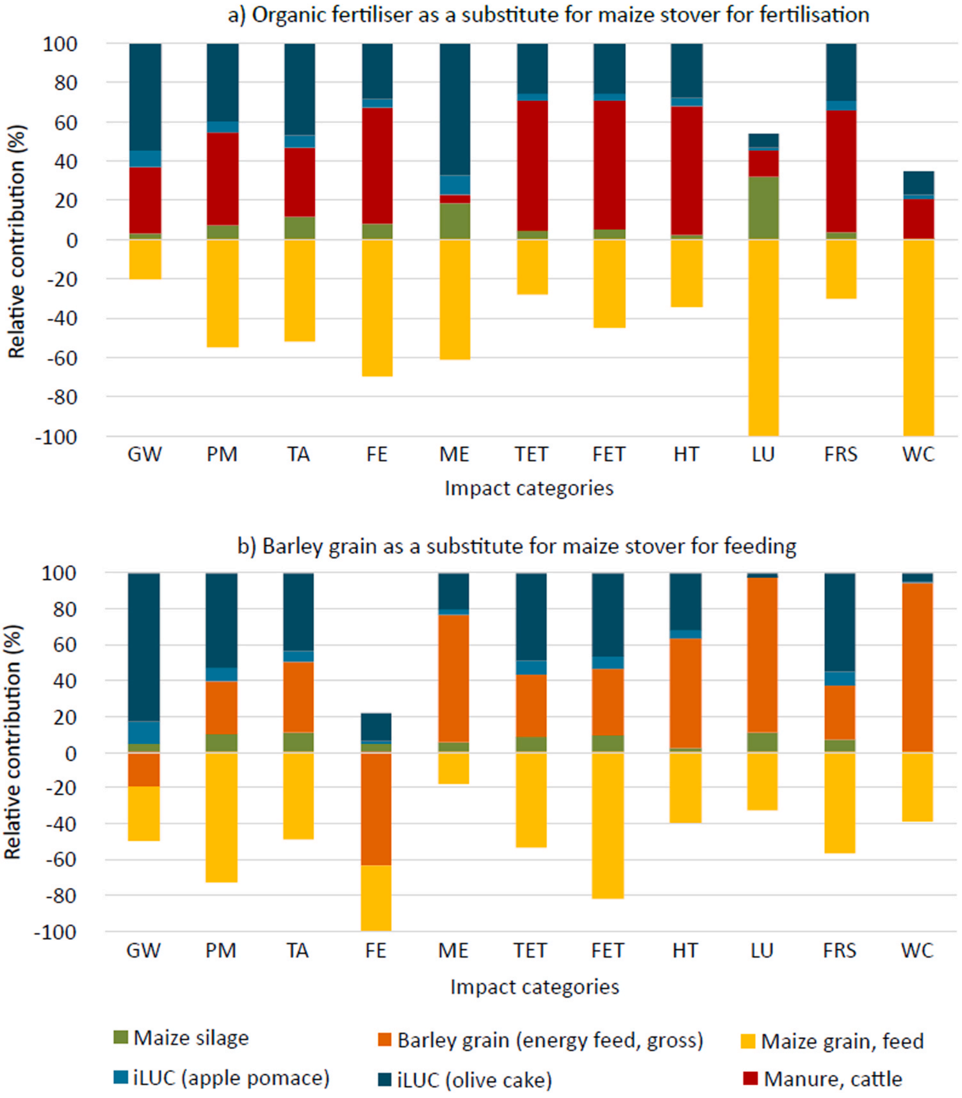


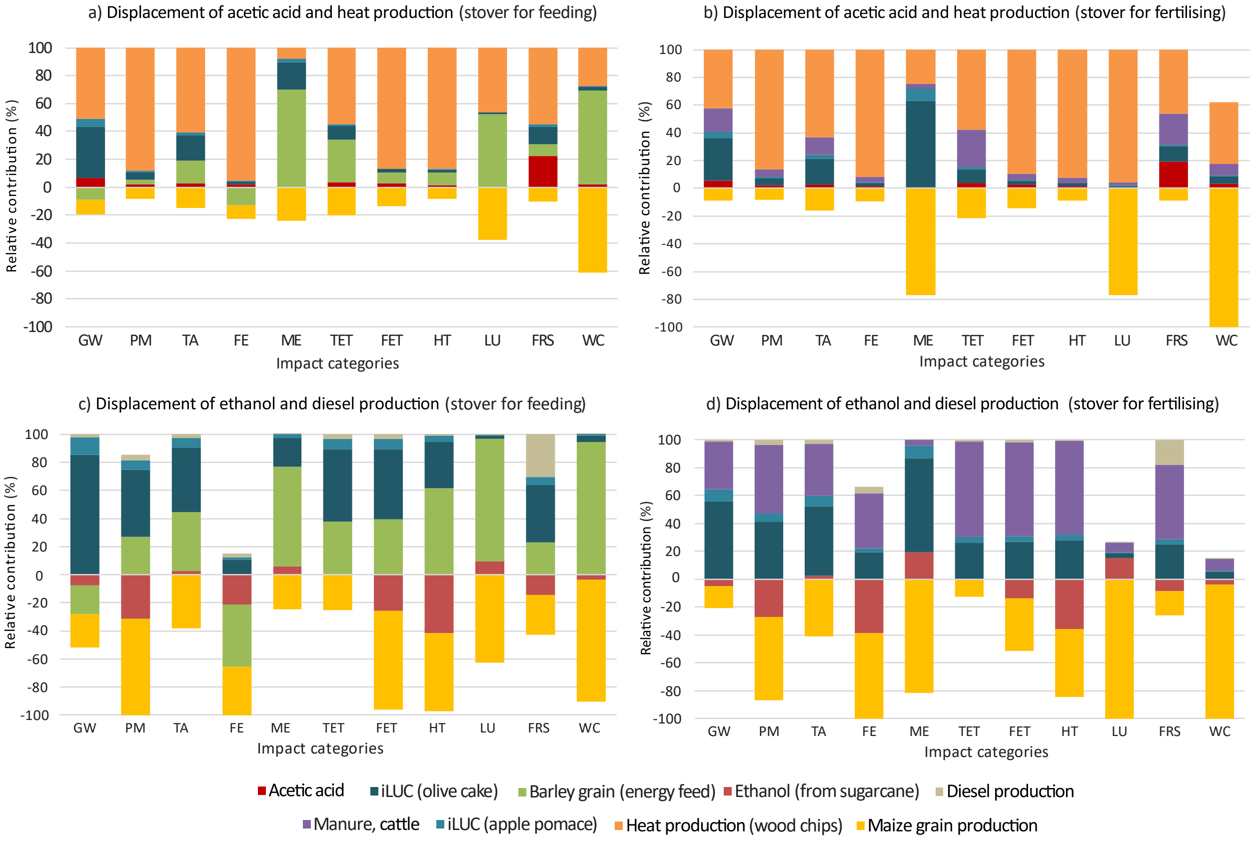
Fig. 3. Contribution analysis in the consequential LCA approach for the baseline scenario.

3.2.1. Sensitivity analysis: Bioproducts and bioenergy displaced

The environmental impacts of the consequential LCA perspective in the case that subproducts (i.e., apple pomace and olive cake) could restrict the bioproducts or bioenergy production is also shown in Table 3. In general, the results indicate that few environmental benefits could be generated. In the case that subproducts could be used for heat and acetic acid production, benefits only appear in the WC category when stover is substituted by synthetic fertiliser (MF-HA). In the case of diesel and ethanol production, benefits appear in PM and FE categories when barley substitutes the maize stover (MB-DE), and in FE, LU and WC categories when stover is compensated by synthetic fertilisers (MF-DE). In addition, the highest impacts were obtained when subproducts could be used for heat and acetic acid production. Particularly, in seven out of 11 categories analysed, when stover could be applied for animal feeding (i.e., MB-HA). The remaining four categories (GW, PM, FE, and FRS) reached the highest impacts when stover should be replaced by synthetic fertiliser (i.e., MF-HA). Thus, the strategy of shifting subproducts for feeding instead of being used in bio-based production models could entail undesirable environmental burdens.

Fig. 4 presents the contribution analysis of these four sensitivity alternatives. From this, when AP and OC subproducts are not available for acetic acid and heat production, the contribution of the substitute for acetic acid was not significantly relevant. The highest share related to acetic acid production (business as usual) was about 22% and 19% in the FRS category, when stover should be substituted for feeding and fertilising, respectively, while in the remaining categories was equal to or less than 10%. On the other hand, heat production (from wood chips) plays a relevant role in most of the categories analysed in both scenarios (see Fig. 4**a** and Fig. 4**b**), due to the demand for other sources as lignite and hard coal for heat production.

If the subproducts could not be used for producing biofuels, the results are different to the above mentioned acetic acid and heat



a) Displacement of acetic acid and heat production (stover for feeding)

b) Displacement of acetic acid and heat production (stover for fertilising)

c) Displacement of ethanol and diesel production (stover for feeding)

d) Displacement of ethanol and diesel production (stover for fertilising)

Fig. 4. Contribution analysis of the consequential LCA approach of displaced bioproduct.

production. Since in this case, the substitute products associated with the maize stover (i.e., barley and synthetic fertiliser) are the main contributors. In the substitution of the stover for feeding, ethanol production (from sugarcane) represents a marginal contribution (see Fig. 4**c**), where its highest contribution was in the LU category with about 9%, while diesel production (business as usual) encompassed the highest contribution in the FRS category with about 30%. In the substitution of stover for fertilising (see Fig. 4**d**), ethanol production represents about 15% in LU category, and diesel production encompassed the highest contribution in the FRS category with about 18%.

3.2.2. *Moving maize grain for bioeconomy models*

Here we present the results of a potential scenario where the unused fraction of maize grain for pig feed is destined for bio-based markets, also taking into account the bio-based products displaced in the previous analysis. The environmental burdens estimated were presented in Table 4, where the results show that in both alternatives of displaced products, the same tendency was observed. Furthermore, taking advantage of the maize grain to produce PLA to avoid PET (granulate) production was the best option whatever the displaced products by the subproducts. In general, environmental burdens were highest when the displaced products were acetic acid and heat production, where benefits were only obtained in the FRS category regardless of the type of fossil granulate product. In contrast, most benefits were identified when the displaced products were related to ethanol and diesel production.

Fig. 5 shows the contribution analysis of moving maize to PLA production. From this, avoiding the production of high-density polyethylene leads to the greatest benefits in categories such as GW, PM, TET, FET, and FRS when biofuels production was displaced because the use of subproducts for pig diets (see Fig. 5**a**). In this case, ethanol production from sugarcane implies relevant benefits in the PM and FE categories due to the bagasse treatment, which consists of its use in cogeneration systems. However, it has a significant contribution in the LU category. Concerning the avoid of PET production (see Fig. 5**b**), the benefits obtained were relevant to offset iLUC emissions in most categories when biofuels were displaced, which is also the case when PP production was avoided (see Fig. 5**c**). In the three plastic alternatives where acetic acid and heating production were displaced, the latter was mainly responsible for emissions that could not be offset by avoided impacts. Thus, taking advantage of a potential oversupply of maize grain to produce PLA (to avoid its fossil counterpart) will depend on the current use of the by-products (i.e., OC and AP), specifically whether any of them could be used for energy generation. This is explained by the fact that the substitute for heating production considered here was wood chips, which is a restricted market, leading to an increasing demand for fossil resources such as natural gas.

4. Conclusions

This research assesses the environmental impacts attributed to fattening pig diets that use subproducts such as apple and olive pomace to replace maize grain. In the attributional perspective, results indicate that they may reduce the environmental impacts of pig diets, with respect to the control diet, in all categories when the functional unit was one kilogram of diet, being the diet D1 the best alternative. Nevertheless, when measured based on kg of weight gain, diet D1 is still the best option but not in all categories, and diet D2 entails the highest burdens in global warming, eutrophication, and fossil resource scarcity. Furthermore, the sensitivity analysis demonstrates that the allocation method selected is crucial for recommending this feeding strategy, as a mass allocation may result in a higher profile than the control diet, and an economic allocation factor higher than 10% for the olive (or apple) subproduct may restrict its recommendation.

In general, the consequential LCA approach shows that using these subproducts for a feeding strategy does not necessarily represent environmental benefits. In the baseline scenario, the two potential scenarios analysed show a positive net environmental impact. As the burdens are mainly due to the production of substitutes, which are not offset by the avoidance of maize grain. Furthermore, the indirect land use emissions have a relevant contribution in the global warming category. In addition, in the case that apple pomace and olive cake can be used to obtain bioproducts, the highest impacts were observed when the by-products could be used for the production of heat and acetic acid, with heat generation contributing most to the impacts. The potentially limiting the use of by-products for biofuels production could imply burdens related to fossil resource demand. Moreover, changing the use of maize grain for granulated PLA could imply both growth and reduction of environmental burdens, where the latter could occur when PLA production avoids its fossil-

Table 4
Environmental burdens of maize grain displacing fossil-based polymers.

Impact category	Unit	Subproducts displaced ethanol and diesel			Subproducts displaced acetic acid and heating production		
		HDPE avoided	PET avoided	PP avoided	HDPE avoided	PET avoided	PP avoided
GW	kg CO_2 eq	0.151	-0.107	0.161	1.150	0.891	1.160
PM	g $PM_{2.5}$ eq	-0.261	-0.796	-0.226	6.190	5.655	6.225
TA	g SO_2 eq	0.959	0.454	0.999	6.490	5.985	6.530
FE	g P eq	-0.123	-0.319	-0.116	1.840	1.644	1.847
ME	g N eq	0.343	0.323	0.343	0.369	0.349	0.369
TET	kg 1,4-DCB	-0.062	-0.464	0.031	1.395	0.992	1.487
FET	g 1,4-DCB	-4.971	-21.371	-4.516	39.600	23.200	40.055
HT	g 1,4-DCB	-16.042	-26.728	-12.051	69.499	58.813	73.490
LU	m^2a crop eq	0.047	0.026	0.047	0.332	0.311	0.332
FRS	kg oil eq	-0.317	-0.321	-0.324	-0.098	-0.101	-0.105
WC	m^3	-0.004	-0.012	-0.003	0.030	0.022	0.030

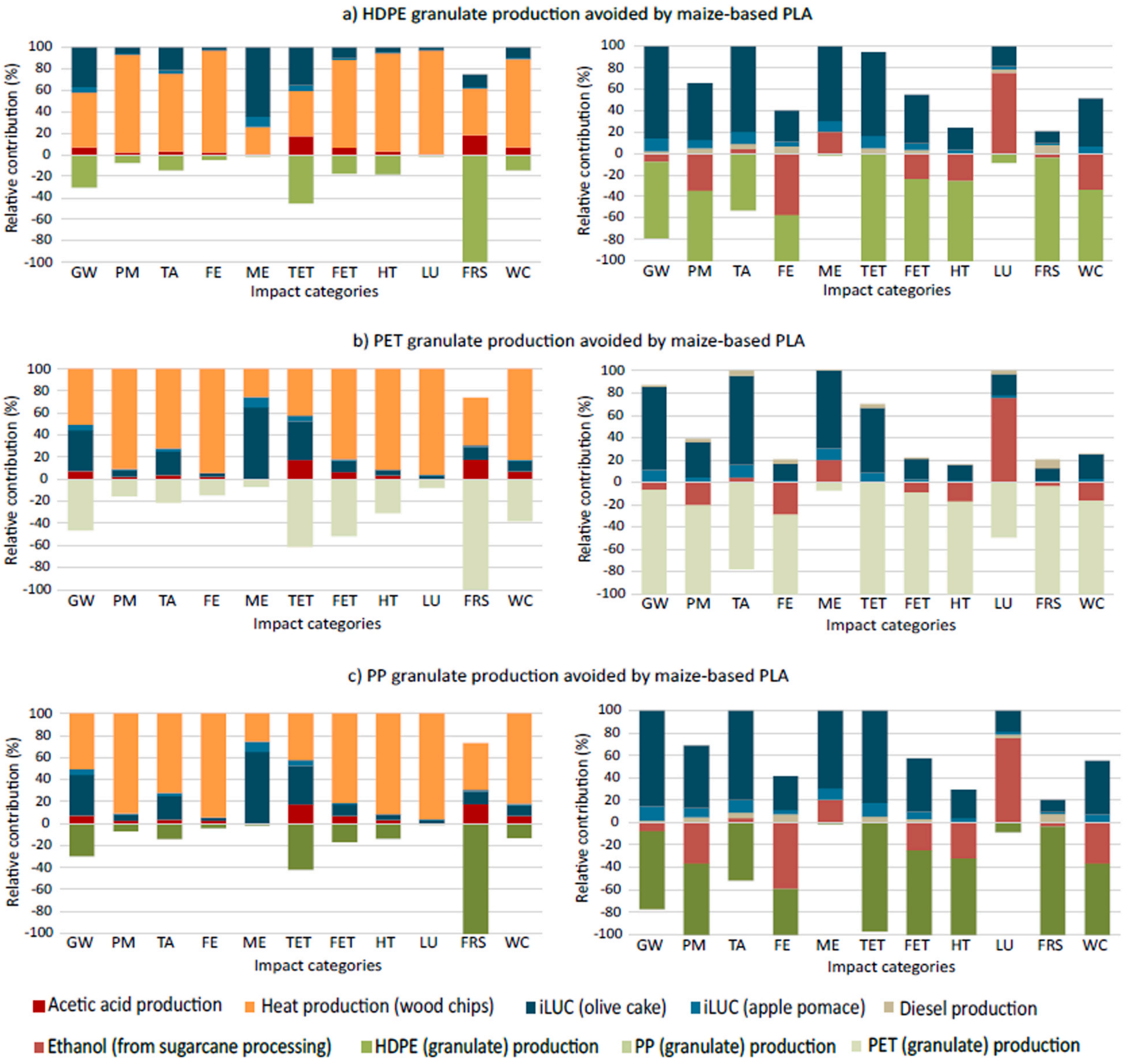


Fig. 5. Contribution analysis of moving maize grain to PLA (granulate) production.

derived polymer. In this sense, avoiding PET (granulated) production was the best option, regardless of the products displaced by the by-products. This research provides information that supports the proper use of subproducts from food industry toward those market that implies lower environmental consequences.

CRediT authorship contribution statement

Moreira Maria Teresa: Supervision, Validation, Writing – review & editing. **Hernández Diógenes:** Formal analysis, Resources, Writing – review & editing. **González-García Sara:** Funding acquisition, Supervision, Validation, Writing – review & editing. **Rebolledo-Leiva Ricardo:** Conceptualization, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Acknowledgments

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eti.2024.103549.

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