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Re-Livestock
RESILIENT FARMING SYSTEMS

Deliverable D4:

Carbon footprint of novel food co-products as feed materials: database and report



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Executive Summary

Feed production is a major contributor to the environmental footprint of pig and beef production, while protein supply is particularly important because of its associated land, energy, water and greenhouse-gas emissions. The Re-Livestock research activities therefore evaluated a range of feeding strategies aimed at reducing dependence on imported soybean products, improving nutrient-use efficiency and increasing the use of locally available or circular feed resources.

In the course of 10 experiments across 5 institutions, a total of 55 diets were offered to pigs (48) and beef cattle (7). Each feed ingredient was assigned a value for the carbon footprint (CFP) of its production, expressed as kg CO2e/t of ingredient. The primary source of these data was the Global Feed Life Cycle Assessment (LCA) Institute (GFLI), with gaps filled from other available databases and literature searches. Data were used to calculate the CFP of each diet formulation (kg CO2e/t diet). No account was taken of emissions generated during feed processing (e.g., pelleting) or transport.

Changes in the CFP of diet formulations could be associated with improvements or reductions in the CFP of livestock production (reported in Deliverable 4), generating either additive benefits or trade-offs in terms of the CFP of the production of animal sourced foods. For one experiment, a LCA from cradle to livestock farm gate was undertaken. For other experiments, effects of diets on animal performance (growth rate and feed efficiency) were used as proxies for the CFP of livestock production.

Using **alternative legumes** to soya products in pig diets did not always reduce diet CFP, and sometimes increased diet CFP, depending on the source of the soya products being displaced, as well as the source of the alternative. Pig performance was unaffected or improved. Care is needed to manage trade-offs when considering this approach, bearing in mind possible options to switch to low CFP soya sources.

Fruit pomaces showed potential to reduce diet CFP while maintaining pig growth performance.

Reducing protein concentration generally reduced diet CFP. Penalties of lower pig performance could be avoided by using synthetic amino acids (which modestly increased diet CFP).

Insect proteins have potential to lower CFP, depending on the feedstocks used, but had varying effects on pig performance, highlighting the need for continued zootechnical research.

It was feasible to formulate **lower CFP beef diets** using a range of common local feed materials, such as food co-products brewers' and distillers' grains and sugar beet pulp, and alternative proteins such as field beans, without reducing animal performance.

Overall, results illustrate the potential to reduce the CFP of livestock production through the formulation of diets with less embedded carbon. Success depends on accurate information on the origin of available feed ingredients and origin specific data on ingredient CFP.

This work could be advanced and enriched by further LCA analyses, to improve the assessment of the CFP of animal food production (net of upstream emissions in feed ingredients and emissions generated on livestock farms) and to simultaneously assess other environmental impacts. This could be supported by a techno-economic assessment (TEA) to check for trade-offs between environmental and economic sustainability.

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An additional exercise for this deliverable has been to expand the **CiFoS model food by-product database**. The existing CiFoS database was reviewed to identify gaps in the representation of food-industry co-products that could potentially be used as feed for pigs, dairy cattle and beef cattle. A total of 38 feed-related products were identified for inclusion or refinement, covering a diverse range of food-processing streams, including cereal and oilseed co-products, fruit pomaces and pulps, vegetable and potato residues, and other processing by-products. For each product, the information required for its representation in CiFoS was compiled, including nutritional composition, processing fractions, geographical applicability and maximum dietary inclusion levels for the three livestock categories. This expansion provides a more comprehensive basis for assessing the potential contribution of food co-products to circular and lower-carbon livestock production.

Introduction

The carbon footprint of animal feed

Production and delivery of feed materials, individually or compounded, to the point of consumption by the animal generates emissions of CO2e, largely in the form of CO2 (from the burning of fossil fuels in land cultivation, manufacture of fertilisers and other crop inputs, crop harvesting, primary crop processing, animal feed manufacturing (e.g., milling and pelleting) and transport (e.g., field to feed mill to farm). Mining and preparation of minerals and synthesis (chemical or biological) of feed additives also generate CO2, primarily from the use of fossil fuels.

These embedded emissions constitute a significant proportion of the total emissions generated in the production of animal sourced food. As broad, aggregated statistics for the European continent, the Global Livestock Emissions Assessment Model (GLEAM) of the FAO[1] shows that feed production (including land use change associated with the growth of soya and palm) accounted for just under 50% of the carbon footprint of pig meat production and 21% of the carbon footprint of cattle-sourced foods (meat and milk). The lower proportion attributable to feed production for cattle versus pigs reflects the greater proportion attributable to methane from enteric fermentation.

In a review, Yang et al. (2023) cited a range in feed production emissions, as a percentage of the total emissions of pig meat production and distribution, between 26 and 68%, with the wide range reflecting differences in production system and calculation methodology. Sykes et al. (2019) reported feed embedded emissions of beef production as the second largest, after enteric fermentation. In short, efforts to manage greenhouse gas emissions from pork and cattle (beef and dairy) production must address the emissions created by the production of animal feed.

Numerous models and tools have been developed in recent years to account for the carbon footprint embedded in animal feed. An early implementation is the tool ‘Feedprint’ arose from the project ‘Carbon Footprint Animal Nutrition’ of the Dutch Product Board for Animal Nutrition, initiated in 2009. Feedprint accounts for both on-farm emissions and upstream

[1] FAO GLEAM v3 Dashboard. https://foodandagricultureorganization.shinyapps.io/GLEAMV3_Public/, accessed 24 Aug 2026.

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emissions, including from feed production. Upstream emissions include inputs of fertilisers, fossil fuels, pesticides and agricultural machinery, with background data for the production and emissions of these inputs derived from available databases, as described by Vellinga et al. (2013).

The Global Feed Lifecycle Assessment Institute (GFLI) evolved from FeedPrint in response to the need for a harmonised, transparent, globally applicable tool. The transition from Feedprint to GFLI (as an independent, non-profit institute) was financed by international feed associations such as FEFAC, AFIA, IFIF, and ANAC.

GFLI now maintains a global database of over 1,800 Life Cycle Assessment datasets for individual raw feed ingredients (e.g., grains, oilseeds and co-products of their processing).

GFLI uses Ecoinvent as its background database. When GFLI models the impact of a specific feed ingredient (e.g., soy processing), it uses data from Ecoinvent for background environmental costs of the energy, electricity and materials used during processing. The GFLI database contains values for 16 primary footprint categories, including carbon emissions, with or without accounting for land use change. Allocation of emissions between co-products of crop processing (e.g., hulls, oil and meal from oilseeds) can be according to economic value, mass, or energy. Management of GFLI is contracted to Agribusiness Service BV, an Associate Partner in the Re-Livestock project.

The modern Feedprint uses the raw GFLI ingredient data to help individual feed mills, suppliers, and nutritionists calculate the total environmental footprint of complete compound feed formulations, taking into account such specific factors as distances between ports and feed mills, and feed mills and farms, and the mill specific consumption of energy (e.g., for mixing and pelleting).

Agribalyse is an example of a food footprinting tool, developed and used in France. It covers more than 2,500 finished food products consumed by humans (e.g., an apple, a cut of meat, or a ready-to-eat meal). Agribalyse aligns its livestock feed inputs with data models structured similarly to GFLI when calculating food embedded emissions.

GFLI, Feedprint and Agribalyse all align with the European Union's PEFCR-Feed (Product Environmental Footprint Category Rules for Feed).

Method

Carbon footprint of ingredients used in experiments in Re-Livestock Work Package 2

Formulations of diets used in 10 experiments (8 pig, 2 beef) in Task 2.1 (see Deliverable D5 for detail) were collated into a database. Discussions between project partners took place to resolve ambiguities in ingredient names and to clarify country of origin, where possible.

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Data for the carbon footprint of individual feed materials and feed additives used in diets in experiments in Work Package 2 were collected and used to calculate the carbon footprint of each experimental diet. Carbon footprint data for the individual ingredients are up to the exit gate of the factory in which they were produced, or to the exit gate of the farm at which they were stored. The functional unit is the mass (metric ton) of each feed material or feed additive at the dry matter content at which it would be used in the manufacture of compound feed or offered directly to livestock. No attempt was made to account for carbon emissions associated with the manufacture (e.g., carbon costs of pelleting) or distribution of the diets in which these ingredients were used.

For most feed ingredients, data were provided by Agribusiness Service BV and are from the GFLI database LCIA version 4.0 (publication date September 2026), EF3.1 impact assessment method with Economic Allocation. Data were provided with and without LUC, with data including LUC used in the calculations.

Where GFLI provided multiple values for the same commodity feed material, the source most closely matching that used in the individual countries was chosen (e.g., it was assumed that cereal grains originated in the country where the experiment was carried out).

Where data were not available from GFLI, estimates were sought from Feedprint NL (version 2022.00, 9Dec22, Download FeedPrint NL), from the Swedish online resource Carbon Cloud (https://carboncloud.com/) and by conventional literature review.

Effects of diet formulation on the carbon footprint of diets and the carbon footprint of animal production.

Differences in embedded carbon between diet formulations may be offset, or may add to, differences in carbon generated by animals consuming those diets. To identify conflicts, trade-offs and ‘win-wins’, differences in carbon footprint between diet formulations were compared with the differences in animal performance (bodyweight gain and feed efficiency) reported in Deliverable D5 For one experiment (beef at CSIC, Spain) a LCA to the beef farm gate was available, providing a net picture of the carbon emissions embedded in the diet and those generated when cattle were fed that diet.

Results

Carbon footprint of ingredients used in experiments in Re-Livestock Work Package 2

Local legumes as alternatives to soya products in pig diets

Several different soya sources, with different carbon footprints, were used in these experiments (Table 1).

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Table 1. Carbon footprint of soya and alternative legumes used in experiments in WP2

Feed Material name	kg CO2e/t product, as fed
Soybean: Meal, from solvent extraction; Factory gate {RER}	1177
Soybean: Meal, from solvent extraction; Factory gate {ESP}	1441
Soybean: Meal, expeller from pressing; Factory gate {RER}	1179
Pea: Bean dry, dried production mix; Storage gate {RER}	1197
Pea: Bean dry, dried production mix; Storage gate {ESP}	977
Pea: Bean dry, dried; Storage gate {POL}	1766
Broad bean: Bean, dried; Storage gate {GBR}	813
Lupin: Seed, dried; Storage gate {POL}	1170
Chick pea: Bean, dried; Storage gate {TUR}	1187
Lentil: no value in GFLI. Assumed = pea.	977

The GFLI database includes several sources of chickpea, but no values are available for chickpeas grown in Spain (as used in experiments in ADA and CSIC, see report on Deliverable D5). The database value for Turkey - a major exporter of chickpeas – was used by default. Similarly, the value for 'broad beans' (= field beans, *Vicia faba*) grown in Great Britain was assumed to apply in Poland.

Of note, the CFP of soyabean products varies markedly according to origin, and soyabean sourcing offers another opportunity to reduce the CFP of livestock diets. In this exercise the default was to use 'Soybean: meal from solvent extraction: factory gate {RER}. This value is weighted according to the volumes of soyabean meal used in Europe, from direct imports, European production of soyabeans, and European processing of imported soyabeans.

Dried berry and apple pomaces for pigs

No data are available from GFLI (or the manufacturers) for the carbon footprint of dried blackcurrant and chokeberry pomaces, evaluated in pig diets by PULS, or apple pomace evaluated by Agroscope. Historically, most residues from fruit juice extraction have gone to landfill, or been composted (Osorio et al., 2021), generating greenhouse gases during their decomposition. Drying enables storage and transport of fruit and vegetable residues, thus facilitating their use as animal feed materials. Fruit and vegetable residues are rich sources of potentially valuable bioactive compounds, ranging from proteins to essential fatty acids and polyphenols (De Ancos et al., 2015), Raczkowska and Serek, 2024), and there is extensive literature on their extraction and preservation through biorefining (e.g., see Solarte-Toro and Cardona Alzate, 2023).

Lunesu et al. (2026) calculated the carbon footprint of 1kg of dried grape, olive and tomato pomaces, according to the ISO 14067:2018 standard. Their economic allocation methodology

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allocated all emissions associated with primary crop production to juice, leaving drying, milling, mixing and pelleting as the contributors to the carbon footprint of dried pomace. The energy used in drying depends on the moisture content of the pomace, so that the carbon footprint estimates of Lunesu et al. (2026) were 220, 260 and 310kg CO2e/kg dried product for olive, grape and tomato pomace, respectively. At around 80%, the moisture content of fresh apple pomace (Feedipedia), is higher than that reported for blackcurrant and chokeberry pomaces (Azman et al., 2021; Agraso Otero et al., 2025). Therefore, we used values of 250kg CO2e/kg dried product for blackcurrant and chokeberry pomaces, and 300kg CO2e/kg dried product for apple pomace.

Low protein diets for pigs

Deliverable D5 describes three experiments at Agroscope attempting to reduce the crude protein concentration of pig diets without reducing animal performance.

A common approach in all three was increased use of a number of synthetic amino acids, produced either by fermentation (e.g., lysine) or chemical synthesis (e.g., methionine). Carbon footprints for branded feed-grade amino acids are not included in the GFLI database and are not publicly available. Amino acids are produced by fermentation (lysine, threonine, tryptophan, valine) or chemical synthesis (methionine). An LCA conducted by Garcia-Launay et al. (2014) shows lower CFP for methionine (3050kg CO2e/t), with the production of tryptophan and valine generating almost twice as much carbon as production of lysine and threonine (4300kg CO2e/t). These values were used in this exercise.

In the third experiment conducted at Agroscope, testing low protein diets for pigs, treatment diet 3 included 10% of the dried microalgae *Chlorella vulgaris*, largely displacing soyabean meal and potato protein. No CFP value is available in GFLI for the *C.vulgaris*. A review by Smetana et al. (2017) concluded that the carbon footprint of *C.vulgaris* powder was not lower than that of plant proteins such as soyabean and rapeseed meals, but that changes in C source and electricity source offered significant potential for improvement. D'Imporzano et al. (2018) explored five different scenarios for the production of 1kg of microalgal biomass, comparing autotrophic with mixotrophic growth (i.e., using energy from light or a mix of light and organic compounds) and evaluating a range of carbohydrate and nitrogen sources. Carbon footprint ranged from 1050 to 3070kg CO2e/t DM. In this exercise, a mid-point estimate was used in initial calculations, followed by a sensitivity analysis.

Diet 4 in Agroscope's third experiment included dried grass. With no data available from GFLI, a value of 2350kg CO2e/t from Feedprint was used.

Insect proteins for pigs

The specific sources of insect protein used in experiments at CSIC are not represented in the GFLI database, and values for their CFP were not available from the supplier. For *Hermetia illucens* (black soldier fly), a value of 377 kg CO2e/t, provided by French manufacturer Innovofeed (included as a Branded Product in the GFLI database) was used.

For *Tenebrio molitor* (mealworm), Thevenot et al. (2017) conducted a LCA of the pilot production facility of French company Ynsect and obtained a value of 3800kg CO2e/t, after mill processes (blanching, cold pressing and drying), and this value was used in this exercise. Paris et al.

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(2024), studying a production system in Quebec, obtained a figure of approximately 7800kg CO2/t when mealworms were produced from animal feedstuffs, with much lower figures if grown on food and other organic wastes.

Alternative proteins for beef cattle

Against control diets containing soyabean meal, experiments at The University of Reading and CSIC evaluated Brewer's grains, field beans (*Vicia faba*) and Distiller's grains with solubles as the primary alternatives.

Data are available from GFLI for field beans grown in Great Britain (813kg CO2e/t). For dried brewers' grains a value provided by GFLI for NL was used (829kg CO2e/t), while the value taken from GFLI for maize distiller's grains produced in Europe was 951kg CO2e/t.

With no values available in GFLI, the rumen-protected (encapsulated) lysine and methionine used in CSIC's beef experiment were assumed to have the same CFP as unprotected amino acids used in pig diets.

Effects of diet formulation on the carbon footprint of diets and the carbon footprint of animal production.

The mean carbon footprint (including land use change) of 55 treatment diet formulations (7 beef, 48 pig grower or finisher) was 706 kg CO2e/t as fed, (SD=149.6), with a range from 203 to 1067. The maximum value was for a pig diet including mealworms, based on Thevenot et al. (2017): the CFP of mealworm production requires further investigation. As expected, the lowest values were for the three diets offered to beef cattle at the University of Reading, which contained 64% forage (DM basis). The highest value was calculated for a pig diet at ADA which contained a high proportion of chickpeas.

For pig diet formulations, the mean CFP was 733kg CO2e/t (SD=78.9). This figure is higher than published estimates. For example, Kool et al. (2009) reported a range of 400-650kg CO2e/t feed across several north European countries, including the carbon costs of feed milling. Reasons for these differences merit further investigation.

Of more interest is the effect of changes in diet formulation. Published studies have shown lower CFP embedded in pig feeds formulated with lower proportions of cereals and oil meals and higher proportions of alternative protein sources such as peas, faba beans, or high protein coproducts (e.g., Mackenzie et al., 2016; Garcia-Launay et al., 2018).

A full LCA of pig production (including feed production) has not been undertaken for each of the pig experiments in Work Package 2. Growth rate and feed efficiency (gain/feed) may serve as proxies for the CFP of the animal production phase. In the following sections, a simple 'traffic light' system has been used to indicate effects of diet reformulation on the CFP of feed production (using a difference of 5% from the control diet to indicate an effect) and animal production (based on the statistical significance of differences between treatments reported in Deliverable D5). Increases or decreases versus the control diet are indicated by '+' or '-' symbols. Changes that reduce CFP are indicated in green: changes that increase CFP in red.

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Local legumes as alternatives to soya products in pig diets

Consistent with the broad similarity in their CFP (Table 1), substitution of local legumes for soya proteins did not consistently reduce (improve) the CFP of diet formulations (Table 2).

Table 2. Effect of inclusion of local legumes on CFP of diet formulations and metrics related to CFP of animal production.

Site	Pig	Local legume	Diet CFP (kg CO_2e/t as fed)	Growth (kg/d)	Feed efficiency (gain/feed)
PULS	Grower	Field bean (*V. faba*)	=	=	=
		Lupin	+	−	=
	Finisher	Field bean (*V. faba*)	=	=	=
		Lupin	+	−	+
ADA		Pea	+	+	=
		Chickpea	+	+	=
		Lentil	+	+	=
CSIC	Cosmopolitan	Pea	=	=	=
		Chickpea	=	=	=
		Lentil	=	=	=
	Iberian	Pea	=	=	=
		Chickpea	=	=	=
		Lentil	=	=	=

At PULS, the high CFP of lupin (2000kg CO2e/t) predictably drove a higher diet CFP when used to replace soyabean meal (1177kg CO2e/t).

Introduction of pea, chickpea and lentil at CSIC only partially substituted for soyabean meal, and the favourable effect on diet CFP was somewhat compensated for by a partial switch from maize (CFP = 492kg CO2e/t) to wheat (CFP = 679kg CO2e/t). However, considering that both lentils and chickpeas were materials discarded from human consumption, their inclusion in pig diets could result in more favorable CFP values than those estimated in the present study. That would depend on the allocation criteria used.

Because of their low inclusion rate, synthetic amino acids made only a small contribution (2-3%) to diet CFP. Changes in amino acid inclusion rate therefore do not account for differences in CFP between diets.

Dried berry and apple pomaces for pigs

In most cases, inclusion of fruit pomaces reduced the CFP of the diet formulation without affecting pig performance (Table 3).

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Table 3. Effect of inclusion of fruit pomaces on CFP of diet formulations and metrics related to CFP of animal production.

Site	Pig	Fruit pomace	Diet CFP (kg CO_2e/t as fed)	Growth (kg/d)	Feed efficiency (gain/feed)
PULS	Grower	Blackcurrant	-	=	=
		Chokeberry	-	=	=
	Finisher	Blackcurrant	-	=	=
		Chokeberry	-	+	-

Low protein diets for pigs

Reducing diet crude protein concentration reduced the CFP of diets (by 8%) but negatively affected the performance of grower pigs (average daily gain reduced by approximately 8%: see Deliverable D5 for data), whether kept in good or poor hygiene conditions (Table 4). This suggests a net benefit (lower diet CFP plus equal animal production CFP) of lower protein in finisher diets, and a need for more detailed LCA for grower pigs.

Table 4. Effect of low protein diets CFP of diet formulations and metrics related to CFP of animal production. In experiment Agroscope 1, the comparison is of low protein diets with standgard protein diets in two hygiene conditions. In experiment Agroscope 2, the comparison is of amino acid supplemented low protein diets with an unsupplemented low protein diet. In experiment Agroscope 3, the comparison is of three different low protein diets with a standard protein diet.
'na' = data on animal performance in experiment Agroscope 3 not yet available.

Experiment	Conditions	Pig	Diet strategy	Diet CFP (kg CO_2e/t as fed)	Growth (kg/d)	Feed efficiency (gain/feed)
Agroscope 1	Good hygiene	Grower	Low protein	-	-	-
		Finisher	Low protein	-	=	=
	Poor hygiene	Grower	Low protein	-	-	-
		Finisher	Low protein	-	=	=
Agroscope 2	Poor hygiene	Grower	Low + AA	-	=	+
			Low ++ AA	-	=	+
		Finisher	Low + AA	-	=	=
Agroscope 3	Poor hygiene	Grower	Low + algae	-	n.a.	n.a.
			Low + grass	=	n.a.	n.a.

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In experiment Agroscope 2, adding amino acids to an already low protein diet improved feed efficiency (but not bodyweight gain) in grower pigs, with only a small (<5%) increase in the diet carbon footprint, arising from increased use of synthetic amino acids. This supports the net benefit of this strategy to the CFP of grower pig production.

In experiment Agroscope 3 (for which final pig performance data are not yet available), inclusion of microalgae reduced diet CFP by 6.6%, compared with the standard protein grower diet. This differential increased to almost 20% at the lower end of the range of CFP posited for *C. vulgaris* by D'Imporzano et al. (2018) was used.

Insect proteins for pigs

Pigs offered mealworms (*Tenebrio molitor*) instead of soyabean meal tended to grow slower, with lower feed efficiency, on a diet calculated to have a higher CFP (Table 5). In contrast, black soldier fly larvae (*Hermetia illucens)* tended to improve growth rate, improved feed efficiency, and reduced diet CFP.

There was a large difference in the values used for the CFP of these two insect products, and there could be large effects of production method (e.g., CFP of different feedstocks for insect growth). Given the large potential for both improved animal performance and lower diet CFP, continued investment in species and site specific LCA of insect protein production is warranted.

Table 5. Effect of insect proteins on diet CFP and performance of grower pigs

Site	Insect protein	Diet CFP (kg CO_2e/t as fed)	Growth (kg/d)	Feed efficiency (gain/feed)
CSIC	*H. illucens*	-	+	+
	T. molitor	-	=	-

Alternative proteins for beef cattle

Two experiments, at CSIC and University of Reading, are reported in Deliverable D5. In contrast to pig studies in Work Package 2, a LCA was conducted for the experiment at CSIC. The functional unit was 1kg of bodyweight gain and the analysis was undertaken with SimaPro v9.3, using data on feed-embedded carbon emissions from the Agri-footprint database.

Back-calculating from LCA results for embedded CO2e/kg bodyweight gain and rates of bodyweight gain and feed intake, feed-embedded emissions can be calculated for each diet and compared with those calculated directly from feed formulations and GFLI data. As expected, both

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approaches indicate similar proportional reductions when local ingredients (cereals, beet pulp, distillers' grains) displaced imported ingredients such as soyabean meal (Table 6).

Table 6. Two estimates of the diet-embedded carbon footprint of beef diets evaluated at CSIC

Diet embedded carbon (kg CO_2e/t as fed)	Control	Diet A	Diet B	Diet C
From GFLI (this exercise)	559	488	486	486
From LCA (Deliverable D2.2)	503	459	421	425

As discussed in Deliverable 2.2, there was no significant difference between the four diets in growth rate or feed efficiency, so LCA favoured diets A, B and C over the control (for the impact category of global warming).

At the University of Reading, use of either brewers' grains (dried) or field beans as the main means of reducing use of soyabean meal reduced the CFP of the diet, as calculated using the GFLI database, by 12% and 16%, respectively (Table 7). As reported by Christodoulou et al. (2025), use of brewers' grains or field beans had no significant effect on growth rate or feed efficiency.

Table 7. Effect of brewers' grains and field beans on diet CFP and performance of beef cattle

Site	Diet / feed strategy	CFP of diet formulation (kg CO_2e/t as fed)	Growth (kg/d)	Feed efficiency (gain/feed)
CSIC	Diet A	-	=	=
	Diet B	-	=	=
	Diet C	-	=	=
University of Reading	Brewers' grains	-	=	=
	Field beans	-	=	=

While these data (diet CFP and animal performance) favour increased use of brewers' grains and field beans for beef diets, this simple analysis does not consider the value of alternative uses to which these materials could be put. Davison et al. (2026) used data from this experiment to evaluate the environmental and economic impact of using brewers' grains for either animal feed or energy generation via anaerobic digestion. Results of this exercise are presented in Deliverable report D5.

Discussion

A number of general points arise from this exercise.

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Firstly, it is apparent that the emissions generated in the production of many feed materials vary significantly by source, reflecting differences in agronomic practices, in the processing of primary crops and in the manufacturing of feed additives. This highlights the importance of correct and precise identification of feed materials and continued investment in databases such as GFLI, with materials disaggregated as much as possible by source and process.

Secondly, calculation of the CFP of feed ingredients should ideally form part of a LCA, to more accurately account for trade-offs and synergies. This has been done for the beef production experiment at CSIC: data from our other experiments would allow similar analysis of other propositions, such as the use of insect proteins or fruit pomaces in pig diets.

Thirdly, no account has been taken of the relative cost of the various feed materials used across these experiments. Together, techno-economic assessment (TEA) and life cycle analysis (LCA) provide a comprehensive evaluation process that assesses both the profitability of a production process and its environmental impact through all stages of production, from raw materials to product consumption.

Finally, livestock nutrition is competing for the use of materials as feed ingredients with other opportunities to extract environmentally responsible economic value from those materials. This was explored for brewers' grains, comparing use as feed for cattle versus anaerobic digestion, as described in Deliverable D5. However, the principle applies to most, if not all, of the feed ingredients used in experiments within WP2. Another example is the extraction of bioactive polyphenols from fruit pomaces (creating new residues with potential as feed materials).

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Expansion of the food by-product database in CiFoS model

Introduction to CFoS

The Global Circular Food System (CiFoS) model is a linear optimization model that explores alternative configurations of the food system and their implications for food supply, resource use and environmental pressures. It links crop and livestock production, food processing, human food demand, biomass allocation, land use, nutrient cycling, transport and greenhouse gas emissions. This whole-system representation allows evaluation of feed and co-product use alongside the upstream production and downstream environmental changes they induce.
CiFoS is designed to test circular use of biomass. It can allocate edible resources to human food and lower-opportunity-cost biomass, including grass, food-processing co-products and eligible food losses, to animal feed, subject to scenario controls, resource availability and nutritional constraints. Livestock can therefore upcycle biomass that is not demanded for direct human consumption, although the realized allocation is an optimization outcome rather than an a priori hierarchy.
This perspective is relevant to Re-Livestock because feed innovations can alter not only livestock emissions but also crop demand, land, fertilizer use, manure flows and transport. The D4 database expansion improves the representation of potential feed materials and enables analysis of their system-wide contribution to circular, lower-emission livestock production.

Representation and use of food by-products in the CiFoS model

CiFoS represents food-processing co-products as outputs linked to specific raw commodities and processing activities. Their supply is therefore endogenous: it depends on how much of the associated commodity is processed and on the specified output fraction. The expanded dataset comprises 38 linked model items: 21 processing co-products, 9 feed-only products, and 8 main products required to complete the processing and feed relationships (Table 8).
When enabled, eligible co-products enter a common regional availability balance and may be allocated to human food where applicable, animal feed, as fertilizer or an unused pathway. This balance prevents the same material from being counted twice. Food losses and waste are represented separately and are available only to non-ruminants.
Feed rations are endogenous. CiFoS chooses feed quantities to satisfy nutrient requirements and feed-intake constraints while respecting feed suitability, regional availability, species eligibility and product-specific maximum inclusion shares. The model represents chickens, pigs and several ruminant species and production systems, including buffalo, cattle, goats and sheep. In the Re-Livestock derived-feed scenarios, eligibility is restricted to pigs or to active ruminants, depending on the scenario.

The maximum-inclusion values are upper bounds on the share of an individual product in total herd feed dry matter and apply when the corresponding scenario control is active. A blank cell means that the active input table contains no explicit product-specific cap for that animal group; it does not mean that the ingredient is unconstrained, because nutritional, intake, suitability, availability and scenario constraints still apply.
Environmental impacts are evaluated at food system level. The benefit of a co-product depends on the feed and production it displaces and on the resulting changes in crop production, livestock production, manure management and transport, rather than on a stand-alone product carbon footprint. The current European implementation counts production within its four model regions; embodied production land, production emissions and external freight associated with imports are outside the model boundary. The contribution of each co-product is therefore a context-specific optimization result, not a fixed property of the ingredient.

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Table 8. List of additional by-products included in the CIFoS model

Product	Type*	DM (g kg^{-1} fresh matter)	Ash (g kg^{-1} DM)	CP (g kg^{-1} DM)	GE (MJ kg^{-1} DM)	N (g kg^{-1} DM)	P (g kg^{-1} DM)	Pig max inclusion (% feed DM)	Ruminant max inclusion (% feed DM)
almond_hulls	1	895	65	55		8,8			20%
apple_pomace_dry	1	896,7	20,9	111,1		17,776	2,8	8%	15%
avocado_seeds	1	890	58,3	87,4	18,7	13,98			10%
barley_malt_culms	1	898	53	203	16,5	32,48	54		
blackkurrant_pomace_dry	1	916,2	39,3	182,2		29,152	5,1		
buckwheat_husk	1	879,8	16,5	49,8		7,968	0,8		
chokeberry_pomace_dry	1	918,7	26,8	104,5		16,72	2,3		
citrus_pulp_dry	1	903	62	63	15,9	10,08	9	13%	25%
distillers_grains	1	883	60	246	17	39,36	84		25%
grape_pomace_dry	1	912	67	124	17,4	19,84	25	8%	10%
linseed_meal_expelled	1	912	57	323	19	51,68	85		
linseed_meal_extracted	1	879	57	320	17,1	51,2	88		
maize_gluten_feed	1	878	57	189	16,4	30,24	86	13%	
maize_gluten_meal	1	909	18	616	21,8	98,56	37	13%	
olive_cake_exhausted	1	897	88	109		17,44	2	11%	13%
olive_leaves	1	913	109	84		13,4	0,9		15%
olive_pulp	1	885	71	109	16,2	17,44	15	10%	
orange_pulp_dry	1	903	62	63	15,9	10,08	9	24%	25%
potato_peel	1	201	55	100	17,1	16	26		20%
rapeseed_meal_extracted	1	890	68	339	17,2	54,24	11,3		
wheat_gluten	1	940	9	798	21,4	127,68	18		
bread_crumbed	2	882	25	113	16,9	18,08	17	40%	20%
maize_grain_ensiled	2	670	10	62	12,4	9,92	21		
maize_grain_ground	2	863	12	76	16,1	12,16	25		
maize_grain_steam_flaked	2	863	12	76	16,1	12,16	25		
oat_feed	2	879	29,5	109	19,5	17,44	36		
oat_grain	2	876	25	94	17	15,04	31		
peas	2	881	28	206	1,4		4		
potato_chips_cooked	2	385	19	56	21,3	8,96			
rapeseed_crushed	2	924	40	186	26,9	29,76	67		
almond_nuts	3	945	36	220		35,2			
avocado_pulp	3	330	77	548	26,1	87,68	1,27		
barley_alcohol	3	913	49	257	19,3	41,12	78		
buckwheat_whole	3	903		160		25,6	3,5		
linseed_whole	3	920	39	207	24,9	33,12	58		
lupin_seed	3	875,2	29,9	310,6	19,1	49,696	4,6		
maize_starch	3	882	2	7	15,4	1,12	2		

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wheat_starch	3	897	9	41	17,6		15%

**1: Processing co-product, 2: Feed-only product; 3: Main product*

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