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Research Article

Toward a Circular Economy Approach for Integrated Intensive Livestock and Cropping Systems

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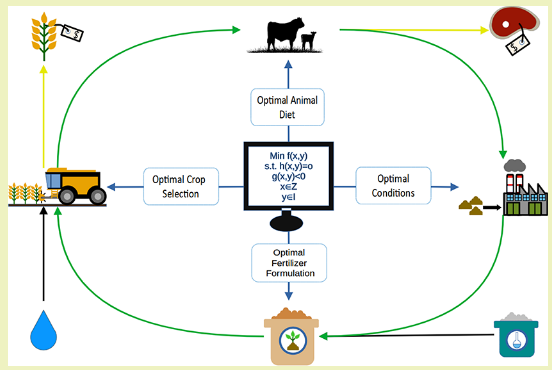
ABSTRACT: The separation between cropping systems and livestock has caused an imbalance in the nutrients, increasing the environmental impact of both industries. In this work, an integrated system comprising intensive livestock and crop management is compared with traditional systems, from the economic and environmental points of view. A model for estimating energy and nutritional requirements of beef cattle, a waste treatment process, a nutrient recovery system, and crop management is integrated into a mathematical optimization framework. This integrated model allows relating the formulation of the feed of the animals with the composition of their feces, the necessary cultivation area, the crops, and the fertilizers required as well as carrying out the economic and environmental evaluation of the entire system, balancing the nutrients between both industries. Through the application of the model to a representative case study with 1000 animals, a 62% reduction in the environmental impact of the combined agricultural system has been achieved, with a 14% decrease in the profit compared to the nonintegrated system. The fertilizer formulation is optimized to add exactly the required amount of each nutrient to reduce nutrient pollution. 30% of the nitrogen and 56% of the potassium needed for the crops can be obtained from the livestock waste. The correct formulation of the feed can reduce the amount of phosphorus in the feces down to 0.01%. The results show that the integrated system makes it possible to significantly reduce the environmental impact, but it is still not economically promising yet.



KEYWORDS: *product design, circular economy, sustainable processes, integrated crop and livestock systems, beef cattle, nutrient recovery, multiobjective optimization*

1. INTRODUCTION

Nowadays, the specialization in the production of crops and the intensification of livestock farming has separated both sectors so that dairy or meat production is concentrated in one place and crops are grown in another.[1] This leads to a dependence on mineral fertilizers in crop-growing areas and an excess concentration of nutrients in livestock production areas.[2] On the one hand, livestock is one of the main generators of anthropogenic CO_2.[3] The mismanagement of the waste generated can produce a series of environmental impacts, such as contamination of soils, eutrophication of nearby water resources, or generation of bad odors.[4] In addition to these impacts, the emissions from the transportation of animal food to livestock facilities must also be considered. On the other hand, the increase in the population worldwide has pushed crop systems to increase their production and cultivation areas, increasing the consumption of mineral fertilizers. Supplying a higher amount of fertilizers than required by the crops does result not only in an increase in the carbon footprint due to the energy used to obtain the mineral fertilizer but also in problems associated with nutrient pollution such as eutrophication and hypoxia of water bodies.[5]

Some technologies such as anaerobic digestion,[6] struvite production,[7] and ammonia stripping[8] have been used to produce biogas and digestate as a means to reduce the environmental impact of livestock. Nevertheless, most of these studies start directly from a generated waste and analyze whether it is possible to obtain valuable products from it, yet its composition is invariant.[9] In addition, it is necessary that the digestate meets certain requirements so that it can be used as a fertilizer.[10]

Integrated crops and livestock systems promote nutrient recycle by converting cellulosic ruminant feed into protein and nutrients from livestock manure into the cell structure of crops.[11] The application of manure through grazing in organic farming has already shown to improve nutrient recycling and pest suppression by promoting soil quality and biodiver-

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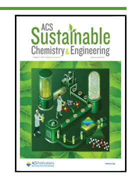

sity.[12−14] Whole farm models and nutrient balance approaches, which require the assessment of nutrient reserves, inputs, exports, and losses, can be used to evaluate and establish the best management systems for ruminant production,[15,16] reducing the environmental impact of agriculture.[17] However, even a small imbalance in nutrients can lead to soil depletion or over fertility.[18] So far, these integrated systems have been developed for small organic farms (extensive livestock) where such integration consists of a grazing activity where manure is deposited naturally[19] and, to the best of our knowledge, the literature has not analyzed such integration in the case of intensive livestock farming. Models from the literature[20] allow estimating the formulation of the feed based on the age, weight, breed, and sex of the animals, as well as the maintenance costs associated with a livestock farm. Nevertheless, they do not provide the analysis of waste treatment, estimation of the necessary cultivation area, environmental impact, or multi-objective options. To consider these systems, it is necessary to integrate these models into a larger framework.

In this work, an integrated model is developed for the optimal operation of intensive livestock and crop production. The framework integrates a model for estimating energy and nutritional requirements applied to beef cattle, a model of the waste treatment process, and a nutrient recovery system. In addition, the optimization framework considers the area for the crops and other supplementary materials such as water, food supplements, and chemicals. The optimal fertilizer formulation is also considered. A multi-objective (economic and environmental evaluation) approach of the integrated system is carried out, comparing the results with the traditional intensive livestock.

2. FRAMEWORK DEVELOPMENT

This work addresses the multi-objective evaluation of an intensive livestock system integrated. First, a model to estimate the energy (energy contained in the food necessary for the maintenance and growth of animals) and nutritional requirements (amount of minerals and proteins) for beef cattle is adapted from the literature.[20] This model is also used to relate the formulation of the animal feed with the composition of the waste generated. Next, a waste treatment system based on anaerobic digestion is modeled using first principles, such as mass and energy balances, phase equilibrium, and empirical yields. Finally, a nutrient recovery system (ammonia stripping) is included in the framework, modeled using experimental data. Experimental yields are used to estimate the necessary crop area and raw materials to obtain feed for livestock. A fraction of these crops, which is not used for animal feed but is obtained as byproducts, is sold. The environmental evaluation is performed using a composite index, which accounts for the emissions associated with the mineral fertilizers used as well as the water used for irrigated crops. In addition, the integrated system is compared with a nonintegrated one. The following subsections present the different models.

2.1. Model of Energy and Nutritional Requirements for Beef Cattle. The model developed to determine the energy and nutritional requirements for the cattle in this work is adapted from the model presented in the literature.[20] The detailed model is shown in the Supporting Information. Correlations based on experimental data are used to estimate energy, protein, and mineral requirements throughout the life cycle of the beef cattle, as well as the dry matter intake (DMI) per time unit. Degradation and passage rates are used to analyze the digestion of the feed by the cattle in order to estimate the composition of waste produced. In addition, the energy and nutritional properties and degradation rates of the ingredients considered in this work can be found in the same reference.[20] Mass and energy balances, together with this information, are used to choose the formulation of the feed and estimate the composition of waste per unit of time.

The time step of the original model is a day. However, to adapt the model to the residence time of the digester, the time unit (TU) is taken to be 24 days.[9] The model is reformulated as an optimization problem and extended to include waste treatment and crop management. The growing stages of the beef cattle from birth to slaughter, when the animal is 72-time units old in the case of the cows and 20-time units old in the case of the male yearling, can be seen in Figure 1. The growth

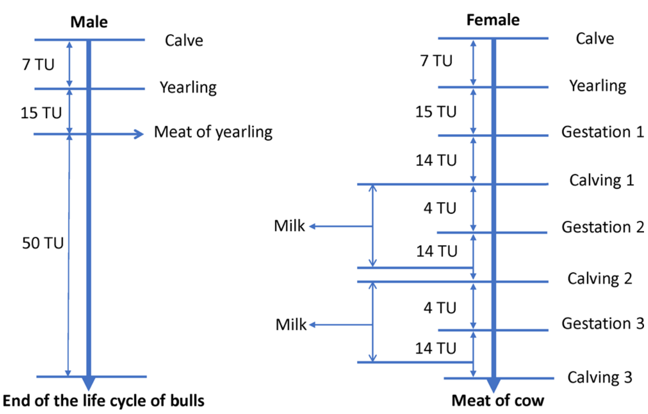

Figure 1. Life cycle of the beef cattle by sex.

of cows and bulls is modeled as two uncoupled optimization problems since there are no variables that link both problems. The results are presented together by adding both solutions. In this way, the optimization can be done in parallel. The only data that relates to both models is the ratio of the number of bulls per cow. This value is established before the optimization based on literature information, 1 bull for every 25 cows.[21] The meat of the bulls is not sold.

In addition, a series of assumptions are considered:

1. The maximum difference allowed between the energy available and that needed for livestock growth is 10%.
2. Calcium and phosphorus supplements are used for the stages that require it.

The model considers up to 12 different ingredients, which can be consulted in the Supporting Information together with their nutritional and energetic properties (Table S4). It is considered that the surplus of barley grain and wheat straw produced can be sold as a byproduct[22] if they are not chosen as animal feed. However, the rest of the crops are adjusted to the needs of the animal (whether they are selected as ingredients) so that there are no surpluses for sale. Since the main objective of the exploitation is the production of meat, the crops are sold as byproducts. The straw of the rest of the crops is not considered for sale after analyzing the market.[21]

2.2. Waste Treatment. Anaerobic digestion is used to transform waste into biogas and digestate. The composition of these products depends on the lipids, proteins, and carbohydrates of the waste and can be estimated using a model from previous work.[9] The global reactions that are carried out in the digester are as follows:

Lipids:

$$C_{57}H_{104}O_6 + 23.64\ H_2O + 1.45\ NH_3 \rightarrow 36.36\ CH_4 + 13.34\ CO_2 + 1.45\ C_5H_7NO_2$$

Protein:

$$CH_{2.03}\ O_{0.6}N_{0.3}S_{0.001} + 0.31\ H_2O \rightarrow 0.41\ CH_4 + 0.42\ CO_2 + 0.030\ C_5H_7NO_2 + 0.001\ H_2S + 0.26\ NH_3$$

Carbohydrates:

$$C_6H_{10}O_5 + 0.35\ H_2O + 0.22\ NH_3 \rightarrow 2.46\ CH_4 + 2.46\ CO_2 + 0.22\ C_5H_7NO_2$$

This model uses these stoichiometric ratios and experimental conversions to estimate the composition of the products and water and ammonium requirements. These and other considerations can be found in the Supporting Information.

Biogas upgrading is performed using a bed of Fe_2O_3 to remove H_2S, a scrubber to reduce the ammonia content down to 5%, and a pressure swing adsorption system to remove water, CO_2, and ammonia.[23] The stoichiometric ratios and adsorption yields, found in the Supporting Information, are used to estimate the final biogas composition and size of the adsorbent bed required.

2.3. Nutrient Recovery Systems. The liquid and solid effluents, which exit the digester, are separated using a decanter centrifuge. It is considered that 25% of the ammonia is retained by the solid phase[24] and is lost in the storage process, while the liquid effluent is treated by an ammonia-stripping process, which can recover 89% of the ammonia dissolved.[8] It is necessary to use 27.5 g Ca $(OH)_2$ per liter of effluent to promote the formation of ammonia and 2.88 kg of H_2SO_4 per kilogram of NH_3 recovered.[8]

The liquid effluents from the different stages of the ammonia stripping process are stored together with the solid effluent from the decanter and are naturally dried in a controlled warehouse, ensuring that the phosphorus and potassium amounts are maintained in the final product. The amount of phosphorus and potassium recovered is the difference between the one required for the animals and that supplied with the feed and supplements. The mass balances as well as the process flowsheet can be found in the Supporting Information.

2.4. Crops Growing and Management. The work considers the most common crops that can be used for animal feed. On the one hand, the relationship between the amount of each crop and the required crop area is estimated using yields from the literature.[25,26] On the other hand, technical reports are used to obtain the water[27] and fertilizer[25] requirements and the cost of crop production (tillage, sowing, and harvesting).[28] The reference considers fertilizer losses due to leaching and an average concentration of nutrients present in the soil to estimate the amount of fertilizer per unit of hectare, and therefore, it is not necessary to add a correction factor.

This information as well as the completed list of the crops can be found in Table S3 in the Supporting Information. Storage is necessary to ensure the availability of all types of crops throughout the year since there are crops that grow in spring and others that grow in winter.

2.5. Fertilizer Formulation. Fertilizer formulation is calculated to avoid any excess or deficiency of nutrients in the soil. Ammonium nitrate (34-0-0), simple superphosphate (0-20-0), and potassium sulfate (0-0-50)[29] are used to supply nitrogen (0.34 kgN/kg), phosphorus (0.20 kgP_2O_5/kg), and potassium (0.50 kgK_2O/kg) to the soil, respectively. The amount of each type of fertilizer is fixed by using mass balances, which can be found in the Supporting Information, between the nutrients recovered from the digestate and the nutrients required from the selected crops.

2.6. Environmental Impact Index. Global warming potential (GWP), eutrophication potential (EUp), and water footprint (WF) are used to analyze the impact of the integrated livestock system. Technical reports[30] are used to obtain the values of GWP and EUp per ton of fertilizer, while the water footprint is estimated as the water consumed by irrigation (see Section 2.4).

A composite index is developed to consider simultaneously the different impacts. The indexes (I_i) are standardized (In_i) using the minimum−maximum standardization approach (eq 1), and an additive aggregation method (eq 2)[31] is used to compute the composite indicator (CI). The weights are estimated using a technical report.[32]

$$In_i = \frac{I_i - \min(I_i)}{\max(I_i) - \min(I_i)}\ i = \{GW, EUp, WF\} \tag{1}$$

$$CI = \sum_i weight \times Ii_i \tag{2}$$

The values of GWP, EUp, and WF per ton of each type of fertilizer as well as the weights of each index are found in Table S1 in the Supporting Information.

2.7. Solution Procedure. The objective function is based on the profit (Pro), and it is shown in eq 3

$$Pro = In_M + In_P + In_{crops} + In_{bio} - Cst_{growth} - Cst_{Field} - Cst_{Fertilizer} - Cst_{Storage} - Cst_{Supplement} - Cst_{Manpower} - Cst_{Aux} \tag{3}$$

The terms In_M, In_P, In_{crops}, and In_{bio} correspond to the income of meat, potential, crops, and biogas, respectively.

The income from the meat (In_M) is calculated by eq 4

$$In_M = In_{cows} + In_{YearlingM} + In_{YearlingF} \tag{4}$$

where In_{Cows}, $In_{YearlingM}$, and $In_{YearlingF}$ are the incomes from the sale of cows, male yearling, and female yearling, respectively. Each income can be estimated using their final weights, the meat yield, and the official price of the meat from the literature. The potential income (In_P) is the profit that can be obtained out of the new calves, which are gestated along the life cycle of cows (see Figure 1) when they become yearling and are sold. During its life cycle, each cow can give birth up to three calves. This income is calculated by eq 5

$$In_P = NA_{CalNew} \times Pot \tag{5}$$

where NA_{CalNew} corresponds to the new calves that can be male or female. Pot is the potential value of the calves and is calculated as the difference between the selling price of the yearling and the feeding costs of calves and yearlings.

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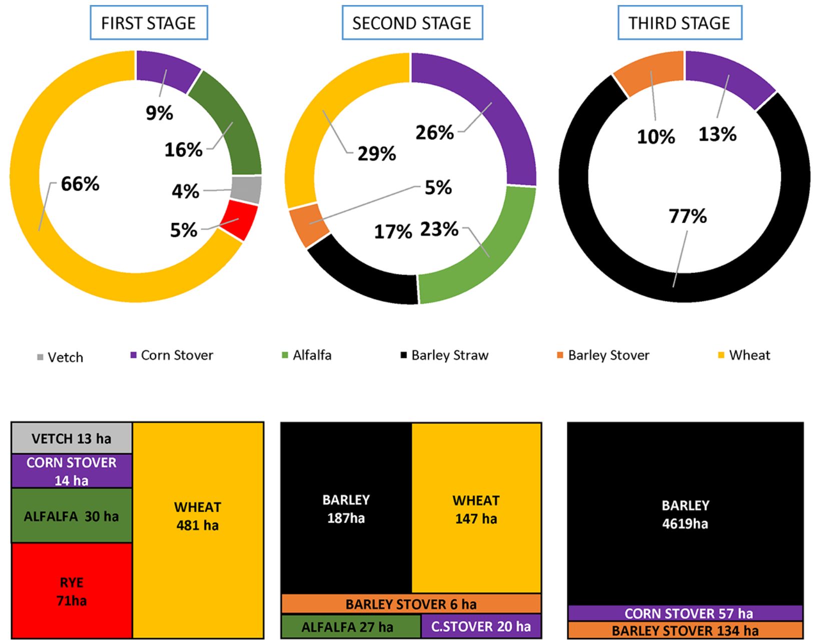

Figure 2. Optimal formulation of the feed and cultivation areas in the economic scenario.

The income obtained from the crops (In_{crops}) is calculated by eq 6

$$In_{Crops} = BarlGn \times Pri_{Barley} + BarlSw \times Pri_{Barley.Straw} + WhtGn \times Pri_{Wheat} + WhtSw \times Pri_{Wheat.Straw} \quad (6)$$

BarlGn and BarlSw correspond to the amount of barley (grain and straw, respectively) that is not used as animal feed and can be sold. WhtGn and WhtSw represent the rest of the wheat plant (grain and straw) that can also be sold. Both crops can be used as animal feed, and therefore the model selects the destination of these crops based on the objective function. The prices, Pri_i, are reported in Table S3 in the Supporting Information.

The income obtained from selling biogas (In_{bio}) is calculated by eq 7

$$In_{bio} = Amt_{Biogas} \times yd_{Biogas} \times Pri_{power} \quad (7)$$

where Amt_{Biogas} is the amount of purified biogas. The yield to the power is assumed to be 40%, and the heat of combustion takes the value of 14 kWh[33] per kilogram of biogas (yd_{Biogas}). Pri_{power} is the sale price of power produced using biogas from livestock manure and its value is 200 €/MWh.[34]

The crop production cost of each ingredient (Cst_j) is the sum of the cost of tillage, sowing, and harvesting (eq 8) (this cost does not include the cost of fertilizer, field, manpower, and storage) and can be found in Table S3 in the Supporting Information.

$$Cst_j = Cst_{tillage_j} + Cst_{sowing_j} + Cst_{harvesting_j} \quad (8)$$

Cst_{growth} is the cost of production of the crop fed to calves (Cst_{Calves}), yearlings ($Cst_{Yearling}$), cows (Cst_{Cow}), and bulls (Cst_{bulls}) (eq 9).

$$Cst_{growth} = Cst_{Calves} + Cst_{Yearling} + Cst_{Cow} + Cst_{bulls} \quad (9)$$

These costs are calculated using the dry matter intake per TU (DMI_t), the number of each type of animal (NA_{calves}, $NA_{yearling}$, NA_{cows}, and NA_{Bulls}), and the crop production cost of the feed ($CstM_t$), which depends on the Cst_j and the proportion of each ingredient "j" in the feed($x_{t,j}$). All-female calves are grown into cows, while male calves are grown into meat. Between TU 0 and TU 6, the animals are calves, between 7 and 20 are yearlings, and between 21 and 72 can be cows or bulls.

The crops profit (Pro_{crops}) is defined by eq 10

$$Pro_{crops} = In_{crops} - Cst_{growth} \quad (10)$$

The rest of the costs are calculated by eqs 11−15. These costs correspond to renting the field needed to grow the crops (Cst_{Field}), the mineral fertilizers ($Cst_{Fertilizer}$), the storage cost of the crops ($Cst_{Storage}$), the cost of labor ($Cst_{Manpower}$), and the auxiliary cost (Cst_{aux}). These costs are not included in Cst_{growth} to facilitate the analysis of results.

$$Cst_{field} = Pri_{rent} \times AreaT \times LC_{animal} \quad (11)$$

$$Cst_{Fertilizer} = Amt_N \times Pri_N + Amt_P \times Pri_P + Amt_K \times Pri_K \quad (12)$$

$$Cst_{storage} = Pri_{storage} \times \left(\sum_t DMI_t\right) \times \frac{LC_{animals}}{LC_{silo}} \quad (13)$$

$$Cst_{ManPower} = Pri_{MP} \times AreaT \quad (14)$$

$$Cst_{Aux} = Cst_{WaterAgri} + Cst_{WaterLiv} + Cst_{water} + Cst_{Supl} + Cst_{Bass} + Cst_{Acid} \quad (15)$$

The field used to grow the crops is rented at a price of 137 €/ha·yr[35] (Pri_{Rent}), while AreaT is the maximum total area used per year. The prices of ammonium nitrate (Pri_N), superphosphate ($Prin_P$), and potassium sulfate ($Prin_K$) are 334, 202, and 353 €/t,[36] respectively. The price of storing the crops ($Pri_{storage}$) is 26 €/t.[37] LC_{silo} is the life cycle of the silo (25 years), while $LC_{animals}$ is the life cycle of the animals (6 years, see Figure 1). The cost of labor is calculated using the price of manpower per unit of area (Pri_{MP}), whose value is 50 €/ha.[38]

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Table 1. Nutrient Balance and Requirement of Fertilizer in the Economic Scenario

scenario		needed (t)			recovered (t)			
objective function	type	N	P	K	N	P	K	fertilizer needed (t)
MinN	needed	212	149	483	121	25	284	1291
MinP		231	102	461	88	24	297	1129
MinK		240	105	459	87	24	291	1185
MaxN		599	258	655	111	25	266	3397
MaxP		562	261	623	115	27	269	3227
MaxK		428	187	715	101	30	229	2666
MinN	recovered	293	127	509	84	26	284	1566
MinP		303	177	583	114	0.3	252	2098
MinK		347	154	589	97	30	204	2055
MaxN		216	177	518	139	25	277	1481
MaxK		405	176	478	102	22	305	2052
MaxP		333	183	569	126	42	260	1920
optimal		328	159	584	95	0.4	264	2109

The auxiliary costs (Cst_{Aux}) correspond to the cost of water in the case of the irrigate crops ($Cst_{WaterAgri}$) (corn is the only irrigate crop considered in this work), water for the beef cattle ($Cst_{WaterLiv}$), nutritional supplement of calcium and phosphorus (Cst_{Supl}), calcium hydroxide (Cst_{Bass}), and sulfuric acid (Cst_{Acid}) necessary to recover nitrogen. Further details are included in the Supporting Information. In addition, a new constraint must be added in the optimization framework to limit the use of the supplement of phosphorus (eq 16)

$$Amt_{supl_t} \leq Pneed_t \qquad (16)$$

where Amt_{Suplt} is the amount of supplement of phosphorus in the TU "t" and $Pneed_t$ is the phosphorus requirement of the beef cattle in the TU "t".

In the multiobjective case, the ε-constraint method is used to include the environmental objective (composite index) into the solution procedure.

3. RESULTS AND DISCUSSION

One thousand calves are used as a starting point (500 females and 500 males). The female calves grow into cows, producing three new animals (which can be two males and one female and vice versa). Two results are presented, the optimal economic and the multi-objective, considering both the economic and the environmental objectives. It is considered that the soil has an average concentration of nutrients.

3.1. Optimal Economic Solution. After carrying out an analysis of the feed formulations in each of the time units during the life cycle of the animals, it is observed that the main changes occur in time units 21 and 37, corresponding to the first and second gestations. Therefore, the average formulations between the time units 0−20 (first stage), 21−37 (second stage), and 38−72 (third stage) can be used, which can be seen in Figure 2. During the first stage, the main ingredients are wheat, alfalfa, and corn stover. For the first stages of growth of the animals, the amount of food ingested is small and the energy needed for growth and maintenance is high; therefore, it is necessary to use high-density energetic crops (concentrate intakes). Among the most energetic concentrates are corn and wheat grain (see Table S4 in the Supporting Information). Corn has a lower crop production cost than wheat (0.02 vs 0.04 €/kg), but as it is an irrigated crop, water consumption must also be considered. Therefore, with the cost of water, the production cost of corn reaches 0.11 €/kg, which is higher than that of wheat. As a result, the consumption of wheat is prioritized. Rye is also used as an energy crop. The consumption of alfalfa, corn stover, and vetch provides the largest fraction of the minerals required. Nevertheless, calcium and phosphorus supplements are necessary to meet the nutritional requirement (63 t), which represent 0.64% of the total food of all animals.

When the animals are older, along the second stage, the DMI is higher and the energy required per mass of food is lower; therefore, the feed formulation tends to use less concentrates. In addition, during this second stage, the cows are gestating and begin to produce milk, requiring a larger amount of minerals and proteins. The feed formulation changes toward a higher concentration of forage compared to the previous stages (71 vs 29%) since forage has a higher concentration of minerals than the concentrated ingredients. In addition, changes are observed in the type of forage. Vetch is replaced by barley straw. This is because a lower amount of energy is required in this section, which can be supplied by straw.

In the third stage, a gradual increase in the presence of forage, mainly barley straw, is observed in the formulation of the feed, reaching values of 100%. The use of barley straw involves the production of barley grains since both come out of the barley crop. The barley grains can be sold, obtaining an additional income. For this reason, it is the main crop produced.

The area required for the cultivation of each of the crops can also be seen in Figure 2. In the first stage, most of the cultivated area is devoted to wheat, with a small area used for the cultivation of rye, alfalfa, corn stover, and vetch. From the second stage, the cultivation of rye, vetch, and wheat are displaced by the cultivation of barley due to the less need for concentrates (since only barley straw is used for animal food) and the large benefit that the sale of barley grain provides. This trend is consolidated in stage 3 where the main crop is barley. Furthermore, if the necessary cultivation area is analyzed year by year, it can be concluded that the last years require a much larger area than the first ones since the animals need less food when they are younger. Since the maximum area needed is rented from the first year, but it is not used for animal feed, it can be used to obtain an additional profit by selecting a crop that does not cause a strong deterioration of the soil. However, this possibility has not been considered in this work, to focus the study on livestock.

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A sensitivity study is carried out by changing the objective function to minimize and maximize the nitrogen, potassium, and phosphorus needed (N_{nd}, K_{nd}, and P_{nd}) and nitrogen, potassium, and phosphorus recovered (N_{rec}, K_{rec}, and P_{rec}), respectively, instead of the profit (see eq (129)−(131) and Table S3 in the Supporting Information). In addition, the results of the economic scenario are also included in this study as "optimal". The results are shown in Table 1. It is observed that the amount of phosphorus recovered is extremely low in the "optimal" case. This is because the model prioritizes the reduction of fertilizer consumption by using crops that consume fewer nutrients. In the case of phosphorus, the most used ingredient, barley straw, is one of the crops with the lowest phosphorus content (see Table S4 in the Supporting Information), so its content in the feces is low. For this reason, it is necessary to use phosphorus supplements to compensate for this deficiency in some stages.

A correct selection of ingredients in the feed and, therefore, of the crops, can reduce the amount of additional N, P, and K down to 2.85, 2.55, and 1.55 times, respectively. The margin of difference between the maximum and minimum values of N and K recovered is much smaller. In this case, it is possible to increase the amount of N 1.65 times and 1.49 times in the case of K. In the case of phosphorus, the amount varies between almost total adjustment with the requirements of the animal, as it occurs in the optimal case, up to almost 40 tons recovered. This indicates that the correct selection of crops, together with rational use of feed supplements, could substantially reduce the amount of this nutrient in livestock waste.

On the one hand, the crops selected in the economic scenario show a consumption in the middle of the maximum and the minimum value in the three nutrients. This is so because there is a balance between the crop production cost, the fertilization costs, and the sales income. On the other hand, in the case of nutrients recovered, there are clear differences. Nitrogen is close to the minimum since the selected crops do not allow a higher recovery and priority is given to reducing the necessary nitrogen versus increasing the nitrogen recovery, to reduce the difference between the two and thus the contribution of nitrogen fertilizer. Despite this, the nitrogen recovered represents 29% of the total required. Finally, the amount of potassium recovered is situated between the maximum and minimum possible values, representing 45% of the necessary value.

3.2. Multiobjective Feed Design. First, the upper and lower limits of the three different indexes are calculated to compute the composite index, CI. These values are shown in Table S2 in the Supporting Information. The relationship between the composite index and the maximum profit obtained during the complete cycle of the animal can be seen in Figure 3. There are two regions clearly delimited by a point from which profits begin to fall sharply, 0.28. Therefore, three scenarios can be considered, the economic (CI = 0.46), the multiobjective (CI = 0.28), and the eco-friendly (CI = 0.18).

A techno-economic evaluation is carried out to understand the change in the slope, and the main results are presented in Figure 4. The case of the nonintegrated system is also included in the comparison. The incomes or costs that have the same value for all the scenarios considered are not included in the figure, but they can be found in Table S6 in the Supporting Information, together with a more detailed information of this evaluation.

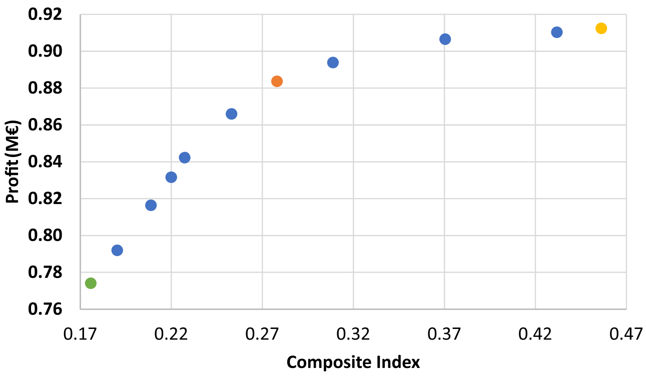

Figure 3. Pareto curve for the design of the feed formulation (green: ecofriendly scenario, orange: multi-objective scenario, and yellow: economic scenario).

Between the economic scenario and the multiobjective one, a slight decrease in profit down to 3% is observed, but a large decrease in the composite environmental index of 39% is achieved, which turns this point into a tradeoff between the cases of economic and environmental optima. The decrease in the profit is limited because the loss in the profit from the crops (the difference between the income for the sale of the crops and the costs of their cultivation, see eq 10) is partially offset by the savings in fertilizer costs, the renting cost of the field, and the manpower cost due to the changes in the crops and the area used. There are three reasons for the drop in income from the sale of crops: the reduction of the cultivation of barley, the use of a part of the barley grains for animal feed, and the reduction of the cultivation of wheat, whose straw is also sold. In addition, the change of crops from corn stover (0.019 €/kg) to barley stover (0.058 €/kg) increases the crops' production cost.

A faster decrease in profit is observed with respect to the composite index between the multiobjective and eco-friendly scenarios. In this region, 36% of the total variation in CI corresponds to 80% of the total variation in profit.

This occurs due to two important changes in the formulation of the feed. Wheat and rye are replaced by corn, which requires an artificial water supply, increasing the auxiliary costs. In addition, there is a significant decrease in income from crop sales due to lower barley production (13,524 t vs 15,124 t) and wheat substitution. These changes reduce fertilizer consumption (1323 t vs 1651 t) and, therefore, the fertilizer cost. Nevertheless, the savings in fertilizer cost does not compensate for the increase in the auxiliary costs and the decrease in the income from the crops. Therefore, the drop in the profit is so prominent between these scenarios.

The nonintegrated case can be seen as an extreme case of the economic scenario of the integrated system since it has a higher benefit (1.03 M€) than any of the integrated scenarios (11.6% higher than the economic case and 14.5% higher than the multi-objective case) but also a larger environmental impact, with a composite index of 0.74, 76% higher than the eco-friendly case.

A difference can be observed between the profit of the crops in the integrated and nonintegrated cases. The main reason is that to produce straw in the integrated cases, it is necessary to cultivate the cereal and include the crop production cost. Later, the straw is used for animal feed while the grain can be sold, obtaining an income that compensates for the crop production

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Figure 4. Techno-economic analysis of the different considered scenarios.

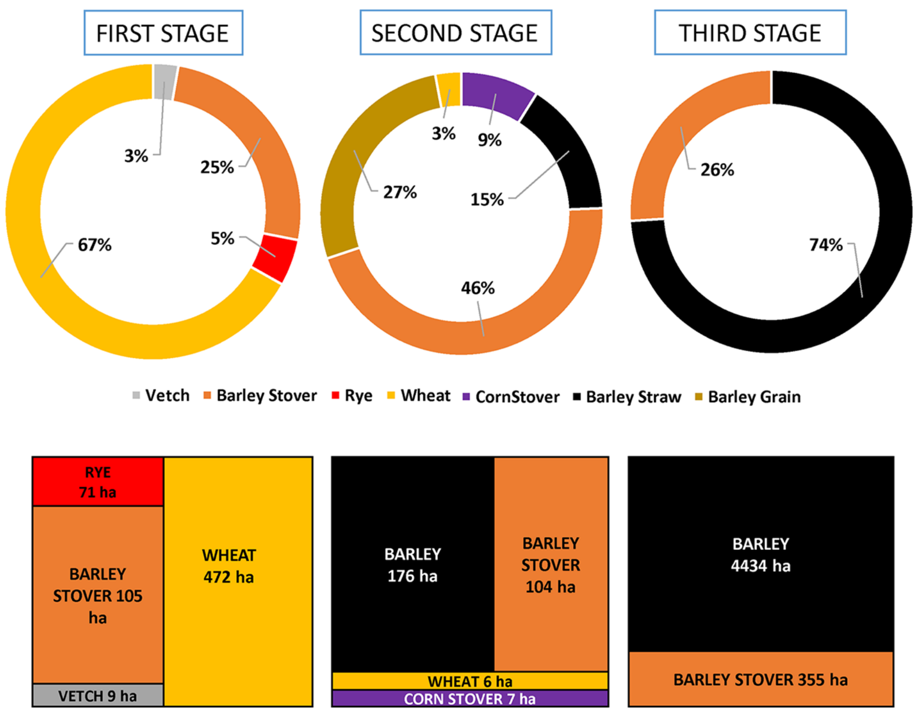

Figure 5. Optimal formulation of the feed and cultivation areas in the multi-objective scenario.

cost. In fact, in the three integrated cases, the income from selling the crops outweighs the crop production costs, resulting in a profit. Given that the nonintegrated case does not require the cultivation of cereal to obtain the straw, because it is bought directly from a distributor, acquisition costs are lower (0.035 €/t), despite these costs including the costs of fertilizer, storage, labor, and land. For this reason, these costs are equal to 0 for the nonintegrated case, as can be seen in Figure 4. However, the income from the crops is also zero, and therefore, the crop profit is negative. However, the total cost of the integrated scenarios is higher than the costs of the nonintegrated scenario due to the rest of the costs, which do not include the crop production cost (field, fertilizer, storage, manpower, supplement, and auxiliary), making the non-integrated case the most profitable from an economic point of view. This result is in line with the current situation of both industries, which tends toward a specialization of crops to seek the highest economic performance through economies of scale. However, the environmental impact of the nonintegrated scenario is the highest of all the cases presented, with fertilizer consumptions 19% higher with respect to the economic scenario, 36% higher than the multiobjective scenario, and 49% with the eco-friendly scenario. In addition, the GWP per consumer benefit (CB), that is, 1 kg of consumed, boneless, edible beef in the United States, is calculated corresponding to 29% of the live weight.[39] The total weight of the yearlings and

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cows slaughtered is 440 t, and therefore, the CB is 127.6 t. The values of GWP for the cases considered in this work can be found in Table S6 in the Supporting Information. The values obtained are 5.27, 7.87, 10.1, and 13.73 $kgCO_2$ eq per CB for the eco-friendly, multi-objective, economic, and nonintegrated cases, respectively. These values are comparable with others found in the literature such as 8 and 10 $kgCO_2$ eq/CB.[39]

In the case of the breeding of bulls, only the economic impact has been considered because the environmental impact is not significant compared to that of cows (2% in the footprint and 1.7% in the eutrophication potential), and therefore, there is no additional interest in finding a tradeoff between the economic and environmental optimum. For this reason, the cost is the same in all three scenarios.

For the multiobjective case, the optimal formulations for each stage can be found in Figure 5. It is observed that the main changes occur at the same points as in the case of the economic optimum, so the same procedure described in the previous section is used here.

In the first months of the life of the animals, the results of the multi-objective scenario are slightly different from the economic optimum. On the one hand, alfalfa, and corn stover are completely replaced by barley stover since this crop has a lower requirement of phosphorus and potassium.

Similar to the optimal economic case, during the second growth phase, an increase in the amount of forage consumed is observed (70 vs 28%), which is supplied by a mixture of corn stover, barley straw, and barley stover. The most important change is the use of barley grain as an energy crop (concentrate) instead of wheat, saving area and fertilizer. This causes a reduction in the income because this part of the barley crop was destined for sale in the economic case, and in this case, at least a fraction of it is used for animal feed.

In the last stage, the energy needs are even lower and the nutritional and mineral needs are higher. Therefore, the amount of forage is higher (100%) and the barley grain and wheat are totally replaced by barley straw and barley stover. The fraction of barley straw is lower than in the economic case, and therefore, the sales income is also lower.

In Figure 5, the areas needed for each crop for the three stages can also be observed. The discussion is similar to the analysis of the crop portfolio. The total area and the fertilizer consumption are lower than in the economic case and, therefore, the environmental impact is also lower.

A sensitivity study is also performed for this case. Unlike the values presented in Table 1 (economical optimum), it can be observed that the optimal values for the fertilizers tend more toward the minimum with a value of 284 tons of nitrogen, 125 tons of phosphorus, and 513 tons of potassium since the environmental impact has been limited compared to the economic case and a part of the economic benefit must be sacrificed to reduce the amount of fertilizer needed. In the case of nutrients recovered, 86 tons of nitrogen and 290 tons of potassium are recovered, which represent 30 and 56% of the nitrogen and potassium needed, respectively. These values are consistent with other studies in literature, with values of 23% for nitrogen[19] and 50% for potassium.[40]

4. CONCLUSIONS

In this work, an integrated model has been developed to optimize self-sufficient intensive livestock systems considering the management of waste and the crops necessary for the nutrition of the animals. Waste treatment and nutrient recovery favor a circular economy. The techno-economic analysis of the farm has been carried out and a composite index has also been developed, including the effect on the atmosphere and the water resources of the fertilizers used, as well as the water consumed, to evaluate the environmental impact.

The results show that it is possible to significantly reduce the environmental impact down to 62% of a livestock farm by assuming a loss of 14% (between the nonintegrated and the multiobjective case) in the profit, that can be compensated for with some incentives oriented to the development of sustainable operation of livestock facilities.[41] Since in the integrated cases, the nutritional and mineral requirements can be covered by a large variety of ingredients, the appropriate selection of crops allows reducing the environmental impact down to 39%, keeping the reduction in the profit within 3% (between the economic and multi-objective cases of the integrated systems), opting for a tradeoff between the economic and environmental objectives. In addition, the model designs a fertilizer that, for the selected crops, balances the amount of nutrients supplied and required, reducing the possibility of overfertilization of the land.

The sensitivity analysis shows that it is possible to substantially reduce the environmental impact by minimizing the nutrients needed for the crops, as these can be reduced to three times in some cases. Furthermore, by correctly adjusting the phosphorus supplied through feed supplements and crops, it is also possible to substantially reduce its presence in the residues. Finally, note that an important fraction of the nutrients, up to 41%, can be recovered from the animal feces and the crop surpluses have been sold to improve the economic performance of the system.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acssuschemeng.1c04014.

Models for estimating nutritional and energy needs of the cattle, waste treatment, and nutrient recovered systems; fertilizer formulation; environmental impact index; crop properties; and detailed calculations of the solution procedure and techno-economic evaluation of the considered scenarios (PDF)

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Notes

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