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Carbon Footprint of By-Product Concentrate Feed: A Case Study

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Abstract: Using by-products in livestock feed can be an additional strategy for safeguarding land use in agriculture and reducing the environmental impact of animal production. Studies conducted on farms to assess the environmental impact of milk and meat production using life-cycle assessment (LCA) tools reveal that feeding accounts for approximately one-third. This study aimed to calculate the carbon footprint (CF) of three different concentrated feeds for livestock, both with and without the inclusion of by-products in the formulation. Three different formulations of concentrated feeds for dairy cows were developed homogeneously regarding energy content and crude protein. The LCA approach assessed CF in kg CO_2 eq.; the functional unit was 1 kg of concentrate feed. A sensitive analysis of soybean meal's association with deforestation was formulated. The concentrated feed with by-products demonstrated a lower impact on CF of 23.7% and 37.0% compared to concentrated feed with a mix of raw material and by-products, and solely with raw material, respectively. Using agricultural by-products to produce concentrated feed for livestock sectors can be an environmentally sound alternative in terms of carbon footprint.

Keywords: livestock; animal nutrition; cattle; deforestation; life-cycle assessment; by-products; global warming potential; feed industry; greenhouse gas emissions; mitigation strategy

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1. Introduction

Animal-based products play a crucial role in global nutrition, serving as rich sources of both macro and micronutrients. Products from livestock contribute 18% of the world's caloric intake and 34% of the global protein consumption, while also offering vital micronutrients such as vitamin B12, iron, zinc, and calcium, which can be challenging to obtain in sufficient amounts solely from plant-based foods at the local level [1,2]. By 2050, the global population is projected to reach 9.6 billion, with 70% residing in urban areas and an average income nearly double that of today. Consequently, the demand for animal products is expected to increase, playing an essential role in ensuring global food security and nutrition [3]. The demand for animal-based products has risen significantly with the growing human population and rapid urbanisation in developing countries. By 2050, the demand for food is expected to increase by 25–70% compared to current levels [4]. Simultaneously, there is an abundance of agricultural and industrial wastes or by-products that could potentially be utilised. Agriculture currently covers approximately 38% of the world's land area [5] and is responsible for 23% of the total net anthropogenic greenhouse gas emissions [6]. A major current criticism is the low efficiency of livestock in converting feed into protein suitable for human consumption, as well as the competition between using cereals for livestock feed versus direct human consumption. However, studies estimate that 86% of livestock feed is unsuitable for human consumption. Without being utilised by livestock, a significant portion of crop residues and by-products, especially, could go to waste as the human population grows and increasingly consumes processed foods [1]. Using by-products in livestock feed can be an additional strategy for safeguarding land use in agriculture and reducing the environmental impact of animal production. For a long time, roughage and by-products from human food processing and the biofuel industry have served as feed for ruminants. In the diets of high-producing dairy cows, it is common to blend by-products with cereal and legume grains in concentrate feeds, creating a nutrient-rich ration that meets the animals' dietary needs. Including cereal grains and protein-dense legumes, such as soybean meal, in livestock diets poses a potential challenge to global food security. These commodities are highly valuable as direct sources of human nutrition and are frequently grown on prime agricultural land ideally suited for cultivating crops dedicated to feeding the human population. Allocating such resources to animal feed reduces their availability for direct human consumption. It may contribute to competition for arable land, potentially exacerbating food scarcity in regions with a limited agricultural capacity [7]. In Italy, the soybean meal used for livestock is predominantly imported from Brazil, where its production is linked to significant environmental concerns. The cultivation of soybeans in this region is often associated with high greenhouse gas emissions, primarily resulting from land-use changes such as deforestation. Additionally, this practice contributes to substantial biodiversity loss, as natural habitats are destroyed or degraded to make way for agricultural expansion [8,9]. A growing supply of literature indicates that repurposing by-products for livestock feed enhances sustainability and mitigates the environmental impacts associated with livestock production [10–13]. Incorporating crop by-products as a substitute for forages and/or concentrates in livestock diets offers several potential benefits. These include allowing for forage savings, lowering feed costs, enhancing milk production, and reducing the incidence of ruminal acidosis [14]. In intensive systems, ruminant diets are generally composed of a forage-to-concentrate ratio of 60:40; developing feed formulations that are nutritionally efficient, environmentally friendly, and involve less competition with human food resources, which could be a valuable area for research and development in the feed industry. In 2023, the industrial production of concentrated feed in Italy reached 15 million tons, with the bovine sector accounting for approximately 20% of the total [15]. Studies conducted on farms to assess the environmental impact of milk and meat production using life-cycle assessment (LCA) tools reveal that feeding accounts for approximately 30% of the carbon footprint [16–18]. Off-farm production, notably the purchase and production of concentrated feeds, contributes around 10 to 15% [19,20]. This study seeks to comprehensively evaluate the carbon footprint associated with three distinct types of concentrated livestock feeds. The analysis will consider formulations that include by-products as part of their composition and those that exclude them. By assessing the environmental impact of these feed variations, the research aims to provide valuable insights into how the incorporation of by-products might influence the overall greenhouse gas emissions associated with livestock feed production. This will contribute to understanding sustainable feeding practices and their role in reducing the environmental footprint of livestock systems.

2. Materials and Methods

Using the commercial software Supermix® v. 4.0 [21], three different formulations of concentrated feeds for dairy cows were developed. The three focused feeds were classified as concentrate feed formulated exclusively using agro-industrial by-products (by-product-concentrate feed = BCF), conventional feed formulated with raw materials and by-products (mixed concentrate feed = MCF), and a concentrate formulated exclusively using raw feed materials (concentrate raw feed = CRF); the feeds were homogeneous in terms of energy content and crude protein, as can be seen in Table 1. In detail, the main ingredients that constitute the BCF were 49.1% wheat bran, 21.6% biscuit meal, and 19.5% corn gluten meal. The MCF consisted of a mix of by-products and ingredients that can also be used for human consumption, with 31.0% maise flour, 27.8% soybean meal, 22.6% wheat bran, and 13.5% barley meal. The CRF concentrate was formulated exclusively with ingredients that compete with human food consumption, with the following composition: 43.6% soybean extraction meal, 26.3% maise meal, and 26.3% barley meal. We estimated that processing a typical ton of feed ingredients in a feed mill requires 41 kWh of electricity and 73.8 MJ/ton of natural gas with regard to energy consumption [22,23]. The carbon footprint (CF), expressed in kg of CO_2 eq./kg of functional unit (FU), of the three concentrated feeds under study was determined using the commercial software openLCA 2.0.1 and the Agribalyse v. 3.0.1 database. The FU was 1 kg of concentrate feed. The ReCiPe midpoint (H) method was used [24], and the characterisation factors employed for CF were 1, 34, and 298 CO_2 eq. for CO_2, CH_4, and N_2O, respectively. Table 2 depicts the main ingredients selected from the software's database Agribalyse, which best reflect the characteristics of the production cycles and the associated environmental impacts. The Agribalyse database is developed by INRAE, based in France, and is best suited to the characteristics of the Italian region.

Table 1. Feed and chemical composition (on a dry-matter basis); the energy required for three different concentrate feeds.

Feed Ingredients (%)	BCF	MCF	CRF
Wheat bran	49.1	22.6	-
Biscuit meal	21.6	-	-
Corn gluten meal	19.5	-	-
Sunflower meal	5.8	-	-
Soybean meal	-	27.8	43.6
Maise flour	-	31.0	26.3
Barley meal	-	13.5	26.3
Flaxseed oil	1.4	2.4	1.3
Mineral mix	2.6	2.7	2.6
Energy required			
Electricity medium voltage (Kwh/ton)	41.0	41.0	41.0
Natural gas (MJ/ton)	73.8	73.8	73.8
Nutritional value (%)			
Crude protein	22.1	22.0	22.1
Crude lipid	7.4	7.0	8.0
Starch	32.6	27.5	33.0
MFU [1]	1.09	1.09	1.09

By-product-concentrate feed (BCF); mixed concentrate feed (MCF); concentrate raw feed (CRF); [1] MFU = unit/kg dry matter; milk forage unit (MFU) = 7.11 MJ of net energy for lactation.

Table 2. Main ingredients selected from the software's database Agribalyse.

Feed Ingredients	Description	Agribalyse Database
Wheat bran	Wheat bran, animal feed, at plant/FR U	Agricultural/animal feed/feed ingredients/transformation/cereal-based/imported from SimaPro v. 9.5.
Biscuit meal	Biscuit meal, and animal feed, at the retailer's gate	Agricultural/animal feed/feed ingredients/transformation/others

Table 2. *Cont.*

Feed Ingredients	Description	Agribalyse Database
Corn gluten meal	Corn gluten meal (gluten 60)	Agricultural/animal feed/feed ingredients/transformation/cereal-based
Sunflower meal	Sunflower meal and oil, with low dehulling, at the transformation plant	Agricultural/animal feed/feed ingredients/transformation/oil seed-based
Soybean meal not associated with deforestation	Soybean meal BR, crushed in France, animal feed, at a French mill, not associated with deforestation/FR U	Agricultural/animal feed/feed ingredients/transformation/legume-based
Maise flour	Maise flour at an industrial mill	Agricultural/food/transformation
Barley meal	Barley, feed grain, conventional, stored and transported, processing/FR U	Agricultural/animal feed/feed ingredients/transformation/cereal-based
Soybean meal associated with deforestation	Soybean meal BR, crushed in France, animal feed, at a French mill, associated with deforestation/FR U	Agricultural/animal feed/feed ingredients/transformation/legume-based

2.1. Wheat Bran

In detail, wheat bran is a by-product generated during the dry-milling process of common wheat (*Triticum aestivum* L.) into flour, and it plays a significant role as an agro-industrial by-product in animal feed. It is primarily composed of the outer layers of the wheat kernel, including the cuticle, pericarp, and seed coat, along with slight traces of the starchy endosperm. Additionally, wheat bran can also result as a by-product from other wheat-processing industries that involve bran removal, such as durum wheat (*Triticum durum* Desf.) milling for pasta and semolina, as well as starch and ethanol production [25,26].

2.2. Biscuit Meal

Biscuit meal is an agro-industrial by-product generated in large quantities by biscuit manufacturing industries in various industrial regions. It is a highly palatable, energy-dense feed with wheat flour, skimmed milk powder, vegetable fat, sugar, salt, and flavouring agents. Nutritional analysis of this waste meal revealed that it contains significant amounts of protein, energy, and minerals, making it suitable for supporting animal growth and performance [11,27]. In particular, since biscuit meals are derived from leftover bread, they are regarded as residual products, and therefore, no upstream emissions are attributed to their production [26].

2.3. Soybean Meal

Soybean meal is the leading protein source in animal feed, accounting for two-thirds of global protein feed production, including all significant oilseed meals and fish meals. Its nutritional value exceeds any other plant-based protein source, making it the benchmark for comparison with other protein feeds. Soybean meal is the by-product of the extraction of soybean oil. The agricultural production process of soybeans in Brazil was selected from the Agribalyse database and is not associated with deforestation. The soybeans are then transported with 14% moisture to the French port of Brest in the Brittany region [28] by boat. Crushing takes place in France (Brest), with transport from the port to the processing plant over a distance of 20 km. Before crushing, the grains are further dried using French drying, reducing the moisture content from 13% to 11%. Economic impact allocation was applied to divide the environmental impact of soybean oil extraction from soybean meal production [26].

2.4. Corn Gluten Meal

Corn gluten meal is a by-product generated during wet milling to produce maise starch and occasionally ethanol. It is a protein-dense feed with approximately 65% crude protein (dry matter). It is utilised as a source of protein, energy, and pigments in the diets of various livestock species, including fish. The production and extraction process is located in France [28], includes maise production, drying and storing, transport from the farm to the store agency, transport from the store agency to the transformation plant, and the extraction of corn starch, with 1000 kg of maise starch from 1515 kg of grain maise, 374 kg of corn gluten feed, 40 kg of corn oil, and 75 kg of corn gluten meal (gluten 60) [26].

2.5. Sunflower Oil and Sunflower Meal

Sunflower oil and sunflower meal, with low dehulling, are in France's economic allocation, based on the Olympic average of 2008–2012 prices from La Depeche. A total of 1 kg of low-dehulled sunflower grains are used for 0.505 kg of crude oil and 0.476 kg of the meal. Prices: La Depeche, Olympic average 2008–2012, sunflower crude oil; Rotterdam: EUR 871/t, Sunflower meal 32%; Lezoux: EUR 186/t [29]. Production volume: 476 kg meal and 0.505 kg oil, including the entire process: This module describes the crushing of 1 kg of lowly dehulled sunflower grains. The transport of sunflower grains from the storing agency to the crushing plant is included in the dehulling step. The products are 0.476 kg of sunflower meal with medium protein content (32%) and 0.505 kg of sunflower crude oil, with an average French plant efficiency.

2.6. Maize Flour

Maise flour (*Zea mays* L.) is one of the most important staple grains globally, especially in regions like Africa, Latin America, and Asia, and it serves as a primary animal feed in more developed nations. Maise has many applications for food (such as grain, flour, syrup, and oil) and non-food products (including cosmetics, adhesives, paints, and varnishes). Maise starch and oil are among their key derivatives. It is a central feed grain in livestock diets, valued primarily for its energy content, and is often used as a benchmark when assessing the nutritional quality of other grains. Many by-products of maise processing—such as hominy feed, bran, germs, and oil meal from flour production, corn gluten feed and meal from starch production, and distillers' dried grains and soluble from alcohol or biofuel industries—are also used in animal feed [30]. Breeders have developed numerous maise varieties tailored to specific environmental and agronomic conditions and uses. "Dent corn" is the most widely cultivated type, predominantly used for animal feed. Other varieties, like flint corn, popcorn, sweet corn, and flour corn, are more commonly used in food production. Specific cultivars have been bred to enhance their industrial or nutritional qualities, including varieties with high lysine, high tryptophan, high oil, high amylose, or low phytate content. Brown midrib maise, for example, has a lower lignin content, which makes it more digestible for livestock. The maise production in the Agribalyse database was the average of maise from 6 case studies in the west, east, centre, and south of France. Representativeness: case studies are based on reliable expertise and statistical regional data (extrapolated from the data of the 1st quartile of the agricultural population and yields = regional mean 10%). Allocation between crops: N and P from organic fertilisers; P and K are the minerals.

2.7. Barley Meal

Barley meal (*Hordeum vulgare* L.) is one of the most important cereal crops globally. In 2009, global barley grain production reached 150 million tons, making it the fourth most-produced cereal after maise, rice, and wheat [25]. Approximately 25% of the global barley cultivation area is in developing countries. Feed barley, with 85% DM, included the following processes: the inventory consists of soil cultivation, sowing, weed control, fertilisation, pest and pathogen control, irrigation, harvest, and transport to the farm. Boundaries: from harvest to harvest. Excluded processes: soil enrichment products and post-harvest operations. Representativeness: statistical data in France, based on surveys and reliable expertise. All background data originate either from eco invent 3.4, INRA, or Agribalyse.

2.8. Sensitive Analysis of Soybean Meal Association with Deforestation

The issue of global deforestation is closely linked to soybean production in countries such as Brazil [31]. This phenomenon further exacerbates the problem of global warming due to the clearing of primary forests and the subsequent change in land use to intensive farming. To highlight this phenomenon and evaluate its effects on carbon footprint, in the formulation of conventional and mixed animal feed, a scenario has been considered where soybean meal is sourced from plots of land in Brazil associated with the deforestation of the Amazon rainforest. The following two types of feed have been formulated (Table 2): mixed concentrate feed with soybean meal from deforestation (MCFSD) and conventional raw feed with soybean meal from deforestation (CRFSD).

3. Results

3.1. Carbon Footprint

The results are shown in Figure 1. The BCF has a carbon footprint of 0.29 kg CO_2 eq. per FU. The MCF was 23.7% more impactful than BCF, with a 0.38 kg CO_2 eq. value per FU. The CRF shows a value of 0.46 kg CO_2 eq. per FU, which is 37% and 17.4% more impactful than BCF and MCF, respectively. The primary pollutants are shown in Table 3. The main pollutants for the considered feeds are CO_2 from fossils, N_2O, and CH_4 from fossils. The BCF shows that 63.4% of its carbon footprint comprises CO_2 from fossil sources, followed by N_2O (33.1%) and fossil-derived CH_4 (3.5%). The MCF shows that 69.9% of its carbon footprint impact is due to CO_2 from fossil sources, 27.2% to N_2O, and the remaining 2.9% to fossil-derived CH_4. Similarly, for CRF, 71.1% of its pollutants are attributable to CO_2 from fossil sources, 26.0% to N_2O, and 3.0% to fossil-derived CH_4.

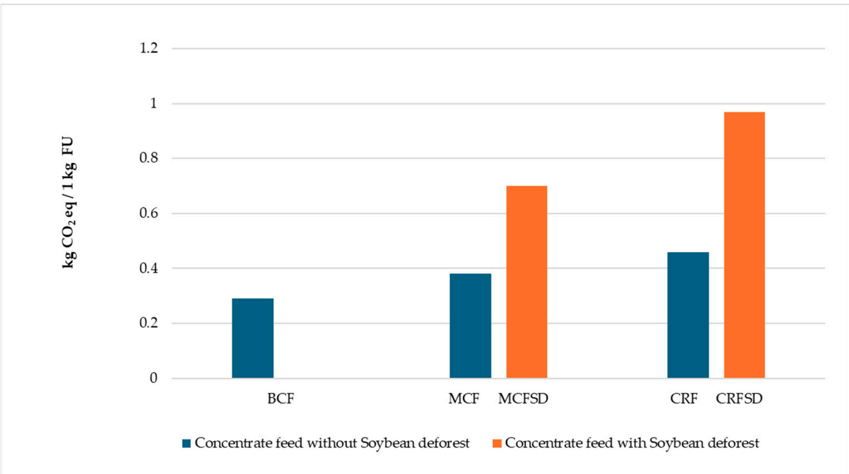

Figure 1. Carbon footprint of different concentrate feed. By-product-concentrate feed (BCF); mixed concentrate feed (MCF); conventional raw feed (CRF); mixed concentrate feed with soybean meal from deforestation (MCFSD); conventional concentrate feed with soybean meal from deforestation (CRFSD); FU = functional unit—1 kg of concentrate feed.

Table 3. Primary pollutants emitted into the air in percentages for different concentrated feeds.

Pollutants in Air (%)	BCF	MCF	MCFSD	CRF	CRFSD
CO_2 Land Transformation	0	0	42.9	0	48.5
CO_2 Fossil	62.1	68.9	40.0	69.6	33.0
N_2O	32.4	26.8	14.6	25.4	12.1
CH_4 Fossil	3.4	2.9	1.6	2.9	1.5

Cut-off, 1%; by-product-concentrate feed (BCF); mixed concentrate feed (MCF); conventional concentrate feed (CRF); mixed concentrate feed with soybean meal from deforestation (MCFSD); conventional raw feed with soybean meal from deforestation (CRFSD).

3.2. Sensitive Analysis Soybean Meal Association with Deforestation

The results of the conventional feed production scenario using soybean meal derived from deforested areas are shown in Figure 1. The BCF shows no change in its carbon footprint nor in terms of percentage of pollutants' distribution, as it does not contain soybean meal (0.29 kg CO_2 eq. per FU). The MCFSD feed has an environmental impact in terms of carbon footprint that is 58.8% higher than that of BCF and 47.7% higher than MCF, with an absolute value of 0.70 kg CO_2 eq. per FU, and the primary pollutant emitted into the air is CO_2 from land transformation, constituting 42.9%, followed by CO_2 from fossil combustion with 40.0%, and finally N_2O with 14.6%, as can be seen in Table 3. Meanwhile, the CRFSD feed demonstrates an increase in the environmental impact of 70.1% compared to BCF in terms of carbon footprint and 52.6% compared to CRF, with a value of 0.97 kg CO_2 eq. per FU, and the primary pollutant emitted into the air is CO_2 from land transformation, at 48.5%, followed by CO_2 from fossil combustion at 33.0% and finally N_2O at 12.1%, as can be seen in Table 3.

4. Discussions

Livestock production has to focus more on reducing natural resource use per unit of animal product, measured as the footprint per product, including metrics like the "water footprint", "mineral footprint", and "land footprint", whether arable or total land [32]. The carbon footprint generated by the concentrated feed based on by-products (BCF) is lower compared to a mixed concentrated feed (MCF) and a conventional concentrated feed (CRF) containing ingredients such as soybean meal and corn meal. A recent study on dairy cows demonstrated that enhancing the efficiency of on-farm feed procurement practices can significantly reduce greenhouse gas (GHG) emissions, with observed reductions ranging between 36% and 44% [33]. This finding underscores the substantial environmental benefits of improved resource management at the farm level. Similarly, research conducted in Sweden on dairy farming systems revealed that incorporating by-products into concentrated feed formulations can further contribute to environmental sustainability; in particular, the study found that substituting conventional feed components with by-product-based ingredients resulted in a 20% reduction in overall environmental impact [34]. These results suggest that optimising feed composition—particularly by leveraging agricultural by-products—presents a viable strategy for reducing the ecological footprint of dairy production. Enhancing the nutritional value of farm co-products and food waste secondary by-products generated alongside primary goods for human consumption has been proposed as a practical approach to improve resource use efficiency, minimise competition between food and feed, and promote sustainability within agricultural systems [35]. Using by-products from the farming industry fosters a circular economy that yields benefits not only from an economic standpoint but also from an environmental perspective [36]. This approach prevents these materials from ending up in landfills, where they would contribute to environmental issues if not repurposed within other industrial production cycles [37].

The current approach to soybean extraction meal is controversial, as it is technically considered a waste product, and thus a by-product, of the industrial process primarily aimed at extracting soybean oil. This oil is widely used both for human consumption and in the production of industrial and cosmetic products, as well as for energy production by biodiesel [38]. However, soybean meal, due to its high protein content, digestibility, and energy value, is one of the primary feeds used in livestock farming for meat and dairy production [39]. However, this by-product of soybean oil extraction does not compete with human food resources. The current LCA approach for estimating the carbon footprint per kilogram of soybean meal involves distributing its environmental impact through economic allocation. Since this by-product has a market, it proportionally contributes to greenhouse gas emissions. However, this method overlooks that its end-of-life destination would likely be landfilled without the livestock sector utilising this by-product, further exacerbating its environmental impact. Several studies have observed that using agricultural and food by-products does not affect the production performance of different livestock species [40–42].

5. Conclusions

Using agricultural by-products to produce concentrated feed in the livestock sector presents a potentially environmentally sustainable alternative to relying on raw vegetable materials that might otherwise compete with human food resources. This approach addresses concerns over land use and food security and offers a pathway to reduce the environmental footprint of livestock production. However, further research is essential to understand this practice's implications fully. Detailed evaluations are needed to investigate the digestibility properties of feeds formulated exclusively from agro-industrial by-products, their effects on animal performance metrics, and the quality of livestock products derived from such diets. Additionally, a thorough examination of the role of soybean meal in livestock nutrition and its associated environmental impacts is critical for developing comprehensive strategies to enhance sustainability in the sector. These studies will help inform evidence-based decisions and promote more eco-friendly feeding practices in animal agriculture.

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