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EVALUATION OF SUSTAINABLE STRATEGIES IN THE SUPPLY CHAIN OF RAW MILK PRODUCTION IN MEXICO”

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SAMUEL QUINTERO HERRERA

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Evaluation of sustainable strategies in the supply chain of raw milk production in Mexico

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A mi familia

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ABSTRACT

Title: Evaluation of sustainable strategies in the supply chain of raw milk production in Mexico

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 Mexico with three strategies: (1) identifying and quantifying strategic agro-industrial wastes in dairy cattle in the country; (2) optimizing dairy cattle diet via incorporating a strategic agro-industrial waste with high nutritional value; and (3) optimizing crop fertilizer blends in livestock feed production systems. The potential reduction of environmental impacts of each strategy was estimated using a life cycle assessment and linear programming models. The effect of the optimized scenarios was evaluated on the life cycle of a dairy supply chain in the Mexican Bajio region. Three analysis tiers were considered: livestock feed production, dairy cattle diet, and dairy farming system. The results indicated 52 municipalities where strategies for using agro-industrial wastes in the diet of dairy cattle can be implemented with 29 strategic agricultural foods, including maize, carrots, broccoli, cotton, and potato. One of them, broccoli stems, was used to optimize the diet, reducing greenhouse gas emissions by 118 g CO_2 eq kg^{-1} fat-and-protein corrected milk (FPCM and agricultural land occupation by 0.002 m^2a kg^{-1} FPCM but increased fossil depletion by 4 g oil eq kg^{-1} FPCM. This waste can replace 11.1% of conventional feeds and maximize the incorporation of 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 broccoli stems to remain environmentally viable was 19.28 USD t^{-1} on a fresh matter basis. In addition, the results indicated that with the use of optimized fertilizer blends, a reduction of GHG emissions up to 22 g CO_2 eq kg^{-1} FPCM could be achieved compared with those conventional ones. Focused on the Mexican Bajio region, this contribution implies up to 2.2% of Mexico's commitments in the COP21 agreement for the livestock sector. This research is the cornerstone to developing a market of by-product feeds in a circular economy scheme and a cleaner production of livestock feed that reduces environmental impacts and costs in the dairy industry.

Keywords: Life cycle assessment; linear programming; cattle diet formulation; agro-industrial wastes; fertilizer blends

RESUMEN

Título del Estudio: Evaluación de estrategias sustentables en la cadena de suministro de la producción de leche cruda en México

La producción de piensos en la industria lechera tiene importantes impactos ambientales. Este estudio evaluó el potencial de reducción de impactos ambientales de la producción de leche en México de tres estrategias: (1) identificar y cuantificar los residuos agroindustriales estratégicos en el ganado lechero del país; (2) optimizar la dieta del ganado lechero a través de la incorporación de residuos agroindustriales; y (3) optimizar las mezclas de fertilizantes de cultivos usados como alimentos para el ganado. La reducción potencial de los impactos ambientales de cada estrategia se estimó mediante un análisis del ciclo de vida y modelos de programación lineal. Se evaluó el efecto de los escenarios optimizados en el ciclo de vida de una cadena de suministro de la producción lechera en la región del Bajío mexicano. Se consideraron tres niveles de análisis: la producción de alimentos para el ganado, la dieta del ganado lechero y el sistema de producción lechera. Los resultados indicaron que hay 52 municipios donde se pueden implementar estrategias de uso de residuos agroindustriales en la dieta del ganado lechero con 29 residuos agroindustriales estratégicos, incluyendo maíz, zanahoria, brócoli, algodón y papa. Uno de ellos, el tallo de brócoli se utilizó para optimizar la dieta y se comprobó que reducía las emisiones de gases de efecto invernadero en 118 g de CO_2 eq kg_{-1} de leche corregida en grasa y proteína (FPCM) y el uso del suelo agrícola en 0,002 m^2a kg^{-1} FPCM, pero aumentaba el agotamiento de recursos fósiles en 4 g de petróleo eq kg^{-1} FPCM. Este residuo puede sustituir el 11,1% de los piensos convencionales y maximizar la incorporación de piensos con bajo impacto ambiental en la dieta, como el heno de alfalfa y el ensilado de maíz. Un análisis de sensibilidad de la asignación económica mostró que el precio máximo del tallo de brócoli para seguir siendo ambientalmente viable era de 19,28 USD t^{-1} con base en la materia fresca. Además, los resultados indicaron que con el uso de mezclas optimizadas de fertilizantes se podía lograr una reducción de las emisiones de GEI de hasta 22 g de CO_2 eq kg^{-1} FPCM en comparación con las mezclas convencionales. Aplicado a la región del Bajío mexicano, esta contribución supone hasta un 2,2% de los compromisos de México en el acuerdo COP21 para el sector ganadero. Esta investigación es la piedra angular para desarrollar un mercado de piensos a partir de subproductos en un esquema de economía circular y una producción más limpia de piensos convencionales que reduzcan el impacto ambiental y los costos en la industria lechera.

RÉSUMÉ

Titre : Évaluation des stratégies durables dans la chaîne d'approvisionnement de la production de lait cru au Mexique.

La production d'aliments pour bétail destinés à l'industrie laitière intensive a un impact environnemental important. Cette étude a évalué le potentiel de réduction des impacts environnementaux de la production laitière au Mexique grâce à trois stratégies : (1) l'identification et la quantification des déchets agro-industriels stratégiques dans le bétail laitier du pays ; (2) l'optimisation du régime alimentaire du bétail laitier via l'incorporation d'un déchet agro-industriel stratégique à haute valeur nutritionnelle ; et (3) l'optimisation des mélanges de fertilisants de culture dans les systèmes de production d'aliments du bétail. La réduction potentielle des impacts environnementaux de chaque stratégie a été estimée à l'aide d'une analyse du cycle de vie et de modèles de programmation linéaire. L'effet des scénarios optimisés a été évalué sur le cycle de vie d'une chaîne d'approvisionnement en produits laitiers dans la région du Bajio au Mexique. Trois niveaux d'analyse ont été pris en compte : la production d'aliments pour le bétail, le régime alimentaire des bovins laitiers et le système d'élevage laitier. Les résultats ont indiqué 52 municipalités où des stratégies d'utilisation des déchets agro-industriels dans l'alimentation du bétail laitier peuvent être mises en œuvre. 29 aliments agricoles stratégiques, dont le maïs, les carottes, le brocoli, le coton et la pomme de terre. L'un d'entre eux, les tiges de brocoli, a été utilisés pour optimiser le régime alimentaire. Cela a permis de réduire les émissions de gaz à effet de serre de 118 g d'éq. CO_2 kg^{-1} de lait corrigé en matières grasses et en protéines (MCRP) et l'occupation des terres agricoles de 0,002 m^2a kg^{-1} MCRP, mais a augmenté l'épuisement des ressources fossiles de 4 g d'éq. pétrole kg^{-1} MCRP. Ce déchet peut remplacer 11,1 % des aliments conventionnels et maximiser l'incorporation d'aliments à faible, impact environnemental dans le régime alimentaire, tels que le foin de luzerne et l'ensilage de maïs. Une analyse de sensibilité de l'allocation économique a montré que le prix maximum des tiges de brocoli pour rester écologiquement viable était de 19,28 USD t^{-1} sur une base de matière fraîche. En outre, les résultats ont indiqué qu'avec l'utilisation de mélanges d'engrais optimisés, une réduction des émissions de GES allant jusqu'à 22 g CO_2 eq kg^{-1} MCRP pourrait être réalisée par rapport à celles conventionnelles. Centrée sur la région mexicaine du Bajio, cette contribution représente jusqu'à 2,2 % des engagements du Mexique dans l'accord COP21 pour le secteur de l'élevage. Cette recherche est la pierre angulaire du développement d'un marché des aliments dérivés dans un schéma d'économie circulaire et d'une production plus propre d'aliments pour le bétail qui réduit les impacts environnementaux et les coûts dans l'industrie laitière.

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ABBREVIATIONS AND ACRONYMS

$AFac_{BPS}$	Allocation factor of the broccoli production system
$AFac_{DPS}$	Allocation factor of the dairy farming system
AW	Agro-industrial wastes
BPS	Broccoli production system
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 farming system
GHG	Greenhouse gas
LCA	Life cycle assessment
OCD	Optimized conventional diet
ODBS	Optimized diet with broccoli stems
PM	Particulate matter formation
DM	On a dry matter basis
NMVOC	Non-methane volatile organic components
N–P–K	% nitrogen as N, phosphorus as P_2O_5, and potassium as K_2O

NOMENCLATURE

Subscripts

i	*i*-th livestock feed, including by-products
j	*j*-th fertilizer
k	*k*-th municipality
m	*m*-th agricultural food
s	*s*-th livestock category
t	*t*-th nutrient in livestock diet

Parameters and Variables

a	Allocation factor for the product to estimate the fraction for human consumption
AFI_s	Maximum as-fed intake of s-th livestock category [kg FM d^{-1}]
AW_{pre}	Agro-industrial wastes of pre-harvest stage of the agri-food supply chain [t y^{-1}]
$BF_{i,k}$	Manufacture of AW into by-product feed [t DM y^{-1}]
b_j	Price of *j*-th fertilizer, [USD kg^{-1}]
c	Conversion factor applied to estimate the food edible of each agricultural food
$DIET$	Environmental impact of the diet [Pt FU_{DPS}^{-1}];
D_k	Desirability in the k-th municipality
$d_k(DP_k)$	Smoothing the data d_k in the set of *k*-th municipalities was done to avoid data masking with atypical values for DP_k
DM_i	Fraction of i-th livestock feed or by-product [kg DM kg^{-1} FM]
DM_m	Fraction of m-th agricultural food on a dry matter basis [kg DM kg^{-1} FM]
DP_k	Dairy production in the k-th municipality [Ml y^{-1}]
DP_k	National milk production in the *k*-th municipality [Ml y^{-1}]
e	Fraction of agri-food processed fresh
f	Fraction of food for human consumption concerning the production quantity available
F	Food for human consumption [t y^{-1}]
f_j	N content of *j*-th fertilizer
FMP_{si}	Maximum proportion of i-th livestock feed in the cattle diet formulation for s-th livestock category.
GD_k	Global desirability in the k-th municipality
GE_k	Potential gross energy in the k-th municipality [MJ Kg^{-1} DM]

GE_m	Gross energy of m-th agricultural food [MJ Kg^{-1} DM]
g_j	P_2O_5 content of *j*-th fertilizer
h_j	K_2O content of *j*-th fertilizer
if_s	Minimum percentage of forage in diet of the s-th livestock category
Inf_{st}	Minimum percentages of the t-th nutrient in the livestock diet for the s-th livestock category
in_s	Minimum amount of dry matter intake for the s-th livestock category
k_i	K_2O requirements of *i*-th livestock feed [kg kg^{-1} DM]
LIE_{DP}	Lower value of the DP_k dataset
LIE_{ME}	Lower value of the $ME_{i,k}$ dataset
L_{mill}	Regional loss factor of agricultural food that are milled
L_{post}	Regional loss factors for the post-harvest stage of the agri-food supply chain
L_{pre}	Regional loss factors for the pre-harvest stage of the agri-food supply chain
L_{proc}	Regional loss factors for the processing stage of the agri-food supply chain
LSE_{DP}	Upper value of the DP_k dataset
LSE_{ME}	Upper value of the $ME_{i,k}$ dataset
ME_i	Metabolizable energy for ruminants of the *i*-th by-product feed [MJ kg^{-1} DM]
$ME_{i,k}$	Potential metabolizable energy for ruminants of *i*-th by-product feed in the k-th municipality [MJ Kg^{-1} DM]
n_i,	N requirements of *i*-th livestock feed [kg kg^{-1} DM]
n_{ti}	Contribution of the t-th nutrient in livestock diet of the i-th livestock feed
p_i	P_2O_5 requirements of *i*-th livestock feed [kg kg^{-1} DM]
r	Fraction of processed food for human consumption concerning the production quantity available
R	Processed food for human consumption that contains multiple types of products [t y^{-1}]
RT_s	Ratio of the s-th livestock category to the livestock total on the farm
sp_s	Maximum percentage of forage in diet of the s-th livestock category
sup_{st}	Maximum percentages of the t-th nutrient in livestock diet for the s-th livestock category
su_s	Maximum amount of dry matter intake for the s-th livestock category
T_{DP}	Target value calculated as a percentile of the DP_k dataset
$TF_{i,m}$	Transformation factor that describes the mass change due to the treatment in the AW_m to produce the *i*-th by-product feed
T_{ME}	Target value calculated as a percentile of the $ME_{i,k}$ dataset

U	Environmental impact of the N–P–K blend per t of *i*-th livestock feed [mPt t^{-1} DM]
upp_s	Minimum amount of as-fed intake acepted for the s-th livestock category
v_i	Environmental impact indicator of the i-th livestock feed [Pt kg^{-1} DM]
v_j	Environmental impact indicator of *j*-th fertilizer, [mPt kg^{-1}]
w_{DP}	Weight to represents the importance of dairy production
w_i	Parameterized weight between the two objective functions ($Z_1(x)$ and $Z_2(x)$)
w_{ME}	Weight to represents the importance of metabolizable energy
x_{ij}	Amount of *j*-th fertilizer for *i*-th livestock feed [kg DM t^{-1}]
X_{si}	Amount of the i-th livestock feed for the s-th livestock category [kg DM FU_{DPS}^{-1}]
y_{ij}	Amount of *j*-th fertilizer for *i*-th livestock feed [kg kg^{-1} DM]
$Z_1(x)$	Environmental impact of the N–P–K blend per t of *i*-th livestock feed [mPt t^{-1} DM]
$Z_2(y)$	Price of the N–P–K blend per t of *i*-th livestock feed on a dry matter [USD t^{-1} DM]
α_{DP}, β_{DP}	Exponents that serve to choose the desired form of the transformation of the DP_k dataset
α_{ME}, β_{ME}	Exponents that serve to choose the desired form of the transformation of the $ME_{i,k}$ dataset
γ_{pre}	Factor that describes the logistical capacity to use the AW in the dairy industry for the pre-harvest stage
γ_{post}	Factor that describes the logistical capacity to use the AW in the dairy industry for the post-harvest stage
γ_{proc}	Factor that describes the logistical capacity to use the AW in the dairy industry for the processing stage

Chapter 1

INTRODUCTION

Cattle generate 7.1 Gt of CO_2 eq y^{-1}, corresponding to 14.5% of global greenhouse gas (GHG) emissions; approximately a third of these are 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 CO_2, 37% of CH_4, and 65% of N_2O). Milk is one of the most produced and valuable agricultural commodities worldwide. Global milk production reached nearly 861 Mt in 2020, valued at USD 307 billion, placing it third in production tonnage and the second agricultural commodity in economic terms worldwide (OECD and FAO, 2021). Global milk production is expected to increase at 1.7% p.a (to 1,020 Mt by 2030, faster than most other primary agricultural commodities).

In Central America and the Caribbean, milk production grew by 1.6% p.a. (18Mt). Mexico's production is expected to increase in this proportion (FAO, 2021). However, the Mexican dairy industry is characterized by low levels of profitability —with yield milk of 1.8 t $cow^{-1}y^{-1}$ being one of the lowest in the world, only surpassing Brazil, and India (Loera and Banda, 2017)— and severe environmental impacts (GCMA, 2020; Rendón-Huerta et al., 2018). The emissions mainly come from agricultural livestock feed production, enteric fermentation, nitrification, and denitrification processes in manure. The livestock industry generates two-thirds of the anthropogenic emissions of ammonia (NH_3), which is responsible for terrestrial and water acidification (FAO, 2017).

Mexico committed to the Paris Agreement to reduce 22% of its GHG from the livestock sector by 2030, i.e., 7 Mt CO_2 eq (SEMARNAT-INECC, 2018). However, it is necessary to propose alternatives to reduce environmental impacts at low costs. This aspect is critical in countries like Mexico, where government budgets are limited to mitigating environmental impacts; only 1.1% of the budget is spent on climate change adaptation and mitigation strategies (Fonseca and Grados, 2021). Several strategies to mitigate the environmental impacts of dairy production were studied; e.g., reducing wastes in the supply chain (Bajželj et al., 2014), implementing manure management strategies such as anaerobic digestion systems (Rivas-García et al., 2015), sustainable agriculture (Hristov et al., 2013), minimizing the use of fertilizers and pesticides (Röös et al., 2017), and replacing conventional feeds in livestock diets with those less polluting.

The environmental impact of dairy farming systems can be evaluated through the life cycle assessment methodology (LCA); a systematic approach that estimates potential environmental impacts and resource consumption considering all stages of its life cycle —agricultural feed production, feed-processing plant, transportation, dairy farm operation, and manure management— (ISO, 2006a, 2006b). The purpose of LCA is not just to account for the environmental burdens of a product, process, or service but also to identify possibilities for optimization and mitigation within the production system (Mazzetto et al., 2020). LCA provides quantitative indicators of the environmental impacts of processes that can be used in mathematical optimization models to propose optimized scenarios considering technical, environmental, economic, and cost-benefit analysis (Sefeedpari et al., 2019).

LCA is conducted using different approaches, the two most widely accepted are attributional and consequential. Attributional LCA provides information on the impacts of the processes used to produce, consume, and dispose of a product but does not consider indirect effects arising from changes in the production of a product. It answers the question: *What are the total process emissions and material flows used directly in a product´s life cycle?* Consequential LCA must provide information on the consequences of changes in the production (consumption and disposal) of a product, including effects outside the process, answering the question *what is the total change in emissions and material flows used as a result of a change in the process of a product?* These methodologies help evaluate the sustainability of the alternatives process, as in the case of the dairy industry.

There are different alternatives to increase the dairy industry's sustainability, including identifying and incorporating wastes into cattle diets and reducing fertilizer use in agricultural feed production.

The global dairy herd consumes approximately 2.5 billion tons of dry matter feed annually, 33% of which are human edible materials (Mottet et al., 2017). One-third of all food produced globally for human consumption is lost or wasted; representing a significant waste of resources spent making, processing, and transporting food as well as a threat to food security (FAO, 2019; Yang et al., 2021). The pre- and post-harvest steps in the food supply chain generate 39% of the total food loss and wastes in North America (CEC, 2017). However, these residues are rarely used in cattle 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). A waste 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). The availability of wastes and their proximity to the Mexican milk-producing regions have not been quantified at the national level.

Wastes are generated at every stage of the agricultural food supply chain, some of which are called agro-industrial wastes (AW). When AW are recovered and undergo a treatment process, they can be transformed into by-product feeds. Currently, 19% of the feed consumed in the livestock diet is composed of crop residues (FAO, 2018). Figure 1 illustrates the by-product feeds from numerous industrial production sectors for further utilization in animal feeding (Salami et al., 2019).

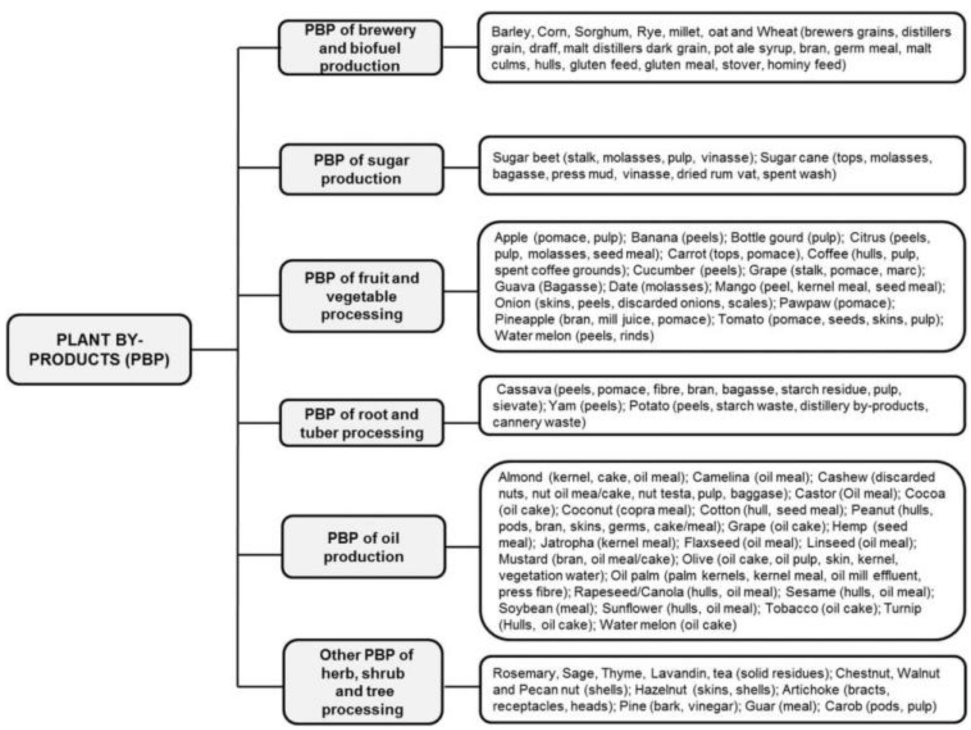

Figure 1. Schematic diagram of plant by-product feeds from different agro-industrial processes (Salami et al., 2019)

Some by-product feeds from AW have nutritional compositions that make them suitable for use as partial substitutes for conventional feeds in cattle diets (Díaz et al., 2013). These by-product feeds could have lower environmental impacts and costs than conventional feeds and are in greater abundance (García-Rodríguez et al., 2019). However, it is essential to develop tools that optimize its incorporation in dairy diets.

Within the agricultural production process, fertilization is a valuable hotspot in environmental terms. Different fertilizers could be used for each N–P–K blend (percentage of all three major nutrients in fertilizers, Nitrogen as N, phosphorus as P_2O_5, and potassium as K_2O). They have different environmental and economic impacts on crop production, dairy cattle diets, and milk production; thus, it is relevant to understand how fertilization affects each life cycle of the dairy supply chain (Chaudhary et al., 2017).

Reducing environmental impacts on dairy farming systems by reducing fertilizer consumption and incorporating AW into cattle diets can be studied using mathematical optimization models (Uyeh et al., 2018; von Ow et al., 2020). These models could be structured through linear programming, with defined variables such as fertilizer or feed quantities, objective functions such as minimization of costs, environmental impacts of fertilizer blends, or feed diet.

This study proposes the integration of studies on location, quantification, incorporation, and optimization of AW in the cattle diet and optimizing fertilizer blends in livestock feed production to improve the sustainability of the supply chain of raw milk production in Mexico. For this purpose, the LCA was used to evaluate the environmental impact of the strategies proposed, linear programming models were developed to optimize diets and fertilizer blends, and geographic information systems were applied to locate AW spatially.

Chapter 2

BACKGROUND

There are several mitigation options in the milk production supply chain to help livestock orient or reorient its current development trend toward alternative production systems (Hristov et al., 2013). However, there are a lot of challenges and barriers to transformative adaptation in dairy farming systems (Salman et al., 2019), such as a lack of data to develop environmental models (Escarcha et al., 2018), or a lack of local capacity to adopt and adapt new livestock technologies and methodologies (Ugochukwu and Phillips, 2018). Initiatives aimed at reducing the environmental impact of feed production and substituting virgin materials in the cattle diet stand out in the intensive dairy farming system.

According to LCA studies of intensive dairy farming systems, livestock feed production has the greatest environmental impact (Wattiaux et al., 2019). In Mexico, livestock feed production was responsible for 60%, 48%, and 36%, of terrestrial acidification, freshwater eutrophication, and GHG emissions, respectively (Rivas-García et al., 2015). Forage and grain crop production accounts for 60% of GHG emissions in the dairy farming system, primarily nitrous oxide (N_2O) emissions from nitrogen fertilization (Yue et al., 2017). It is for that; it is necessary to define alternatives to replace livestock feeds (Section 2.1), incorporate them into the livestock diet (Section 2.2), or reduce the environmental impact of their production (Section 2.3).

2.1 Identification, quantification, and location of agro-industrial wastes valuable in dairy farming systems

According to the Food Waste Reduction Alliance (Tavill, 2020), the food recovery hierarchy prioritizes feed animals over strategies such as industrial uses, composting, incineration, or landfill disposal. Despite the importance of by-product feed in the dairy industry, its commercialization remains a marginal market. Some efforts have been made to responsibly offer by-product feeds, like the University of Missouri, which lists prices of these and suppliers throughout the country (AgEBB, 2022). Another case is Feedpedia, an online encyclopedia of animal feeds that includes 166 plant products and by-product feeds with information to characterize and adequately use to develop the livestock sector sustainably (INRAE et al., 2022). Developing by-product feed use is particularly important in emerging and developing countries, where local feed resources are often under-utilized due to a lack of information. These by-product feeds can be incorporated directly into the livestock diet through food production facilities interacting directly with local farmers (pre-harvest and post-harvest). However, the standard approach is via an intermediary that collects AW from several producers and transforms them into by-product feeds (Tavill, 2020).

By-product feeds mainly include stalks and residues. Stalks, leaves, and stems are high in acid detergent fiber (>40%) and neutral detergent fiber (>60%) but low in protein (<6%) and minerals. Residues derived from agro-industry, including oil-seed-meals, plant shells, seeds, fruit pulp, fruit pomace, and mushroom substrate, are low in acid detergent fiber (<50%) and neutral detergent fiber (<40) but high in crude protein (>40%) (Gowda et al., 2004; Yang et al., 2021). The livestock industry should explore the possibility of increasing the consumption of this type of biomass because it provides farmers with a cheaper alternative while also benefiting the health of the animals (Adawiyah Zayadi, 2021). In addition, dairy production is transitioning to intensive systems due to scarcity of grazing land, the need for more control over animals, and higher returns from feeding systems. The broader use of by-product feeds is a recognized approach to improving the productivity of animal resources (Yang et al., 2021).

By-product feeds have techno-economic and environmental challenges. Technical difficulties include identification, availability quantification, and location. Moving toward emerging markets based on AW valorization is necessary to overcome these. The energy content of agricultural residues has been used to identify the AW potential, with established methodologies based on the theoretical biomass potential (Avcıoğlu et al., 2019). In Mexico, the National Renewable Energy Inventory published an atlas of energy potential, in which the production of 20 different food waste products across the country was quantified and geographically located. The approach adopted in Mexico to quantify AW focuses on biotechnological and energetic uses (Mejías Brizuela et al., 2016).

The location of by-product feeds with valorization characteristics in livestock diets has been examined in traditional markets (Noegroho et al., 2021) and at the district level (Ali et al., 2019) using surveys, interviews, and observations in place. Mehta et al. (2016) used a geographic information system to map the spatial distribution of macro-nutrients from AW in Australia; through survey data of different industries and nutritional information of crops. Although surveys are the best approach to obtain realistic data on the quantification of AW in a country, it is not a practical methodology. The Commission for Environmental Cooperation (CEC, 2017) presented a promising method for quantifying waste volumes at various stages of the agri-food supply chain based on FAO data (FAOSTAT, 2022) and factors proposed by Gustavsson et al. (2013).

2.2 Agro-industrial wastes into the cattle diet of the dairy farming system

Environmental studies of AW search the wastes valorization by incorporating other processes (Alexandri et al., 2020). Kim and Kim (2010) presented an LCA study to evaluate feed manufacturing using different food wastes disposal options finding that from wet feeding process (production of by-product feed on a fresh basis from food wastes) has a carbon footprint of 61 kg CO_2 eq t^{-1}, 94% lower than confining wastes in a landfill (1010 kg CO_2 eq t^{-1}). Ermgassen et al. (2016) argued that by replacing feed grains with feed derived from food waste, the potential for land use reduction in Europe is up to 20%, equivalent to 1.8 M ha. However, they do not explore the economic viability of this land use reduction.

Angulo et al. (2012) propose that fruit and vegetable wastes can replace between 6 and 18% of conventional concentrated feeds without affecting the nutritional quality of cattle diet. Pardo et al. (2016) assessed through LCA the use of tomato wastes and olive by-product silages in a dairy goat diet in Spain and revealed that the two dietary strategies achieve GHG reductions (~12–19% per kg milk). Schader et al. (2015) analyzed used the strategy in which livestock feed components that compete with direct human agricultural food production are reduced; thus, animals are fed only from grassland and by-product feeds from food production. The proposed diet reduces environmental impacts compared with the reference scenario of 18%, 26%, and 46% for GHG emissions, arable land occupation, and N-surplus, respectively. Ondarza and Tricarico (2021) proposed using human-inedible by-product feeds in the US. The results showed that feeding by-product feeds to milking cows to replace non-by-product feeds such as forages and whole grains generates 70 g CO_2-eq kg^{-1} DM by-product of non-CO_2 GHG emissions while landfill disposal, composting, and combustion emits 3448, 328, and 31 g CO_2-eq kg^{-1} DM by-product, respectively.

Another by-product is the broccoli stems, which have been incorporated into animal diets in Ecuador (Diaz Monroy et al., 2014), China (Yi et al., 2015), and Canada (Mustafa and Baurhoo, 2016). Ertl et al. (2015) replaced a complete substitution of a typical concentrate mixture with a by-product concentrate mixture from the food processing industry, proving that milk yield and solids were not affected by treatment. These authors confirm the technical feasibility of using these wastes, but the environmental and economic viability was not explored.

Kim et al. (2011) evaluated the economic viability of eight wastes treatment strategies, including dry feeding and wet feeding. The market prices of by-product feeds and carbon prices derived from greenhouse gas reduction were evaluated by converting environmental value to monetary value from global warming. The benefit-cost ratio was USD 0.26 kg^{-1} for dry feeding and USD 0.42 kg^{-1} for wet feeding. These indicators could help to evaluate the economic-environmental behavior of use by-product feeds in the Mexican market framework.

The agri-food sector in Mexico, composed of the primary sector and agribusiness, participated in 8% of the Gross Domestic Product (INEGI, 2019). More than 70 Mt y^{-1} of residual agricultural biomass is generated in the country; 79.4% are primary wastes (e.g., straw from cereals, fruit and vegetable processing, crop, and forest residues), while the remaining are industrial crops (e.g., rice, coffee, tobacco, and sugar cane) (Sánchez Cano, 2019). For example, Guanajuato produces the most broccoli (420,770 t in 2018) (SIAP, 2020a) which is estimated to produce a similar amount of broccoli stems. Additionally, in Guanajuato, 920,000 m^3 of milk was produced in 2018 (SIAP, 2020b). Identifying agro-industrial residues in Mexico's dairy basins is crucial in incorporating these by-product feeds into the cattle diet. Conditions in Guanajuato, such as the broccoli stem, could encourage the use of AW as a substitute for conventional feeds in cattle diets. These initiatives could establish a semi-formal market for their commercialization and reduce AW sent to sanitary landfills and open dumps.

Nevertheless, the issue of incorporating AW into the diet is not limited to the identification. It is necessary to incorporate a by-product into the diet when deemed strategic. Mathematical optimization models can be used to investigate how incorporating AW into cattle diets reduces environmental impacts. Although solution strategies mainly focus on optimizing costs (Guevara, 2004; Munford, 1996), minimizing environmental impacts has also been considered to be an objective. Tozer and Stokes (2001) reduced environmental impact by reducing N and phosphorus (P) excretion in manure; (Moraes et al., 2012) minimized methane (CH_4) 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 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).

2.3 Fertilization impact on dairy farming systems

In the livestock feed production chain, fertilization stands out as the most polluting process. The environmental burdens derived from the industrial production of fertilizers and their application in the soil are from volatilization in the air and leaching and runoff to underground and surface water bodies of nitrogen and phosphate species (Jayasundara et al., 2019). Fertilizer production and application account for 33.8% and 24.9% of the GHG in the livestock feed production process (Chen and Holden, 2018). Hasler et al. (2015) suggested that industrial fertilizer production accounts for 70–90% of GHG in the cradle-to-field fertilizer supply chain. It also has high values in other impact categories, such as fossil fuel depletion and acidification, whereas resource depletion is dominant for production and transportation stages. Mineral fertilization accounts for 39% of feed crop production costs, according to Baum and Bieńkowski (2020). The reports provided by the Trust Funds for Rural Development in Mexico (FIRA, for its acronym in Spanish) indicate that fertilization accounts for up to 30% of corn production costs (FIRA, 2020).

Efforts should be made to identify sustainable alternatives, improve fertilizer production technology, simplify cultivation operations, and use optimized fertilizer blends (Baum and Bieńkowski, 2020). Government entities, such as the National Institute of Ecology and Climate Change of Mexico, have proposed reducing the use of synthetic fertilizers in feed crops as part of their initiatives (Hidalgo Gallardo et al., 2017). Some strategies proposed to improve fertilizer efficiency are precision agriculture (Monteiro et al., 2021), organic forms as substitution of chemical fertilizer (Tang et al., 2022), conservation agriculture (Mutsamba et al., 2020), automated monitoring (Akhil et al., 2018), use optimization (Lemaire et al., 2021) and decision support system to sense N–P–K requirements (Bhatnagar and Poonia, 2018).

Environmental studies in feed production have shown that optimized fertilization conditions could decrease the carbon footprint of corn grain, wheat bran, and alfalfa by 18%, 22%, and 42%, respectively (Liu et al., 2017). This evidences that a proper N–P–K blend in crop production could reduce the environmental impact of milk production. Medina-Cuéllar et al. (2021) propose the tendency modeling between crop yield and fertilizer blend to determine optimal fertilization. This approach was based on estimating crop yield responses to individual fertilizer elements for determining the optimum fertilization rate for maximum yield. These models thoroughly identify solutions by optimizing an objective function constrained by the nature of the modeling (Olson, 2003). Kaizzi et al. (2017) developed a fertilizer optimization model with linear programming to maximize profit due to fertilizer use. Even though it allows for selecting crop-nutrient-rate combinations that are most profitable given a budget constraint, environmental concerns were not considered. Machet et al. (2017) presented a dynamic decision-making tool for calculating the optimal rates of N application for 40 annual crops in France, considering the varied sources of soil N and diverse growing conditions. Although identifying fertilizer rates according to the soil characteristics for maximum yield might seem promising, the economic and environmental impacts were not calculated. Meza-Palacios et al. (2020) proposed a decision support system based on fuzzy models, using soil analysis parameters to calculate N–P–K blends. The results showed a reduction of 11% of the environmental impact of food production.

LCA studies of dairy farming systems tend to consider implementing strategies such as mineral fertilizer substitution with organic fertilizers before optimizing (Hanserud et al., 2018). However, 70% of the planted area in Mexico uses synthetic fertilizers. Thus, optimizing the environmental and economic impacts of fertilizer N–P–K blends could be a more straightforward strategy with more scalable results (Guzmán Flores, 2018).

2.3 Discussion

In Mexico, reducing the environmental impacts of the dairy industry is a challenge. Localizing wastes in Mexico has been partially made by calculating the bioenergy potential of the National Renewable Energy Inventory. However, there is no generalized method to quantify wastes from agri-food supply chains on a national scale, nor has a systematic approach been determined to assess which wastes are strategic and promising for use in the dairy industry. The quantification at the national scale is a crucial issue to help policy-makers propose and assess greenhouse gas emissions scenarios and link them with the national climate commitments. Once strategic AW in the dairy industry has been identified, they must be introduced into the cattle diet using a model that minimizes environmental impacts. However, by-product feeds are far from completely replacing conventional feeds, so looking for strategies to reduce the environmental impact of their production processes is another alternative.

Fertilization is an essential process in the environmental profile of milk production. No studies have looked at fertilizer blends' economic and environmental effects on intensive dairy production systems instead of agricultural crop production. A method that quantifies the optimal amounts of fertilizers in Mexico based on soil characteristics, crop requirements, and environmental and economic factors can be viable for producers to reduce environmental impacts that are relatively simple to implement and returns promising results.

The current study is unique in that it develops a strategy to:

- To locate and quantify strategic AW in the Mexican dairy industry
- To evaluate the potential use of AW as livestock feed in the Mexican dairy industry
- To formulate optimized fertilizer blends of conventional feeds

considering the LCA at three levels of Mexico's raw milk production system: livestock crop production, dairy cattle diet, and milk production. An inventory of the localized generation of AW with potential for use in dairy cattle diets in Mexico through a spatial approach is presented. For this purpose, the agricultural and AW generated in the pre-harvest, post-harvest, and processing stages were quantified, and their by-product feeds were examined. Their nutritional composition was investigated and statistically correlated with the dairy-producing regions of the country via the geographic information system. This work shows the nutritional potential of AW around the intensive dairy industry at the national scale, promoting emerging markets for wastes recovery to integrate the agro-industrial and dairy sectors and helping decision-makers to implement strategies based on the circular economy.

Two optimization models based on linear programming were proposed to calculate blends from several commercial fertilizers and formulate dairy cattle diets. When AW were incorporated into the cattle diet, the environmental impact of dairy farming systems in Mexico was calculated through an LCA approach. In addition, a sensitivity analysis examined the effects of AW prices and various environmental burden allocation methods in the dairy farming system. The models, developed with specific constraints, can be applied to different fertilizers, dairy cattle diets, AW, and livestock categories.

Chapter 3

HYPOTHESIS AND OBJECTIVES

3.1 Hypothesis

The integration of the location, quantification, and use of agro-industrial wastes in the cattle diet, and the optimization of fertilizer blends in livestock feed production, through the life cycle assessment methodology, will improve the sustainability of the supply chain of raw milk production in Mexico.

3.2 Scientific contribution

This research generates knowledge to increase the sustainability of the Mexican dairy industry under a technical-economic-environmental approach. The identification of agro-industrial wastes with potential for use as livestock feed for dairy cattle, the use of agro-industrial wastes in the cattle diet, and the optimization of fertilizer blends in livestock feeds production are considered to accomplish this contribution.

A method is made to build a national inventory of agro-industrial wastes in the dairy industry; as a result, the Mexican map of them with potential for dairy cattle feed use is presented.

Life cycle inventories in the dairy industry are scarce in Mexico and Latin America; this research will generate inventories according to the ISO standards (14040/44), which support the realistic evaluation of the life cycle assessment of this industry.

3.3 Objectives

To evaluate strategies of environmental impact reduction in the dairy sector, integrating fertilization and agro-industrial wastes into the cattle diet in the supply chain of raw milk production in Mexico through an environmental and spatial approach.

This general objective is met through the following specific objectives.

1. To make an inventory of the localized generation of agro-industrial wastes with potential use in dairy cattle feed in Mexico, with a spatial approach.
2. To incorporate strategic agro-industrial wastes in the dairy cattle diet, considering the nutritional characteristics of the feeds as constraints.
3. To analyze the environmental behavior of the Mexican dairy farming system when the use of strategic agro-industrial wastes in the cattle diet is incorporated.
4. To develop a model to formulate optimized fertilizer blends in livestock feed production, considering environmental and economic issues.
5. To evaluate the effect of the fertilizer blends optimization on three analysis tiers: livestock crop production, dairy cattle diet, and whole milk production system, through the life cycle assessment methodology.

Chapter 4

MATERIALS AND METHODS

The schematic structure of the methodology is presented in Figure 2; the colors visualize the three research papers developed in this thesis. Section 4.1 includes the description of the dairy farming system used as the basis for the study along with the supply chain that interacts with it (strategic food production system). Section 4.2 details the method to locate and identify strategic AW for dairy farming systems. Section 4.3 presents the LCA of the strategic food production system as a basis for determining the environmental impact of by-product feeds derived from AW. Section 4.4 presents the optimization model to formulate dairy cattle diets including by-product feeds. Section 4.5 presents the optimization model for fertilizer blends, including the general characteristics of the economic-environmental optimization model for fertilizer blends used in livestock feed production. Finally, Section 4.6 presents the general structure of the LCA of the dairy farming system, focusing on the agricultural feed production system.

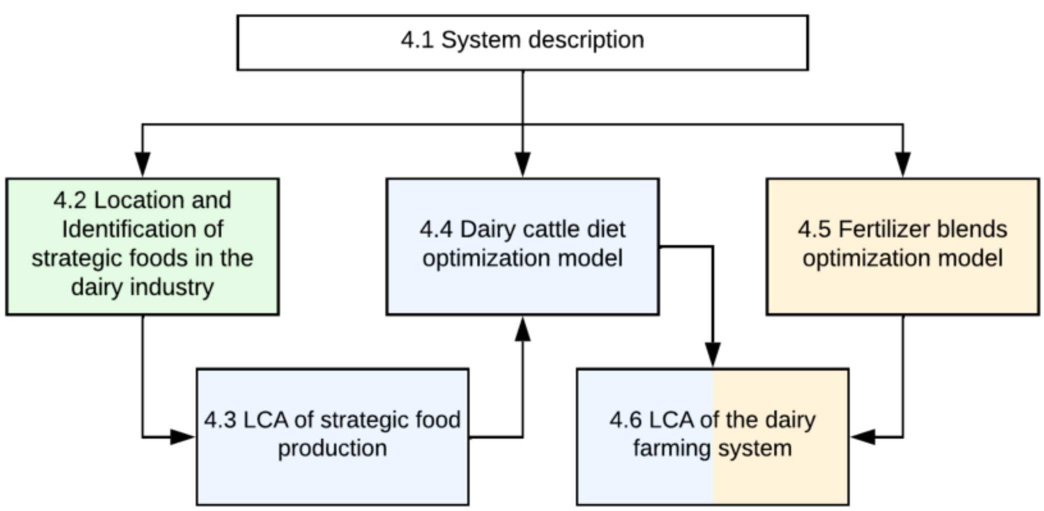

Figure 2. General structure of the study, LCA: life cycle assessment

4.1 System description

Section 4.2 was developed on a national scale, considering the agri-food supply chains of the different agricultural foods produced in Mexico that generate AW. Some of these wastes can be transformed into by-product feeds with the potential to be incorporated into livestock diets. The study was conducted at the municipal level, considering 2,463 municipalities and 80 agricultural foods. Then, Sections 4.3-4.6 were evaluated considering a specific dairy farm with the considerations described below.

4.1.1 Description of the study scenario for the dairy farming system

This work considers a supply chain in the dairy basin of central Mexico in Leon, Guanajuato (Table 1). The system was framed in an LCA with two supply chains, the dairy farming system, and the strategic food production system (Figure 3). Figure 3b is presented in Section 4.3. The connection between the two systems are the by-product feeds from AW. The by-product feed enters to the dairy farming system through the diet model presented in Section 4.4 and the global LCA is presented in Section 4.6.

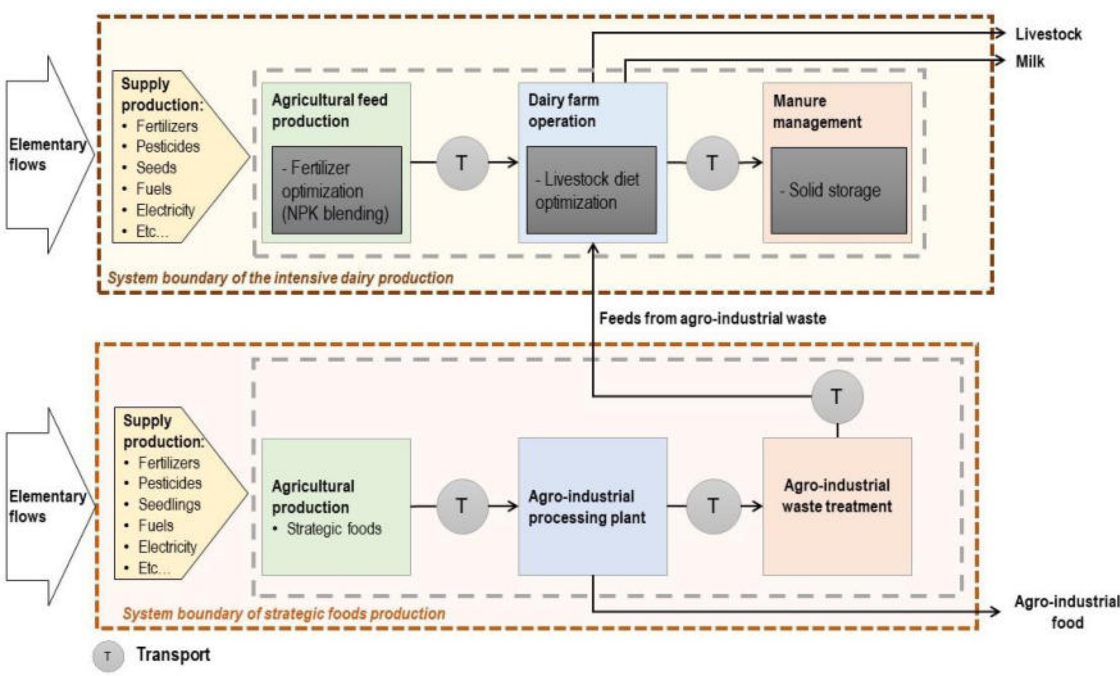

Figure 3. System boundaries of (a) Dairy farming system and (b) Strategic food production system

Table 1. Characteristics of the dairy farm.

Aspect	Amount	Unit
Livestock category		
Calves	174	head
Replacement heifers	174	head
Cows in production	522	head
Dry cows	130	head
Production features		
Milk production	4,763	$m^3\ y^{-1}$
Livestock production	145.49	$t\ y^{-1}$
Manure production[b]	13,647	$t\ y^{-1}$
Milk characterization		
Milk density[a]	1,029	$kg\ m^{-3}$
Milk fat[a]	3.67	%
Lactose[d]	4.85	%
Other features		
Mean annual temperature	20.5	°C
Area[c]	8	ha

[a]Obtained from the study of Juárez et al. (2015).

[b]Calculated from results of Wilkerson et al. (1997).

[c]According to Rivas-García et al. (2015).

[c]According to NRC (Timpka et al., 2001).

Primary livestock feeds were selected from the most relevant in Mexico (Appendix I of the Annexes). The resulting crops were alfalfa, grain maize, forage maize, and sorghum grain (Table S1). These crops are transported through the field crop, feed-processing plant (where they are converted into maize silage, rolled maize, and sorghum grain, respectively), and finally to the dairy farm. Alfalfa is delivered as alfalfa hay directly to dairy farms.

The baseline dairy farm has 1,000 heads considering four livestock categories: calves, replacement heifers, cows in production, and dry cows, with a distribution based on the regional characteristics and the method proposed by Moraes et al. (2012). According to local data, the mean yield of the cows in production is 25 L milk d^{-1}. Cattle raising, mechanized milking, and manure management were considered on-farm activities. The manure management strategy consisting of solid storage in open-air piles for later use as a soil improver was considered (Rivas-García et al., 2015).

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 Appendix II of the Annexes (Figures S1, S2 and S3, Tables S2 and S3). 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.

4.1.2 Description of the study scenario for strategic food production systems

The system consisted of three modules: agricultural production, agro-industrial-processing plant, and treatment to transform the AW in by-product feed, including transport between modules and the dairy farming system (Figure 3b). A processing plant; located in Irapuato, Guanajuato; was considered as baseline for the study. In Irapuato, the main broccoli processing plants are located.

Agricultural production of strategic food includes land preparation activities, greenhouse germination of seedlings, transplantation, and tillage and harvest practices. Once the agricultural cycle is complete, food is transported 20 km to the processing plant, where a fraction of the food is discarded as AW. The remaining biomass becomes in food which is exported; however, these activities were excluded from the study. Finally, the feed derived from AW is transported 60 km to the dairy farm.

4.2 Location and quantification of agro-industrial wastes

The concept of strategic agricultural foods was defined based on the following criteria:

- Evidence of previous use of the AW as raw material for animal feed.

- Knowledge about existing treatments to transform AW into by-product feeds.
- Knowledge of the availability of AW.
- Information on the nutritional composition of AW and by-product feeds.
- The synergy fostered by using AW in the dairy industry through statistical analysis tools.

The methodology used to identify strategic agricultural foods in the dairy cattle diet is resumed in Figure 4. The figure includes four sections divided into colors that will be explained in detail below.

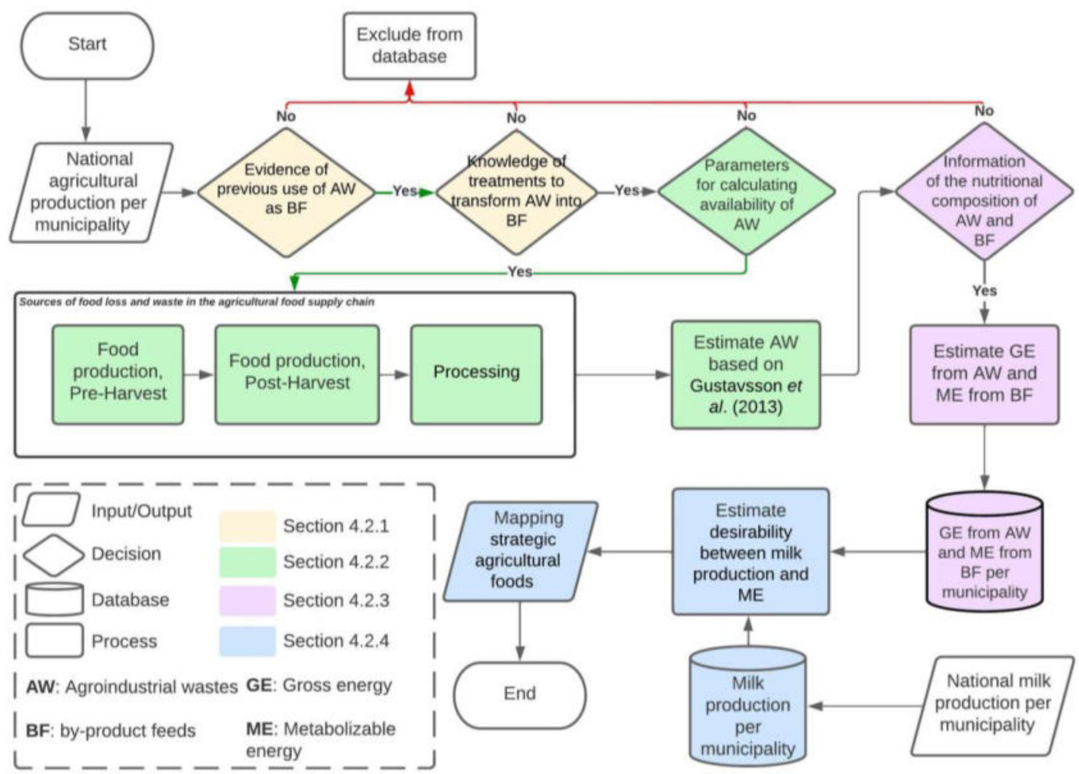

Figure 4. Methodology for the identification of strategic agricultural foods in the dairy industry

4.2.1 Use and treatments of agro-industrial wastes in the livestock diet

The national agricultural production per municipality was taken from the open database of the Ministry of Agriculture and Rural Development of Mexico in 2020 (SIAP, 2020a), considering all the agricultural foods. Then, a detailed investigation of the AW generation of these foods, the use of these wastes as animal feed, and these treatments to transform the wastes into by-product feeds were carried out. It was considered the feed recommended by the Subcommittee on Dairy Cattle Nutrition from National Research Council (2001) and a bibliographic review. The study excluded agricultural foods for which neither the use of their AW in animal diets nor the treatments to transform their wastes into by-product feeds could be found.

4.2.2 Quantification of agro-industrial wastes

The quantification of AW from each agri-food supply chain was estimated with an adjustment to the Food Loss and Waste Quantification Method proposed by Gustavsson et al. (2013) and documented by the Commission for Environmental Cooperation (CEC, 2017). The food loss and waste method include all the residues generated in the agri-food supply chain; however, this study considered AW only in the pre-harvest, post-harvest, and processing stages. Wastes from distribution and consumption are outside the interest of dairy cattle diets because it is not ensured that these remain in the production area and that the quality of these remains fit for consumption by dairy cattle.

Regional loss factors for the pre-harvest (L_{pre}), post-harvest (L_{post}), and processing (L_{proc}) stages of the agri-food supply chain were included for each product type to estimate AW. Allocation (*a*) and conversion (*c*) factors were applied to estimate the fraction for human consumption and the agricultural food (edible) fraction.

AW for the pre-harvest stage (AW_{pre}) in the agri-food supply chain for cereals, oilseeds, pulses, roots, tubers, fruits, and vegetables was estimated (Eq. 1)

$$AW_{pre} = P \frac{L_{pre}}{1 - L_{pre}} a \qquad \text{Eq. (1)}$$

where L_{pre} is the regional loss factor of the pre-harvest stage of the agri-food supply chain, *a* is the allocation factor for the product to estimate the fraction for human consumption (Table S4 of the Annexes), and *P* is the production quantity [t y^{-1}] extracted from the agricultural production statistics 2020 database of SIAP (2020a) (Table S5 of the Annexes).

AW for the post-harvest stage (AW_{post}) in the agri-food supply chain for cereals, oilseeds, pulses, roots, tubers, fruits, and vegetables was estimated (Eq. 2)

$$AW_{post} = PL_{post}a \quad \text{Eq. (2)}$$

where L_{post} is the regional loss factor for the post-harvest stage of the agri-food supply chain (Table S4 of the Annexes).

AW was estimated for the processing stage (AW_{proc}) in the agri-food supply chain for cereals (Eq. 3).

$$AW_{proc,cereals} = P(L_{mill} + L_{proc}c - L_{proc}L_{mill})f + PL_{proc}r \quad \text{Eq. (3)}$$

where L_{proc} is the regional loss factor of the processed stage in the agri-food supply chain, L_{mill} is the loss factor of agricultural food that are milled, c is the conversion factor applied to estimate the food edible of each agricultural food (Table S4 of the Annexes), f is the fraction of food for human consumption concerning the production quantity available (Eq. 4), and r is the fraction of processed food for human consumption concerning the production quantity available (Eq. 5).

$$f = \frac{F}{imports + P - (stocks_{final} - stocks_{initial})} \quad \text{Eq. (4)}$$

$$r = \frac{R}{imports + P - (stocks_{final} - stocks_{initial})} \quad \text{Eq. (5)}$$

where R is the processed food for human consumption that contains multiple types of products [t y^{-1}] and F is the food for human consumption [t y^{-1}], both extracted from the Food Balance Sheets of FAO (FAOSTAT, 2022) considering the average between 2010 and 2019 in Mexico (Table S5 of the Annexes).

AW was estimated for the processing stage (AW_{proc}) in the agri-food supply chain for oilseeds and pulses (Eq. 6).

$$AW_{proc,oilseeds} = L_{proc}P(r+f) \quad \text{Eq. (6)}$$

AW was estimated for the processing stage (AW_{proc}) in the agri-food supply chain for roots and tubers, fruits, and vegetables (Eq. 7).

$$AW_{proc,roots} = L_{proc}P[r+f(1-e)] \quad \text{Eq. (7)}$$

where e is the fraction of agri-food processed fresh (Table S4 of the Annexes).

4.2.3 Nutritional composition of agro-industrial wastes and by-product feeds

The literature review also included the nutritional characteristics of the agricultural foods, AW, and by-product feeds in each agri-food supply chain (Table S6 of the Annexes). Nutritional compositions from scientific articles were prioritized, and the information was complemented with the USDA Food Composition Database (USDA, 2022) and the Feedpedia database (INRAE et al., 2022). It was considered that the nutritional composition of AW before being transformed into by-product feeds is the same as that of agricultural foods. The study excluded agricultural foods for which their nutritional characteristics were not found.

$AW_{m,k}$ for each m-th agricultural food for each k-th municipality [t y^{-1}] was calculated considering the logistical capacity (Eq. 8).

$$AW_{m,k} = AW_{pre}\,\gamma_{pre} + AW_{post}\,\gamma_{post} + \left(AW_{proc,cereals} + AW_{proc,oilseeds} + AW_{proc,roots}\right)\gamma_{proc} \cdots \forall k \quad \text{Eq. (8)}$$

where γ_{pre}, γ_{post}, and γ_{proc} are factors that describe the logistical capacity to use the AW in the dairy industry, with 0 being impossible to use and 1 being possible. These factors were estimated based on the bibliographic review in Section 2.1 considering the classification of residues described by Sadh et al. (2018) (Table S7 of the Annexes).

The potential gross energy of *m*-th agricultural food for each *k*-th municipality ($GE_{m,k}$, MJ y^{-1}) was obtained (Eq. 9).

$$GE_{m,k} = 1000\sum_{m=1}^{n} AW_{m,k} GE_m DM_m \cdots \forall k \quad \text{Eq. (9)}$$

where GE_m is the gross energy of *m*-th agricultural food [MJ kg^{-1} DM] and DM_m is the fraction of dry matter content of the *m*-th agricultural food concerning its fresh matter basis [kg DM kg^{-1} FM]. $GE_{m,k}$ was spatially assessed using geographic information systems software QGIS 3.18.

The manufacture of AW into by-product feed ($BF_{i,k}$, t DM y^{-1}) was estimated (Eq. 10)

$$BF_{i,k} = \sum_{m=1}^{n} AW_{m,k} TF_{i,m} DM_m \cdots \forall i,k \quad \text{Eq. (10)}$$

where $TF_{i,m}$ is the transformation factor that describes the mass change due to the treatment in the AW_m to produce the *i*-th by-product feed. These factors were investigated in a bibliographic review (Table S7 of the Annexes). Then, the potential metabolizable energy for ruminants of the *i*-th by-product feed in the *k*-th municipality ($ME_{i,k}$) was estimated (Eq. 11).

$$ME_{i,k} = 1000\sum_{i=1}^{n} BF_{i,k} ME_i DM_i \cdots \forall k \quad \text{Eq. (11)}$$

where ME_i is the metabolizable energy for ruminants of the *i*-th by-product feed [MJ kg^{-1} DM], and DM_i is the fraction of dry matter content of the *i*-th by-product feed concerning its fresh matter basis. $ME_{i,k}$ was spatially assessed using geographic information systems software QGIS 3.18.

4.2.4 Spatial evaluation between agro-industrial wastes generation and milk production

The national milk production in the *k*-th municipality (DP_k) was obtained from the livestock production statistics 2020 database of SIAP (2020b). The methodology proposed by George (1994) was used to correlate DP_k and $ME_{i,k}$. It consists of defining a function in the spatial factor that measures the global desirability of each point of DP_k and $ME_{i,k}$, thus converting the multivariate optimization problem into a univariate optimization problem.

Since DP_k and $ME_{i,k}$ have different units, a normalization of the data was used to handle a standard scale between 0 and 1 without distorting the differences in the intervals of values or losing information. Additionally, a smoothing of the data d_k in the set of *k*-th municipalities was done to avoid data masking with atypical values for DP_k (Eq. 12) and $ME_{i,k}$ (Eq. 13).

$$d_k(DP_k) = \begin{cases} \left[\dfrac{DP_k - LIE_{DP}}{T_k - LIE_{DP}}\right]^{\alpha_{DP}} \cdots LIE_{DP} \leq DP_k \leq T_{DP} \\ \left[\dfrac{DP_k - LSE_{DP}}{T_{DP} - LSE_{DP}}\right]^{\beta_{DP}} \cdots T_{DP} \leq DP_k \leq LSE_{DP} \cdots \forall k \\ 0 \cdots DP_k \leq LIE_{DP} or DP_k \leq LSE_{DP} \end{cases} \quad \text{Eq. (12)}$$

$$d_k(ME_{i,k}) = \begin{cases} \left[\dfrac{ME_{i,k} - LIE_{ME}}{T_{ME} - LIE_{ME}}\right]^{\alpha_{ME}} \cdots LIE_{ME} \leq ME_{i,k} \leq T_{ME} \\ \left[\dfrac{ME_{i,k} - LSE_{ME}}{T_{ME} - LSE_{ME}}\right]^{\beta_{ME}} \cdots T_{ME} \leq ME_{i,k} \leq LSE_{ME} \cdots \forall k \\ 0 \cdots ME_{i,k} \leq LIE_{ME} or ME_{i,k} \leq LSE_{ME} \end{cases} \quad \text{Eq. (13)}$$

where LIE_{DP} and LSE_{DP} are the lower and upper value of the DP_k dataset, LIE_{ME} and LSE_{ME} are the lower and upper value of the $ME_{i,k}$ dataset, T_{DP} was the target value calculated as a percentile of the DP_k dataset, T_{ME} was the target value calculated as a percentile of the $ME_{i,k}$ dataset, α_{DP}, α_{ME} ,β_{DP}, and β_{ME} are exponents that serve to choose the desired form of the transformation and thus reflect the desires of the experimenter (Figure 5). If large values are taken (e.g., $\alpha,\beta \geq 10$), it means that the desirability d_k only takes large values when it falls close to its target value; if small values are taken for α and β (i.e., $\alpha,\beta \leq 0.1$), it means that any value of DP_k within the interval [LIE_{DP}, LSE_{DP}] is equally desirable; when there is no idea of degrees of desirability. A sensitivity analysis was carried out to determine the appropriate values of T_{DP}, T_{ME}, LIE_{DP}, LSE_{DP} LIE_{ME}, LSE_{ME}, α_{DP}, α_{ME}, β_{DP}, and β_{ME} for smoothing the data.

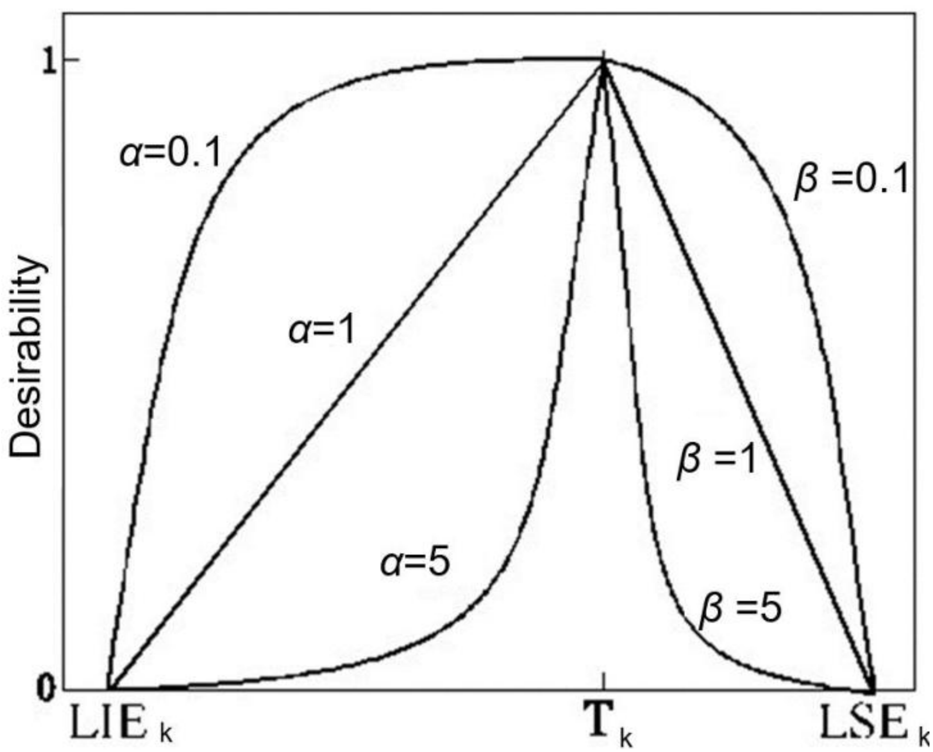

Figure 5. Desirability function (de la Vara Salazar and Domínguez Domínguez, 2011).

The global desirability (GD_k) was obtained as the geometric mean of the individual desirabilities for each *k*-th municipality (Eq. 14).

$$GD_k = \left[d_k(DP_k)^{w_{DP}} \, d_k(ME_{i,k})^{w_{ME}} \right]^{\frac{1}{d_k(DP_k)+d_k(ME_{i,k})}} \quad \text{Eq. (14)}$$

where w_{DP} and w_{ME} are weighted functions representing the importance of each of the variables involved, in this way, a characteristic value represents an approximation between the milk and AW productions at a geographical level.

DP_k and GD_k were spatially assessed separately using geographic information systems software QGIS 3.18.

4.3 LCA of strategic food production system

4.3.1 Goal and scope of the strategic food production system

The strategic food production system consisted of three modules: agricultural production, agro-industrial processing plant, and AW treatment including transport between both modules and the dairy farming system (Figure 3b). The agro-industrial processing plant is in Irapuato, Guanajuato.

Agricultural food production includes land preparation activities, greenhouse germination of seedlings, transplantation, and tillage and harvest practices. Once the agricultural cycle is complete, the agricultural food is transported 20 km to the processing plant, where 50% (by mass) becomes by-product (R. Covarrubias-Kaim 2019, personal communication). The remaining biomass becomes in food for human consumption, which are frozen, packed, and exported; however, these activities were excluded from the study because the LCA scope ended at the cutting stage when the agricultural waste were removed from the plants. Finally, the by-product without any stabilization treatment is transported 60 km to the dairy farm.

4.3.2 Definition and scope for the strategic food production system

LCA boundaries of the strategic food production system were established from the cradle to the dairy farm gate, that is, from supply production to AW transport, to the dairy farm (Figure 3b). Functional unit (FU_{BPS}) was defined as the production of 1 t of the food on a fresh matter basis (FM) without any subsequent cooking or packaging. This AW are considered a co-product of low economic value.

4.3.3 Inventory analysis for the agro-industrial food production system

The inputs inventory of the agricultural production module is described below. Agricultural chemicals and seeds were taken from the agricultural production guidelines of Guanajuato State (SAGARPA, 2017). Diesel consumption by tillage practices was estimated using the factors of West and Marland (2002). Water for irrigation was predicted using the CROPWAT© model (v. 8.0; FAO, Rome, Italy), using historical weather data from CONAGUA (2020), as well as crop data from Allen et al. (1998). Electricity use for irrigation was estimated according to the World Food LCA Database (Nemecek et al., 2014).

The emissions inventory of the agricultural production module included environmental burdens to air, water, and soil. GHG emissions from N-fertilization were estimated based on the 2019 refinement to the 2006 IPCC Guidelines, Chapter 11 (IPCC, 2019). Non-GHG emissions of NH_3, NO_x, non-methane volatile organic components (NMVOC), and particulate matter (PM) were calculated according to the EMPEP/EEA Guidebook, Chapter 3D (EMEP/EEA, 2019a). Agricultural machinery emissions were predicted using the GREET model (GREET, 2018). Emissions to water and soil included 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 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). The pesticides are presented in Table S9 of the Annexes.

In the agro-industrial-processing plant module, water requirements were estimated by an expert (R. Covarrubias-Kaim 2019). Electricity used to separate the AW from food was estimated with the technical specifications of a Silex Single Lane (AIT® brand) Machine.

4.3.4 Impact assessment for the strategic food production system

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 materials and energy production were taken from ecoinvent v. 3.3 (Wernet et al., 2016). The environmental impact was assessed using the ReCiPe method v. 1.13 considering midpoint and endpoint evaluation levels through the hierarchist (H) perspective proposed by (Goedkoop et al., 2013). Economic allocation factors ($AFac_{BS}$) were used. The prices came from a local-producing company in the region (R. Covarrubias-Kaim 2019, personal communication).

4.4 Linear programming model for agro-industrial wastes incorporation in cattle diet

An optimization model is proposed to evaluate environmentally each diet formulated in the dairy farming system (Figure 6). The model includes the environmental impact of the conventional crops and the by-product feeds from AW through the LCA. Different diet scenarios are proposed, from a diet with conventional feeds to an optimized diet with by-product feeds from AW. The model considers:

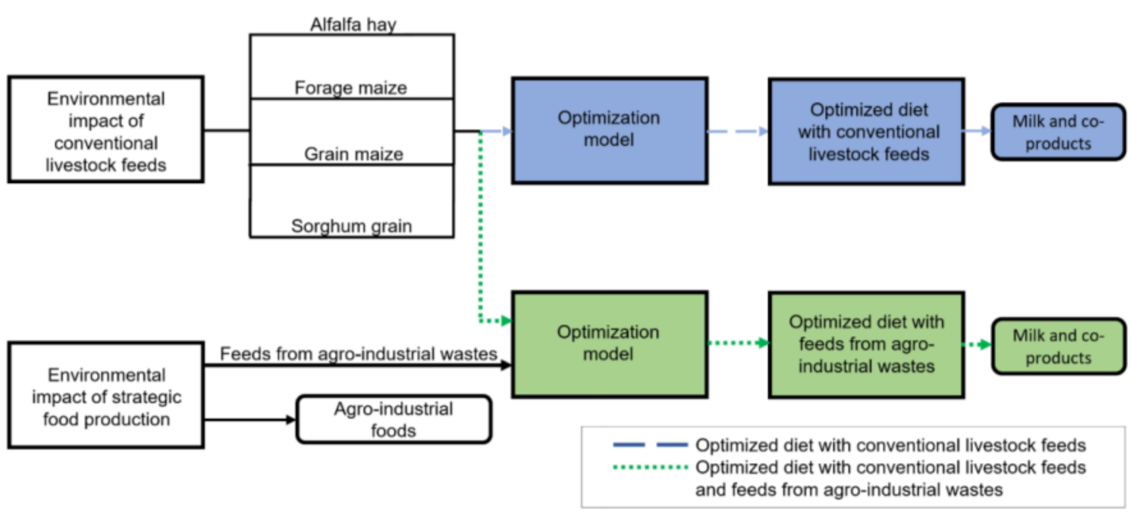

Figure 6. Structure of the diet formulation process

1. Four livestock categories (*s*= {1,2,3,4}): calves, replacement heifers, cows in production, and dry cows (Table 1).
2. Five nutrients within the constraints (*t*= {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).

3. An unknown number of livestock feeds (i= {1,2,3,4,…,n}): four conventional feeds (maize silage, alfalfa hay, sorghum grain, and rolled maize) and the by-product feeds from AW identified. Forages are considered a subset of feed (i'= {1,2,3}).

4.4.1 Parameters

Contributions of t-th nutrient in livestock diet of i-th livestock feed (n_{ti}) are determined (Table 2). Data for conventional feeds comes from the Animal Feed Resources Information System database developed for the FAO (Heuzé et al., 2017b, 2017a, 2016, 2015), while data for by-product feeds from AW comes from the USDA Food Composition Database (USDA, 2018).

Requirements of t-th nutrient in livestock diet for s-th livestock category are determined (Table 3). Each type of constraint was differed in nomenclature to facilitate construction and comprehension of the optimization model.

Table 2. Nutritional information of the feeds used in the diet formulation. For i>4 a study case of broccoli stems is presented.

Contributions of the t-th nutrient in the livestock diet of the j-th livestock feed (n_{it})	i =1: **Maize silage**	i=2: **Alfalfa hay**	i=3: **Sorghum grain**	i=4: **Rolled maize**	i=5: **Broccoli stems**
t=1: **Metabolizable Energy [Mcal kg^{-1} DM]**	2.63	2.03	3.22	3.27	1.22
t=2: **Crude protein [kg kg^{-1} DM]**	0.068	0.183	0.108	0.095	0.032
t=3: **Crude fiber [kg kg^{-1} DM]**	0.198	0.286	0.028	0.023	0.133
t=4: **Calcium [kg kg^{-1} DM]**	1.9E-4	0.022	3E-4	2E-4	1.46E-3
t=5: **Phosphorus [kg kg^{-1} DM]**	1.7E-3	2.7E-3	3.3E-3	2.9E-3	5.9E-4
Dry matter [kg DM kg^{-1} FM]	0.442	0.903	0.886	0.881	0.093
Max. proportion, FMP_{si}	0.5	0.5	0.3	0.3	0.2
Reference	(Heuzé et al., 2017a)	(Heuzé et al., 2016)	(Heuzé et al., 2015)	(Heuzé et al., 2017b)	(Hu et al., 2011; USDA, 2018)

Table 3. Requirements of *t*-th nutrient in livestock diet for *s*-th livestock category

Constraints	s=1: **Calves**		s=2: **Replacement heifers**		s=3: **Cows in production**		s=4: **Dry cows**		**Reference**
Inf_{st} ; sup_{st}	inf_{1t}	sup_{1t}	inf_{2t}	sup_{2t}	inf_{3t}	sup_{3t}	inf_{4t}	sup_{4t}	
t=1: Metabolizable Energy [Mcal d^{-1}]	8	13	16.4	26.5	22	40	12	22	(Timpka et al., 2001)
t=2: Crude protein [%]	12	16	10	14	13	19	10	16	(Maiztegui, 2001)
t=3: Crude fiber [%]	17	22	17	22	16	22	17	22	(Moran, 2005)
t=4: Calcium [%]	0.41	1	0.4	1	0.6	1	0.44	1	(SNV, 2017)
t=5: Phosphorus [%]	0.23	0.39	0.18	0.30	0.25	0.42	0.22	0.26	(SNV, 2017)
in_s ; su_s	in_1	su_1	in_2	su_2	in_3	su_3	in_4	su_4	
Dry matter intake [kg DM d^{-1}]	2.90	5.5	8.6	13.1	15	20	8.6	12	(Timpka et al., 2001)
upp_s		upp_1		upp_2		upp_3		upp_4	
As-fed intake [kg FM d^{-1}]		15.27		43.2		60.0		60	(Timpka et al., 2001)
if_s ; sp_s	if_1	sp_1	if_2	sp_2	if_3	sp_3	if_4	sp_4	
Forage:concentrate Ratio [%]	35	70	60	80	40	60	60	88	(Ryan et al., 1997)

4.4.2 Objective function

Next, the model of diet formulation for environmental impacts is presented. The objective function determines the environmental impact generated by the cattle diet formulation (Eq. 15):

$$MinDIET = \sum_{s=1}^{4}\sum_{i=1}^{5} x_{si} v_i RT_s \qquad \text{Eq. (15)}$$

where *DIET* is the environmental impact of the diet [Pt FU_{DPS}^{-1}]; x_{si} is the amount of i-th livestock feed for s-th livestock category, [kg DM FU_{DPS}^{-1}]; v_i is the environmental impact indicator of i-th feed or by-product, [Pt kg^{-1} DM], which is calculated using the single score indicator of the ReCiPe *Endpoint* (H) method; and RT_s is the ratio of the s-th livestock category to the livestock total on the farm.

4.4.3 Constraints

Nutrition requirements: ME includes requirements for maintenance, growth, gestation, and lactation, is restricted as follows (Eq. 16):

$$\inf_{si} \le x_{si} n_{ti} \le \sup_{si}, \forall s, i = 1 \qquad \text{Eq. (16)}$$

as t=1 (Table 3), then $\inf_{s1}$ and $\sup_{s1}$ are the minimum and maximum requirement of ME for s-th livestock category [Mcal FU_{DPS}^{-1} d^{-1}] and n_{1j} is the ME contribution of j-th livestock feed [Mcal kg^{-1} DM].

The nutritional requirements of CP, CF, Ca, and P (t=2 to 5, Table 3) are presented as intervals in percentages of DM and are restricted as follows (Eq. 17):

$$\inf_{st} \le \frac{x_{si} n_{ti}}{\sum_{i=1}^{5} x_{si}} 100 \le \sup_{st}, \forall s, \forall t \ne 1 \qquad \text{Eq. (17)}$$

where $\inf_{st}$ and $\sup_{st}$ are the minimum and maximum percentages of t-th nutrient in livestock diet for s-th livestock category. Eq. 17 was multiplied by the denominator to be transformed into a linear function.

Dry matter intake: The sum of all feeds on a dry-matter basis [kg DM d^{-1}] for s-th livestock category. (Eq. 18):

$$in_s \le \sum_{i=1}^{5} x_{si} \le su_s, \forall s \qquad \text{Eq. (18)}$$

where in_s and su_s are the minimum and maximum amount of dry matter intake for s-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}] is restricted as follows, assuming that an animal consumes a maximum of 10 % of its weight per day (Timpka et al., 2001) (Eq. 19):

$$\sum_{i=1}^{5} \frac{x_{si}}{DM_i} \leq AFI_s, \forall s \qquad \text{Eq. (19)}$$

where DM_i is the dry matter content of s-th livestock feed [kg DM kg^{-1} FM] and AFI_s is the maximum as-fed intake of s-th livestock category [kg FM d^{-1}] (10 % of animal liveweight).

Feed: The maximum proportion of each feed in the cattle diet is defined as follows (Eq. 20):

$$\frac{x_{si}}{\sum_{i=1}^{5} x_{si}} \leq FMP_{si}, \forall s \qquad \text{Eq. (20)}$$

where FMP_{si} is the maximum proportion of j-th livestock feed in the cattle diet formulation for s-th livestock category.

These constants FMP_{si} were defined according to Moraes et al. (2012) (Table 3). For broccoli stems, a literature review determined that the maximum proportion of by-product feeds from AW in the cattle diet formulation was 0.20 (Amaral-phillips and Hemken, 2006; Shaver, 2001; Stalling, 2009). Eq. 20 was multiplied by the denominator to be transformed into a linear function.

Forage: The appropriate forage:concentrate ratio between energy-concentrated feeds is restricted with Eq. 21, which models the percentage of j'-th forage, in the total mass of feed.

$$if_s \leq \frac{\sum_{i'=1}^{3} x_{si'}}{\sum_{i=1}^{5} x_{si}} 100 \leq sp_s, \forall s \qquad \text{Eq. (21)}$$

where $x_{si'}$ is the amount of *i*'-th livestock feed (forage) for s-th livestock category, [kg DM FU_{DPS}^{-1} d^{-1}], and if_s and sp_s are the minimum and maximum percentage of forage in s-th livestock category. Eq. 21 was multiplied by the denominator to be transformed into a linear function.

4.4.4 Description of the optimization model scenarios

Microsoft Excel's Solver Tool is used to solve the model using the Simplex LP resolution method. Two scenarios are defined:

1. An optimized conventional diet (OCD), where the cattle diet is formulated from the four conventional feeds *i* (i=1 to 4) and
2. An optimized diet with by-product feeds from AW, the particular case of study was the broccoli stem. (ODBS), where, in addition to the four conventional feeds, by-product feeds from AW can be used as a substitute (*i*=5 to *n*).

4.5 Linear programming model of fertilizer blends

4.5.1 General features of the optimization model

The optimization model calculates N–P–K blends according to functions that minimize the environmental and economic impact of the blend, considering aspects such as crop requirements and fertilizer content (Figure 7). Main livestock feeds in Mexico were evaluated (Table S1), four crops were selected (alfalfa, sorghum grain, forage maize, and grain maize) according to a general review of the most relevant livestock feeds of the study region (Appendix II of the Annexes). The fertilizer crop requirements were obtained from different sources considering the soil type, seed variety, and weather conditions (Table 4).

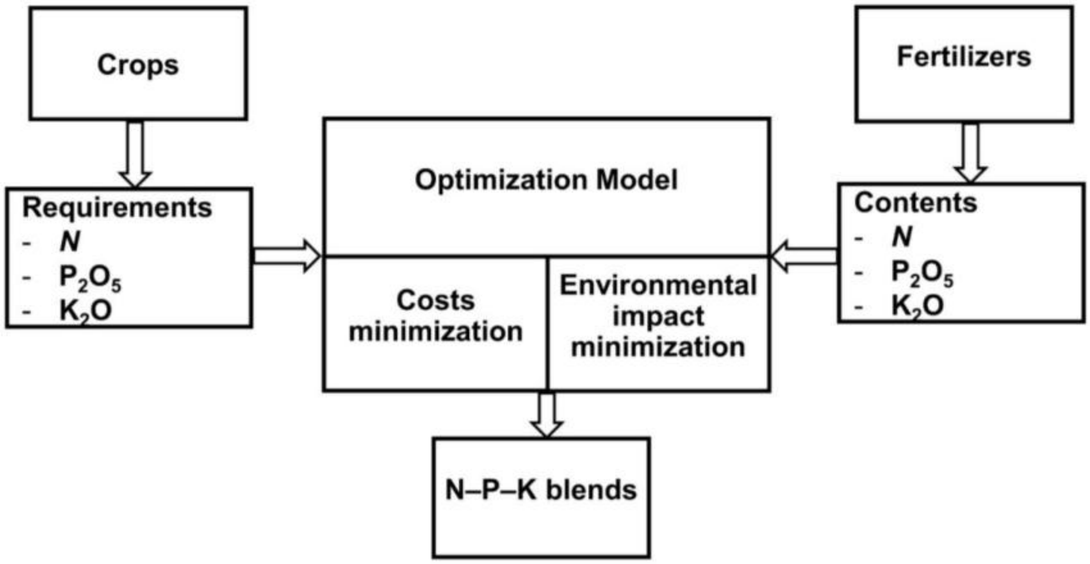

Figure 7. The programming model for N–P–K blends for each crop.

Table 4. Fertilizer requirements of dairy cattle feed.

	Requirement [kg ha-1]			Crop yield [t ha-1]	Reference
	N	**P_2O_5**	**K_2O**		
Feed	*nomenclature* n_i	p_i	k_i		
Alfalfa	30	277.5	0	72.2	(Lara-Macías and Jurado-Guerra, 2014; Lloveras-Vilamanyà, 2010)
Forage maize	146.5	72.9	21.5	21.2	(INIFAP-CIRNE, 2010; SAGARPA, 2017; Villanueva-Betancourt, 2018)
Grain maize	156.7	52.3	9.4	9.0	(SENASICA-INIFAP, 2015a, 2015b)
Sorghum grain	190	41.5	13.6	5.4	(SENASICA-INIFAP, 2015b)

Twelve fertilizers were chosen based on their use in the country (Table S8 of the Annexes) and the availability of their eco-inventories in the ecoinvent database v. 3.3. Table 5 shows the N–P–

K content, price, and environmental impact in producing these fertilizers. The price of fertilizers was obtained using agricultural input information from the National Market Information and Integration System (SNIIM, for its acronym in Spanish) through the average price between January and December 2020 in the State of Guanajuato (http://www.economia-sniim.gob.mx/). The environmental impact was quantified using the background data in SimaPro® software v. 8.3 (PRé Consultants bv, Amersfoort, The Netherlands) using the single score indicator of the recipe endpoint (H) method.

Table 5. Fertilizers characteristics

Fertilizer	**Content [%]**			**Price**	**Environmental impact**
	N	**P_2O_5**	**K_2O**	**USD kg^{-1}**	**mPt kg^{-1}**
Urea	46%			$0.36	392.5
Urea Ammonium Nitrate	35%			$0.36	467.2
Ammonium Nitrate	34%			$0.36	564.0
Ammonium Sulfate	21%			$0.24	169.2
Calcium Nitrate	15%			$0.49	157.1
Diammonium Phosphate	18%	46%		$0.50	346.4
Monoammonium Phosphate	11%	52%		$0.49	362.5
Triple Superphosphate		46%		$0.43	254.5
Single Superphosphate		21%		$0.19	293.1
Potassium Sulfate			50%	$0.49	161.7
Potassium Nitrate			34%	$0.49	145.1
Potassium Chloride			60%	$0.49	17.3

Two individual models (environmental and economic) were proposed to develop the optimization model. Then, an approximation to combine both schemes was made through parametric linear programming. The model considers the following factors:

1. Four livestock feeds (i= {1,2,3,4}): Table 4.
2. Twelve fertilizers (j= {1, 2, …, 12}): Table 5.

4.5.2 Environmental approach

The objective function determines the environmental impact generated by the N–P–K blend (Eq. 22):

$$MinZ_1(x) = \sum_{j=1}^{12} x_{ij} v_j \;, \forall i \qquad \text{Eq. (22)}$$

where $Z_1(x)$ is the environmental impact of the N–P–K blend per t of i-th livestock feed on a dry matter (DM) [mPt t^{-1} DM]; x_{ij} is the amount of j-th fertilizer for i-th livestock feed [kg t^{-1} DM]; v_j is the environmental impact indicator of *j*-th fertilizer, [mPt kg^{-1}], represented by the single score indicator of the ReCiPe *Endpoint* (H) method.

Equations 23–25 represent the constraints of the fertilizer amount in each crop subject to its N–P–K requirements, and Eq. 26 restricts to positive values:

$$\sum_{j=1}^{12} x_{ij} f_j = n_i \;, \forall i \qquad \text{Eq. (23)}$$

$$\sum_{j=1}^{12} x_{ij} g_j = p_i \;, \forall i \qquad \text{Eq. (24)}$$

$$\sum_{j=1}^{12} x_{ij} h_j = k_i \;, \forall i \qquad \text{Eq. (25)}$$

$$f_j \geq 0, g_j \geq 0, h_j \geq 0 \qquad \text{Eq. (26)}$$

where n_i, p_i, and k_i are the N, P_2O_5, and K_2O requirements of i-th livestock feed [kg kg^{-1} DM] (Table 1), respectively; while f_j, g_j, and h_j are the N, P_2O_5, and K_2O content of j-th fertilizer, respectively (Table 5).

4.5.3 Economic approach

The mathematical structure of the economic model is the same as that of the environmental model, except for some differences, such as the objective function determines the economical price generated by the N–P–K blend (Eq. 27):

$$MinZ_2(y) = \sum_{j=1}^{12} y_{ij} b_j \quad ,\forall i \qquad \text{Eq. (27)}$$

where $Z_2(y)$ is the price of the N–P–K blend per t of i-th livestock feed on a dry matter [USD t^{-1} DM]; y_{ij} is the amount of j-th fertilizer for i-th livestock feed [kg kg^{-1} DM]; b_j is the price of *j*-th fertilizer, [USD kg^{-1}].

The constraints limit the amount of fertilizer in each crop, like the environmental model (Equations 28–31).

$$\sum_{j=1}^{12} y_{ij} f_j = n_i \quad ,\forall i \qquad \text{Eq. (28)}$$

$$\sum_{j=1}^{12} y_{ij} g_j = p_i \quad ,\forall i \qquad \text{Eq. (29)}$$

$$\sum_{j=1}^{12} y_{ij} h_j = k_i \quad ,\forall i \qquad \text{Eq. (30)}$$

$$f_j \geq 0, g_j \geq 0, h_j \geq 0 \qquad \text{Eq. (31)}$$

4.5.4 Parametric linear programming model

Parametric linear programming was proposed to simultaneously minimize environmental (Z_1) and economic impacts (Z_2). The method presented allows to make a multivariable optimization (environmental and economic) in a linear optimization. For this purpose, the model takes the results of the models developed in Sections 4.5.2 and 4.5.3. Each solution $Z_1(x)$ has an equivalent $Z_1(y)$, and vice versa, $Z_2(y)$ has an equivalent $Z_2(x)$ (Figure 8). Between the environmental approach and the economic approach, a line integrates the objective functions by w_i, a parameterized weight between the two objective functions ($Z_1(x)$ and $Z_2(x)$) assigned by the decision-maker. Note that there are multiple solutions at each point (w_i, 100-w_i), but it only corresponds to optimization.

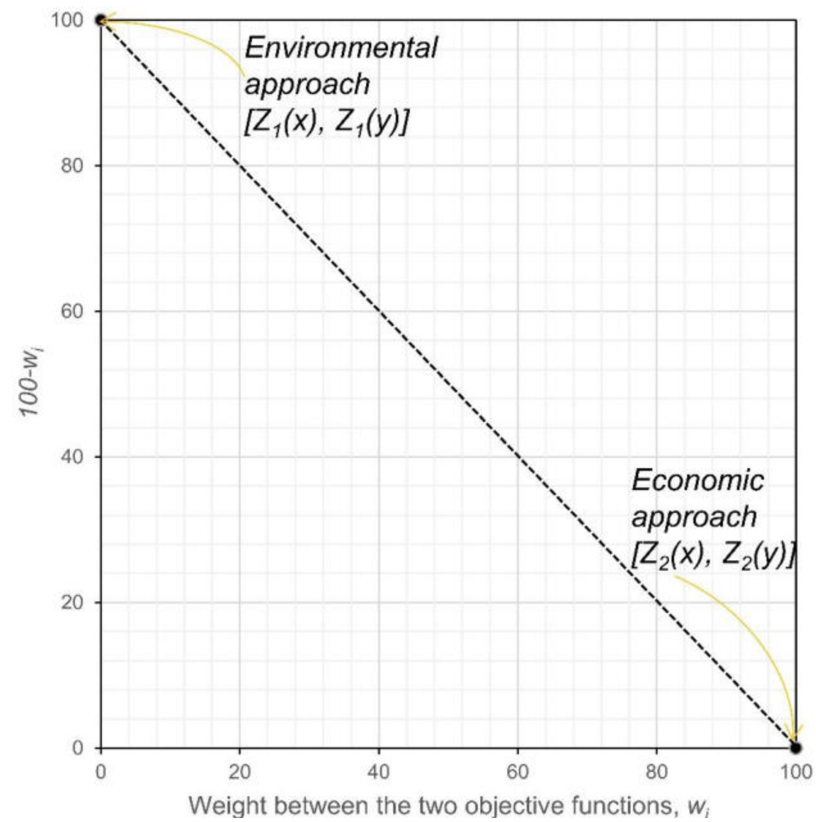

Figure 8. Representation of the environmental and economic optimization model based on the weights assigned to the objective functions

The function objective of environmental impact (Z_1) was selected, while Z_2 was added to the constraints. The environmental impact was selected as an objective function as specified by Eq. 32, where U is the environmental impact of the N–P–K blend per t of i-th livestock feed on a dry matter [mPt t^{-1} DM].

$$MinU = \sum_{j=1}^{12} x_{ij} v_j \quad , \forall i \qquad \text{Eq. (32)}$$

The constraints are the same as those used in the environmental model (Section 4.5.2) but include a new restriction that weighs environmental and economic impacts (Eq. 33):

$$\sum_{j=1}^{12} x_{ij} b_j \leq Z_2(x) + \frac{Z_1(x) - Z_2(x)}{100} w_i \ , \forall i \qquad \text{Eq. (33)}$$

note that the right side of Eq. 33 parameterizes the environmental and economic model results on a percentage scale that depends on w_i.

4.5.5 Description of the optimization model scenarios

Three optimized scenarios for N–P–K blends for each crop were considered according to the triple bottom line concept (Henriques and Richardson, 2004):

1. Scenario Planet (environmental stewardship), which the optimized blend prioritizes the use of fertilizers with a lower environmental impact (w_i = 0);
2. Scenario Viable, which selects fertilizers giving equitable importance between environmental and economic impact (w_i = 50);
3. Scenario Profit (economic prosperity) which prioritizes the use of the most economical fertilizers (w_i = 100);
4. Baseline Scenario to compare the proposed scenarios with the recommended blends of the livestock feed production guidelines of Guanajuato State (SAGARPA, 2017).

4.6 LCA of the dairy farming system

4.6.1 Goal and scope of the dairy farming system

The system description of the dairy farming system is presented in Figure 3a. Figure 9 presents the boundaries of the dairy farming system. The scope of the system comprises from the cradle to the farm gate, i.e., from supplies production up to raw milk production. The production of 1 kg of fat-and-protein-corrected milk (FPCM) leaving the farm without any processing was considered as a functional unit (FU_{DPS}), following the standards of the International Dairy Federation (IDF, 2015). Due to a lack of data and to be consistent with other dairy production LCA studies that did not consider these factors, capital goods (machinery and infrastructure) and veterinary medicines were not included in the system (Baldini et al., 2017).

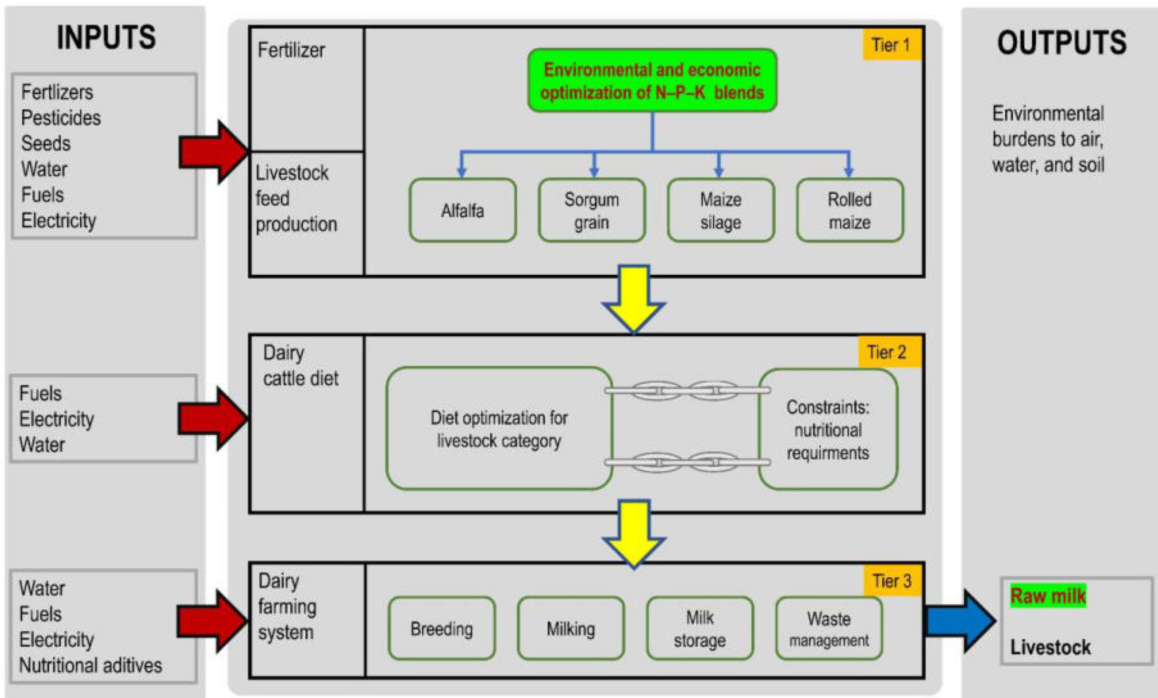

Figure 9. System boundaries of the dairy farming system.

The environmental performance of optimized N–P–K blends were evaluated on three tiers of the dairy farming system (Figure 9):

- Tier 1: on livestock feed production, no co-products were considered.
- Tier 2: on the livestock diet of the farm, considering the scenarios of Section 4.4.4.
- Tier 3: the overall life cycle of raw milk production which is described below

4.6.2 Inventory analysis of the dairy farming system

The life cycle inventory included the evaluation of inputs, products, co-products, and environmental burdens, according to Figure 9. The N–P–K blends in the crop production module (Tier 1) were estimated with the parametric linear programming model proposed in Section 4.5. The diet formulation was calculated according to the model developed in Section 4.4.

For the agricultural production module and transport, the amount pesticides, crop yields, water, energy requirements for irrigation, diesel consumption, as well as the environmental burdens of seedling and feed production were estimated using the same tools, procedures, and assumptions described for the strategic food production system (Section 4.3.3).

The crops are transported to the farm, where the diet is formulated according to the model presented in Section 4.4 (Tier 2). Inputs of fuels for transportation were estimated according to Rivas-García et al. (2015), electric consumption using the method of Nemecek et al. (2014), and water consumption by livestock was estimated according to the method of Dahlborn et al. (1998). The emissions inventory to air included the transportation fuel use were predicted using the GREET model according to the distances of Table S3 of the Annexes.

In the dairy farm, inputs of water, fuels, electricity, and nutritional additives were estimated according to Rivas-García et al. (2015). The emissions inventory, including GHG emissions from enteric fermentation and manure management to air, was estimated using the IPCC Guidelines, chapter 10 (IPCC, 2019). Manure management emissions to air (NH_3, NO_x, NMVOC, and PM) and water (NH_3 and NO_x) were determined according to the EMPEP/EEA Guidebook (EMEP/EEA, 2019b) and the IPCC Guidelines (IPCC, 2019) considering the solid storage system.

4.6.3 Impact assessment of the dairy farming system

The impact assessment of the dairy farming system was performed in the same way as for the strategic food production system (Section 4.3.4). Economic allocation factors were used to estimate the environmental burdens of milk and co-products —livestock (newborn calves and dry cows)— that leaves the product system (Figure 9). Although the biophysical relationship is recommended for allocating co-products in dairy farming systems, allocation based on economics is equally valid based on previous research (Flysjö et al., 2011). In addition, economic indicators are more accurate than physical ones in the study region because of data availability. All scenarios proposed in sections 4.4.4 and 4.5.5 were considered.

4.6.4 Sensitivity analysis

4.6.4.1 Sensitivity analysis of by-product feeds price in environmental impact of milk

A sensitivity analysis was performed to assess the influence of the price of by-product feeds from AW and its associated environmental impacts. The analysis considered a gradual increase in by-product price until its environmental impact was such that the formulation model did not allow incorporation of by-product in the livestock diet, according to their constraints. For this evaluation, the economic allocation was used (Eq. 34).

$$AFac_{\varepsilon} = \frac{\xi_i \omega_{\varepsilon}}{\sum_{\varepsilon=1}^{n} \xi_i \omega_{\varepsilon}} \quad \text{Eq. (34)}$$

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

4.6.4.2 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 farming 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.

Chapter 5

RESULTS AND DISCUSSION

5.1 National inventory of strategic agro-industrial wastes in livestock diet in Mexico

5.1.1 Uses, treatment, and nutritional composition of agro-industrial wastes in the livestock diet

The annualized open data of basic agricultural statistics at the municipal level for 2020 allow identifying 80 agricultural foods. The proposed methodology filtered out 29 potentially strategic agricultural foods. The evidence of the previous use of AW as by-product feeds and the knowledge of treatment to transform AW into by-product feeds was investigated based on more than 70 scientific publications (Table 6).

Table 6. Identification of by-product feeds and treatments of crops grown in Mexico strategic in the livestock diet.

Crop	By-product feeds	Description	Treatment	Country	Reference
Agave	Agave bagasse	After the agave heads are cooked, crushed, ground, and sugars extracted with water, the residual fiber can be used as a corn substitute. Agave bagasse has high lignin content, which generates low digestibility.	The fiber is separated mechanically, then dried in the sun before being cut into smaller fibers for use. For use, it is cut into smaller fibers. A pre-treatment process with calcium hydroxide reduced lignin content and increased digestibility.	Mexico	(Ramírez-Cortina et al., 2012)
Apple	Apple pomace	Apple pomace remains the solid residue after milling and pressing apples for cider, apple juice, or puree production. A by-product for sheep and dairy cows.	Its usage requires its preservation by dehydration or ensiling. Ensilage is cheaper than drying. The apple waste is aerobically fermented with urea, ammonium sulfate, and minerals added.	Mexico Iran	(Alarcon-Rojo et al., 2019)
Eggplant	Brinjal peel	Cows fed brinjal produced significantly (14.3%) more milk, almost as if they had been treated with a light hormone for only 42 days.	Fresh samples were cut into 1 cm sieve-sized pieces and placed in a hot air oven to dry. The dried samples were ground to create a homogeneous powder which mixed.	Bangladesh	(Hossain et al., 2015)
Banana	Fermented banana peel	Banana peels were obtained from a local banana fritter seller and a local market.	The material was ensiled in two 120 kg plastic drums with an air-tightened cap for 28 days.	Malaysia	(Afiq Bin Jais et al., 2017)
	Banana leaf, peel, and pseudostem hay	Come from ripe fruits of the cultivar Prata-Anã.	The banana leaves and pseudostem were crushed in a stationary machine and were stirred to dehydration. The peel was dehydrated by exposure to the sun (5 days), crushed in a stationary mincer to obtain 3 to 4 cm particles, and packed in nylon bags for storage in a covered shed.	Brazil	(Rigueira et al., 2021)

	Ripe banana peel	The peel accounts for 18-20% of the banana's total waste.	Fresh samples were cut into 1 cm sieve-sized pieces and placed in a hot air oven to dry. The dried samples were ground to create a homogeneous powder which mixed.	Bangladesh	(Hossain et al., 2015)
Beans	Beans waste	The bean residue was composed of whole grains (crushed, wrinkled, spotted, spelled, and others), broken (healthy bands), or shattered (healthy pieces) with impurities and extraneous matter.	Harvested beans were used without further processing.	Brazil	(Rodrigues Magalhães et al., 2008)
Blackberry	Mulberry fruit in feed blocks. Black mulberry aerial part	Blocks were made from fresh blackberries and other ingredients. Daily milk production increased by 30-50%, visibly improving their health and intake capacity.	Fresh blackberries were ground into a paste, along with urea, wheat bran, and dried alfalfa leaves. The mixture was poured into a wooden mold (6 x 6 x 4 inches) and pressed.	Pakistan	(Habib, 2004)
Broccoli	Florets and steams	Broccoli florets and stems are processed broccoli by-products that are high in protein and fiber. A by-product for sheep (Sánchez Cano, 2019) and livestock.	Broccoli waste was separated into groups, cut, and dried at 40 °C until constant weight was achieved.	Spain	(Sánchez Cano, 2019)
	Pelletized broccoli by-products	The by-products of processed broccoli are rich in protein, vitamins, and phenolics.	The broccoli waste was separated into groups, cut, and dried at 40 °C until a constant weight and pelletized.	China	(Yi et al., 2015)
Carrot	Fresh carrot	After juice extraction, surplus carrots, carrot tops, and carrot pomace are typically culled (graded out).	These can be fed whole or chopped, ensiled, or dehydrated.	India	(Wadhwa and Bakshi, 2013)
Cauliflower	Stems, Sprouts, and Leaves	They are highly degradable protein and dry matter sources that rumen microorganisms can rapidly ferment. A by-product for livestock and poultry.	In a pilot-scale alfalfa dehydrator, commercially grown cauliflower leaf residues were dehydrated to produce dehydrated meals suitable for poultry and livestock feed.	Spain	(de Evan et al., 2020)

Chickpea	Chickpea Straw and grain	Chickpea straw contains slightly more protein than cereal straw but remains a fibrous forage. Chickpea seeds are mainly used as a concentrate feed, replacing soybean meal and cereal grains.	The secondary compounds appear to be inactivated by 12-24 h of in vitro incubation with rumen liquor. Processing techniques, including dehulling, germination, and thermal treatment, remove toxic substances and improve intake and digestibility.	Greece	(Bampidis and Christodoulou, 2011)
Coffee	Coffee pulp dehydrated and hulls	The coffee pulp can be fed at levels below 20% of the diet without affecting milk production in cows. Coffee waste and by-products have been used in ruminants at a rate of 10-30%.	Coffee pulp is obtained when the coffee is harvested and processed wet, while the coffee husk is obtained when the coffee is processed dry. Cattle will only accept coffee pulp as feed if it is supplemented with highly palatable feeds, forages, and protein concentrates.	Ethiopia	(Wogderess, 2016)
Cotton	Cotton straw	Cotton crop residues such as cotton straw, cotton sticks, and cottonwood can range from 5 to 7 t/ha.	It is produced from nearby cotton fields and was ground with an 8 mm sieve.	India	(Kirubanath et al., 2003)
Grape	Grape pomace, dehydrated	Grape pomace is a mixture of skins, pulp, and seeds that remain after making wine or juice from grapes.	Grape pomace is dried, crushed, sieved, and pelletized with steam conditioning at 80 °C.	Romania	(Eleonora et al., 2014)
Guava	Guava, waste, dried	Guava waste is made of variable proportions of peels, seeds, and stone cells. By-product for sheep	Collected, dried, and crushed in a disc crusher before being thoroughly mixed and stored in a well-ventilated area.	Egypt	(Hassan et al., 2016)
Lemon	Lemon fruits, dried	Dried citrus pulp is a by-product created after the juice from citrus fruits is extracted.	The remaining citrus pulp is dried, crushed, and compressed from the citrus juice production.	Greece	(Belibasakis and Tsirgogianni, 1996)
Mango	Ensiled mango peel	The peel has a high value of antioxidant activity and glucose retardation index, while its aroma and flavor are pleasant but high moisture and acidity content.	To produce good silage from mango peel would be desirable to mix it with dry materials to adjust moisture (rice Straw) and increase protein (Leucaena leaves) for proper fermentation of the ensiled products.	Thailand	(Sruamsiri and Silman, 2009)

Orange	Orange peels, silage	Oranges (60 %), grapefruits, and lemons are commonly used to make citrus pulp. It is perishable due to its high water and soluble sugar content.	It should be sun-dried and pelleted or ensiled to increase density. Lime is added during drying to neutralize free acids, bind fruit pectin, and release water.	Greece	(Belibasakis and Tsirgogianni , 1996)
Papaya	Papaya pomace, dried	The papaya pomace is the by-product containing peels and seeds obtained after juice extraction from fruit. It is a potential alternative feedstuff since it has a high protein content	the residues collected in the juice industries were stored in a cold chamber at -20 °C. Then, it was pre-dried (± 4 hours) in the sun and coarse grinding in a forage crusher to break the endocarp.	Brazil	(Augusto Gomes Azevêdo et al., 2011)
Cucumber	Silage cucumber wastes	Cucumber waste was collected from greenhouses after the primary yield was harvested.	Collected vegetables were cleaned and cut into 5-10 cm pieces before being mixed with 5% palm molasses and firmly compressed, closed, and strapped. They were then left to ferment at room temperature for 30 days.	Saudi Arabia	(El-Waziry et al., 2013)
Pineapple	Ensiled Pineapple	Pineapple waste primarily comprises residual pulp, peels, and skin with high moisture content. By-products can account for a significant portion of a crop (70-75 % w/w).	The pineapple waste was sealed in plastic bags and stored for at least 21 days before being opened.	Thailand	(Suksathit et al., 2011)
Potato	Potato skins and fragments	Potato processing wastes include potato pulp, culls, skins, and grafts.	The potatoes were steam-dried to remove the skin, and those not for human consumption were cut.	United States	(Montoro et al., 2019)
Rice Palay	Rice bran	The husk, bran, or flour obtained from polishing is used to make animal feed. Rice bran has been recommended because of its fatty acid composition.	After hulling, the germ and outer bran are removed in a set of huller reels and pearling cones, in which the waxy cuticle is scoured off by the friction between the high-speed abrasive cone and its casing.	Brazil	(Laerte Nörnberg et al., 2004)
Sesame	Sesame straw	Sesame by-products in the diet improve protein and fiber digestibility in animals. Besides a high amount of oxalate and phytic acid, sesame seed contains almost no antinutritional factors.	No treatment.	Iran	(Kabinda et al., 2022; Shirzadegan and Jafari, 2014)

Sugar cane	Sugarcane tops	They are generally bulky, have low protein (protein less than 6 % DM), and have fibrous material.	No treatment.	India	(Bandeswaran et al., 2012)
Tangerine	Taringe peel	It could be used directly or after pre-treatments for animal feed.	It can be used as fresh or dry animal feed.	Morocco	(el Barnossi et al., 2021)
Tomato	Tomato pomace	The tomato pomace is a residue of skins, pulp, and seeds obtained after extracting tomato juice. By-product for goats	Tomato pomace can be dried in the sun or with an industrial process. Tomato pomace is crushed after it has dried.	Brazil	(Mizael et al., 2020)
Soybean	Soybean hulls	Soybean hulls are a by-product of the extraction of oil from soybean seeds. The beans are then cracked, and their hulls, consisting mainly of the outer coats, are removed.	After entering the oil mill, soybeans are screened to remove broken and damaged beans and foreign material.	United States	(Ipharraguerre and Clark, 2003)
Maize grain	Maize cobs	Maize cobs are a by-product of the maize crop, consisting of the central fibrous rachis.	No treatment. Adding 1% molasses may help to improve intake.	United States	(Jansen et al., 2012)
Wheat grain	wheat bran	Cows were fed a high-forage diet (75% silage DMI), supplemented with wheat bran and dried sugar beet pulp.	All feedstuffs, except for forages, were ground (hammer milled) and premixed from a commercial feed mill.	Austria	(Ertl et al., 2015b)

All by-products are manufactured for livestock, except those indicated in the description.

The bibliographic review allows setting that, in recent years, the interest in using some by-product feeds has decay due to other more interesting applications have been found, such as the case of agave, whose current focus is on the generation of bioenergy (Alemán-Nava et al., 2018). In addition, the use of fresh maguey to feed livestock is not recommended because of the high saponin content, which can induce severe diarrhea in farm animals (Pérez-Zavala et al., 2020). The current trend focuses on valorizing vegetable waste such as eggplant, broccoli, and cauliflower. According to Statista, between 2000 and 2020, the global production volume of vegetables increased significantly, from 752 Mt in 2000 to more than 1,268 Mt in 2020 (Shahbandeh, 2020). Fruits also play a significant role in animal feed; recent studies have found apple, banana, guava, grape, watermelon, and mango (el Barnossi et al., 2021; Wadhwa and Bakshi, 2013).

It is also noted that energy grains have received little attention in recent years; this is understandable given that beans and chickpeas do not have high AW and have a high energy potential for human consumption (Bampidis and Christodoulou, 2011). Some conventional feeds (soybean, maize, and wheat) have residues such as hulls, cobs, bran, husk, and straws, and their application in diets has been studied deeply (Sadh et al., 2018).

The main problem with using AW as by-product feeds is moisture. In most treatments, dehydration is done, which can be solar or thermal. However, silage is still the most widely used treatment. This treatment consists of preserving the by-products using fermentations that maintain them in a very similar state when fresh. The nutritive elements locked up in the plant cells and partially released at their death are used by lactic bacteria and transformed into lactic acid. These produce a decrease in pH and prevent the development of other harmful species (Yang et al., 2019).

By-product feeds used are complement conventional feed, and they did not exceed 20% of the diet on a dry basis. Although Mexican studies were prioritized, it was observed that there are few studies in the country focused on the identification of by-products in animal feed, considering that more than 70 Mt y^{-1} of residual agricultural biomass is generated in the country (Sánchez Cano, 2019).

The nutritional characteristics of AW and by-product feed in each agri-food supply chain were collected (Table S6 of the Annexes). AW compositions show that vegetables have high gross energy contents, but their high moisture content makes them seem less relevant. This deficiency could be compensated with treatments that are problematic regarding economic impact. Treatments and transportation costs could affect the viability of using by-product feeds in the diet; however, research on these issues is needed.

The highest energy contents are found in beans, rice, and chickpea. However, recent studies do not focus on incorporating this type of food because of the priority given to its use for human consumption. Fruits have a GE_m of around 50 MJ kg^{-1} DM and DM_m of less than 20%. By-product nutrient compositions show that treatment is a crucial factor. When crop food wastes are transformed into by-product feeds, the compositions change significantly, mainly the moisture, which in the case of the agricultural foods studied decreased by 60%. These treatments improve the nutritional components of by-product feeds and make them competitive with conventional feeds.

5.1.2 Milk and agro-industrial wastes availability

The availability of AW on the national scale is expressed in gross energy (Eq. 9) presented in Figure 10. The results consider the pre-harvest, post-harvest, and processing stages, according to Table S7, for the 29 strategic foods selected. The gross energy availability is in line with national agricultural production since the two regions with the highest gross energy potential have the highest agricultural production in the country (southeast and center-west regions with 76.5Mt y^{-1} and 74.2 Mt y^{-1}, respectively) (SIAP, 2022). Agricultural food production is concentrated in the center of the country, from Veracruz to Jalisco and in the northwest towards the state of Sinaloa. The Jenks natural breaks classification method (Jenks, 1967) was used to show the gross energy availability in 5 groups. The municipalities with the most significant GE potential are in the states of Sinaloa and Veracruz, with maize cobs and ensiled pineapple as the main by-product feeds. Sugarcane represents 88.9% of the national agro-industrial share (SIAP, 2022) and their AW generation is high. In this research, the interest is sugarcane top, however; its applicability in the animal industry is controversial, mainly because, at best, it is a poor-quality forage (Sruamsiri, 2007). The interval between 29.6M and 64.4M MJ y^{-1} includes 26 municipalities, 5 of which are in the state of Veracruz, where the production of sugar cane, pineapple, carrot, and lemon residues stands out.

Figure 11 shows the annual milk production for each municipality in Mexico. The lagoon in the north-eastern region and the Bajio in the central-western region are the two most important dairy basins in Mexico, accounting for 32 and 40% of national production, respectively. The municipality with the highest production is Gomez Palacio Durango, which belongs to the lagoon basin. However, in the top 10 municipalities with the highest production, four municipalities in the state of Jalisco belong to the Bajio basin. These results show that areas with high agricultural production are located on the coasts and in the south of the country, as Veracruz and Sinaloa are far from the areas with the highest milk production in the center and north. However, in the center of the country, milk production is significant, as is waste production.

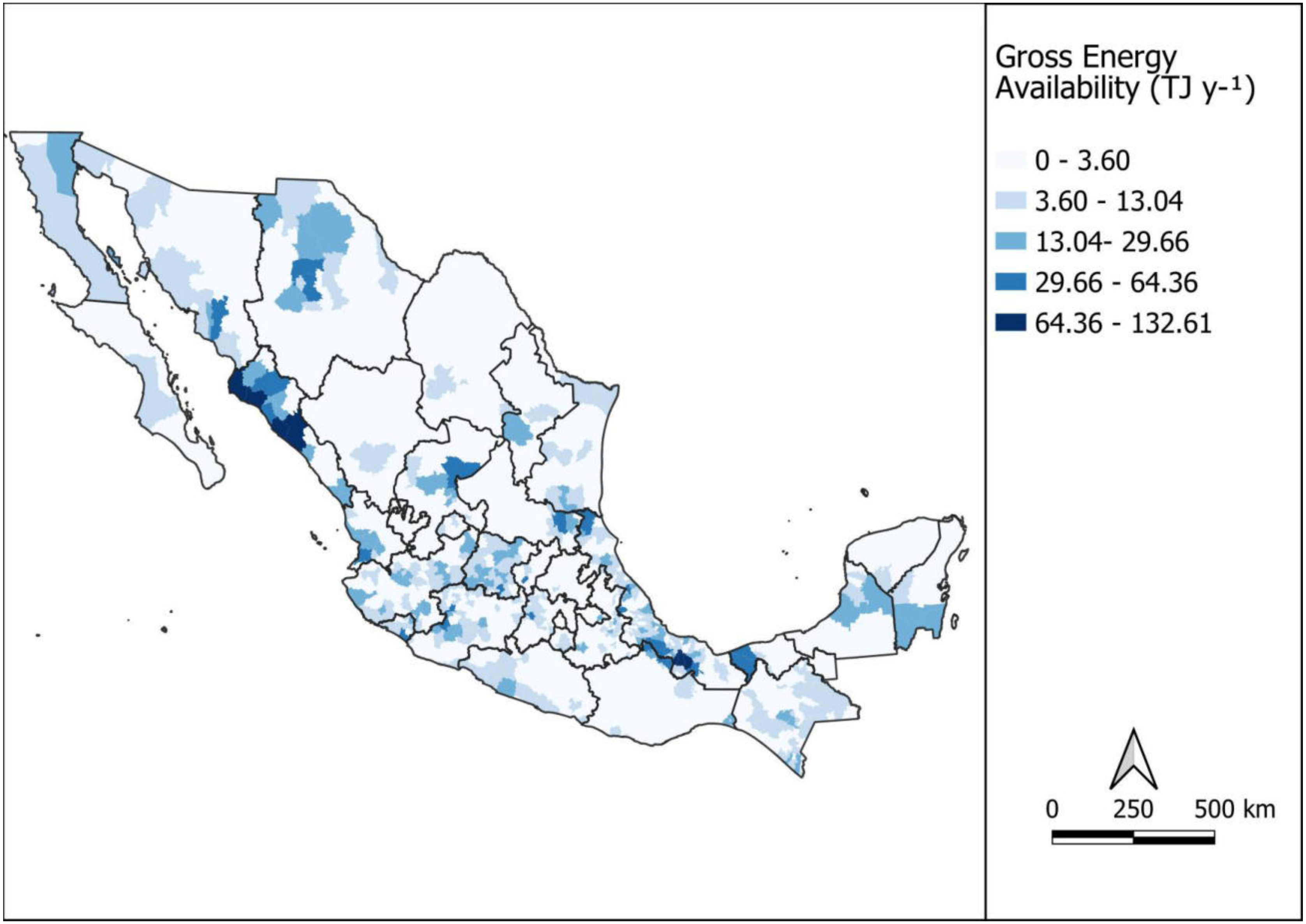

Figure 10. Availability of gross energy in strategic agro-industrial wastes of Mexico

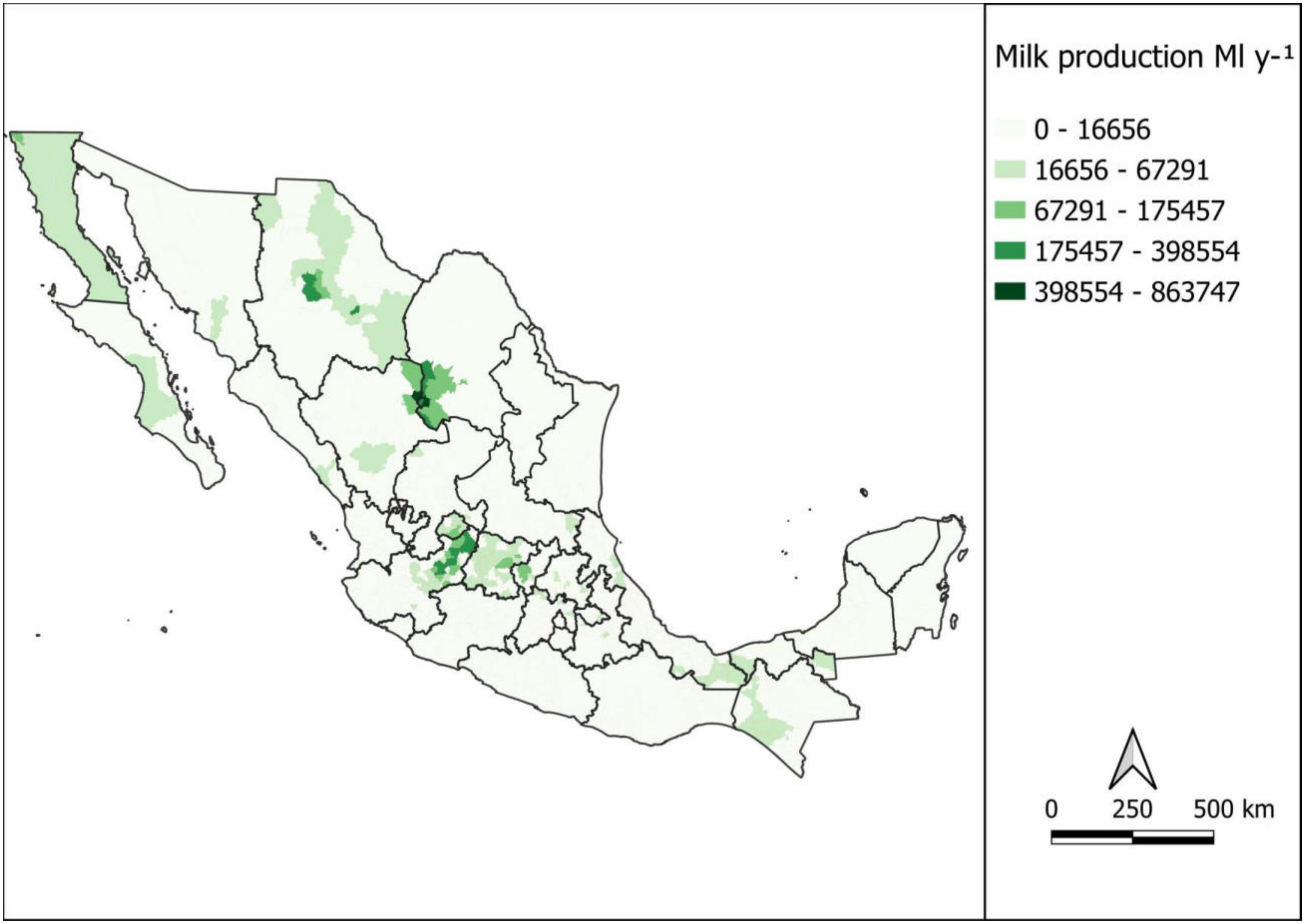

Figure 11. Milk production in Mexico by municipality

5.1.3 Proximity to dairy basins

Figure 12 presents the results of the correlation between ME and DP corresponding to the desirability function (Eq. 14). Table S10 of the Annexes presents the factors selected to evaluate Eq. 12 and Eq. 13 through a sensitivity analysis. The desirability function was categorized into five groups based on the pretty algorithm of the statistical package R. The municipalities identified with the highest potential for the use of AW are Nimiquipa Chihuahua and San Luis de la Paz Guanajuato, each belonging to the lagoon and the Bajio dairy basins, respectively.

The interval between 0.6 and 0.8 includes 50 municipalities, 14 of which belong to Guanajuato State. This state is key in agricultural production, and it is the fifth in milk production volume with 7% of national participation. The results are also crucial in Jalisco, the state with the highest production in the country (21%), which include eight municipalities. However, the most significant potential lies in the areas where agricultural production is most important.

Another interesting case is Sinaloa, the state with a high AW generation. According to Figure 10, only one municipality with the potential to implement the strategy proposed, due to the low milk production of this state, in part because the geographical conditions of the Sierra Madre Occidental Mountain range system discourage intensive production in dairy farming systems. Finally, the states of Coahuila, Durango, and Chihuahua, which account for 30% of national milk production, only present three municipalities with a high potential for AW use because agricultural production in the north of the country is not as important as in the center due to the presence of the Chihuahuan Desert in this zone.

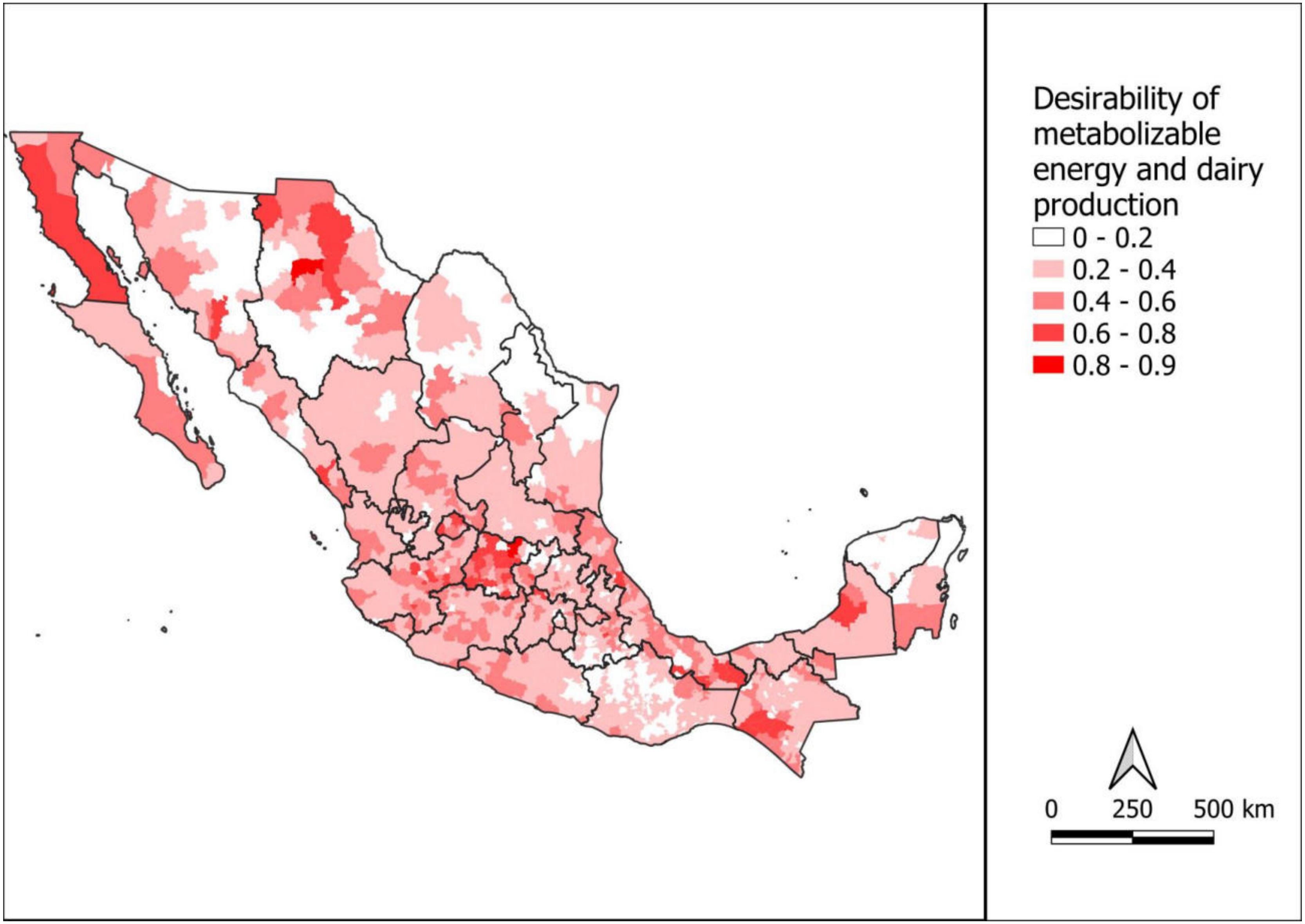

Figure 12. Desirability function between metabolizable energy and milk production in Mexico by municipality

There are 262 municipalities with a desirability between 0.4 and 0.6. These municipalities are scattered throughout the national territory. Therefore, no patterns indicate a high potential for implementing the proposed strategy. However, these municipalities should also be considered; they are geographically focused on the same dairy basins. The possibility of waste collection between nearby municipalities could be explored to facilitate the economic feasibility of implementing the use of these wastes in the dairy industry, because the centralized management of AW improve the economic feasibility (Babu et al., 2022). The remaining 2149 municipalities are in the range of GD values < 0.4. These municipalities are discarded to explore further the mitigation strategy proposed in this research.

In conclusion, 314 municipalities were identified with some potential use of AW in the dairy industry, of which 52 have the most significant potential for implementation. Table S11 of the Annexes presents the strategical foods according to the highest GD_k values. Maize, the most produced and consumed food in Mexico, is the crop with the most significant potential to use in the dairy industry for these municipalities. Other important crops are carrots, sugar cane, broccoli, and cotton. Broccoli stands out as a strategic vegetable in the Guanajuato region, with 15 municipalities with high broccoli production and GD_k > 0.6, encouraging researchers to investigate different strategies for utilizing this AW as the developed bellow in this research.

5.2 Environmental impact of livestock feed production systems (Tier 1)

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 inputs (Tables 7 and S9). 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 7). Foreground emissions related to crop production were a consequence of tillage practices (Table 8).

Table 7. Inventory of supplies to produce livestock feed per 1 t of feed on a fresh-matter basis.

Feature	Alfalfa hay	Maize silage	Rolled maize	Sorghum grain	Broccoli	Reference
Crop yield [t ha^{-1}]	80.00	47.85	10.23	6.09	16.17	(SIAP, 2020a)
Dry matter content [kg DM kg^{-1} FM]	0.903	0.442	0.881	0.886	0.093	(SIAP, 2020a)
Fertilizers (Baseline scenario)						(SAGARPA, 2017)
P_2O_5- Simple superphosphate [kg]	6.00	20.93	10.95	18.16	13.44	
N- urea [kg]	1.33	41.86	65.70	109	40.32	
K_2O- Potassium chloride [kg]	-	-	-	-	19.94	
Seeds [kg]	0.144	2.964	3.780	3.758	5564[a]	(SAGARPA, 2017)
Water consumption						
Irrigation requirement [m^3]	37.56	441	795.2	903	335.4	CROPWAT 8.0
Processing [m^3]	-	-	-	-	0.82	R. Covarrubias-Kaim, pers. comm.
Electricity						
Irrigation [kWh]	8.98	105.4	190.1	215.8	83.48	(Nemecek et al., 2014)
Processing [kWh]	-	-	-	-	3.33	R. Covarrubias-Kaim, pers. comm.
Fuels						
Diesel for agricultural activities [kg]	1.54	7.76	10.17	12.54	4.01	(West and Marland, 2002)
Diesel for silage [kg]	-	0.43	-	-	-	(González-García et al., 2016)
Diesel for transport [kg]	1.10	10.97	5.50	5.47	4.79	

[a]Number of seedlings

Table 8. Inventory of emissions from agricultural activity per 1 t of feed on a dry-matter basis (conventional feeds) or fresh-matter basis (broccoli).

Emission	**Alfalfa hay**	**Maize silage**	**Rolled maize**	**Sorghum grain**	**Broccoli**
Emissions to air					
Agricultural production					
Direct N_2O [kg N_2O][a]	6.22	10	2.86	2.68	9.21
Indirect N_2O volatilized [kg N_2O][a]	1.1E-03	3.3E-02	1.0E-01	8.7E-02	3.2E-02
Indirect N_2O leached [kg N_2O][a]	1.03	1.65	0.47	0.44	1.52
CO_2 for urea [kg CO_2][a]	0.98	30.74	48.38	80.23	29.64
Ammonia NH_3 [kg NH_3][b]	0.13	3.93	6.19	10.27	1.26
Nitric oxide NO [kg NO][b]	0.02	0.77	1.21	2.01	0.25
Nomethane volatile organic compounds [kg NMVOC][c]	1.2E-01	2.1E-01	6.2E-04	4.1E-02	2.3E-03
Particulate matter formation PM_{10} [kg PM_{10}][b]	0.042	0.160	0.188	0.105	0.076
Particulate matter formation $PM_{2.5}$ [kg $PM_{2.5}$][b]	0.023	0.023	0.027	0.034	0.01
Fuel emissions: Transport and agricultural production module[d]					
Volatile organic compounds [g VOC]	0.573	40.027	3.415	3.970	2.274
Carbon monoxide [g CO]	5.608	392.053	33.446	38.886	22.271
Nitrogen oxides [g NO_x]	5.147	359.847	30.699	35.692	20.441
Particulate matter formation [g PM_{10}]	0.974	68.095	5.809	6.754	3.868
Particulate matter formation [g $PM_{2.5}$]	0.448	31.289	2.669	3.103	1.777
Sulphur oxides [g SO_x]	0.063	4.382	0.374	0.435	0.210
Black carbon [g BC]	0.007	0.489	0.042	0.048	0.028
Organic Carbon, [g OC]	0.012	0.850	0.072	0.084	0.048
Methane [g CH_4]	0.460	32.177	2.745	3.192	1.828
Nitrous oxide [g N_2O]	0.017	1.187	0.101	0.118	0.067
Carbon dioxide [g CO_2]	8,988	628,317	53,602	62,320	30,045
Emissions to water					
Dissolved ammonia [kg NH_3][a]	0.089	2.810	4.422	7.334	2.710
Nitrate [kg NO_3^-][a]	0.326	10.248	16.128	26.746	9.882
Phosphate [kg PO_4^{3-}][e]	0.017	0.058	0.030	0.051	0.112
Pesticides, [g active ingredient][f]	4.8E-04	3.09E-03	4.8E-03	4.44E-03	6.88E-03

[a]Calculated using IPCC methodology (IPCC, 2019)

[b]Calculated using EEA methodology (EMEP/EEA, 2019a)

[c]Calculated using emission factors proposed of Grönroos et al. (2017)

[d]Calculated using the GREET model (GREET, 2018)

[e]PO_4^{3-} emissions calculated according to Zamudio-González et al. (2007)

[f]Calculated using *Pesticide Water Calculator* v 1.52

N_2O emissions from alfalfa production were more than twice those of grain production (6.22 and 2.86 kg N_2O t^{-1} DM, respectively); however, alfalfa required less N fertilizer (Table 7). 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 considering the Baseline scenario of fertilizer blends (Section 4.5.5). 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).

5.2.1 Impact assessment of conventional feeds and a by-product feed case

The strategic food production system considers broccoli florets as a product and broccoli stems as a co-product. $AFac_{BS}$ was 99.65% (equivalent to 425 USD t^{-1}) for broccoli and 0.35% (equivalent to 1.5 USD t^{-1}) for broccoli stems. This allocation factor considers the sold price out of the processing plant. If the transportation costs are included, $AFac_{BS}$ was 97.32% (equivalent to 425 USD t^{-1}) for broccoli and 2.68% (equivalent to 11.70 USD t^{-1}) for broccoli stems. The environmental impact of broccoli stems and conventional feeds is shown in terms of the endpoint single score indicator because it was used as the environmental optimization parameter in the model (Section 4.4.2). Indeed, the single score of broccoli stems was lower than that of conventional feeds (Figure 13). The environmental impact of feeds had an inverse relationship with crop yield; crops that needed more inputs (Table 7) had more significant environmental impacts (Figure 13). 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 (Figure 13).

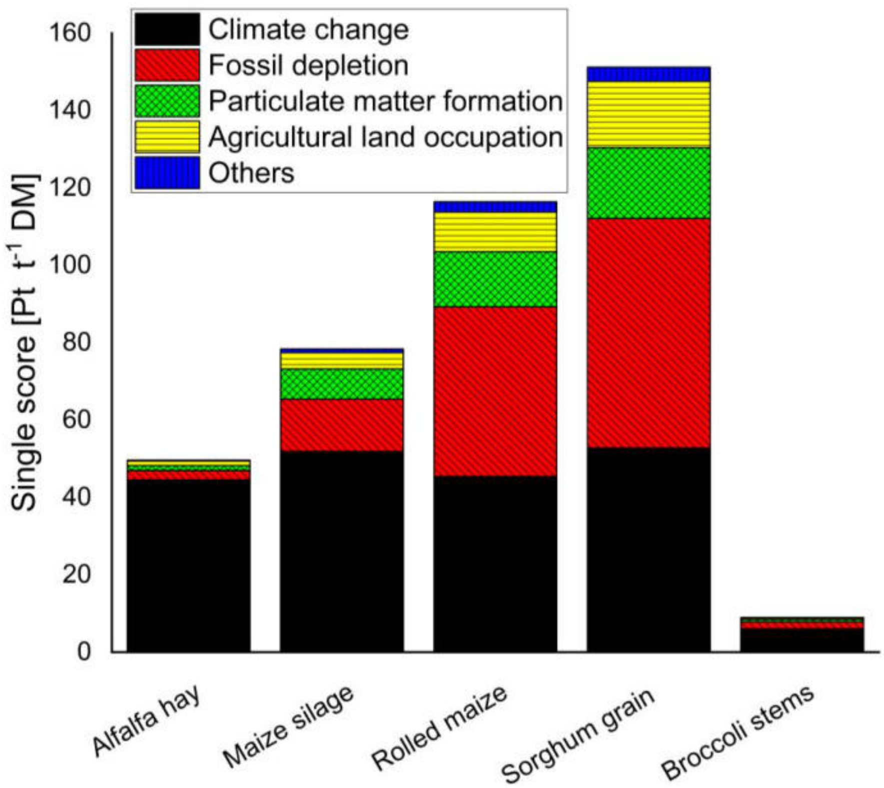

Figure 13. Contributions of midpoint impact indicators to the single score environmental impact of each feed per 1 t of dry matter basis according to the ReCiPe endpoint method (H). DM: on a dry matter basis.

5.2.2 Influence of fertilizer blends optimization

This study was carried out exclusively for the 4 conventional elements studied. The N–P–K optimized blend for each crop (specifying the type of fertilizer) and their manufacturing economic and environmental impacts for the three scenarios (*wi*=0, *wi*=50, *wi*=100) are shown, making a comparison with the Baseline scenario (Table 9). The optimization model selected only six of the twelve types of fertilizers available. Among the nitrogen fertilizers, priority was given to urea because of its higher nitrogen content (46%) and ammonium sulfate due to its lower environmental impact and lower price (Table 5). In phosphate fertilizers, preference was assigned to fertilizers with high P_2O_5 content and nitrogen. Potassium chloride was chosen for potassium fertilizers because of its lower environmental impact.

Table 9. N–P–K blends and their effect in livestock feed production (Tier 1) for optimized and non-optimized scenarios. Results are presented per ton of each crop on a dry matter basis.

Feeds	Scenario	Blends			Single score	Fossil depletion	Particulate matter formation	Climate change	Economic impact
		N	P_2O_5	K_2O	[Pt t^{-1}]	[kg oil eq t^{-1}]	[kg oil eq t^{-1}]	[kg CO_2 eq t^{-1}]	[USD t^{-1}]
Alfalfa	Baseline	U	TSP	-	69.41	6.14	0.118	1967.7	3.92
	Planet	DAP	TSP	-	69.10	5.35	0.108	1965.1	3.60
	Viable	DAP	MAP/TSP	-	69.03	5.20	0.106	1964.4	3.67
	Profit	MAP	TSP	-	68.96	5.04	0.103	1963.8	3.75
Forage maize	Baseline	U	TSP	PC	65.81	27.99	0.766	1621.2	10.71
	Planet	AS	DAP	PC	62.85	18.16	0.687	1609.1	8.95
	Viable	U	AS/DAP	PC	62.95	19.25	0.690	1604.5	10.07
	Profit	U	MAP	PC	63.28	20.96	0.700	1601.8	11.19
Corn grain	Baseline	U	TSP	PC	67.39	76.08	2.226	1131.0	25.22
	Planet	AS	DAP	PC	57.96	43.30	2.041	1085.7	19.06
	Viable	U	AS/DAP	PC	58.23	46.23	2.051	1073.5	22.08
	Profit	U	MAP	PC	58.88	50.20	2.070	1064.4	25.10
Sorghum grain	Baseline	U	TSP	PC	89.77	126.37	3.709	1229.4	42.06
	Planet	AS	MAP	PC	78.78	84.72	3.465	1204.5	35.77
	Viable	AS	AS/DAP	PC	79.36	90.93	3.486	1178.6	42.17
	Profit	AS	MAP	PC	80.43	98.53	3.519	1156.8	48.57

U: Urea. **AS**: Ammonium sulfate. **DAP**: Diammonium phosphate. **MAP**: Monoammonium phosphate. **TSP**: Triple superphosphate. **PC**: Potassium chloride.

For illustrative purposes and to better understand the environmental profile of the fertilizers prioritized in the optimization model of N–P–K blends, Figure 14 presents the distribution of the ReCiPe midpoint indicators, using as a basis 1 kg of the components (N, P_2O_5, and K_2O). In the case of nitrogen fertilizers, the Baseline scenario predominantly uses urea, while the optimized scenarios prioritize ammonium sulfate, which has lower environmental impacts and a lower cost. The similar phenomenon occurs with phosphate fertilizers since the Baseline scenario uses triple superphosphate, whose environmental impact is 4.1 and 8.6% higher than monoammonium phosphate, and diammonium phosphate, respectively.

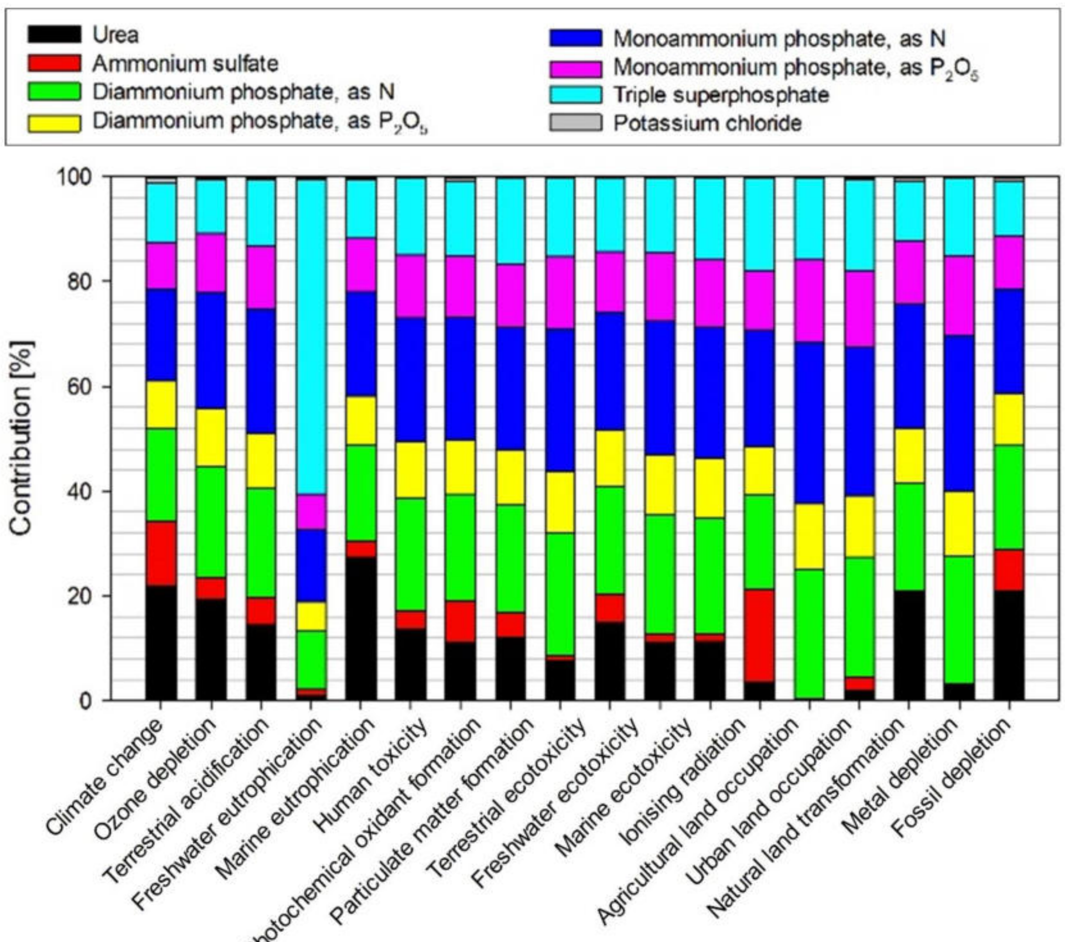

Figure 14. Distribution of the environmental impact and cost of fertilizers selected by the model using the midpoint indicators of ReCiPe method.

Figure 15 depicts the environmental (as measured by the endpoint indicator single score) and economic impact for the study scenarios. A noticeable difference between crops can be attributed to the crop yields, with alfalfa producing 72.2 t ha^{-1} and sorghum grain yielding 5.4 t ha^{-1}. Specifically, in the livestock feed production module, crops with low yields require more supplies than high-yield crops on a mass basis. This behavior explains why alfalfa is the most significant livestock feed in the country, accounting for more than 27% of the national market participation (3.6 Mt yr^{-1}) (SIAP, 2020a).

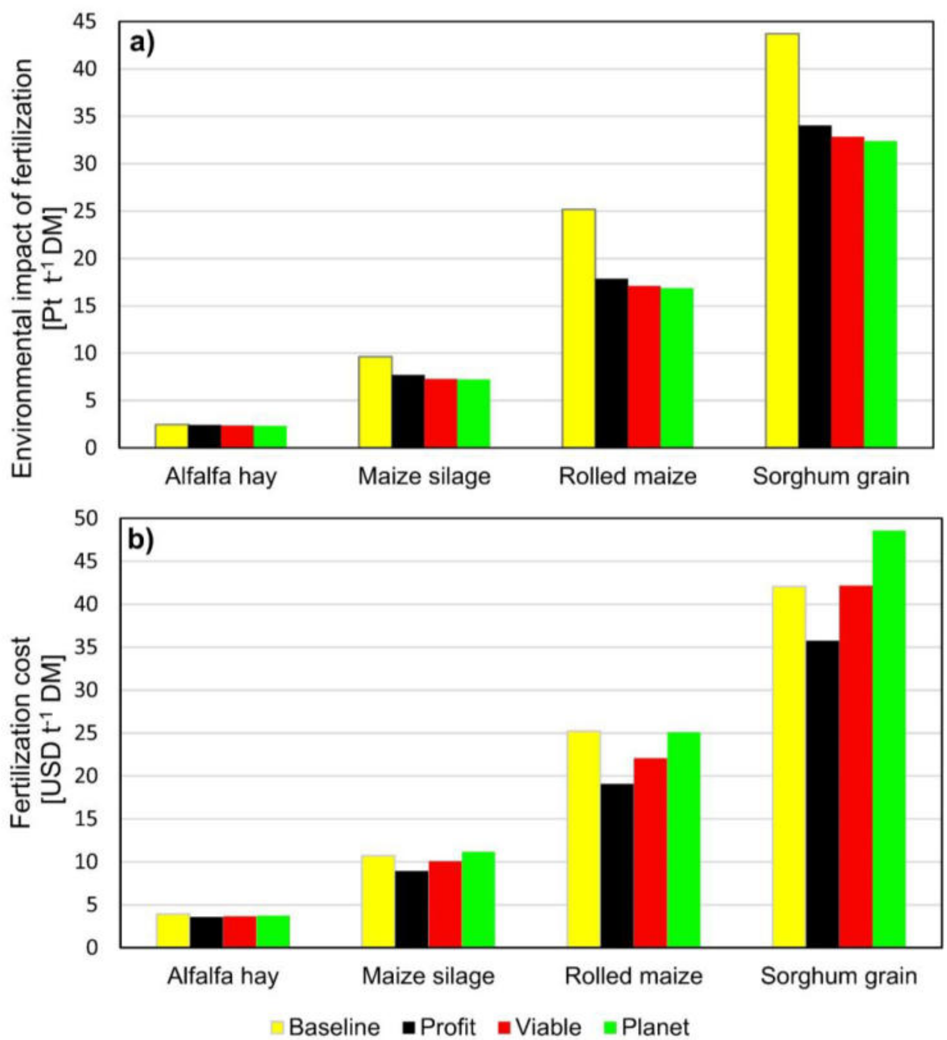

Figure 15. Results of the optimization model for economic (Profit, w_i=0), intermediate (Viable, w_i=50), and environmental (Planet, w_i=100) scenarios and the Baseline (a) environmental results $Z_2(y)$, (b) economic results $Z_1(x)$. DM: On a dry matter basis

Compared to the Baseline scenario in the environmental results, all scenarios demonstrated a reduction (Figure 15a). Notably, there is no significant reduction in environmental impact between the three scenarios —Profit, Viable, and Planet—; however, mitigation is predominant in the Baseline scenario, indicating that the fertilizer strategies proposed in the study region have a high environmental impact. Grains are the crops with the most significant potential for reducing environmental effects; for example, in the Planet scenario, sorghum can reduce GHG by up to 24.9 kg CO_2 eq t^{-1}. Crops focused on foliage production, on the other hand, demonstrate a lower potential for environmental mitigation due to their large yields per hectare. Because of its nature as a legume that fixes nitrogen in the soil and has minimal N-fertilizer requirements, alfalfa does not show considerable reductions.

Figure 15b illustrates economic results that are antagonistic to the environment. There is a significant difference between the three optimized scenarios —Profit, Viable, and Planet— in this case, but not all demonstrate marginal reductions compared to the Baseline scenario. In both Viable and Planet scenarios, the cost of sorghum grain rises. A comparison between Profit and Planet Scenarios reveals the optimization is more significant in economic terms; reducing the environmental impact by 1% would raise fertilizer costs by 5.5%.

In Table 9, diammonium phosphate was the fertilizer most recommended by the model because it provides N and P_2O_5 in a proportion that allows for supplementation with other fertilizers (18–46–0), is inexpensive, and has a low environmental impact (Table 5). Scenarios Planet and Viable had higher costs than the Baseline, suggesting that scenario Profit would be the most appropriate, reducing the environmental impact of fertilization at the lowest possible cost.

Table 9 shows that the reductions in economic terms are significant for the study region. For sorghum grain, for example, whose production in Guanajuato is 0.76 Mt y^{-1}, the reduction in fertilizer costs between the Baseline and scenario Profit is 15%, equivalent to 4.8 M USD y^{-1} (SADER-SIAP, 2019). However, potential savings are most evident in corn grain (10.6 M USD y^{-1}) due to the high regional production (3.85 Mt y^{-1}).

5.3 Dairy cattle diet optimization (Tier 2)

5.3.1 Influence of broccoli stems on dairy cattle diet

The optimization model formulated the OCD and ODBS for the farm's herd (Figure 16, Tables S13 and S14 of the Annexes) 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 (Figure 16). 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, broccoli stems 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 broccoli stems, the percentage of high-energy feeds (sorghum grain and rolled maize) tends to increase.

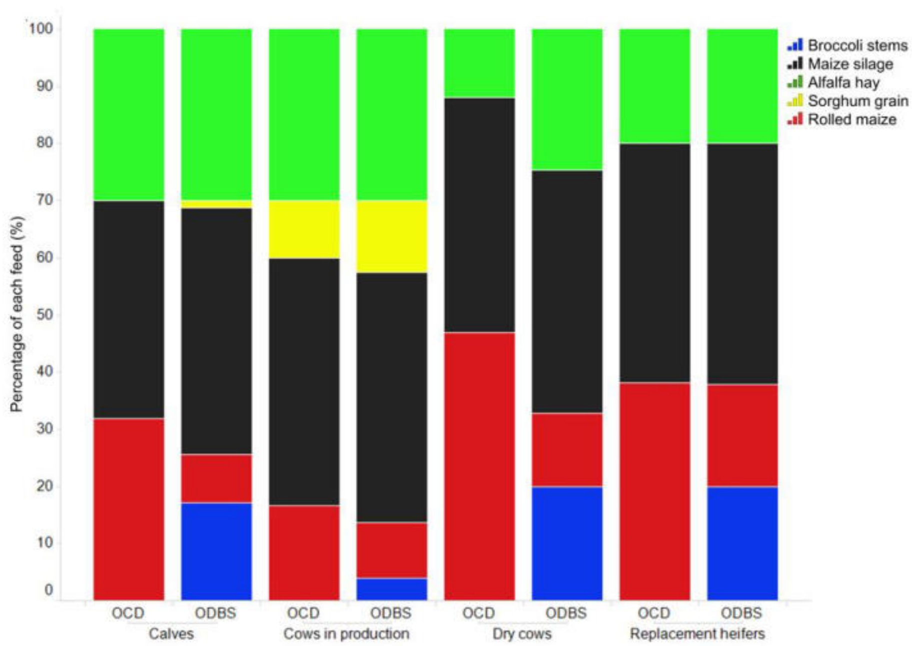

Figure 16. Feeds distribution in the optimized conventional diet (OCD) and the optimized diet with broccoli stems (ODBS) by livestock categories.

The model constraint parameters varied among the four categories of livestock used in the study (Table S13 of the Annexes). 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 broccoli stems 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 broccoli stems.

5.3.2 Influence of fertilizer blends on dairy cattle diet

Figure 17 and Table S15 show the Tier 2 results. The figure illustrates the economic and environmental marginal impacts for endpoint indicator single score (Figure 17a), and midpoint indicators fossil depletion (Figure 17b), particulate matter formation (Figure 17c), and climatic change (Figure 17d) in comparison to the Baseline scenario. The figure illustrates the economic and environmental marginal impacts concerning Baseline scenario for endpoint indicator single score (Figure 17a), and midpoint indicators fossil depletion (Figure 17b), particulate matter formation (Figure 17c), and climate change (Figure 17d).

Figure 17a shows that any optimization approach (Profit, Viable, or Planet) results in balanced environmental mitigation, but at different costs. When the environmental impact of optimizing the N–P–K blend is prioritized (Planet scenario), mitigation costs are positive, i.e., more expensive fertilizers are required to achieve environmental mitigation that is only meaningful for the climate change indicator with an investment of 0.006 USD kg^{-1} CO_2eq. The Profit and Viable approaches, on the other hand, demonstrate potential cost savings while mitigating environmental impacts. Surprisingly, the Profit scenario has a 15% lower environmental mitigation potential than the Planet scenario (3.63 Pt t_{diet}^{-1}) but higher cost savings (-0.85 USD Pt^{-1}) for the same scenario.

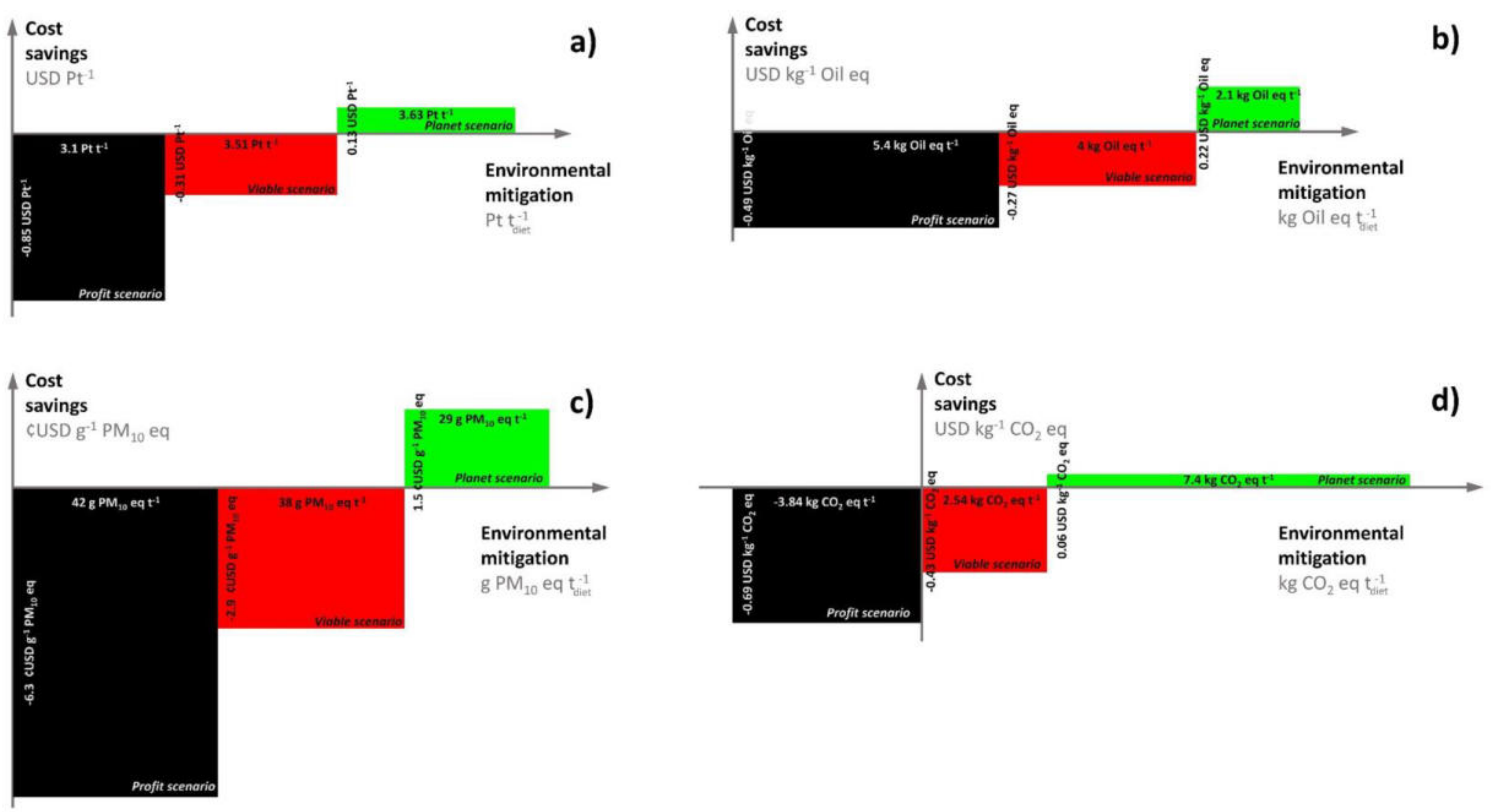

Figure 17. Marginal impacts of the N–P–K blends scenarios in the dairy cattle diet. a) Single score indicator. b) Fossil depletion indicator. c) Particulate matter indicator. d) Climate change indicator

Fossil depletion (Figure 17b) is one of the impacts with the highest incidence among midpoint indicators. Economic minimization, in turn, has the greatest potential for environmental mitigation in this indicator. The Profit scenario has 2.5 and 3.2 times the environmental and economic mitigation potential of the Planet scenario, indicating that the fertilizers with the lowest economic impact – which the model prioritized in the N–P–K blend optimization (Table 9) – also have the lowest environmental impacts in their production (Table 5). The particulate matter formation indicator shows a qualitatively similar pattern, although with smaller cost and environmental savings potential (Figure 17c).

The results of the climate change indicator (Figure 17d) show different behavior than the other indicators. The Planet scenario results in diets with a high GHG mitigation potential at a low cost, as contrasted to the Profit scenario, which sacrifices environmental mitigation to avoid cost savings, as it provides increases of 3.84 USD kg^{-1} CO_2 eq for the Baseline scenario (Table S16). The Profit scenario substitutes ammonium sulfate for urea, resulting in a 33% cheaper fertilizer but 21.9% higher GHG (Table 5, Table S16). When using the farm model proposed, the scenarios Viable and Profit bring savings of 4,334 USD y^{-1} and 10,520 USD y^{-1}, respectively, while the scenario Planet results in a cost increase of 1,853 USD y^{-1}. The model corresponds to a farm with 1,000 heads, 520 dairy cows in production, and consumption of 4,043 t_{diet} y^{-1} on a dry matter basis in one year of operation (Table S13).

5.4 Environmental assessment of the dairy farming system (Tier 3)

5.4.1 Influence of broccoli stems on the life cycle of milk production

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} FU_{DPS}^{-1}, formed by 68% for climate change (including damage to human health and ecosystems), 19% for fossil depletion, 9% for particulate matter formation, and 4% for agricultural land occupation. This trend is reflected in Figure 18 because the emissions of Table S12 of the Annexes.

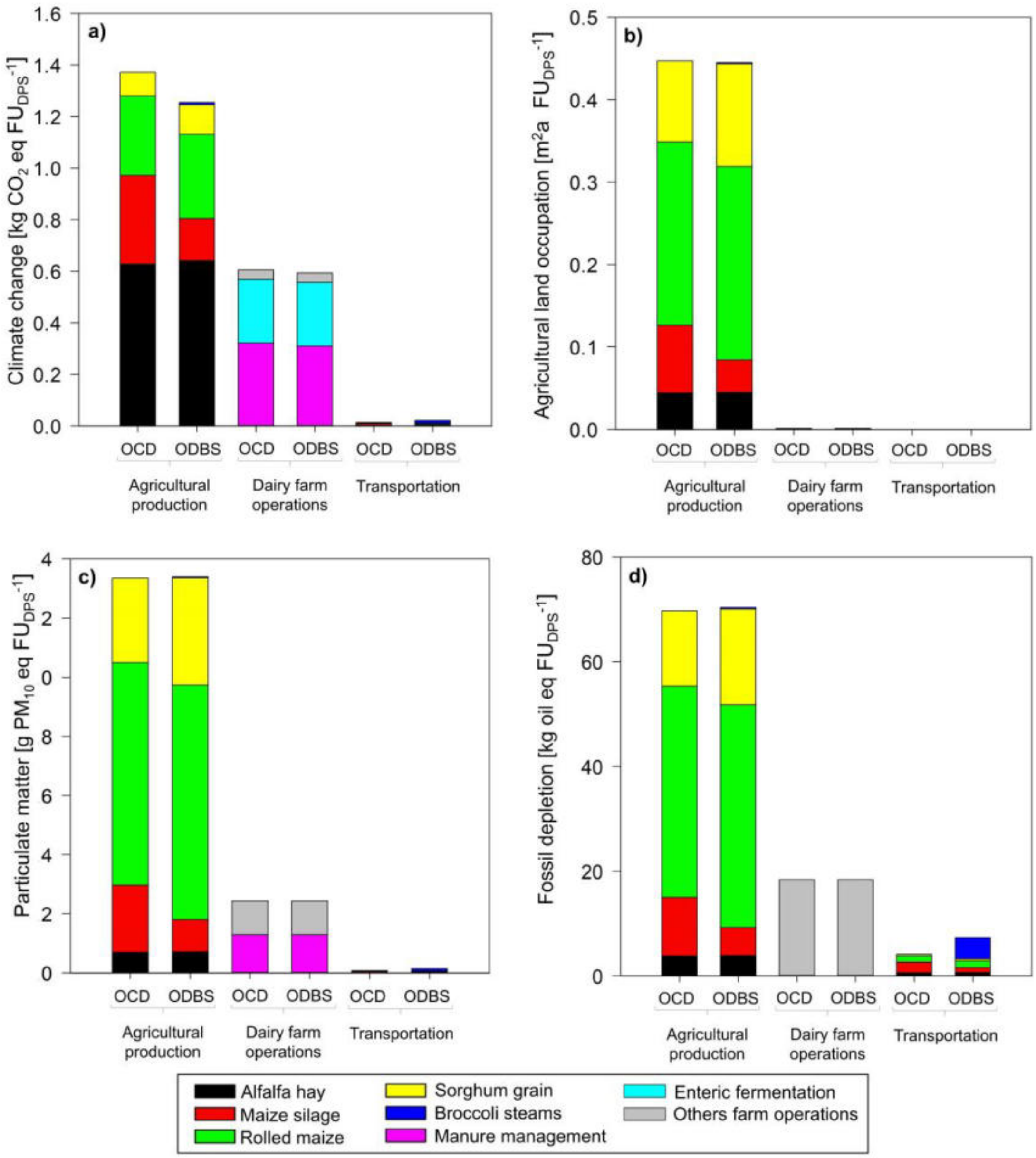

Figure 18. Midpoint impact indicators of the dairy farming system with the optimized conventional diet (OCD) and optimized diet with broccoli stems as agro-industrial waste (ODBS): (a) climate change, (b) agricultural land occupation, (c) particulate matter formation, and (d) fossil depletion. FU_{DPS}: functional unit of the dairy farming system.

Slight variations between the OCD and ODBS (summarized in Table S12 of the Annexes) in the foreground emission inventories of the dairy farm operation module influenced the midpoint indicator of the dairy farming system (Figure 18). 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%) (Figure 18a). 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 S14 of the Annexes), 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 (Figure 18b). 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, Figure 16) meant it has had less impact in the midpoint indicators. Agricultural land occupation was 0.4% (0.002 m^2a FU_{DPS}^{-1}), which was lower in the ODBS than in the OCD, mainly due to the replacement of maize silage with broccoli stems.

PM is mainly formed by emissions of NH_3 from fertilization, which react in the atmosphere with compounds such as sulfuric acid and water to form PM. PM formation was 0.7% lower (0.01 g PM_{10} eq FU_{DPS}^{-1}) in the ODBS than in the OCD (Table S17 of the Annexes) 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 g oil eq FU_{DPS}^{-1}) in the ODBS than in OCD because of the high moisture content of broccoli stems, which requires more diesel for transport (Table S17 of the Annexes). 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 be sufficient for decision-making (Kägi et al., 2016).

A comparison of midpoint indicators between this work and milk production LCA studies results are summarized in Table S18 of the Annexes. The notable variations may be due to differences in the methodology and production strategies. Although the LCA methodology is standardized under ISO 14040-44, 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.

For the endpoint indicator of milk and livestock production in the dairy farming system, 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 11 and S17 of the Annexes). 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.

Table 10. The environmental damage indicators of the milk and livestock in the dairy farming system, according to ReCiPe endpoint method (H).

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

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 dairy farming system 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 broccoli stems.

5.4.2 Sensitivity analysis: Influence of broccoli stems price on environmental impacts of milk

When the broccoli stems price reached 19.28 USD t^{-1} FM, the single score [mPt FU_{DPS}^{-1}] of the ODBS increased by 2.41% (Figure 19), equivalent to increasing the single score of the broccoli stems 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 (Figure 19). Under these conditions, the use of broccoli stems would no longer be environmentally or economically viable. According to the Mexican Institute of Transport, the average transport cost is 0.17 USD km^{-1}. If broccoli stems are transported for more than 104 km, environmental viability is affected.

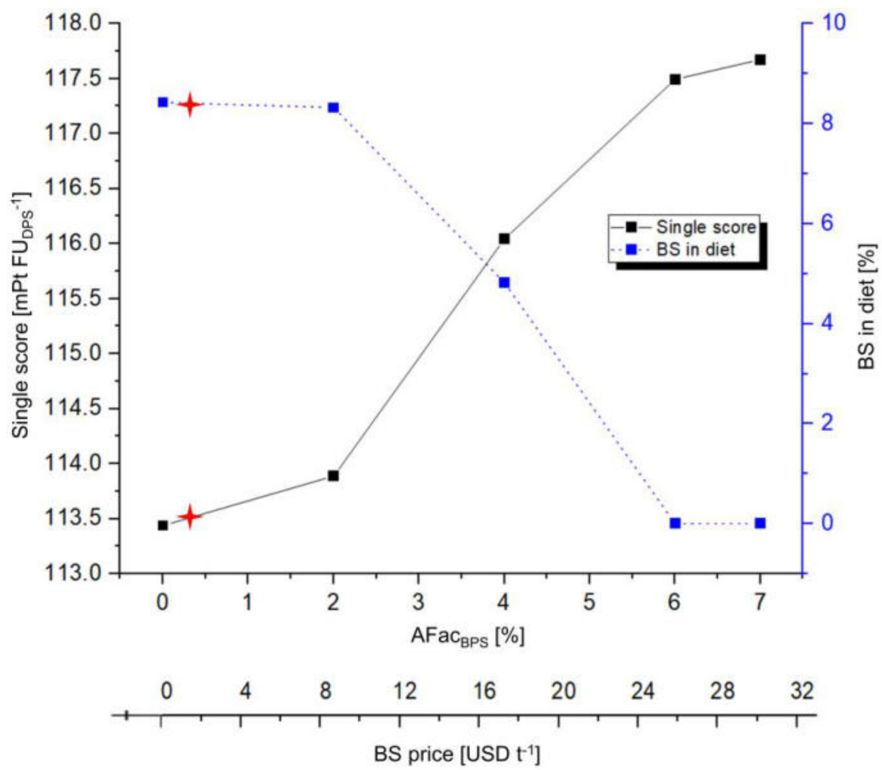

Figure 19. Variation of the single score indicator of the dairy farming system (DPS) concerning broccoli stems (BS) price and the allocation factor of the broccoli production system ($AFac_{BPS}$). Red stars ($AFac_{BPS}$=0.35%) identify the optimized diet with BS (ODBS).

The optimization model allowed the incorporation of the by-product 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 broccoli stems is considered as waste, that is, its price is 0 USD t^{-1} (Table S19 of the Annexes). Therefore, the practical scope of the by-product application is limited. It is also noticeable that $AFac_{BPS}$ is greater than 6% when broccoli stems are 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 AW depends on market demand. In Guanajuato, some of these wastes have experienced demand and valorization: biscuit, bakery, and tortilla waste, and previously burned corn crop residues are now marketed for livestock consumption in areas that have experienced droughts. 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.

5.4.3 Influence of fertilizer blends on the life cycle of milk production

The effect of the N–P–K blend scenarios on the FU_{DPS} is shown in Table 10 through the midpoint, endpoint, and economic indicators. A considerable amount of the table information is undiscussed; however, it was decided to do it this way so it may be helpful to the reader. For all scenarios, the contribution to the single score indicator for climate change (human health and ecosystems) is 69%, fossil depletion is 18%, particulate matter formation 9%, and the remaining 4% is distributed among the rest of the indicators. Table 10 shows that optimizing environmental impacts using the single score indicator represent an efficient alternative since most environmental indicators are reduced.

Table 11. Variation of environmental and economic indicators of the optimized scenarios respect the Baseline scenario. FU_{DPS}: Functional unit of 1 kg of fat-and-protein-corrected milk.

			Variation respect Baseline scenario (%)		
Impact category	**Unit, FU_{DPS}^{-1}**	**Baseline**	**Planet**	**Viable**	**Profit**
Midpoint indicators					
Climate change	kg CO_2 eq	1.99	1.1	0.9	0.7
Fossil depletion	kg oil eq	0.093	9.0	10.3	11.5
Particulate matter formation	kg PM_{10} eq	1.59×10^{-3}	3.7	4.0	4.2
Terrestrial acidification	kg SO_2 eq	6.16×10^{-3}	2.4	2.9	3.3
Ozone depletion	kg CFC-11 eq	3.31×10^{-8}	8.0	11.9	15.8
Marine eutrophication	kg N eq	2.62×10^{-3}	0.2	0.4	0.6
Freshwater eutrophication	kg P eq	5.44×10^{-5}	15.9	14.4	13.0
Human toxicity	kg 1,4-DB eq	1.37×10^{-2}	17.2	22.7	28.3
Photochemical oxidant formation	kg NMVOC	3.77×10^{-3}	1.2	0.6	0.1
Terrestrial ecotoxicity	kg 1,4-DB eq	3.13×10^{-5}	11.3	17.0	23.3
Freshwater ecotoxicity	kg 1,4-DB eq	3.55×10^{-4}	14.8	16.9	18.9
Marine ecotoxicity	kg 1,4-DB eq	2.83×10^{-4}	16.2	24.6	33.4
Agricultural land occupation	m^2a	0.448	0.1	-0.1	-0.3
Ionizing radiation	kg U235 eq	1.54×10^{-2}	5.6	8.5	11.5
Urban land occupation	m^2a	3.68×10^{-3}	-0.5	-5.6	-6.8
Natural land transformation	m^2	4.02×10^{-6}	6.3	1.0	-3.7
Water depletion	m^3	0.235	0.5	1.0	1.5
Metal depletion	kg Fe eq	1.20×10^{-3}	7.7	12.7	19.4
Endpoint indicators					
Single score	mPt	100.2	2.8	3.0	3.0
Damage to human health	mPt	70.6	1.5	1.4	1.2
Damage to ecosystems	mPt	10.8	0.7	0.5	0.3
Damage to resources	mPt	18.9	9.0	10.3	11.5
Economic indicators					
N–P–K cost	¢USD	1.19	-3.4	7.6	19.0

It shows that the reductions in GHG of the optimized scenarios are insignificant compared to the Baseline scenario, at around 1%. The opposite is precise for the indicators of fossil depletion and particulate matter formation, where reductions can be as high as 11.5% and 4.2%, respectively. These two indicators are associated with the same causes because reducing fossil fuels leads to reducing SO_X, NO_X, and $PM_{2.5}$ emissions. It is essential to highlight that despite representing a key aspect in the environmental profile of milk production, the depletion of fossil resources retains little relevance for general perception. Likewise, the effects of gas emissions with particulate matter formation potential cannot be considered global since they depend on the local climatic conditions where they are emitted. These aspects are not addressed in this work, but they represent areas of opportunity for the scientific community.

The endpoint indicator damage to human health is mainly associated with the indicators of climate change and particulate matter formation. However, while the variation percentages in the three scenarios studied are low (Table 10), the overall effect is primarily due to the high contribution of damage to human health indicator to the single score. If the variation percentages are positive, it means that there is a mitigation of the environmental impact. The most considerable mitigation percentages are found in the endpoint damage to resources indicator, nearly equal to the fossil depletion indicator (since it contributes 96% to the endpoint indicator).

According to the National Confederation of Livestock Organizations, milk production in Guanajuato is 0.9 Mt y^{-1} (7% of national production), while the cost of milk production in Mexico is 0.42 USD FU_{DPS}^{-1}, 15.6% is associated with fertilization. If scenario Profit were implemented in this region, the potential savings in fertilizer costs would reach 29.6M USD y^{-1}. This saving is associated with 11,536 t CO_2 eq y^{-1}, 9,286 t oil eq y^{-1}, and 57.9 t $PM_{2.5}$ eq y^{-1}, for climate change, fossil depletion, and particulate matter formation, respectively.

5.4.4 Sensitivity analysis of allocation methods

Among the allocation methods, Case I had the lowest $AFac_{DPS}$ (Table 13) 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 CO_2 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 13). 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).

Table 12. Environmental impact indicators as a function of the environmental burden allocation cases.

Cases	Environmental impact indicator	Co-products	
		Milk[a]	Livestock[b]
Case I: Economic allocation of this study (ODBS scenario)	**$AFac_{DPS}$ (%)**	**85.6**	**14.4**
	Climate change (kg CO_2 eq)	1.870	0.315
	Agricultural land occupation (m^2a)	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: Economic allocation according to (Thoma et al., 2013)	**$AFac_{DPS}$ (%)**	**90.4**	**9.6**
	Climate change (kg CO_2 eq)	1.975	0.210
	Agricultural land occupation (m^2a)	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: Protein-based allocation according to (Thoma et al., 2013)	**$AFac_{DPS}$ (%)**	**91.6**	**8.4**
	Climate change (kg CO_2 eq)	2.001	0.183
	Agricultural land occupation (m^2a)	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 farming system.

The environmental impact indicators are presented per: [a]kg of fat and portein corrected milk and [b]kg of live weight.

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 AW (Avilés Ríos et al., 2009).

5.3 Issues and challenges

The present study presented 29 strategic foods. The model proposed for AW incorporation in cattle diet could be used to evaluate the environmental performance of these by-product feeds. The challenge is to evaluate the environmental impact of by-product feeds from food supply chains. This research presents a study case; however, this is just a proposal. Other methods could be implemented to calculate the environmental impact of by-product feeds. If LCA is chosen, the allocation method is a relevant issue; according to the case different method could be implemented (Ijassi et al., 2021). Background data from foods could be used; however, the treatment to transform AW into by-product feed should be evaluated particularly.

The diet model proposed could also optimize the cost of the dairy diet, changing the parameter *vi* to an economic indicator of i-th feed or by-product in Eq. 15. This indicator could be calculated with the life cycle cost method, as presented by Kim et al. (2011), the transportation cost is a relevant parameter that could limit the economic and environmental viability of the use of AW in dairy diets. The two optimization models proposed have a similar structure. An environmental-economic optimization could be done if the results of the diet model are parametrized as the model of fertilizer blends (Section 4.5.4). Future research could include a life-cycle costing approach and model restructuring to define the economic viability of using AW in the dairy diet. The geographic environmental assessment would also be essential, as having the specific environmental impact for each by-product feed would allow the environmental impact of the potential generation of strategic wastes to be represented. The desirability function can incorporate more variables so that the interaction between milk production, the generation of strategic AW, and their environmental impacts can be represented geographically.

The study of identification and location of AW in the dairy industry considered five technical aspects to consider an AW as strategic. This is the first step to develop a market around AW. This research collected a database of the nutritional composition of AW and by-product feeds, developed a regional quantification of the availability of wastes considering the pre-harvest, post-harvest, and processing stages, and identified the synergy between the waste generation and the milk production. However, two fundamental aspects should be considered: the environmental impact and the economic cost. Although the nutritional contributions can indicate the economic viability, precisely knowing the cost of treating these by-product feeds will be fundamental to confirm them as strategic. Although the environmental impact of AW tends to be much lower than conventional feed, this depends on the treatment used, for example, dehydration processes consume high levels of energy, which could hinder the environmental viability of the process. Additionally, the moisture of the AW increases the costs and environmental impacts of the transportation stage.

As presented in this research, a circular economy approach could benefit the dairy and agricultural production supply chains. Using these by-product feeds could reduce the consumption of conventional feeds, decrease the water stress caused by intensive agriculture, reduce inputs such as fertilizers and pesticides in the agricultural production process, and reduce damage pathways to the environment such as agricultural land use and deforestation.

If all the broccoli stems produced in the state of Guanajuato were 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 CO_2 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 reduce its GHG emissions from 93 to 86 Mt of CO_2 eq by 2030 (Hidalgo Gallardo et al., 2017). Using broccoli stems as a complementary feed could fulfill up to 8% of this goal. It could also decrease agricultural land occupation by 3,327 ha by reducing the land required for feed such as maize silage, which uses 6,904 ha in Guanajuato (INEGI, 2017).

This study did not consider the effects of broccoli stems use on milk or livestock quality. This point is essential because broccoli stems could influence the organoleptic profile of milk. For cows in production, it has been demonstrated that feed substitution up to 20% with broccoli stems does not result in changes in milk quality and production (Yi et al., 2015).

To place the fertilizer blends optimization in the national context, if entire dairy production in Guanajuato State adopts the fertilizer optimization strategy, it could be reduced by up to 0.15 Mt CO_2 eq between the years 2022–2030, which represents 2.2% of the GHG reduction commitment in the agricultural sector under Paris COP21 agreement. A simple issue in the life cycle of raw milk production, such as optimizing N–P–K blends in livestock feed production, can have potential economic and environmental benefits. This aspect is critical in countries like Mexico, where government budgets dedicated to mitigating environmental impacts are limited; only 1.1% of the government budget is spent on climate change adaptation and mitigation strategies (Fonseca and Grados, 2021). The potential savings in fertilizer costs could be used to incentivize other strategies to reduce environmental impacts, such as exploring more efficient fertilization strategies, incorporating AW into the dairy cattle diet, implementing anaerobic digestion as an alternative for manure management, or improving dairy herd modernization.

However, there are several challenges and issues to consider while implementing the strategies described in this study:

1. The market of by-product feeds is not developed their treatments keeps unknown for stakeholders. Administrative decision-makers (government and private sector) and farmers has weak communication making it difficult to transfer knowledge and strategies. An alternative to making this communication more efficient is through livestock associations.
2. The use of broccoli stems as by-product feeds should explore the possibility of treat the moisture content because the transportation cost limits the implementation.
3. Changes in fertilizer use at the regional/national scale would indirectly impact supply chains that interact with the dairy cattle industry, such as the Mexican fertilizer market. In order to study and evaluate these interactions, a consequential approach must be used in the life cycle inventory (Ijassi et al., 2021).
4. Some data quality requirements must be met to implement the proposed model. A soil study specific to the area is necessary to determine realistic fertilizer requirements. Fertilizers should be specified based on their region availability and transportation costs.
5. The LCA model considered simplified analysis by using deterministic data, excluding uncertainties in inputs and outputs of life cycle inventory. Stochastic analysis should be included to improve decision-making, which could be done using Monte-Carlo and Latin Hypercube Sampling strategies (Loya-González et al., 2019). These methods require knowledge of the probability distribution of critical variables in the life cycle (e.g., crop yields, fertilizers, energy, water, fuel consumptions, and elementary flow emissions). This is an opportunity area for future research.

This research allows us to reflect on some broader considerations as a basis for achieving cleaner production. With the conditions of the study region, favoring intensive agriculture allows higher yields and lower impacts. However, using fossil-based fertilizer prevents reducing GHG emissions; alternatives should continue to be explored. Milk is still an inefficient way to produce protein for humans; other alternatives should continue to be explored, especially in a country like Mexico, where there is no environmental culture on these relevant issues.

5.4 Achievements

The present research has resulted in three scientific articles according to Figure 2. A manuscript entitled "Turning food loss and waste into animal feed: a spatial inventory of potential generation of agro-industrial wastes for livestock feed" has been submitted to peer review. The article aims to inventory the localized generation of agro-industrial wastes with potential for use in dairy cattle feed in Mexico, using a spatial approach. It is aligned with objective 1 of the thesis.

The article "The use of broccoli agro-industrial waste in dairy cattle diet for environmental mitigation" covers the objectives 2 and 3 of the thesis (Quintero-Herrera et al., 2021). This article is available in Appendix XIII of the annexes.

The article "The role of livestock feed fertilization as an improvement of sustainability in the dairy sector" corresponds to objectives 4 and 5 (Quintero-Herrera et al., 2022). This article is available in Appendix XIV of the annexes.

Partial results of this research have been presented at the 5th National Congress on Environmental Engineering, Science and Management (AMICA); The 8th World Sustainability Forum; and PubliER2022.

Chapter 6

CONCLUSIONS AND FUTURE PERSPECTIVES

A methodological structure was developed to elaborate a national inventory of strategic agro-industrial waste in the dairy industry. This methodology was applied in Mexico and found 52 municipalities with the most significant potential for the use of agro-industrial wastes in the local dairy industry. Maize cobs, carrots, florets and steams of broccoli, cotton straw, and potato skins were identified as strategic by-product feeds based on criteria as evidence of previous use as animal feed, treatments to convert them into feed, nutritional characteristics, availability, and proximity to dairy basins.

Treatment and transportation costs and the environmental impact of the transformation of agro-industrial wastes into by-product feeds should be explored to complete the definition of strategic food. The results of this research allow identifying which foods are strategic and where efforts in valorizing agricultural wastes should be directed. This methodology could be used in other countries of the region with similar or different agro-industrial panorama since the desirability allows an adaptation of the agro-industrial and dairy industries of a country.

The environmental impact of broccoli production was studied, evaluating the effect that the integration of broccoli stems in the cattle diet has on the life cycle of intensive dairy production. The results indicated that incorporating broccoli stems in the diet reduced greenhouse gas emissions by 118 g CO_2 eq kg^{-1} FPCM and agricultural land occupation by 0.002 m^2a 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 broccoli stems 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 farming systems by incorporating strategic agro-industrial waste into cattle diets.

The environmental impact of N–P–K blends in livestock feed production also was investigated in this study, which assessed the integration of four different fertilizer scenarios (three optimized and the Baseline) on the life cycle of intensive dairy production. According to the proposed optimization model, the N–P–K blends for all the livestock crops studied showed antagonistic behavior between economic and environmental impacts. When cheaper N–P–K blends are prioritized (Scenario Profit), fertilizer costs are reduced between 21 – 4% (corresponding to savings of 18.2 to 0.2 USD t^{-1} DM), while environmental impacts increase by 7 – 3% (corresponding to 2.3 to 1×10^{-3} Pt t^{-1} DM for ReCiPe endpoint single score).

Optimizing fertilizer blends is more sensitive to cost reductions than environmental impacts, which is key in the current fertilizer market. In the case of urea, its sale price increased by 357% between March 2021 and February 2022 in Mexico.

Incorporating optimized N–P–K blends in the feed production reduced greenhouse gas emissions by 22 g CO_2 eq kg^{-1} FPCM, particulate matter formation by 0.06 g PM_{10} kg^{-1} FPCM, and fossil depletion by 8.4 g oil eq kg^{-1} FPCM. Even though these environmental benefits appear to be marginal, the strategy proposed is a simple issue with potential economic and environmental benefits in the life cycle of raw milk production.

If N–P–K blends prioritize employing the most economical fertilizers in the Mexican Bajio region, the potential savings in fertilizer costs will reach 29.6 M USD y^{-1} compared to the Baseline scenario. These potential savings could be used to implement other environmental mitigation strategies, e.g., in fertilization, using slow- and controlled-release fertilizers, foliar, and liquid application; or in the dairy farming system, breeding technification, anaerobic digestion as manure management, and by encouraging the use of agro-industrial wastes in the cattle diet as the case of broccoli stems.

From the perspective of this study and considering the nutritional and nutraceutical content of the strategic agro-industrial wastes, there is a need to investigate eco-efficient alternatives to generate new healthy products for human consumption. The economic evaluation is the last and no less important aspect to consider agro-industrial wastes as strategic. This is a great challenge considering a significant lack of knowledge in evaluating costs, especially in the treatments to convert waste into a by-product. Furthermore, by substituting agro-industrial wastes for conventional feed, there will be a change in demand, which will alter the environmental profile of milk production and can be quantified using a consequential LCA approach. This is also a previously unexplored area of opportunity.

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ANNEXES

Supporting information contains

Appendix VI. Parameters to evaluate the desirability function

Appendix VII. Main municipalities identified to apply the strategy for the use of agro-industrial residues in livestock diets

Appendix VIII. Inventory of emissions

Appendix IX. Livestock diet formulation model

Appendix X. Marginal impacts in the livestock diet

Appendix XI. Model results in livestock feeds

Appendix XII. Environmental evaluation of strategic agro-industrial wastes

Appendix I. Feeds production in Mexico

The study considered the six States with the highest milk production in Mexico (Jalisco, Coahuila, Durango, Chihuahua, Guanajuato, and Veracruz) (SIAP, 2020b). The national production, the participation of States, and the imports were considered in the study. Grain maize is the most demanded crop of the country, with imports reaching 10.6 %; the leading production states are Sinaloa and Jalisco with 5.8 and 3.8 Mt y^{-1}. Forage maize is an essential livestock feed; in Mexico, its area planted exceeds 600 thousand hectares, predominantly located in Jalisco. Table S1 shows a summary of the national situation of these crops.

Table S1. Main livestock feeds in Mexico. Elaboration from SADER-SIAP (2019)

i	Feed	National Production (kt)	Strategic states participation (%)	Participation in forages (%)	Imports (kt)	Exports (kt)
1	**Forage maize**	16,165	56.49	13.2	63.43	0.012
2	**Grain maize**	28,251	28.91	N/A	13,955	1,654
3	**Sorghum grain**	5,006	18.41	4.1	0	0.015
4	**Alfalfa**	33,120	46.06	27	0.16	25.25
5	**Forage Sorghum**	3,037	51.33	2.5	0	0.015
	Forage oats	10,476	58.69	8.5	3.86	1.17
	Grain barley	978	38.80	1.6	74	0.001

Sorghum grain has the highest production value in Tamaulipas and Guanajuato, with 40.5 and 20.1%, respectively. Alfalfa is the second in harvest volume importance, with a scale close to 33.9 Mt y^{-1}. Forage sorghum is an important feed, particularly in the states of the lagoon basin (Chihuahua, Durango, Coahuila). Together with sorghum grain, they are the only livestock feeds whose demand is satisfied with the local market (SADER-SIAP, 2019). National production includes forage oats; however, the country imports around 23% of this crop to meet domestic demand. The barley grain is destined for other sectors; mainly brewing the use in the livestock industry is limited. Against this background, the strategic crops considered for this research are forage maize, grain maize, sorghum, and alfalfa.

Appendix II: Transport distances determination

The distances between the different modules of the system were established using the following methodology:

The main polygons corresponding to the agricultural fields (AF) surrounding the dairy farm (DF) and the food processing plant (FPP) were geographically identified. Only the intensive agricultural production areas were considered, as they presented the highest crop yields (Figures S1 and S2). These areas were taken from land use layers obtained by the Ministry of Agriculture and Rural Development (SIAP, 2020a). Centroids were generated from each AF; subsequently, the corresponding distances between these and the DF and FPP were evaluated considering the access roads closest to the AF, taken from the National Road Network (INEGI, 2020). This evaluation was developed using the software Qgis 3.14.

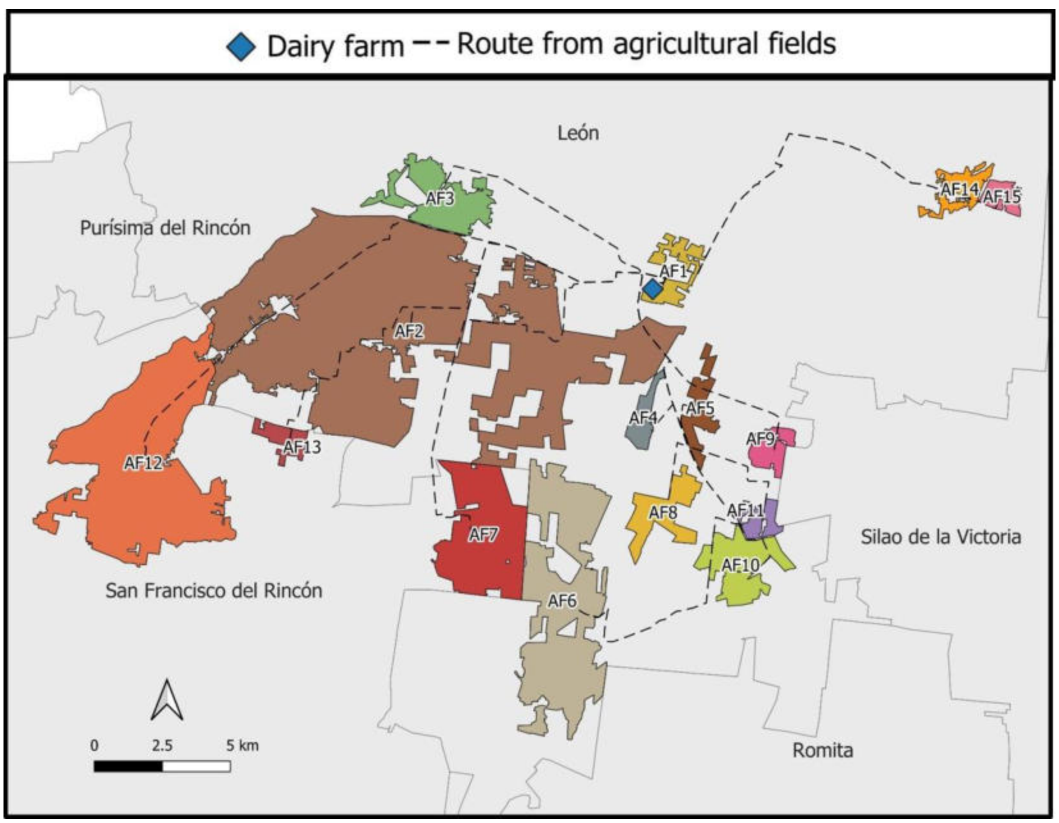

Figure S1. Intensive production agricultural fields (AF) surrounding the dairy farm (DF).

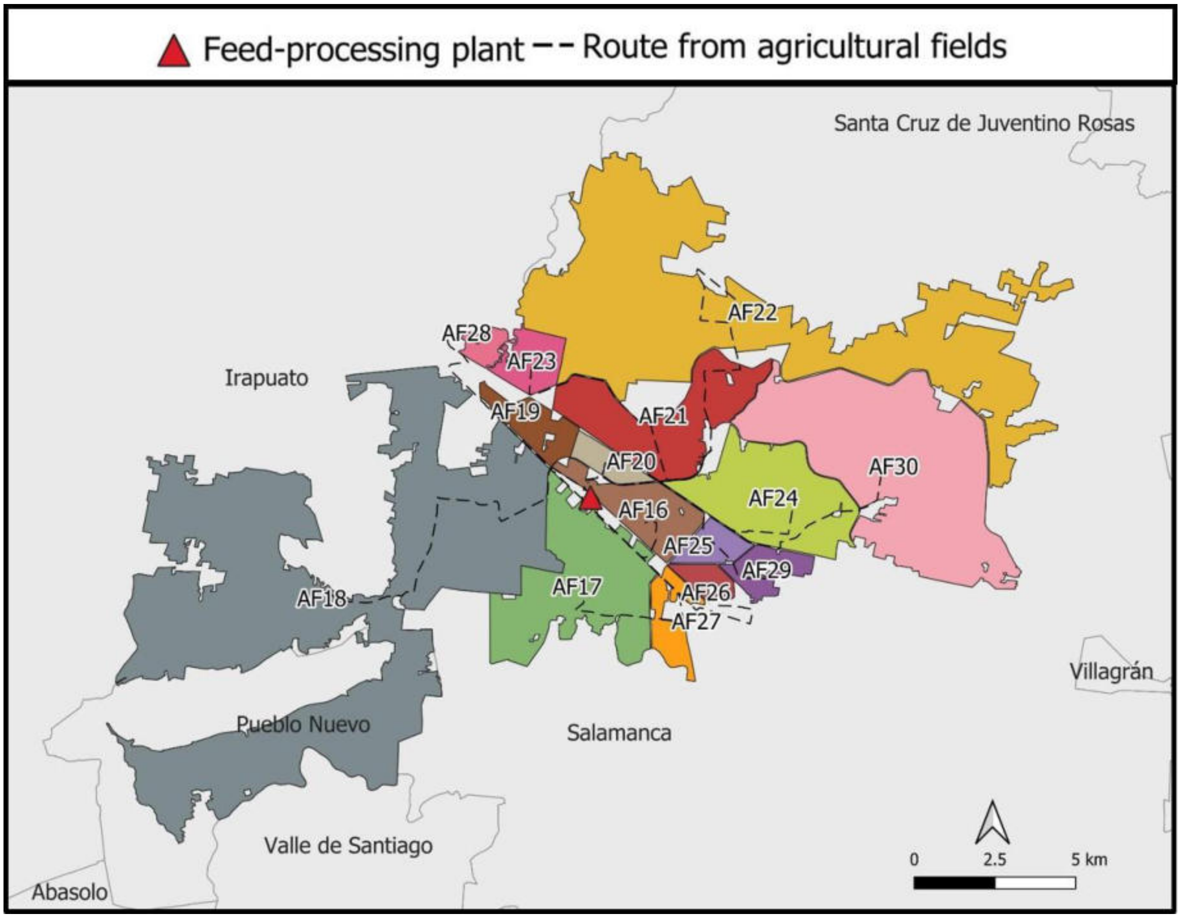

Figure S2. Intensive production agricultural fields (AF) surrounding the feed-processing plant (FPP).

The average distances between the AF - DF and AF - FPP sites was determined (Equation S1), considering the weighting factors of the areas of each agricultural polygon (term in brackets of the equation) and the respective distances between the AF and DF/FPP (Table S1).

$$\text{Distance}_{AF-DF/FPP} = \sum_{i=1}^{n}\left[\frac{Area_i}{\sum_{i=1}^{n} Area_i}\right]\text{Distance}_i \qquad \text{Eq. S1}$$

Table S2. Agricultural fields areas and their respective distances between the dairy farm (DF) and the feed-processing plant (FPP).

Polygon	$Area_i$ (ha)	$Distance_i$ (m) AF–DF	Polygon	$Area_i$ (ha)	$Distance_i$ (m) AF–FPP
Distances corresponding to DF			*Distances corresponding to FPP*		
AF1	234.396	1012	AF16	535.575	4892
AF2	7800.975	12947	AF17	1606.356	9861
AF3	612.003	10662	AF18	8193.139	13192
AF4	159.355	7985	AF19	316.907	2865
AF5	238.346	10291	AF20	180.932	4703
AF6	2098.465	22968	AF21	1156.266	9397
AF7	1231.32	19669	AF22	5200.947	15016
AF8	389.353	10780	AF23	309.566	14456
AF9	190.75	10666	AF24	1291.408	8796
AF10	534.432	15314	AF25	201.153	5846
AF11	135.899	13241	AF26	134.15	9674
AF12	3132.002	24503	AF27	269.143	6076
AF13	156.142	21103	AF28	120.427	9088
AF14	215.522	15361	AF29	244.097	8100
AF15	130.255	17269	AF30	3209.308	12169

The distance between the FPP and the DF was also determined using Ggis 3.14 (Figure S3). The results of the distances evaluated between the different modules of the dairy farming system are shown in Table S2.

Figure S3. Distance between feed-processing plant and dairy farm.

Table S3. Distances between locations (km).

Transport between sites	Forage maize	Maize grain	Sorghum	Alfalfa
AF → FPP	12.16	12.16	12.16	-
FPP → DF	68.75	68.75	68.75	-
AF→ DF	-	-	-	16.55

AF: agricultural field. FPP: feed-processing plant. DF: dairy farm.

Appendix III Parameters and variables to calculate availability of agro-industrial wastes

Table S4. Parameters used to estimate the food loss and waste of agricultural foods.

m-th agricultural food	Food production Pre-Harvest (L_{pre})	Food production Post-Harvest (L_{post})	Processing and packaging (L_{proc})	Fraction utilized fresh (e)	Allocation factor for a product (a)	Conversion factor for a product (c)
Broccoli[1]	0.20	0.10	0.20	0.50	1.00	0.80
Tomato[1]	0.20	0.10	0.20	0.50	1.00	0.80
Beans[2]	0.06	0.03	0.08	0.00	0.12	1.00
Grape[1]	0.20	0.10	0.20	0.50	1.00	0.80
Agave[3]	0.14	0.14	0.12	0.20	1.00	0.90
Lemon[1]	0.20	0.10	0.20	0.50	1.00	0.80
Apple[1]	0.20	0.10	0.20	0.50	1.00	0.80
Orange[1]	0.20	0.10	0.20	0.50	1.00	0.80
Tangerine[1]	0.20	0.10	0.20	0.50	1.00	0.80
Cotton[2]	0.06	0.03	0.08	0.00	0.12	1.00
Potato[3]	0.14	0.14	0.12	0.20	1.00	0.90
Coffee[2]	0.20	0.10	0.20	0.50	1.00	0.80
Sugar cane[1]	0.20	0.10	0.20	0.50	1.00	0.80
Carrot[3]	0.14	0.14	0.12	0.20	1.00	0.90
Rice Palay[4]	0.06	0.04	L_{proc}=0.02 L_{mill}=0.07	0.00	0.40	1.00
Guava[1]	0.20	0.10	0.20	0.50	1.00	0.80
Eggplant[1]	0.20	0.10	0.20	0.50	1.00	0.80
Blackberry[1]	0.20	0.10	0.20	0.50	1.00	0.80
Mango[1]	0.20	0.10	0.20	0.50	1.00	0.80
Chickpea[2]	0.06	0.03	0.08	0.00	0.12	1.00
Papaya[1]	0.20	0.10	0.20	0.50	1.00	0.80
Pineapple[1]	0.20	0.10	0.20	0.50	1.00	0.80
Banana[1]	0.20	0.10	0.20	0.50	1.00	0.80
Sesame[2]	0.06	0.03	0.08	0.00	0.12	1.00
Soybean[2]	0.06	0.03	0.08	0.00	0.12	1.00
Maize grain[4]	0.06	0.04	L_{proc}=0.02 L_{mill}=0.07	0.00	0.40	0.69
Wheat grain[4]	0.06	0.04	L_{proc}=0.02 L_{mill}=0.07	0.00	0.40	0.78
Cauliflower[1]	0.20	0.10	0.20	0.50	1.00	0.80
Cucumber[1]	0.20	0.10	0.20	0.50	1.00	0.80

[1]Fruits and Vegetables, [2]Oilseeds and Pulses, [3]Roots and Tubers, [4]Cereals

Table S5. Variables calculated from Food Balance Sheets to estimate the food loss and waste

m-th agricultural food	Production quantity [P, t y^{-1}][b]	Food for human consumption [F, t y^{-1}][a]	Processed food for human consumption [R, t y^{-1}][a]	Fraction of F[c], *f*	Fraction of R[d], *r*
Apple	714203	813004	6306	0.92	0.01
Banana	2464171	1659262	555	0.74	0.00
Beans	1056071	1054082	0	0.86	0.00
Rice Palay	295338	0	174537	0.00	0.77
Carrot	361080	219850	0	0.64	0.00
Broccoli	583646	291395	0	0.55	0.00
Cauliflower	103142	291395	0	0.55	0.00
Chickpea	125823	22794	0	0.12	0.00
Coffee	953683	2216	103084	0.01	0.45
Cotton	674706	0	293991	0.00	0.58
Cucumber	1159934	68724	21748	0.09	0.03
Eggplant	112195	85730	0	0.55	0.00
Grape	470360	124619	114985	0.28	0.26
Lemon	2851427	1342638	148301	0.58	0.07
Maize grain	27424528	0	16082638	0.00	0.45
Mango	2085751	1488643	0	0.75	0.00
Orange	4648620	3246876	771962	0.73	0.18
Papaya	1117437	640609	0	0.76	0.00
Pineapple	1208247	667090	42307	0.79	0.05
Potato	1943910	1549491	0	0.84	0.00
Sesame	51997	23971	37090	0.32	0.47
Soybean	246019	0	2703662	0.00	0.63
Sugar cane	53841557	49377	51440769	0.00	0.94
Tangerine	302721	406498	24615	0.86	0.05
Tomato	3370827	1721873	83039	0.46	0.02
Wheat grain	69016	0	4612350	0.00	0.58
Agave	1913026	0	0	0.00	0.00
Guava	287243	1488643	0	0.75	0.00
Blackberry	215924	813004	6306	0.92	0.01

[a]According to the Food Balance Sheets of FAO (FAOSTAT, 2022).
[b]According to the agricultural production statistics 2020 database of SIAP (2020).
[c]Calculated with Eq. 4.
[d]Calculated with Eq. 5.

Table S6. Nutritional characteristics of the agricultural foods, agro-industrial wastes, and by-product feeds in each agri-food supply chain. The data was collected with information of the USDA Food Composition Database (USDA, 2022), the Feedpedia database (INRAE et al., 2022) and the references of Table 6

m-th agricultural food	Dry matter, [kg DM kg^{-1} FM]	Gross energy [MJ Kg^{-1} DM]	*i*-th by-product, i>4	Metabolizable Energy [MJ kg^{-1} DM]	Crude protein [% DM]	Crude fiber [% DM]	Calcium [g kg^{-1} DM]	Phosphorus [g kg^{-1} DM]	Dry matter [kg DM kg^{-1} FM]	Gross energy [MJ Kg^{-1} DM]
Apple	16.4	16.58	Apple pomace	8.5	8	36	0.6	1.4	91.2	19.4
Banana	21.9	17.1	Fermented banana peel	11.3	5.2	4.6	0.2	0.9	45.67	17.1
Beans	89.1	18.2	Beans waste	13.6	24.8	5.2	2.5	4.9	89.1	18.6
Rice Palay	83.17	28	Rice bran	13.1	14.8	8.6	0.7	17	90.1	21.2
Carrot	25	17.1	Fresh carrot	12.3	9.1	10	3.8	2.9	10.7	17.1
Broccoli	10	30.79	Florets and steams	2.68	2.57	2.4	0.05	0.07	10	16.32
Cauliflower	7.9	10.4	Stems	10	19.9	N/A	2.2	4.4	5.85	10.4
Chickpea	89	19.6	Chickpea straw	7.7	6.5	39	13	0.5	89.6	18.4
Coffee	22	31.12	Coffee pulp dehydrated	9.4	10.9	36	4.5	1.4	90.9	25
Cotton	97	23.77	Cotton straw	5.1	6.4	55.4	8.9	2.9	75.7	18.8
Cucumber	4.8	6.5	Silage cucumber wastes	2.86	9.83	12.26	N/A	N/A	4.8	6.5
Eggplant	7.7	13.5	Brinjal peel	9.3416	12.3	26.8	0.09	0.24	8.9	13.5
Grape	7.5	17.29	Grape pomace, dehydrated	5.5	13.6	24.7	9.9	2.7	91.2	19.1
Lemon	12.1	15.21	Lemon fruits, dried	10.2	8.1	19.9	N/A	N/A	92.1	16.5
Maize grain	89.6	18.5	Maize cobs	6.9	4.4	34.9	1.4	0.7	91.5	18.5
Mango	17.5	25	Ensiled mango peel	13.1	5.27	9.02	N/A	N/A	18.27	16.7
Orange	13.3	16.36	Orange peels, silage	12.6	7.7	14.3	13.8	1	19.6	18.1
Papaya	8.2	17.1	Papaya pomace, dried	N/A	18.2	26.7	18.1	6.1	92.2	17
Pineapple	14	20.9	Ensiled Pineapple	10.8	4.5	17.8	4.9	1.3	88.6	17
Potato	23.7	16.99	Potato skins and fragments	10.3	10	11.4	0.8	2.6	20.1	17.1
Sesame	96.6	29.1	Sesame straw	12.5	5.05	7.3	1.28	1.16	95.3	20.6

Soybean	91.46	18.2	Soybean hulls	11.5	13.1	38.9	5.5	1.6	89.1	18.2
Sugar cane	30	26.11	Sugarcane tops	8	4.9	34	2.8	1.2	26.8	18
Tangerine	13	14.8	Taringe peel	11.55	7	14	17	1	90.3	17.6
Tomato	5.3	17.37	Tomato pomace	9.3	21	39	4.4	3.6	93.5	21.8
Wheat grain	86.9	18.9	wheat bran	11	17.3	10.4	1.4	11.1	87	18.9
Agave	9.2	17.7	Agave bagasse	9.6465	3	77	N/A	N/A	0.95	17.7
Guava	19	16.23	Guava, waste, dried	7.3	10.4	17.6	14.7	1.8	91.9	22.5
Blackberry	34.7	18.2	Mulberry fruit in feed blocks. Black mulberry aerial part	10.8	20.3	13.4	21.5	2.3	34.7	18.2

Table S7. Logistical capacity factors and processing factors between the m-th agricultural food and the i-th by-product. The values were set according to the classification of agro-industrial wastes classification proposed by Sadh et al. (2018)

***m*-th agricultural food**	***i*-th by-product, i>4**	**Transf. factor, TF_i**	**Pre-harvest[a] LC_{pre}**	**Post-harvest[b] LC_{post}**	**Processing[c] LC_{proc}**
Apple	Apple pomace	0.35	0	0	1
Banana	Fermented banana peel	0.1	0	0	1
Beans	Beans waste	1	0	1	0
Rice Palay	Rice bran	1	0	0	1
Carrot	Fresh carrot	1	1	1	1
Broccoli	Florets and steams	1	0	1	1
Cauliflower	Stems	0.218	0	1	1
Chickpea	Chickpea straw	1	1	1	0
Coffee	Coffee pulp dehydrated	0.28	0	1	0
Cotton	Cotton straw	0.66	1	1	0
Cucumber	Silage cucumber wastes	1	0	1	1
Eggplant	Brinjal peel	0.1	0	0	1
Grape	Grape pomace, dehydrated	0.15	0	0	1
Lemon	Lemon fruits, dried	1	0	0	1
Maize grain	Maize cobs	0.187	1	0	0
Mango	Ensiled mango peel	0.5	0	0	1
Orange	Orange peels, silage	0.1	0	0	1
Papaya	Papaya pomace, dried	1	0	0	0
Pineapple	Ensiled Pineapple	1	0	1	1
Potato	Potato skins and fragments	0.1	0	1	1
Sesame	Sesame straw	1	1	1	0
Soybean	Soybean hulls	0.05	0	0	1
Sugar cane	Sugarcane tops	0.15	1	0	0
Tangerine	Taringe peel	0.4	0	0	1
Tomato	Tomato pomace	0.13	0	1	1
Wheat grain	wheat bran	0.19	0	0	1
Agave	Agave bagasse	1	0	0	1
Guava	Guava, waste, dried	0.25	0	1	1
Blackberry	Mulberry fruit in feed blocks. Black mulberry aerial part	1	0	1	0

[a]Field residues: stems, stalks, leaves, and seed pods

[b]Process residues: husks, seeds, roots, bagasse, and molasses

[c]Industrial residues: peel, oil cake, and juice residues

Appendix IV. Fertilizer production in Mexico

The main fertilizers used in Mexico were examined (Table S8). According to information from foreign trade and domestic fertilizer production, Mexico had 4.9 Mt of fertilizer available in 2017, of which 66.4% are nitrogenous, 22.2% are phosphates, 8.1% are potassium, and 3.3% blends. Imported fertilizers account for 79%, with the remainder produced locally. Nitrogenate fertilizers represent the largest volume and value of fertilizer imports (66.7 and 61.3 %, respectively) and are the most used in Mexico (CEDRSSA, 2018).

Table S8. Foreign trade of fertilizers in Mexico in 2017 (CEDRSSA, 2018)

Fertilizers	Import [t]	Export [t]	National production [t]	Available for consumption [t]
Nitrogenates	2,589,304	8,795	683,405	3,263,915
Urea	1,891,973	283	N/A	1,891,691
Ammonium Sulfate	266,007	5,057	N/A	260,950
Ammonium Nitrate	185,220	1,304	N/A	183,916
Calcium Nitrate	138,046	156	N/A	137,890
Sodium Nitrate	2,675	261	N/A	2,414
The mixture of Urea with Ammonium Nitrate	105,384	1,734	N/A	103,650
Phosphates	714,249	670,829	1,045,249	1,088,670
Superphosphates	24	134,038	N/A	134,015
Diammonium Phosphate	276,696	225,460	N/A	51,236
Monoammonium Phosphate	147,047	310,972	N/A	163,925
Fertilizers with nitrogen and phosphorus	42,871	314	N/A	42,557
Fertilizers with phosphate nitrates	247,612	45	N/A	247,567
Potassium	408,134	7,942	N/A	400,192
Potassium Chloride	322,578	7,937	N/A	314,642
Potassium Sulfate	85,556	5	N/A	85,551
N-P-K blends	171,603	10,273	N/A	161,330
Total fertilizers	3,883,290	697,838	1,728,654	4,914,106

Appendix V. Pesticides used in livestock feed production

Table S9. Pesticides used in agricultural production per 1 t of each crop on a dry-matter basis, except broccoli (1 t on a fresh-matter basis). The dose is associated with the active ingredient.

Crop	Pesticide	Dose, g	% Soil	% Water
Broccoli	B.t.k. (103 g kg^{-1})	0.0048	98.166	1.834
	Chlorantraniprol (200 g L^{-1})	0.0025	98.593	1.407
	Methomyl (900 g kg^{-1})	0.0264	99.501	0.499
	Spinoteram (60 g L^{-1})	0.001	96.309	3.691
	Zeta-cypermethrin (109 g L^{-1})	0.0017	98.166	1.834
	Indoxacarb (150 g L^{-1})	0.0037	96.431	3.569
	Methoxyfenozide (240 g L^{-1})	0.0062	98.332	1.668
	Chenopodium ambrosioides (167.5 g L^{-1})	0.0103	98.166	1.834
	Dimethoate (400 g L^{-1})	0.0216	98.166	1.834
	Flonicamid (500 g kg^{-1})	0.0054	99.831	0.169
	Manzate-D (800 g kg^{-1})	0.0742	98.166	1.834
	Zineb (800 g kg^{-1})	0.0742	98.166	1.834
	Oxyfluorfen (240 g L^{-1})	0.0223	98.166	1.834
	Trifluralin (480 g L^{-1})	0.0594	95.626	4.374
Alfalfa	Treflan (480 g L^{-1})	0.0116	99.546	0.454
	Pivot, Imazethapyr (100 g L^{-1})	0.0014	99.892	0.108
	Proul-400 (396 g L^{-1})	0.0192	99.546	0.454
	Poast, Sethoxydim (184 g L^{-1})	0.0051	99.876	0.124
	Endosulfan (520 g L^{-1})	0.0144	98.257	1.743
	Malathion (520 g L^{-1})	0.0144	99.546	0.454
	Metomil (900 g kg^{-1})	0.0037	99.874	0.126
	Chlorpyrifos (480 g L^{-1})	0.0066	99.831	0.169
Forage maize	2,4-D Amine 720 (720 g L^{-1})	0.1361	98.917	1.083
	Carbofuran (50 g kg^{-1})	0.0473	98.917	1.083
	Terbufos (50 g kg^{-1})	0.0473	99.03	0.97
	Malathion (52 g kg^{-1})	0.001	98.304	1.696
	Chlorpyrifos (480 g L^{-1})	0.0091	97.061	2.939
	Methomyl (900 g kg^{-1})	0.017	99.65	0.35
	Oxidemeton Methyl (250 g L^{-1})	0.0118	99.757	0.243
	Ometoate (800 g L^{-1})	0.0227	99.701	0.299

	Dimethoate (400 g L^{-1})	0.0189	98.917	1.083
Grain maize	Atrazine (900 g kg^{-1})	0.3994	99.769	0.231
	Nicosulfuron (240 g L^{-1})	0.0399	99.721	0.279
	Carbofuran (50 g kg^{-1})	0.1109	99.068	0.932
	Diazinon (232 g L^{-1})	0.0257	98.916	1.084
	Chlorpyrifos (50 g kg^{-1})	0.0527	97.463	2.537
	Metomil (900 g kg^{-1})	0.0399	99.623	0.377
	Trichlorophone (800 g kg^{-1})	0.0888	98.916	1.084
Sorghum	Cytolan (240 g L^{-1})	0.0444	99.594	0.406
	Lorsban 480E (480 g L^{-1})	0.0666	99.594	0.406
	Sevin (800 g kg^{-1})	0.3701	99.291	0.709
	Imidacloprid (200 g L^{-1})	0.0074	99.594	0.406
	Atrazine (900 g kg^{-1})	0.4996	99.769	0.231
	Nicosulfuron (240 g L^{-1})	0.0666	99.721	0.279

Appendix VI. Parameters to evaluate the desirability function

Table S10. Parameters to evaluate the desirability function

Parameter	Dairy production (*DP,* Ml y^{-1})	Metabolizable energy (*ME,* MJ y^{-1})
T_x	P_{96}= 22,906	P_{98}= 12,805,751
LIE_x	0	0
LSE_x	863,747	69,574,027
α_x	0.2	0.2
β_x	5	5

Appendix VII. Main municipalities identified to apply the strategy for the use of agro-industrial residues in livestock diets

Table S11. Main municipalities identified to apply the strategy for the use of agro-industrial waste in livestock diets

Municipality	Metabolizable Energy [TJ y-1]									Milk production [Ml y-1]	Desirability function
	Maize grain	Carrot	Sugar cane	Broccoli	Cotton	Potato	Lemon	Other foods*	Total		
Namiquipa	8.05	0	0	0	0	0.19	0	4.6	12.84	56,135	0.9
San Luis de la Paz	0.1	12.59	0	1.43	0	0	0	0.29	14.4	47,813	0.86
Papantla	1.27	0	0	0	0	0	2.4	3.9	7.57	24,998	0.8
Ahumada	3.24	0	0	0	4.57	0	0	0.15	7.96	31,129	0.79
Pénjamo	7.04	0	0	0.17	0	0	0	0.39	7.6	35,414	0.77
Romita	1.09	9.3	0	0.11	0	0	0	0.08	10.59	46,546	0.77
Dolores Hidalgo	0.58	5.1	0	2.11	0	0	0	0.29	8.08	41,441	0.76
Playa Vicente	0.65	0	0.41	0	0	0	0	4.09	5.15	30,183	0.75
Abasolo	3.96	0	0	0.82	0	0	0	0.27	5.05	29,596	0.75
Valle de Santiago	2.93	0.91	0	2.01	0	0	0	0.75	6.6	39,555	0.75
Jaral del Progreso	1.28	1.6	0	0.93	0	0	0	0.06	3.87	23,092	0.75
Silao de la Victoria	1.1	4.46	0	0.2	0	0	0	0.21	5.96	38,639	0.75
Cosío	0.2	3.51	0	0.05	0	0	0	0.09	3.84	24,510	0.75
Pabellón de Arteaga	0.1	4.55	0	0.11	0	0	0	0.05	4.81	34,455	0.74
Cajeme	8.65	1.28	0	0	0.01	7.05	0.09	1.79	18.88	31,580	0.73
Zapotlán del Rey	3.6	0	0	0	0	0	0	0.01	3.61	27,828	0.73
Calvillo	0.03	0	0	0	0	0	0.06	3.88	3.97	31,540	0.73
Celaya	0.94	9.05	0	0.33	0	0	0	0.19	10.52	64,357	0.73
Acámbaro	3.08	0	0	0.01	0	0	0	0.06	3.16	29,938	0.72
Apaseo el Grande	0.9	1.71	0	0.31	0	0	0	0.1	3.02	29,891	0.72
Janos	1.77	0	0	0	2.4	0	0	0.03	4.21	41,329	0.71
Ensenada	0	1.12	0	0.01	0	0	0.01	1.72	2.87	30,824	0.71
La Concordia	1.91	0	0	0	0	0	0.03	0.66	2.6	28,933	0.71
Villa Corzo	1.61	0	0	0	0	0	0.09	0.51	2.21	26,343	0.7
Atotonilco el Alto	4.28	0	0	0	0	0	2.21	0.01	6.49	62,300	0.7
Other municipalities	29.42	11.18	11.78	3.22	1.23	0.26	0.53	7.02	64.65	1,083,295	>0.6

*Other foods include apple, orange, pineapple, guava, mango, tomato, beans, cucumber, blackberry, coffee, cauliflower, banana, chickpea, grape, tangerine, soybean, sesame, and eggplant.

Appendix VIII. Inventory of emissions

Table S12. Inventory of emissions from the dairy farm operation module per FU_{DPS}. OCD: Optimized conventional diet; ODBS: Optimized diet with broccoli stems.

Emission	Quantity		Reference
Emissions to air			
Enteric fermentation	**OCD**	**ODBS**	
Methane, g CH_4	12.82	12.32	(IPCC, 2019)
Manure management			
Methane, g CH_4	11.61	11.6	(IPCC, 2019)
Direct N_2O, g N_2O	0.132	0.130	(IPCC, 2019)
Indirect N_2O volatilized, g N_2O	0.047	0.046	(IPCC, 2019)
Indirect N_2O leached, g N_2O	2.9E-03	2.9E-03	(IPCC, 2019)
Ammonia, g NH_3	6.7E-03	6.6E-03	(EMEP/EEA, 2019b)
Nitric oxide, g NO	5.9E-04	5.7E-04	(EMEP/EEA, 2019b)
No methane volatile organic compounds, g NMVOC	2.93	2.93	(EMEP/EEA, 2019b)
Total suspended particles, g TSP	0.197	0.197	(EMEP/EEA, 2019b)
Particulate matter formation PM10, kg PM_{10}	0.09	0.09	(EMEP/EEA, 2019b)
Particulate matter formation PM2.5, kg $PM_{2.5}$	0.059	0.059	(EMEP/EEA, 2019b)
Emissions to water			
Manure management			
Dissolved ammonia, g NH_3	0.102	0.101	(IPCC, 2019)
Nitrate, g NO_3^-	0.372	0.367	(IPCC, 2019)

Appendix IX. Livestock diet formulation model

Table S13. Results of formulations from the optimization model per livestock category.

Feed	Livestock category	Variable	OCD [kg $FU_{DPS}^{-1}d^{-1}$].	ODBS [kg $FU_{DPS}^{-1}d^{-1}$]
Maize silage	Calves	x_{11}	0.982	0.29
	Replacement heifers	x_{12}	3.287	1.529
	Cows in production	x_{13}	2.488	1.47
	Dry cows	x_{14}	4.033	1.095
Alfalfa hay	Calves	x_{21}	1.178	1.48
	Replacement heifers	x_{22}	3.593	3.631
	Cows in production	x_{23}	6.512	6.556
	Dry cows	x_{24}	3.535	3.664
Sorghum grain	Calves	x_{31}	0	0.044
	Replacement heifers	x_{32}	0	0
	Cows in production	x_{33}	1.500	1.890
	Dry cows	x_{34}	0	0
Rolled maize	Calves	x_{41}	0.926	1.03
	Replacement heifers	x_{42}	1.72	1.72
	Cows in production	x_{43}	4.5	4.5
	Dry cows	x_{44}	1.032	2.121
Broccoli stems	Calves	x_{51}	-	0.59
	Replacement heifers	x_{52}	-	1.72
	Cows in production	x_{53}	-	0.584
	Dry cows	x_{54}	-	1.72

OCD: Optimized conventional diet; ODBS: Optimized diet with broccoli stem gro-industrial waste

Table S14. Calculations of parameters according to the optimization model constraints.

Parameter	Livestock category	Variable	Lower limit	OCD	ODBS	Upper limit
ME: Metabolizable Energy (Mcal kg^{-1} DM)	Calves	b_{11};d_{11}	8	8	8	13
	Replacement heifers	b_{21};d_{21}	16.4	21.56	19.12	26.5
	Cows in production	b_{31};d_{31}	22	39.32	38.70	40
	Dry cows	b_{41};d_{41}	12	21.15	19.35	22
CP: Crude protein (%)	Calves	b_{12};d_{12}	12	12	12	16
	Replacement heifers	b_{22};d_{22}	10	12.14	11.48	14
	Cows in production	b_{32};d_{32}	13	13	13	19
	Dry cows	b_{42};d_{42}	10	11.85	11.65	16
CF: Crude fibre (%)	Calves	b_{13};d_{13}	17	17.91	17	22
	Replacement heifers	b_{23};d_{23}	17	19.98	18.71	22
	Cows in production	b_{33};d_{33}	16	16.67	16	22
	Dry cows	b_{43};d_{43}	17	21.32	17.93	22
Ca: Calcium (%)	Calves	b_{14};d_{14}	0.41	0.91	1	1
	Replacement heifers	b_{24};d_{24}	0.4	1	1	1
	Cows in production	b_{34};d_{34}	0.6	1	1	1
	Dry cows	b_{44};d_{44}	0.44	1	1	1
P: Phosphorus (%)	Calves	b_{15};d_{15}	0.23	0.244	0.232	0.39
	Replacement heifers	b_{25};d_{25}	0.18	0.236	0.214	0.3
	Cows in production	b_{35};d_{35}	0.25	0.265	0.266	0.42
	Dry cows	b_{45};d_{45}	0.22	0.226	0.220	0.26
Dry matter Intake (kg DM d^{-1})	Calves	w_1;y_1	2.9	3.09	3.43	5.5
	Replacement heifers	w_2;y_2	8.6	8.6	8.6	13.1
	Cows in production	w_3;y_3	15	15	15	20
	Dry cows	w_4;y_4	8.6	8.6	8.6	12
As-fed intake (kg FM d^{-1})	Calves	g_1		4.58	9.8498	15.27
	Replacement heifers	g_2		13.37	27.908	43.17
	Cows in production	g_3		19.64	24.1	60
	Dry cows	g_4		14.21	27.417	60
Maize silage (kg DM kg^{-1}DM)	Calves	l_{11}	-	0.318	0.084	0.5
	Replacement heifers	l_{21}	-	0.382	0.178	0.5
	Cows in production	l_{31}	-	0.166	0.098	0.5
	Dry cows	l_{41}	-	0.469	0.127	0.5
Alfalfa hay (kg DM kg^{-1}DM)	Calves	l_{12}	-	0.382	0.431	0.5
	Replacement heifers	l_{22}	-	0.418	0.422	0.5
	Cows in production	l_{32}	-	0.434	0.437	0.5
	Dry cows	l_{42}	-	0.411	0.426	0.5
Sorghum grain (kg DM kg^{-1}DM)	Calves	l_{13}	-	0	0.013	0.3
	Replacement heifers	l_{23}	-	0	0	0.3
	Cows in production	l_{33}	-	0.1	0.126	0.3
	Dry cows	l_{43}	-	0	0	0.3

Rolled maize (kg DM kg^{-1}DM)	Calves	l_{14}	-	0.3	0.3	0.3
	Replacement heifers	l_{24}	-	0.2	0.2	0.3
	Cows in production	l_{34}	-	0.3	0.3	0.3
	Dry cows	l_{44}	-	0.12	0.247	0.3
Broccoli stems (kg DM kg^{-1}DM)	Calves	l_{15}	-	-	0.172	0.2
	Replacement heifers	l_{25}	-	-	0.2	0.2
	Cows in production	l_{35}	-	-	0.039	0.2
	Dry cows	l_{45}	-	-	0.2	0.2
Forage (kg DM d^{-1})	Calves	$v_1 ;h_1$	35	70	68.7	70
	Replacement heifers	$v_2 ;h_2$	60	80	80	80
	Cows in production	$v_3 ;h_3$	40	60	57.4	60
	Dry cows	$v_4 ;h_4$	60	88	75.3	88

OCD: Optimized conventional diet; ODBS: Optimized diet with broccoli stem agro-industrial waste

Appendix X. Marginal impacts in the livestock diet

Table S15. Marginal impacts of the N–P–K blends scenarios in the dairy cattle diet. a) Single score indicator. b) Fossil depletion indicator. c) Particulate matter indicator. d) Climate change indicator

Indicator	Unit	Scenario		
		Profit	**Viable**	**Planet**
Diet cost	Cost, USD t^{-1}	$ 2.63	$ 1.08	$ **-0.46**
Single score	Environmental saving, mPt t^{-1}	3.10	3.51	3.63
	USD saved per Pt mitigated	0.85	0.31	**-0.13**
Climate change	Environmental saving, kg CO_2 eq t^{-1}	**-3.84**	2.55	7.40
	USD saved per kg CO_2 eq mitigated	**-0.686**	0.426	**-0.063**
Particulate matter formation	Environmental saving, kg PM_{10} eq t^{-1}	0.042	0.038	0.029
	USD saved per kg PM_{10} mitigated	62.94	28.55	**-15.72**
Fossil depletion	Environmental, kg oil eq t^{-1}	5.42	4.02	2.10
	USD saved per kg oil eq mitigated	0.485	0.270	**-0.221**

Section XI. Model results in livestock feeds

Table S16 Results of the N–P–K blends model for each crop. kg refers to the fertilizer, t^{-1} DM refers to ton on a dry matter basis

		Urea	Ammonium Sulfate	Diammonium Phosphate as N	Diammonium Phosphate as P_2O_5	Monoammonium Phosphate as N	Monoammonium Phosphate as N as P_2O_5	Triple Superphosphate	Potassium Chloride
Single score, mPt kg^{-1}		392.5	169.2	346.4	211.5	362.5	221.4	254.5	17.3
Fossil depletion, ´kg Oil eq kg^{-1}		1.208	0.460	1.132	0.577	1.144	0.583	0.605	0.044
Particulate matter formation kg PM_{10} kg^{-1}		0.0067	0.0027	0.0114	0.0058	0.0131	0.0067	0.0091	0.0002
Climate change, kg CO_2 eq kg^{-1}		2.96	1.65	2.39	1.22	2.36	1.20	1.53	0.16
Alfalfa, kg t^{-1} DM	baseline	0.90						8.35	
	Planet					0.66	3.12	4.08	
	Viable			0.32	0.83	0.33	1.56	5.06	
	Profit			0.65	1.66			6.04	
Forage maize, kg t^{-1} DM	baseline	15.06						7.49	1.69
	Planet	13.47				1.16	5.47		1.69
	Viable	6.14	13.44	2.11	5.38				1.69
	Profit		27.21	2.11	5.38				1.69
Grain maize, kg t^{-1} DM	baseline	37.79						12.62	1.73
	Planet	35.12				1.95	9.21		1.73
	Viable	16.55	36.59	3.55	9.07				1.73
	Profit		73.72	3.55	9.07				1.73
Sorghum grain, kg t^{-1} DM	baseline	76.42						16.67	4.21
	Planet	72.90				2.58	12.17		4.21
	Viable	35.11	78.06	4.69	11.98				4.21
	Profit		156.85	4.69	11.98				4.21

Table S17. Midpoint and endpoint impact indicators of the intensive dairy production system with the optimized conventional diet (OCD) and optimized diet with broccoli stems (ODBS).

Midpoint indicator	Value		Endpoint indicator (mPt)	Value	
	OCD	ODBS		OCD	ODBS
CC (kg CO_2 eq)	1.989	1.871	**CC human health**	61.22	57.58
			CC ecosystems	6.87	6.46
LO (m^2a)	0.448	0.446	**LO**	3.83	3.81
PM (kg PM_{10} eq)	1.59E-03	1.60E-03	**PM**	9.07	9.13
FD (kg oil eq)	0.092	0.096	**FD**	18.68	19.45

CC: Climate change. LO: Agricultural land occupation. PM: Particulate matter. FD: Fossil depletion.

Table S18. Comparison of midpoint indicators between the diets proposed and milk production LCA studies.

Reference	Functional Unit	Climate change	Terrestrial acidification	Freshwater eutrophication
	FU	kg CO_2 eq	kg SO_2 eq	kg P eq
This work OCD	1 kg FPCM	1.989	6.15	0.12
ODBS	1 kg FPCM	1.871	6.25	0.12
Chen and Corson (2014)	1 kg FPCM	1.052	7.80	7.20
(Basset-Mens et al., 2009)	1 kg milk	0.93	8.10	2.90
	1 kg ECM	0.99	18.00	1.59
(Cederberg and Flysjo, 2004)	1 kg ECM	0.87	10.00	3.80
	1 kg ECM	1	11.00	4.20
(Haas et al., 2001)	1 kg milk	1.3	19.00	7.50
	1 kg milk	1	17.00	4.50
(Thomassen et al., 2008)	1 kg FPCM	1.4	9.50	0.11
	1 kg FPCM	1.4	11.00	0.12
(Thomassen et al., 2009)	1 L milk	1.06	16.20	6.30
Williams et al. (2006)	1 L milk	0.98	16.40	6.10
	1 L milk	1.02	15.90	6.00
	1 L milk	1.03	15.90	6.50
Rivas-García et al. (2015)	1 L milk	0.994	26.00	1.58
	1 L milk	0.872	18.00	2.00
	1 L milk	0.728	11.00	1.70
Battini et al. (2014)	1 kg FPCM	1.21	13.10	0.12
	1 kg FPCM	1.18	12.80	0.12
	1 kg FPCM	1.13	12.30	0.12
Salou et al. (2017)	1 kg FPCM	1.405	12.90	7.60
	1 kg FPCM	0.916	11.10	7.70
	1 kg FPCM	1.038	12.80	6.30
	1 kg FPCM	1.061	10.10	5.50
	1 kg FPCM	0.998	9.40	4.60
	1 kg FPCM	1.257	13.00	6.60
	1 kg FPCM	1.282	12.80	6.30
Wilkes et al. (2020)	1 kg FPCM	3.13	-	-
	1 kg FPCM	2.56	-	-
	1 kg FPCM	2.3	-	-
(Gerber et al., 2013)	1 kg FPCM	3.25	-	-
	1 kg FPCM	3.75	-	-
	1 kg FPCM	1.9	-	-

FPCM, fat-and-protein-corrected milk; ECM, energy-corrected milk; OCD, optimized conventional diet; ODBS, optimized diet with broccoli stems

Appendix XII. Environmental evaluation of strategic agro-industrial wastes

Table S19. Environmental impact indicators in burden allocation cases for different allocation factors for broccoli stems ($AFac_{BPS}$) per FU_{DPS}. CC: Climate change, LO: Agricultural land occupation, PM: Particulate matter formation, FD: Fossil depletion, SS: Single score.

Cases	Environmental impact indicator	$AFac_{BPS}$=0 % (0 USD t^{-1} FM)		$AFac_{BPS}$=2 % (9.04 USD t^{-1} FM)		$AFac_{BPS}$=4 % (18.09 USD t^{-1} FM)		$AFac_{BPS}$=6 % (27.13 USD t^{-1} FM)	
		Milk[a]	Livestock[b]	Milk[a]	Livestock[b]	Milk[a]	Livestock[b]	Milk[a]	Livestock[b]
Case I: Economic allocation of this study	CC (kg CO_2 eq)	1.862	0.312	1.914	0.321	1.970	0.330	1.989	0.334
	LO (m^2a)	0.445	0.075	0.453	0.076	0.447	0.075	0.448	0.075
	PM (kg PM_{10} eq)	1.6E-03	2.7E-04	1.6E-03	2.7E-04	1.6E-03	2.7E-04	1.6E-03	2.7E-04
	FD (kg oil eq)	0.096	0.016	0.097	0.016	0.095	0.016	0.092	0.015
	SS (mPt)	97.1	16.3	99.4	16.7	100.6	16.9	100.8	16.9
Case II: Economic allocation according to Thoma et al. (2013)	CC (kg CO_2 eq)	1.966	0.209	2.021	0.214	2.080	0.221	2.100	0.223
	LO (m^2a)	0.470	0.050	0.478	0.051	0.471	0.050	0.473	0.050
	PM (kg PM_{10} eq)	1.7E-03	1.8E-04	1.7E-03	1.8E-04	1.7E-03	1.8E-04	1.7E-03	1.8E-04
	FD (kg oil eq)	0.101	0.011	0.103	0.011	0.100	0.011	0.097	0.010
	SS (mPt)	102.6	10.9	104.9	11.1	106.2	11.3	106.4	11.3
Case III: Protein-based allocation according to Thoma et al. (2013)	CC (kg CO_2 eq)	1.993	0.182	2.048	0.187	2.108	0.192	2.129	0.194
	LO (m^2a)	0.476	0.043	0.484	0.044	0.478	0.044	0.480	0.044
	PM (kg PM_{10} eq)	1.7E-03	1.6E-04	1.7E-03	1.6E-04	1.7E-03	1.6E-04	1.7E-03	1.5E-04
	FD (kg oil eq)	0.103	0.009	0.104	0.009	0.101	0.009	0.099	0.009
	SS (mPt)	104.0	9.5	106.3	9.7	107.7	9.8	107.8	9.8

The environmental impact indicators are presented per: [a]kg of fat-and-protein-corrected milk and [b]kg of live weight.