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The use of broccoli agro-industrial waste in dairy cattle diet for environmental mitigation



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ABSTRACT

Livestock feed production for the intensive dairy industry has a significant environmental impact. This study evaluated the potential to reduce the environmental impacts of milk production in Guanajuato, Mexico, by incorporating broccoli stems (BS), an abundant agro-industrial waste product with high nutritional value, into dairy cattle feed. The potential reduction of environmental impacts from adding BS to cattle diet formulation was estimated using a life cycle assessment and a linear programming model which considered nutritional requirements as constraints. Two scenarios for milk production were considered: an optimized conventional diet and an optimized diet including BS. The results indicated that incorporating BS in cattle feed could reduce greenhouse gas emissions by 118 g CO₂ eq kg⁻¹ fat-and-protein corrected milk (FPCM) and agricultural land occupation by 0.002 m²a kg⁻¹ FPCM but increased fossil depletion by 4 g oil eq kg⁻¹ FPCM. BS can replace 11.1% of conventional feeds and maximize the incorporation feeds with low environmental impacts in the diet, such as alfalfa hay and maize silage. A sensitivity analysis of the economic allocation showed that the maximum price of BS to remain environmentally viable was 19.28 USD t⁻¹ on a fresh matter basis.

1. Introduction

Cattle are responsible for generating 7.1 Gt of CO₂ eq y⁻¹, corresponding to 14.5% of global greenhouse gas (GHG) emissions; approximately a third of this is attributed to dairy cattle (Gerber et al., 2013). The Food and Agriculture Organization (FAO) stated that the livestock industry is a severe environmental problem; it uses approximately 75% of direct and indirect agricultural land (Foley et al., 2011) and contributes to high percentages of global GHG emissions (9% of CO₂, 37% of CH₄,

and 65% of N₂O). These emissions mainly come from deforestation, enteric fermentation, and nitrification and denitrification processes in manure. Likewise, the livestock industry generates two-thirds of the anthropogenic emissions of ammonia (NH₃), which is responsible for terrestrial and water acidification (FAO, 2017).

Life cycle assessment (LCA) is a methodology used to design alternatives to decrease environmental impacts of processes or services. LCA is a systematic approach that estimates potential environmental impacts and resource consumption at all stages of a process or service, that is, from raw material extraction to manufacturing, use, and final disposal

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Nomenclature	
AFac_{BPS}	Allocation factor of the broccoli production system
AFac_{DPS}	Allocation factor of the dairy production system
BPS	Broccoli production system
BS	Broccoli stems
DM	On a dry matter basis
FM	On a fresh matter basis
FPCM	Fat-and protein-corrected milk
FU_{BPS}	Functional unit of the broccoli production system
FU_{DPS}	Functional unit of the dairy production system
GHG	Greenhouse gas
DPS	Intensive dairy production system
LCA	Life cycle assessment
 OCD	Optimized conventional diet
ODBS	Optimized diet with broccoli stems
PM	Particulate matter formation
<i>Subscripts</i>	
a	a-th livestock category
i	i-th nutrient in livestock diet
j	jth livestock feed
j'	j'th livestock feed (forage)
<i>Constraints</i>	
b_{ai}	Minimum percentages of the i-th nutrient in the livestock
	diet for the a-th livestock category
d_{ai}	Maximum percentages of the i-th nutrient in livestock diet for the a-th livestock category
w_a	Minimum amount of dry matter intake for the a-th livestock category
y_a	Maximum amount of dry matter intake for the a-th livestock category
v_a	Minimum percentage of forage in diet of the a-th livestock category
h_a	Maximum percentage of forage in diet of the a-th livestock category
<i>Variables</i>	
Z	Environmental impact of the diet [Pt FU _{DPS} ⁻¹]
x_{aj}	Amount of the jth livestock feed for the a-th livestock category [kg DM FU _{DPS} ⁻¹]
c_j	Environmental impact indicator of the jth livestock feed [Pt kg ⁻¹ DM]
e_A	Ratio of the a-th livestock category to the livestock total on the farm
n_{ij}	Contribution of the i-th nutrient in livestock diet of the jth livestock feed
DM_j	Dry matter content of the jth livestock feed [kg DM kg ⁻¹ FM]

(ISO, 2006a; 2006b). LCA studies of intensive dairy production systems (DPS) found production of livestock feed generates the largest percentage of environmental impacts (Wattiaux et al., 2019). In Mexico, Rivas-García (2014) reported that livestock feed production was responsible for 36%, 60%, and 48% of GHG emissions, terrestrial acidification, and freshwater eutrophication of the DPS, respectively. Another study identified that forage and grain crop production generates 60% of GHG emissions of the DPS, mainly nitrous oxide (N₂O) emissions from nitrogen (N) fertilization (Yue et al., 2017).

Several strategies have been proposed to mitigate the environmental impacts of dairy production. For example, reducing waste in the supply chain (Bajželj et al., 2014), minimizing the use of fertilizers and pesticides for increasing crop production efficiency (Röös et al., 2017), implementing manure management strategies such as anaerobic digestion systems (Rivas-García et al., 2015), and replacing conventional feeds in livestock diets with feeds with less environmental impact.

Food waste used as a substitute for conventional feeds has a carbon footprint 94% (1010 kg of CO₂ eq t⁻¹) lower than when sent to landfills (Kim and Kim, 2010). Another study suggested that replacing feed grain with food waste could decrease agricultural land use in Europe by up to 20%, equivalent to 1.8 million hectares (ha) (zu Ermgassen et al., 2016). Furthermore, fruit and vegetable waste can replace 6%–18% of conventional concentrated feeds without decreasing the nutritional quality (Angulo et al., 2012).

The pre- and post-harvest steps in the food supply chain generate 39% of the total food loss and waste in North America (CEC, 2017). Agro-industrial wastes have nutritional compositions that make them suitable for use as partial substitutes for conventional feeds in cattle diets (Díaz et al., 2013), with advantages such as lower environmental impact, greater abundance, and lower cost compared to conventional feeds (García-Rodríguez et al., 2019). However, agro-industrial wastes are rarely used in livestock diets because of drawbacks such as variability in nutritional composition and the need for thermal processes such as dewatering that have high costs (Fausto-Castro et al., 2020; ReFED, 2016). Agro-industrial wastes could be considered as strategic alternatives in cattle diets if certain conditions are met, such as: (1) high

availability, (2) produced in the dairy-producing region, (3) sufficient nutritional characteristics, and (4) economically viable treatments to convert them into feed (Hyland et al., 2017).

Broccoli stems (BS) are by-products of broccoli production systems (BPS) (i Canals et al., 2010, 2008) that have recently been incorporated into animal diets in Ecuador (Díaz Monroy et al., 2014), China (Yi et al., 2015), and Canada (Mustafa and Baurhoo, 2016). In Mexico, Guanajuato produces the most broccoli (420,770 t in 2018); (SIAP, 2019), and it is estimated to produce a similar amount of BS. Additionally, 920,000 m³ of milk was produced in 2018 in Guanajuato (SIAP, 2019). These conditions have encouraged BS as a substitute for conventional feeds in cattle diets, leading to the formation of a semi-formal market for its commercialization and reducing the amount BS sent to sanitary landfills and open dumps. This scheme has reduced the environmental impacts of the dairy industry; however, no studies have estimated the environmental impacts of the use of BS and its incorporation into the DPS.

The reduction of environmental impacts by incorporating agro-industrial wastes into cattle diets can be studied using mathematical optimization models. Although solution strategies mainly focus on optimizing costs (Guevara, 2004; Munford, 1996), minimizing environmental impacts has also been considered as an objective Tozer and Stokes (2001) reduced environmental impact by reducing N and phosphorus (P) excretion in manure; Moraes et al. (2012) minimized methane (CH₄) emissions from enteric fermentation; and Babić and Perić (2011) and Castrodeza et al. (2005) used feed-ration optimization to avoid the overestimation of nutrients in diet formulations.

Changes proposed by optimization models are subject to constraints such as for livestock nutritional requirements (Lara, 1993; Munford, 1996; Pratiksha Saxena, 2011), pollutant emissions (Moraes et al., 2012), environmental policies (Castrodeza et al., 2005), and feed proportions in the diet (Uyeh et al., 2018; von Ow et al., 2020). The rigidity of these constraints makes it challenging to obtain feasible solutions; therefore, it is necessary to use iterative models that can modify constraints depending on the variables (Rahman et al., 2010; Uyeh et al., 2018).

Studies that evaluated the environmental impact on the milk supply chain when BS was used as a partial substitute in the cattle diet were not

identified through our state-of-the-art review. Additionally, no studies have determined the environmental profile of broccoli and its co-products (BS). The novelty of this work lies in assessing the DPS and BPS in parallel, which exchanges material flows that influence the environmental profile of products.

This study uses the LCA methodology and a linear programming model with nutritional and environmental criteria to estimate the environmental impacts of the DPS supply chain in Mexico when BS is incorporated into the cattle diet. Additionally, we present sensitivity studies that determine the effects of BS price and different allocation methods of environmental burdens in the DPS. The model, developed with appropriate specific constraints, can be applied to different dairy cattle diets, agro-industrial wastes, and livestock categories.

2. Materials and methods

2.1. Dairy production system

2.1.1. Description of the study scenario for DPS

This work considers a supply chain in the dairy basin of central Mexico in Leon, Guanajuato. The dairy farm under studied is located at 21°00'19.5" "N 101°36'53.9" W (Figures S1 and S3). The study system was divided into three modules: agricultural production, feed-processing plants, and dairy farm operations, including transport between the modules (Fig. 1a).

The agricultural production module was forage maize, grain maize, sorghum, and alfalfa, which are the crops most consumed by the regional dairy industry (SADER-SIAP, 2019). The transport distance between agricultural fields, the feed-processing plant, and the farm was established using the procedure described in Table S2 the Supplementary Material section. Crops of forage maize, grain maize, and sorghum are transported to a feed-processing plant, where they are transformed into maize silage, rolled maize, and sorghum grain, respectively. Subsequently, these feeds are transported to dairy farms. Alfalfa is transported directly to dairy farms as alfalfa hay.

The dairy farm contained 1000 heads of cattle (Table S2). The percentage distribution of each livestock category was determined according to the characteristics of the regional dairy farms and Moraes et al. (2012). Based on data from the DPS of the study region, cows had a mean milk production of 25 L milk d⁻¹. Activities on the farm include raising cattle, mechanized milking, and manure management. The most common

manure management strategy in Mexico is solid storage for several months in open air piles for later use as a soil improver (Rivas-García et al., 2015).

2.1.2. Definition and scope of the product system for the DPS

The LCA boundaries of the DPS were set from the cradle to the farm gate, that is, from supply production up to raw milk production in the farm (Fig. 1a). The functional unit (FU_{DPS}) was defined as the production of 1 kg of fat-and-protein-corrected milk (FPCM) leaving the farm without any processing, following the recommendations of the International Dairy Federation (IDF, 2015). Capital goods (machinery and infrastructure) and veterinary medicines were not considered within the system due to the lack of information and to achieve consistency with other dairy production LCA studies which did not consider these factors (Baldini et al., 2017; Yan et al., 2011).

2.1.3. DPS inventory analysis

For the agricultural production module, the amount of fertilizers, pesticides, and seeds used to produce each crop were taken from agricultural production guidelines of Guanajuato State (SAGARPA, 2017) and the Terralia platform (Terralia, 2019). The average yield of each crop in the state was obtained from the Agri-food and Fisheries Information Service (SIAP, 2019), the diesel consumption by tillage practices was estimated using the factors of West and Marland (2002), and the environmental burdens of seed production were assessed using an allocation factor determined according to the procedure of Lechón et al. (2005). Irrigation water requirements for each crop were predicted using the CROPWAT© model (v. 8.0; FAO, Rome, Italy), using historical weather data from the study region (CONAGUA, 2020), as well as crop data from Allen et al. (1998). Electricity use for irrigation was estimated as per the World Food LCA Database (Nemecek et al., 2014).

GHG emissions from N fertilization were estimated based on the guidelines for GHG inventories of Chapter 11 of the 2019 refinement to the 2006 IPCC Guidelines using a Tier 1 approach (IPCC, 2019). Emissions of NH₃, NO_x, non-methane volatile organic components (NMVOC), and particulate matter (PM) resulting from N fertilization and tillage practices were estimated according to Chapter 3D of the EMPEP/EEA Guidebook (EMEP/EEA, 2019a). Agricultural machinery emissions were predicted using the GREET model (GREET, 2018). It is essential to mention that the EMEP/EEA Guidebook evaluates non-GHG emission factors in a European agricultural context; this inevitably brings

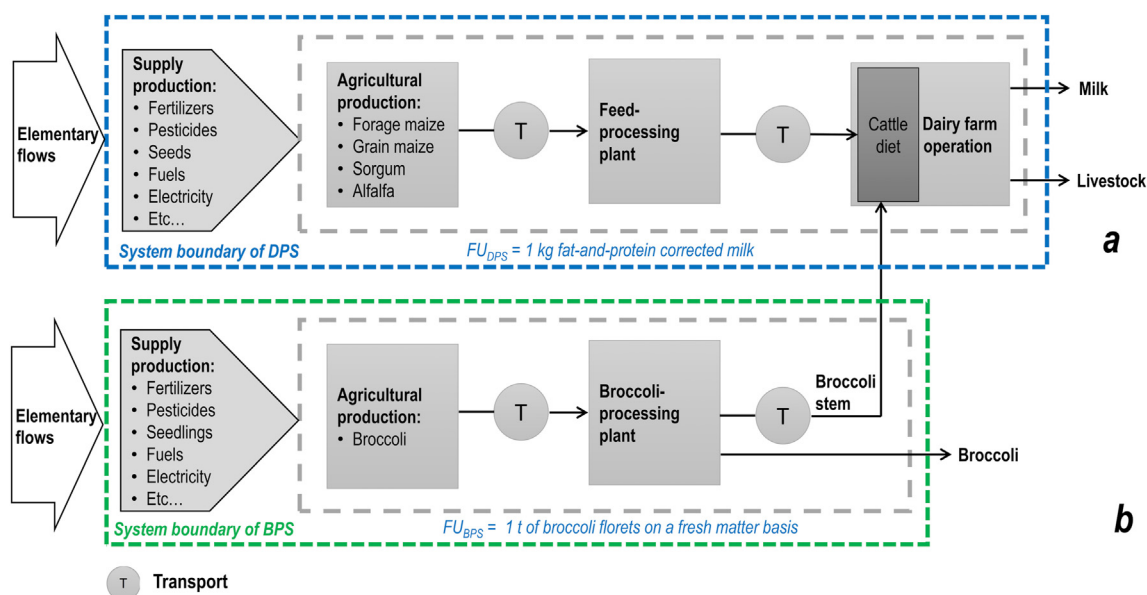


Fig. 1. System boundaries of (a) Dairy production system (DPS) and (b) Broccoli production system (BPS). FU: Functional unit.

uncertainty in environmental burden assessments in the Mexican context. The absence of methodologies for estimating non-GHG inventories in the agricultural sector in Mexico and Latin America is a research gap.

The leaching and runoff of nitrate (NO_3^-) and dissolved NH_3 were calculated based on the IPCC Guidelines emission factors assuming that 50% of N (by mass) is leached and drained as NH_3 and the remaining 50% as NO_3^- . It was assumed that 1.8% of the P applied to soils in the study region was lost by leaching and runoff, as reported by Zamudio-González et al. (2007). Pesticide emissions to water bodies were estimated using the Pesticide Water Calculator v 1.52 (PWC US Environmental Protection Agency, Washington, DC, USA) based on the physicochemical properties of pesticides from the Pesticide Properties Database (University of Hertfordshire, 2016).

Emissions from transport (Table S2) were predicted using the GREET model. On the dairy farm, water consumption by livestock was estimated according to the method of Dahlborn et al. (1998), electric consumption according to the method of Nemecek et al. (2014) using Tier 1, and fuel consumption according to the method of Rivas-García et al. (2015).

GHG emissions from enteric fermentation and manure management on the farm were estimated as per chapter 10 of the IPCC Guidelines (IPCC, 2019) using Tier 2. Emissions to air (NH_3 , NO_x , NMVOC, and PM) and water (NH_3 and NO_x) by manure management were estimated according to Chapter 3B of the EMPEP/EEA Guidebook (EMEP/EEA, 2019b) and Chapter 10 of the IPCC Guidelines (IPCC, 2019) respectively, using Tier 1 and considering the solid storage system.

2.1.4. DPS impact assessment

The LCA followed an attributional approach and was carried out using SimaPro® software v. 8.3, (PRé Consultants bv, Amersfoort, The Netherlands). Eco-inventories for the production of materials and energy were taken from ecoinvent v. 3.3 (Wernet et al., 2016). Environmental impact was assessed using the ReCiPe method v. 1.13, with the objective of transforming a long list of life cycle inventory results into a limited number of indicator scores. These indicator scores express the relative severity of the environmental impact categories. The ReCiPe method works with two levels of 18 midpoint and three endpoint indicators. In this study, all the midpoint indicators were used to calculate a single score (Pt), an environmental impact score estimated through a ponderation process considering the midpoint to endpoint factors of the hierarchist (H) perspective proposed by Goedkoop et al. (2013), which is based on short-term interest, undisputed impact types, and technological optimism concerning human adaptation.

Economic allocation factors (AFac_{DPS}) were used to estimate the environmental burdens of DPS products—milk and livestock (newborn calves and dry cows)—that leave the product system. To this end, we used the price of these products in the Mexican market (April 2019), corresponding to 0.41 USD L^{-1} for milk and 2.25 USD kg^{-1} animal live weight for livestock (Secretaría de Economía, 2019) as well as their annual production (Table S3).

2.2. Broccoli production system

2.2.1. Description of the study scenario for BPS

The BPS consisted of two modules: agricultural production and broccoli-processing plants, including transport between both modules and the DPS (Fig. 1b). The broccoli processing plant is in Irapuato, Guanajuato, located at 20°40'11.1" N, 101°20'06.2" W.

Agricultural production of broccoli includes land preparation activities, greenhouse germination of seedlings, transplanted, and tillage and harvest practices. Once the agricultural cycle is complete, broccoli is transported 20 km to the processing plant, where 50% (by mass) becomes BS (R. Covarrubias-Kaim, 2018; personal communication, 29 October). The remaining biomass becomes broccoli florets, which are frozen, packed, and exported; however, these activities were excluded from the study because the LCA scope ended at the cutting stage when BS were

removed from the plants. Finally, the BS without any stabilization treatment are transported 60 km to the dairy farm.

2.2.2. Definition and scope of the product for BPS

LCA boundaries of the BPS were established from the cradle to the dairy farm gate, that is, from supply production to BS transport, to the dairy farm (Fig. 1b). FU_{BPS} was defined as the production of 1 t of broccoli florets on a fresh matter basis (FM) without any subsequent cooking or packaging. FU_{BPS} was chosen because the main product of the BPS are the broccoli florets, and BS are the co-products of low economic value.

2.2.3. BPS inventory analysis

For the agricultural production module and transport, the amount of fertilizers and pesticides, crop yields, water, energy requirements for irrigation, diesel consumption, as well as the environmental burdens of seedling and broccoli production were estimated using the same tools, procedures, and assumptions described for the DPS (Section 2.1.3).

In the broccoli-processing plant module, water requirements were estimated by an expert (R. Covarrubias-Kaim, 2018; personal communication, 29 October). Electricity used to separate BS from florets was estimated with the technical specifications of a Silex Single Lane (AIT® brand) Broccoli Floretting Machine.

2.2.4. BPS impact assessment

The BPS impact assessment was performed in the same way as for the DPS (Section 2.1.4). The production of broccoli and BS and their respective sales prices (corresponding to 425 USD t^{-1} FM for broccoli and 1.5 USD t^{-1} FM for BS) were used to estimate the economic allocation factors (AFac_{BPS}). The prices came from a broccoli-producing company in the region (R. Covarrubias-Kaim, 2018; personal communication, 29 October).

2.3. Optimization model

The cattle diet formulation model optimizes the environmental impacts of incorporating BS into the dairy cattle diet by considering nutritional criteria. The model considers:

- Four livestock categories ($a = \{1,2,3,4\}$): calves, replacement heifers, cows in production, and dry cows (Table S2).
- Five nutrients within the constraints ($i = \{1,2,3,4,5\}$): metabolizable energy (ME, Mcal kg^{-1}), crude protein (CP%), crude fiber (CF%), calcium (Ca%), and P (%) (Timpka et al., 2001).
- Five livestock feeds ($j = \{1,2,3,4,5\}$): four conventional feeds (maize silage, alfalfa hay, sorghum grain, and rolled maize) and BS as an agro-industrial waste
- Forage crops are considered a subset of the feed ($j' = \{1,2,3\}$).

2.3.1. Parameters

Contributions of the i -th nutrient in the livestock diet of the j th livestock feed (n_{ij}) were determined (Table S4). Data for conventional feeds were obtained from the Animal Feed Resources Information System database developed for the FAO (Heuzé et al., 2015, 2016, 2017a, 2017b), while data for BS were obtained from the Food Composition Database of the United States Department of Agriculture (USDA, 2018); and Hu et al. (2011).

Requirements of the i -th nutrient in the livestock diet were determined according to an in-depth bibliographic review which considered the specific characteristics of each livestock category (Table S5). The constraints differed in nomenclature to facilitate the construction and comprehension of the optimization model.

2.3.2. Objective function

The objective function determined the environmental impact of the

cattle diet formulation (Eq. (1)):

$$\text{Min}Z = \sum_{a=1}^4 \sum_{j=1}^5 x_{aj} c_j e_a \quad (1)$$

where Z is the environmental impact of the diet [Pt $\text{FU}_{\text{DPS}}^{-1}$]; x_{aj} is the amount of the j th livestock feed for the a -th livestock category, [kg DM $\text{FU}_{\text{DPS}}^{-1}$]; c_j is the environmental impact indicator of feed j , [Pt kg^{-1} DM], which is calculated using the single score indicator of the ReCiPe Endpoint (H) method (Sections 2.1.3 and 2.1.4); and e_a is the ratio of the a -th livestock category to the livestock total on the farm.

2.3.3. Constraints

Nutrition requirements: ME includes requirements for maintenance, growth, gestation, and lactation, which were constrained as follows (Eq. (2)):

$$b_{ai} \leq x_{aj} n_{ij} \leq d_{ai}, \forall a, i = 1 \quad (2)$$

When $i = 1$ (Table S5), b_{a1} and d_{a1} are the minimum and maximum requirements of ME for the a -th livestock category [Mcal $\text{FU}_{\text{DPS}}^{-1} \text{d}^{-1}$], and n_{1j} is the ME contribution of the j th livestock feed [Mcal kg^{-1} DM].

The nutritional requirements of CP, CF, Ca, and P ($i = 2$ to 5, Table S5) were presented as intervals in percentages of DM and were constrained as follows (Eq. (3)):

$$b_{ai} \leq \frac{x_{aj} n_{ij}}{\sum_{j=1}^5 x_{aj}} 100 \leq d_{ai}, \forall a, i \neq 1 \quad (3)$$

where b_{ai} and d_{ai} are the minimum and maximum percentages of the i -th nutrient in the livestock diet for the a -th livestock category, respectively.

Dry matter intake: it is the sum of all feeds on a dry matter basis [kg DM d^{-1}] for the a -th livestock category. (Eq. (4)):

$$w_a \leq \sum_{j=1}^5 x_{ja} \leq y_a, \forall a \quad (4)$$

where w_a and y_a are the minimum and maximum amounts of dry matter intake for the a -th livestock category [kg DM d^{-1}].

Moisture: feeds with high moisture could fill an animal's rumen without supplying all nutritional requirements; to avoid this, as-fed intake [kg FM d^{-1}] was constrained as follows, assuming that an animal consumes a maximum of 10% of its weight per day (Timpka et al., 2001) (Eq. (5))

$$\sum_{j=1}^5 \frac{x_{ja}}{DM_j} \leq g_a, \forall a \quad (5)$$

where DM_j is the dry matter content of the j th livestock feed [kg DM kg^{-1} FM], and g_a is the maximum as-fed intake of the a -th livestock category [kg FM d^{-1}] (10% of animal live weight).

Feed: the maximum proportion of each feed in the cattle diet is defined as follows (Eq. (6))

$$\frac{x_{aj}}{\sum_{j=1}^5 x_{aj}} \leq l_{aj}, \forall a \quad (6)$$

where l_{aj} is the maximum proportion of the j th livestock feed in the cattle diet formulation for the a -th livestock category.

These constants l_{aj} were defined according to Moraes et al. (2012) (Table S4). For BS, the l_{aj} maximum was 0.20, according to Yi et al. (2015).

Forage: the appropriate forage: concentrate ratio between energy-concentrated feeds was constrained using Eq. (7), which models the percentage of the j th forage in the total mass of the feed

$$v_a \leq \frac{\sum_{j=1}^3 x_{aj'}}{\sum_{j=1}^5 x_{aj}} 100 \leq h_a, \forall a \quad (7)$$

where $x_{aj'}$ is the amount of the j th livestock feed (forage) for the a -th livestock category, [kg DM $\text{FU}_{\text{DPS}}^{-1} \text{d}^{-1}$], and v_a and h_a are the minimum and maximum percentages of forage in the a -th livestock category, respectively.

2.3.4. Solution

Microsoft Excel's Solver Tool was used to solve the model using the Simplex LP resolution method. The two scenarios were defined as follows:

- An optimized conventional diet (OCD), in which the cattle diet is formulated from the four conventional feeds j ($j = 1$ to 4) and
- An optimized diet with BS (ODBS), in addition to the four conventional feeds, BS can be used as a substitute feed ($j = 1$ to 5).

2.4. Sensitivity analysis of BS price and environmental impacts of DPS

A sensitivity analysis was performed to assess the influence of BS price and its associated environmental impacts. The analysis considered a gradual increase in BS price until its environmental impact was such that the formulation model did not allow incorporation of BS in the livestock diet, according to their constraints (from 0 to 7 USD t^{-1} FM). For this evaluation, the economic allocation was used (Eq. (8)).

$$\text{AFac}_k = \frac{\xi \omega_k}{\sum_{k=1}^n \xi \omega_k} \quad (8)$$

where ξ is the quantity of BS per year [t y^{-1}] and ω_k is its unit price [USD t^{-1}]. The subscript k denotes the different BS prices considered in the sensitivity analysis.

2.5. Sensitivity analysis of allocation method

One of the most debated issues in LCA studies of the dairy industry is how to study its co-products (i.e., milk and livestock) because the allocation method (e.g., economic, mass-based, or protein-based) can significantly influence the results (Baldini et al., 2017). Three environmental burden allocation cases were tested based on three criteria to assess the effect of the allocation method on the environmental impacts of the dairy production system's co-products, these were: (I) economic data from the Mexican market (ODBS scenario) and (II) economic and (III) protein-content correlations from Thoma et al. (2013). The Thoma et al. correlations are empirical relationships for the causal allocation ratio based on 536 dairy farms in the United States.

3. Results and discussion

3.1. Environmental impact assessment of feeds in the diet

3.1.1. Life cycle inventory

Crops grown primarily for their biomass (alfalfa hay and maize silage) required the least inputs (e.g., fertilizers, pesticides, seeds, water, electricity for irrigation, and diesel for farming activities) while grain production required more (Tables S6 and S7). The consumption of supplies to produce feeds was inversely proportional to their yields (t FM ha^{-1}). Notably, broccoli had a high moisture content of 90.7% (Table S6).

Foreground emissions related to crop production were a consequence of tillage practices (Table S8). N_2O emissions from alfalfa production were more than twice those of grain production (6.22 and 2.86 kg $\text{N}_2\text{O t}^{-1}$ DM, respectively); however, alfalfa required less N fertilizer

(Table S6). In this study, 95% of N_2O emissions from alfalfa production came from the decomposition of agricultural residues (above- and below-ground) generated by tillage (IPCC, 2019). While for the other crops, emissions of gaseous N were mainly due to the application of synthetic N fertilizers. For each N fertilizer applied to the soil, 1.08%, 6.8%, and 4% were emitted into the air as N_2O-N , NH_3-N , and NO_x-N , respectively, while 24% was emitted into the water as NO_3-N by leaching and runoff. PM emissions by each crop depended on the tillage practices and climatic conditions of the region. The production of maize silage and sorghum grain had the highest PM emissions of all crops (0.16 and $0.188 PM_{10} t^{-1} DM$, respectively).

3.1.2. Impact assessment of feeds

BPS considers broccoli as a product and BS as a co-product. A_{FacBPS} was 99.65% (equivalent to $425 USD t^{-1}$) for broccoli and 0.35% (equivalent to $1.5 USD t^{-1}$) for BS. Indeed, the single score of BS was lower than that of conventional feeds (Fig. 2). The environmental impact of feeds had an inverse relationship with crop yield; crops that needed more inputs (Table S6) had more significant environmental impacts (Fig. 2). The main input difference between the crops is the diesel used for agricultural activities (e.g., $1.1 kg t^{-1}$ FM in alfalfa hay and $10.97 kg t^{-1}$ FM in sorghum grain). These inputs were reflected in the fossil depletion indicator (Fig. 2).

3.2. Diet optimization

The optimization model formulated the OCD and ODBS for the farm's herd (Fig. 3, Tables S9 and S10) based on the number of the a-th livestock category and its nutritional requirements. The OCD and ODBS had similar masses on a dry matter basis, but different percentages of each feed (Fig. 3). The OCD prioritized feeds with low environmental impact, principally alfalfa hay with 38.2–43.1% and maize silage with 16.6–46.9%. In ODBS, BS can replace an average of 11.1% of the feed in the OCD. The main feed substituted was maize silage, which decreased in all livestock categories. However, to compensate for the use of low-energy feeds such as BS, the percentage of high-energy feeds (sorghum grain and rolled maize) tends to increase. For cows in production, it has been demonstrated that feed substitution up to 20% with BS does not result in changes in milk quality and production (Yi et al., 2015).

The model constraint parameters varied among the four categories of

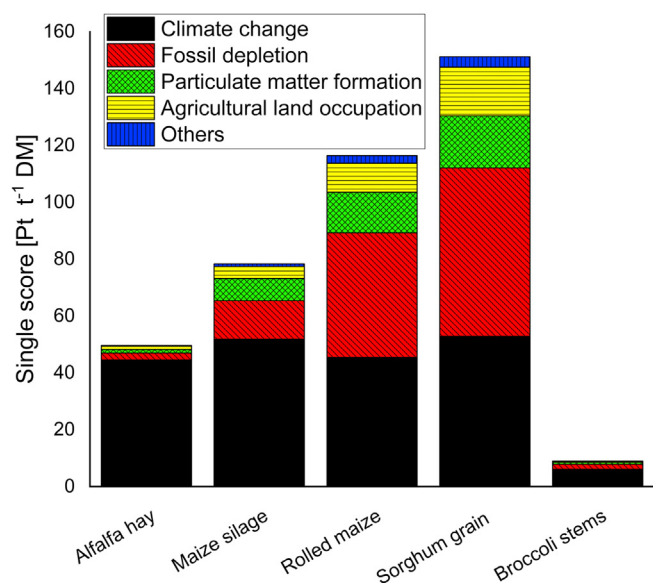


Fig. 2. Contributions of midpoint impact indicators to the single score environmental impact of each feed per 1 t of dry matter basis according to the ReCiPe endpoint method (H). DM: on a dry matter basis.

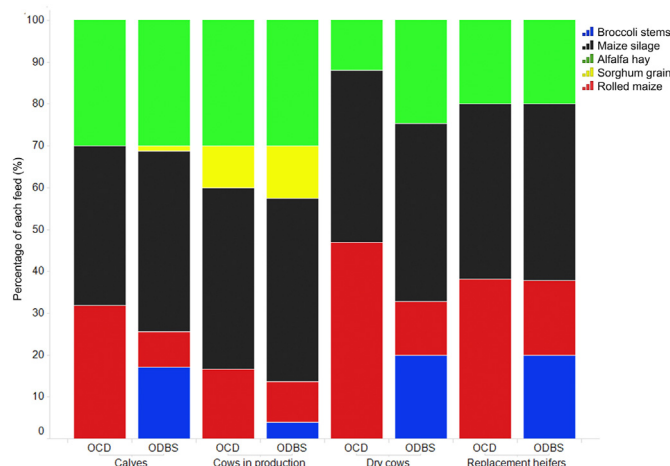


Fig. 3. Feeds distribution in the optimized conventional diet (OCD) and the optimized diet with broccoli stems (ODBS) by livestock categories.

livestock used in the study (Table S10). Although the two formulations met all the constraints, the critical parameters for optimization were ME and dry matter intake. The former lay near the upper limit of the constraint, while the latter approached the lower limit due to high-energy feeds with low dry matter intake that met nutritional requirements. Inclusion of BS in ODBS decreased ME and CP by 5.3% and 1.8%, respectively, compared to that of the OCD, however this decrease was negligible given the ME and CP ranges. In comparison, as-fed intake was 42% higher in the ODBS than in the OCD due to the high moisture content of the BS.

3.3. Environmental assessment of the DPS

The approach used to define the midpoint indicators for discussion and analysis was based on calculating the endpoint single score. In these terms, the OCD scenario has a single score of $116.4 mPt kg^{-1}$ of FPCM, formed by 68% for climate change (including damage to human health and ecosystems), 19% for fossil depletion, 9% for particulate matter formation, 4% for agricultural land occupation. This trend is reflected in Fig. 2.

Slight variations between the OCD and ODBS (summarized in Table S11) in the foreground emission inventories of the dairy farm operation module influenced the midpoint indicator of the DPS (Fig. 4). The climate change indicator changed mainly in the agricultural production module owing to the changes in feed formulation. For the OCD, this indicator was mainly caused by fertilization for feed crops (59.7%), followed by manure management (28.7%). GHG emissions decreased from OCD to ODBS by $118 g CO_2 eq FU_{DPS}^{-1}$ (6%) (Fig. 4a). This decrease was attributed to the use of feeds with lower environmental burdens (specifically maize silage); as well as the intake of feeds with lower content of fiber and lignin (Table S10), which may be associated with decreases of 3.9% in CH_4 emissions from enteric fermentation (Castelán-Ortega et al., 2014). Another factor associated with GHG mitigation is that ODBS reduces N-excretion in livestock by 2.24%, which leads to a 1.4% reduction in N_2O emissions.

Agricultural land occupation was mainly driven by the production of high-energy crops such as grain maize and sorghum with yields ($t DM ha^{-1}$) lower than those of forages (Fig. 4b). However, although sorghum had lower yields than grain maize, its lower percentage in the cattle diet formulation (5.2% and 6.8% in the OCD and ODBS, respectively, Fig. 3) meant it has had less impact in the midpoint indicators. Agricultural land occupation was 0.4% ($0.002 m^2 a FU_{DPS}^{-1}$), which was lower in the ODBS than in the OCD, mainly due to the replacement of maize silage with BS.

PM is mainly formed by emissions of NH_3 from fertilization, which react in the atmosphere with compounds such as sulfuric acid and water

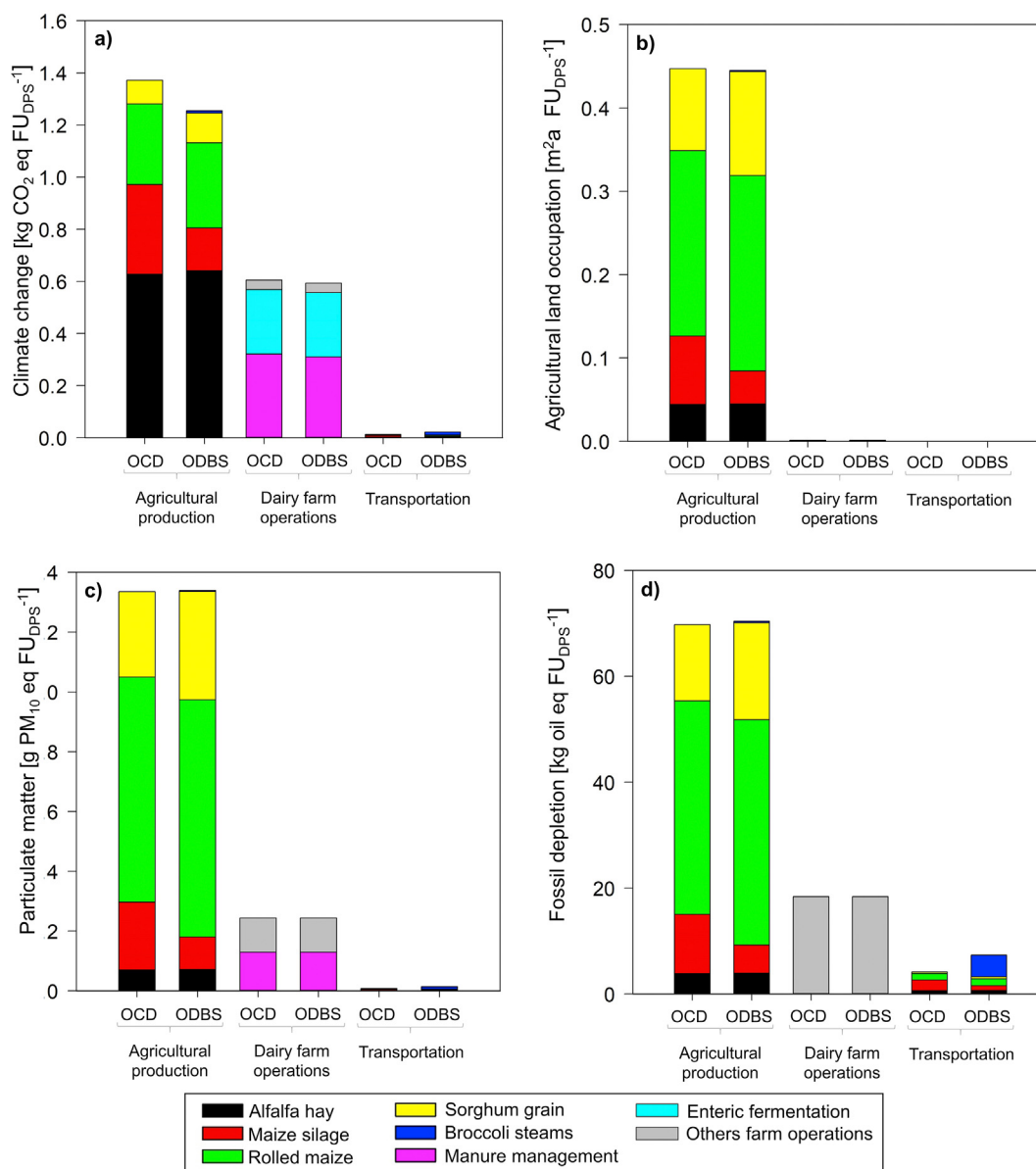


Fig. 4. Midpoint impact indicators of the dairy production system with the optimized conventional diet (OCD) and optimized diet with broccoli stems (ODBS): (a) climate change, (b) agricultural land occupation, (c) particulate matter formation, and (d) fossil depletion. FU_{DPS} : functional unit of the dairy production system.

to form PM. PM formation was 0.7% lower ($0.01 \text{ g PM}_{10} \text{ eq FU}_{DPS}^{-1}$) in the ODBS than in the OCD (Table S12) which means that variation in the percentage of each feed does not change PM significantly.

Fossil depletion was due to fuel consumption by agricultural machinery and electricity generation (45.2%), fertilizer production (30.4%), and transport (4.5%) in the OCD. Fossil depletion was 3.94% higher ($4 \text{ g oil eq FU}_{DPS}^{-1}$) in the ODBS than in OCD because of the high moisture content of BS, which requires more diesel for transport (Table S12). The increase in the fossil depletion indicator reveals that considering an endpoint indicator as a variable to optimize environmental impacts of the cattle diet does not mean that all midpoint indicators will be optimized. However, an endpoint assessment can contribute effectively to decision-making (Kägi et al., 2016).

A comparison of midpoint indicators between this work and milk production LCA studies results are summarized in Table S13. The notable variations may be due to differences in the methodology and production strategies. Although the LCA methodology is standardized under ISO 14040–44 (ISO, 2006a; 2006b), there are some parts of its implementation that are open to interpretation that can affect the design of the

aims and scope (e.g., cradle to gate, the gate to the grave, cradle to grave), functional units, system boundaries, and life cycle inventories methodological approach, as well as the type of environmental impact assessment methodology. On the other hand, the production strategies (intensive, extensive, organic, etc.) and the manure management systems are determinants in the environmental milk profile (Rivas-García et al., 2015).

For the endpoint indicator of milk and livestock production in the DPS, damage to human health was 5% lower in the ODBS than in the OCD, driven by the same factors that led to decreases in climate change (Tables 1 and S12). Damage to ecosystems, which was 3.9% lower in the ODBS than in the OCD, was caused mainly by land occupation, which was proportional to the amount of feed used in the cattle diet.

Natural resource damage was the only endpoint indicator that was higher (4.1%) in the ODBS than in the OCD; this was due to the higher fuel consumption for feed transportation in the ODBS, as mentioned for fossil depletion. The single score indicator of the DPS was 3.2% lower in the ODBS than in the OCD. Since both scenarios had an objective function to minimize the environmental impact of the diet, the single score

indicator decreased due to the replacement of conventional feeds by BS.

If all the BS produced in the state of Guanajuato was used for cattle feed, the diet of 63.2% of milk producing cows in the state could be modified, based on the assumptions in the model used in this study. This would represent a decrease in GHG emissions of 0.55 Mt CO₂ eq y⁻¹. However, a change in diet would have indirect effects on different supply chains that interact with the dairy cattle industry. It is necessary to use a consequential approach in the life cycle inventory to analyze and evaluate these interactions.

In line with the Paris COP21 agreement, the Mexican agriculture industry is committed to reducing its GHG emissions from 93 to 86 Mt of CO₂ eq by 2030 (Hidalgo Gallardo et al., 2017). Using BS as a complementary feed could fulfill up to 8% of this goal. It could also decrease agricultural land occupation by 3327 ha by reducing the land required for feed such as maize silage, which uses 6904 ha in Guanajuato (INEGI, 2017).

LCA simplified the analysis using deterministic data to exclude uncertainties in the life cycle inventory. It is necessary to include a stochastic analysis to improve decision making, which can be done using Monte Carlo and Latin hypercube sampling strategies (Loya-González et al., 2019). These methods require that the probability distribution of critical variables in the life cycle be known (e.g., crop yields, consumption of fertilizers, energy, water, fuel, and elementary flow emissions), but this information is not available. In addition, this study did not consider the effects of BS use on milk or livestock quality. This point is essential because BS could influence the organoleptic profile of milk.

3.4. Influence of BS price on environmental impacts of DPS

When the price of BS reached 19.28 USD t⁻¹ FM, the single score [mPt FU_{DPS}⁻¹] of the ODBS increased by 2.41% (Fig. 5), equivalent to increasing the single score of the BS from 6.1 to 78.5 Pt t⁻¹ DM, giving it a higher environmental impact than alfalfa hay at 73.1 Pt t⁻¹ DM (Fig. 2). Under these conditions, the use of BS would no longer be environmentally or economically viable. However, the optimization model allowed the incorporation of BS until its price reached 25.71 USD t⁻¹ (equivalent to an economic AFac_{BPS} of 6%), which represents an increase in the environmental impact per FU_{DPS} of 5.44% compared to when BS is considered as waste, that is, BS price is 0 USD t⁻¹ (Table S14). Therefore, the practical scope of BS application is limited. It is also noticeable that

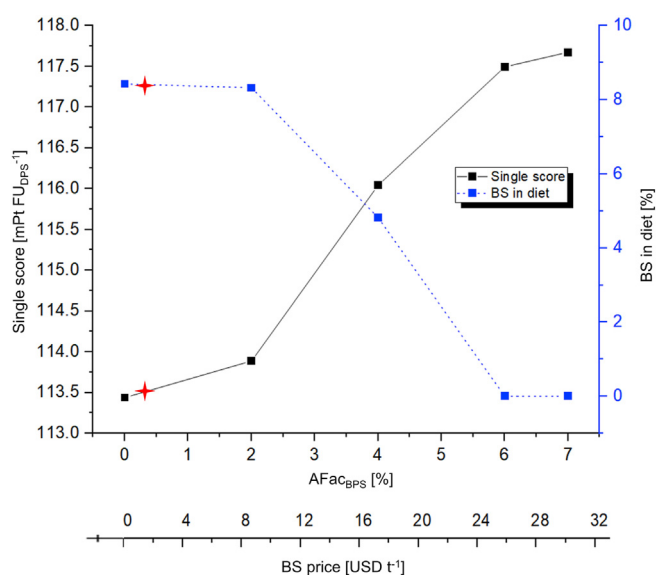


Fig. 5. Variation of the single score indicator of the dairy production system (DPS) concerning broccoli stems (BS) price and the allocation factor of the broccoli production system (AFac_{BPS}). Red stars (AFac_{BPS} = 0.35%) identify the optimized diet with BS (ODBS).

AFac_{BPS} is greater than 6% when BS is no longer present in the diet, corresponding to the results of the OCD scenario.

To incorporate agro-industrial and food wastes in the formulation of livestock diets, the associated production costs must be significantly lower than the market price of conventional feeds of similar nutritional quality. Some countries provide government incentives justified by environmental benefits (Dou et al., 2018; Takata et al., 2012). The allocation of retail prices to agro-industrial wastes depends on market demand. In Guanajuato, some of these wastes have experienced demand and valorization: biscuit, bakery, and tortilla waste (157 USD t⁻¹), and previously burned corn crop residues are now marketed for livestock consumption in areas that have experienced droughts (63 USD t⁻¹). Small farmers collect fruit and vegetable waste discarded by retailers in urban centers. These products do not have a commercial value assigned, but they do have an environmental burden that is not identified or assigned to a production system.

3.5. Sensitivity analysis of allocation methods

Among the allocation methods, Case I had the lowest AFac_{DPS} (Table 2) because of the low sale price of milk in Mexico, which is probably due to commercial imports. Currently, Mexico is the leading importer of powdered milk globally (362,000 t in 2018), mainly from the USA (SIAP, 2018). AFac_{DPS} of milk in Case II was 5.5 percentage points higher than that in Case I (which reflects an increase of 0.105 kg CO₂ eq FU_{DPS}⁻¹ equivalent to 5.5 mPt FU_{DPS}⁻¹) and an increase of 2.1 mPt FU_{DPS}⁻¹ respect OCD scenario (Table 1). The same allocation method applied to LCA studies in different geographic regions will provide different estimates for the environmental impacts of the dairy industry. The protein content in animal feed is usually reflected in the sale price (Nijdam et al., 2012). The protein content difference in milk and livestock in Mexico and the USA could be the cause of the variations in the allocation factors of Cases I and III. The protein content of milk in Mexico is between 29.2 and 33.5 g L⁻¹ (Juárez et al., 2015), while in the USA, it is 37.5 g L⁻¹ (USDA, 2019).

Thoma et al. (2013) suggested that physical (causal) relationships, such as protein-based allocation, are always preferable for defining allocation factors in cases where it is not possible to use other relationships between co-products (e.g., economic value or mass). Protein-based allocation may be a promising alternative when there is uncertainty or variability in the prices of dairy farm co-products, since allocation on an economic and protein basis yielded allocation factors with similar values (Cases II and III). However, these results must be interpreted locally. Mexico is an importer of powdered milk and a relevant importer of corn and soybeans for animal consumption (SADER-SIAP, 2019). On the other hand, it faces droughts, desertification, and migration of agricultural soils due to the production of vegetables and greens for export markets (CEDRSSA, 2020), forcing a shift to a more circular economic system and leading to reducing and taking advantage of agro-industrial waste (Avilés Ríos et al., 2009).

Table 1

The environmental damage indicators of the milk and livestock in the dairy production system, according to ReCiPe endpoint method (H).

Product	Environmental damage indicator (mPt)			
	Human Health	Ecosystems	Resources	Single score
Optimized conventional diet (OCD)				
Milk ^a	71.2	10.8	18.8	100.8
Livestock ^b	11.9	1.8	3.1	16.9
Optimized diet with broccoli stems (ODBS)				
Milk ^a	67.7	10.3	19.5	97.5
Livestock ^b	11.3	1.7	3.3	16.4

The environmental impact indicators are presented per:

^a kg of fat-and-protein-corrected milk and.

^b kg of live weight.

Table 2

Environmental impact indicators as a function of the environmental burden allocation cases.

Cases	Environmental impact indicator	Co-products	
		Milk ^a	Livestock ^b
Case I:	AFac_{DPS} (%)	85.6	14.4
Economic allocation of this study (ODBS scenario)	Climate change (kg CO ₂ eq)	1.870	0.315
	Agricultural land occupation (m ² a)	0.446	0.075
	Particulate matter formation (kg PM ₁₀ eq)	1.6E-03	2.7E-04
	Fossil depletion (kg oil eq)	0.096	0.016
	Single score (mPt)	97.5	16.4
Case II:	AFac_{DPS} (%)	90.4	9.6
Economic allocation according to Thoma et al. (2013)	Climate change (kg CO ₂ eq)	1.975	0.210
	Agricultural land occupation (m ² a)	0.471	0.050
	Particulate matter formation (kg PM ₁₀ eq)	1.7E-03	1.8E-04
	Fossil depletion (kg oil eq)	0.101	0.011
	Single score (mPt)	103.0	10.9
Case III:	AFac_{DPS} (%)	91.6	8.4
Protein-based allocation according to Thoma et al. (2013)	Climate change (kg CO ₂ eq)	2.001	0.183
	Agricultural land occupation (m ² a)	0.478	0.044
	Particulate matter formation (kg PM ₁₀ eq)	1.7E-03	1.6E-04
	Fossil depletion (kg oil eq)	0.103	0.009
	Single score (mPt)	104.3	9.6

AFac_{DPS}: Allocation factor of the dairy production system.

The environmental impact indicators are presented per:

^a kg of fat and protein corrected milk and.

^b kg of live weight.

4. Conclusions and future prospective

In this work, the environmental impact of broccoli production was studied, evaluating the effect that the integration of broccoli stems (BS) in the cattle diet has on the life cycle of intensive dairy production. The results indicated that incorporating BS in the diet reduced greenhouse gas emissions by 118 g CO₂ eq kg⁻¹ fat-and-protein corrected milk (FPCM) and agricultural land occupation by 0.002 m²a kg⁻¹ FPCM but increased fossil depletion by 4 g oil eq kg⁻¹ FPCM. Even though these environmental benefits appear to be marginal, in the agro-industrial context of broccoli and dairy production, these results have the potential to be relevant mitigation measures. The different methodological approaches to environmental evaluation, through allocation factors based on economic and nutritional criteria, are a useful tool to study the dynamics of the valorization and use of co-products. A sensitivity analysis of the economic allocation showed that the maximum price of BS to be environmentally viable as a partial substitute in the livestock diet is 19.28 USD t⁻¹ on a fresh matter basis. The methodology proposed in this study can help design cleaner environmental dairy systems by incorporating strategic agro-industrial waste into cattle diets.

From the perspective of this study and considering the nutritional and nutraceutical content of BS, there is a need to investigate eco-efficient alternatives to generate new healthy products for human consumption.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cesys.2021.100035>.

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