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The finishing stage in swine production: influences of feed composition on carbon footprint

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Abstract Several studies in swine feed composition have demonstrated that protein levels may be modified without significant changes in meat quality in terms of carcass, lean and back fat yield. However, this variation may change certain technical indicators, such as daily weight gain. The aim of this study was to calculate the carbon footprint of the finishing stage in swine production considering four scenarios of feed composition (P18, P16, P15 and P13). The life cycle assessment methodology was applied with a life cycle inventory based on reports in the literature. The feed composition used in P18 (no soybean hulls or maize starch) had the best environmental performance for global warming per kilogram of feed. However, when evaluating the life cycle of finishing swine, P16 (containing soybean hulls, maize starch and synthetic amino acids) exhibited better environmental results; the feed used in this scenario had better technical indicators (in terms of daily weight gain), thereby reducing the feed amount for finishing swine. Using the feed composition for swine P16, the impact may be reduced by an average of 12 % compared with P13 (a high level of soybean hulls, maize starch and synthetic amino acids).

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1 Introduction

Brazilian swine production in 2013 had an average herd of 38.578 million pigs, making it the fourth largest swine producer (and exporter) in the world, as reported by the United States Department of Agriculture (USDA 2013). In this context, the state of Santa Catarina has greater prominence, as it is the largest Brazilian swine producer. This southern state has approximately one-fifth of the national herd, concentrated mainly in the western region (Brasil 2011).

Generally, swine production has a poor image in society (Basset-Mens and van der Werf 2005) due to environmental risks associated with the high density of swine per square meter and impacts that have influences on the quality of life around population centers, such as odors and disease vectors. As with any other human activity, livestock generates environmental impacts, and this particular activity is a potential impact concentrator (Dalla Costa et al. 2008; Oliveira 2004). The origin of this impact and its meaning to the environment are not always easily understood; examples include eutrophication of aquatic ecosystems as a consequence of the manure management system and global warming due to the emission of greenhouse gases (GHG) from the production chain.

In the state of Santa Catarina, due to the large production of swine, great efforts have been directed by the government to control and decrease the environmental impacts of this activity. The Brazilian government body that performs agricultural and livestock research (EMBRAPA) has developed projects that aim to mitigate these impacts and ensure that swine producers comply with current environmental laws. Despite of EMBRAPA efforts, however, one may say that the process of impact generation should be further discussed.

Life cycle assessment (LCA) was developed to quantify environmental impacts from product systems through several stages and has been shown to feasibly analyze the impacts of agricultural systems (van der Werf and Petit 2002). This methodology allows the evaluation of environmental performances of scenarios of interest, identification of hot-spots in the production chain and comparison of alternatives, all in an effort to improve the production system (Baumann and Tillman 2004; Wenzel et al. 2001). LCA enables a clear understanding of the life cycle of the analyzed system, providing a basis for strategic and sustainable decisions and meeting the requirements of domestic and foreign markets.

Previous LCA research on swine production demonstrated that feed is a critical point in the production chain, especially as it relates to crop cultivation (Basset-Mens and van der Werf 2005; Dalgaard 2007; Elferink et al. 2008; Kingston et al. 2009; Kool et al. 2009; Nguyen et al. 2011; Spies 2003; Williams et al. 2006). Diet therefore has a direct influence on impact generation, where each component has a unique production chain and different method of assimilation by the animals in the finishing stage. Due to this influence on the period required for the animal to reach its final weight, feed composition may change the quantity of feed required by the animals, modifying the characteristics of the manure and consequently the emissions produced. The search for new alternatives in animal diets therefore has an extremely important role in sustainable development in the sector. Several authors (Eriksson et al. 2005; Ferreira et al. 2005; Oliveira et al. 2006; Orlando et al. 2001, 2007; Vidal et al. 2010) have already conducted studies varying feed composition in several stages of swine production and concluded that it is technically possible to change the content of crude protein (CP) without significantly altering meat quality in terms of carcass yield, lean yield and thickness of back fat.

The aim of this study was to calculate the carbon footprint (CF) of the finishing stage in swine production considering four scenarios of feed composition (P18, P16, P15 and P13), where animal diet varied according to the level and source of protein.

2 Materials and methods

This study was conducted in accordance with LCA standards issued by the International Organization for Standardization (ISO), NBR ISO 14040 (2009a) and NBR ISO 14044 (2009b).

2.1 Goal and scope definitions

We define as a functional unit (FU) 30 kg of live weight gain in the finishing stage. The boundaries begins with the grain production, drying and processing into feed, while for animal rearing, we consider a swine with an initial weight of 70 kg in the finishing stage and end at the slaughterhouse gate, piglet production and the weaning-to-growing stage was excluded, as shown by the dotted lines in Fig. 1. The concept of 'growing-finishing' pigs describes the increase in weight from 25 kg to market weight (between 100 and 120 kg in Brazil). The age range is from approximately 8 to 22–26 weeks, with pigs spending approximately 8–10 weeks in a growing unit until they reached approximately 70 kg and the last 8–10 weeks in a finishing unit. In terms of outputs, the boundary comprises animal emissions to the air, manure management and manure soil application (counted as avoided fertilizer, see Fig. 1). Within these boundaries, we used background process from the ecoinvent® database for fertilizer production, electricity and transport.

We assume a farm located in Concordia, a major swine-producing city in Santa Catarina, with animal rearing in a building with a concrete floor. During the finishing period, the consumption of electricity, water, food and building materials for the facility were based on (Brazilian Agroindustry; Hörndahl 2008; Tavares 2012; Vidal et al. 2010). The construction aspects were based on data collected by the swine farming industry, including building materials.

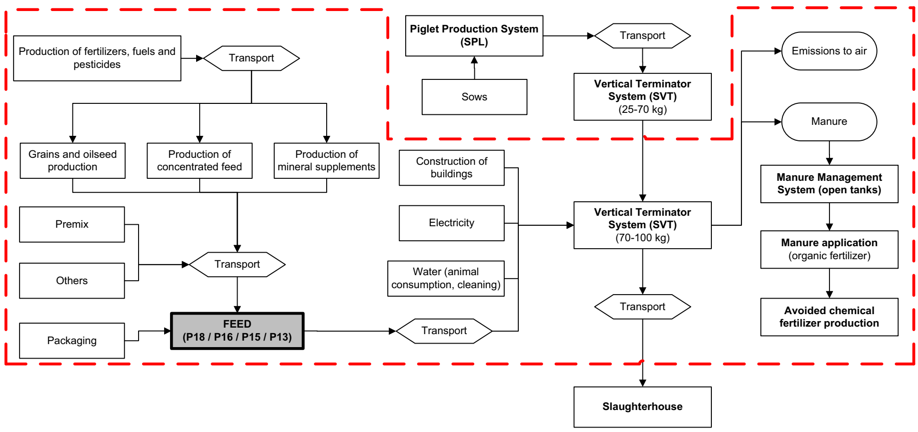

Fig. 1 Inputs, outputs and boundaries of the production system

For manure management, a system was considered in which manure was stored in downspouts outside the building and then transferred by gravity to open tanks. After 120 days of storage, stabilized manure was applied to soil as organic fertilizer. This approach considers manure as a by-product of the ‘finished swine’ system and would imply an allocation of environmental impacts. To avoid this procedure, we considered the substitution method, which represents the environmental benefits of avoiding the manufacture of the product replaced by use of manure (Dalgaard 2007), as oriented by the standard (ABNT 2009b). In this case, manure avoids the production and use of chemical fertilizer. The same approach was used by several authors (Basset-Mens and van der Werf 2005; Dalgaard 2007; Kingston et al. 2009; Kool et al. 2009; Nguyen et al. 2011; Williams et al. 2006).

The avoided fertilizer was modeled considering an average combination of urea, triple superphosphate and potassium chloride equivalent to the fertilizing potential of manure (urea contains 45 % N, triple superphosphate 42 % P_2O_5 and KCl has 60 % K_2O). To estimate the amount of NPK fertilizer avoided, we used efficiency rates of 0.8, 1 and 1 for NPK, for urea, triple superphosphate and KCl, respectively. These indices are used because the concentrations and subsequent release of nutrients in the soil from organic fertilizers are highly variable. Therefore, the amount of these nutrients that will actually be available in the first crop after manure application must be calculated (SBCS 2004). In mathematical terms, the avoided fertilizer (F) is calculated using the following expression (Eq. 1):

$$F_i = \frac{q_i}{\sum_i^n q_i} \times \left(\frac{\frac{\sum_i^n q_i}{0.45} \times 0.8 + \frac{\sum_i^n q_i}{0.42} \times 1 + \frac{\sum_i^n q_i}{0.60} \times 1}{3} \right) \quad (1)$$

where q_i is the amount of the ith nutrient (i.e., N, P_2O_5 and K_2O—Table 4).

A comparative LCA was used to quantify the environmental performance of the scenarios, labeled P18, P16, P15 and P13, which differ only by the compositions of feed involved in the finishing period (source and protein levels) and their influences on animal production. The labels refer to the protein percentage of each feed, as shown in Table 2. Feed composition and technical indicators such as daily feed consumption, daily weight gain, feed conversion rate, carcass yield and meat quality were based on Vidal et al. (2010), as shown in Table 3.

2.2 Inventory

2.2.1 Inputs

For soybean and maize production, we used data from Prudêncio da Silva et al. (2010)and Alvarenga et al. (2012). Soybean processing was based on Prudêncio da Silva et al. (2010), modified to include the production of by-product ‘soybean hulls.’ Economic allocation was used with values described by Moreira et al. (2009), which were in accordance with the Cooperativa Agroindustrial Capal, May 2012. Maize starch was based on Nguyen et al. (2012).

Diet P18, with the highest level of CP, did not include supplemental synthetic amino acid (SAA) The required amino acids for this diet were from maize and soybeans. For the remaining diets (P16, P15 and P13), the protein levels were progressively reduced and supplemented with SAA (L-lysine, DL-methionine, L-threonine, L-tryptophan and L-valine, Table 1). Hence, the nutritional value of the ileal digestible lysine was constant in the four diets (0.810), while the others SAA varied (Vidal et al. 2010) as displayed in Table 2. Data

Table 1 LCI for feed production (per kg of feed)

<table>
<tr><th></th><th>P18</th><th>P16</th><th>P15</th><th>P13</th></tr>
<tr><td>Composition (g)[a]</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Maize</td><td colspan="4">708.44</td></tr>
<tr><td>Soybean meal</td><td>266.96</td><td>228.97</td><td>189.15</td><td>149.05</td></tr>
<tr><td>Soybean oil</td><td colspan="4">2.63</td></tr>
<tr><td>Maize starch</td><td>0.00</td><td>28.47</td><td>57.79</td><td>79.63</td></tr>
<tr><td>Soybean hulls</td><td>0.00</td><td>6.23</td><td>12.76</td><td>19.33</td></tr>
<tr><td>$Ca(HPO_4)$</td><td>7.74</td><td>8.10</td><td>8.47</td><td>8.84</td></tr>
<tr><td>Limestone</td><td>5.44</td><td>5.27</td><td>5.20</td><td>5.13</td></tr>
<tr><td>Salt (NaCl)</td><td>3.54</td><td>3.56</td><td>3.58</td><td>3.60</td></tr>
<tr><td>Inert[a]</td><td>0.00</td><td>1.77[a]</td><td>3.00[a]</td><td>10.73[a]</td></tr>
<tr><td>Vitamin premix</td><td colspan="4">3.00</td></tr>
<tr><td>Mineral premix</td><td colspan="4">1.00</td></tr>
<tr><td>Growth promoter[a]</td><td colspan="4">1.00[b]</td></tr>
<tr><td>Antibiotics[a]</td><td colspan="4">0.25[b]</td></tr>
<tr><td>DL-methionine</td><td>0.00</td><td>0.09</td><td>0.54</td><td>0.99</td></tr>
<tr><td>L-lysine</td><td>0.00</td><td>1.20</td><td>2.46</td><td>3.72</td></tr>
<tr><td>L-threonine</td><td>0.00</td><td>0.02</td><td>0.68</td><td>1.34</td></tr>
<tr><td>L-tryptophan</td><td>0.00</td><td>0.00</td><td>0.07</td><td>0.30</td></tr>
<tr><td>L-valine</td><td>0.00</td><td>0.00</td><td>0.00</td><td>0.18</td></tr>
<tr><td>Packaging (polypropylene) (g)</td><td colspan="4">4.00</td></tr>
<tr><td>Grain transportation (t km)</td><td>86.32</td><td>86.03</td><td>85.68</td><td>84.65</td></tr>
</table>

[a] Feed composition based on Vidal et al. (2010)

[b] Not considered in this LCA due to lack of data

Table 2 Nutritional values of the feed diets (% of natural matter)

<table>
<tr><th></th><th>P18</th><th>P16</th><th>P15</th><th>P13</th></tr>
<tr><td>Metabolized energy (kcal kg^{-1})</td><td colspan="4">3,230</td></tr>
<tr><td>Crude protein (%)</td><td>17.95</td><td>16.45</td><td>14.95</td><td>13.45</td></tr>
<tr><td>Calcium (%)</td><td colspan="4">0.480</td></tr>
<tr><td>Available phosphorus (%)</td><td colspan="4">0.248</td></tr>
<tr><td>Sodium (%)</td><td colspan="4">0.160</td></tr>
<tr><td>Crude fiber (%)</td><td colspan="4">2.670</td></tr>
<tr><td>Ileal digestible lysine (%)</td><td colspan="4">0.810</td></tr>
<tr><td>Ileal digestible methionine + cysteine (%)</td><td>0.536</td><td>0.503</td><td>0.502</td><td>0.502</td></tr>
<tr><td>Ileal digestible methionine (%)</td><td>0.264</td><td>0.251</td><td>0.270</td><td>0.294</td></tr>
<tr><td>Ileal digestible threonine (%)</td><td>0.598</td><td>0.543</td><td>0.543</td><td>0.543</td></tr>
<tr><td>Ileal digestible tryptophan (%)</td><td>0.189</td><td>0.169</td><td>0.154</td><td>0.154</td></tr>
<tr><td>Ileal digestible valine (%)</td><td>0.761</td><td>0.690</td><td>0.620</td><td>0.560</td></tr>
</table>

Nutritional values based on Vidal et al. (2010)

Table 3 Technical indicators for the finishing swine stage (per swine unit)

	P18	P16	P15	P13
Slaughter weight (kg)	100.00	100.00	100.00	100.00
Daily feed consumption (kg)	3.13[a]	2.82[a]	3.09[a]	3.01[a]
Daily weight gain (kg day^{-1})	1.05[a]	1.04[a]	1.12[a]	1.02[a]
Feed conversion rate (g g^{-1})	3.01[a]	2.72[a]	2.76[a]	2.99[a]
Time (day)[b]	28.57[b]	28.85[b]	26.79[b]	29.41[b]
Carcass yield (%)	69.59[a]	70.19[a]	69.57[a]	70.25[a]
% of lean meat	57.01[a]	56.90[a]	57.13[a]	56.93[a]
Back fat thickness (mm)	14.24[a]	13.50[a]	13.37[a]	13.78[a]

[a] Data based on Vidal et al. (2010)

[b] Estimated values for a swine in finishing with 70 kg of initial weight to reach 100 kg of final weight, considering the daily weight gain from Vidal

for the life cycle inventory (LCI) of lysine, threonine and methionine were based on Nguyen et al. (2012). For tryptophan and valine, we assume the same LCI as from lysine production.

Distances for the major feed components described in Table 1, such as maize and soybeans, were based on the real cities involved in the construction of scenarios based on Spies (2003), reflecting the reality in the western state of Santa Catarina. Thus, it considered 850 km of transportation by lorry truck from the grain producer to the feed factory and then 35 km from the feed factory to the swine producer. Feed was packed in raffia bags with a capacity of 50 kg, consisting of 0.2 kg of polypropylene per package.

On farm, the feed intake that is directly influenced by the finishing period and required for the animal to reach 100 kg was estimated through feed conversion rates and varied according to the feed applied (differences in weight gain and finishing periods can be found in Table 3).

With regard to water used for animal consumption, pen cleaning, nebulization, production and manure composition, we used data from Tavares (2012), which represent the reality of swine farms in Concordia-SC, while energy consumption during the process was based on data from Hörndahl (2008).

Data for on-farm buildings were estimated by considering a lifespan of 30 years, based on data by the agroindustry. The LCI is listed in Table 4.

2.2.2 *Outputs*

Methane (CH_4) and nitrous oxide (N_2O) emissions generated from animal rearing (including manure management) were calculated according to IPCC (2006). For enteric fermentation emissions, 1.50 kg of CH_4 pig^{-1} $year^{-1}$ was assumed, which represents the emissions in developed countries (IPCC 2006). The genetic source of animals produced in vertically integrated production systems in Brazil is from European companies. As they have controlled feeding strategies, Brazilian swine show similar enteric fermentation rates to European ones.

For CH_4 emissions from manure storage, we used 'Tier 2' from IPCC, with a methane-producing capacity (B_0) of 0.29 m^3 CH_4 $(kg\ VS)^{-1}$, considering a methane conversion factor of 0.42. Regarding the N-related emissions, we assume no direct N_2O emissions because we considered a slurry tank without natural crust cover. Indirect N_2O emissions due to NH_3 and NO_x volatilization (both in storage and manure application) and NO_3 leaching (specific for manure application) were calculated considering the default emission factors and N losses from IPCC (2006). For manure, besides the amount produced for each feed (based on the period of weight gain), we also considered manure independently from

Table 4 LCI for the finishing swine stage (per functional unit)

	P18	P16	P15	P13
Inputs				
Composition (g)[a]				
Water consumption (m3)	0.217	0.219	0.203	0.223
Water for pen cleaning (L)	15.87	16.02	14.88	16.33
Water nebulization (L)	1.873	1.891	1.756	1.928
Electricity (kWh)	5.102	5.151	4.783	5.252
Feed consumption (kg)[a]	90.30[a]	81.60[a]	82.80[a]	89.70[a]
Swine transport (tkm)	5.00	5.00	5.00	5.00
Building material				
Cement (kg)	6.56E-02	6.62E-02	6.15E-02	6.75E-02
Lime (kg)	3.44E-02	3.47E-02	3.23E-02	3.54E-02
Sand (kg)	4.21E-01	4.26E-01	3.95E-01	4.34E-01
Gravel (kg)	5.73E-01	5.78E-01	5.37E-01	5.90E-01
Water (L)	6.28E-02	6.34E-02	5.88E-02	6.46E-02
Bricks (kg)	2.45E-02	2.47E-02	2.30E-02	2.52E-02
Concrete blocks (kg)	1.49E-01	1.51E-01	1.40E-01	1.54E-01
Metallic tile (kg)	2.42E-02	2.45E-02	2.27E-02	2.49E-02
Steel cable (kg)	7.68E-04	7.75E-04	7.20E-04	7.91E-04
Steel bars (kg)	4.49E-03	4.54E-03	4.21E-03	4.63E-03
Polypropylene curtains (kg)	2.30E-04	2.32E-04	2.16E-04	2.37E-04
Wood (m^3)	9.89E-06	9.99E-06	9.27E-06	1.02E-05
Doors for pens (kg)	3.39E-03	3.42E-03	3.17E-03	3.49E-03
Water pipe (m)	6.07E-04	6.13E-04	5.69E-04	6.25E-04
Sewage pipe (m)	5.50E-04	5.55E-04	5.15E-04	5.66E-04
Wooden door (m^2)	2.41E-05	2.43E-05	2.26E-05	2.48E-05
Water tank (pc)	2.17E-06	2.20E-06	2.04E-06	2.24E-06
Outputs				
Manure (m^3)	0.1294	0.1307	0.1213	0.1332
Manure N (ex-housing/ ex-storage) (kg)	0.7361/0.3828	0.7432/0.3865	0.6901/0.3589	0.7578/0.3940
Manure P_2O_5 (kg)[b]	0.3527	0.3561	0.3307	0.3631
Manure K_2O (kg)[b]	0.3088	0.3118	0.2895	0.3179
In housing emissions				
CH_4 (enteric fermentation) (kg)	0.1174	0.1185	0.1101	0.1209
NH_3 (kg)	0.1060	0.1070	0.0994	0.1091
In storage emissions				
CH_4 (kg)	0.4830	0.4877	0.4528	0.4972
N_2O (kg)	0.0056	0.0056	0.0052	0.0057
NH_3 (kg)	0.0221	0.0223	0.0207	0.0227
On field emissions				
N_2O (kg)	0.0078	0.0078	0.0073	0.0080
NH_3 (kg)	0.1192	0.1203	0.1117	0.1227
Copper (kg)	0.0039	0.0039	0.0036	0.0040

Table 4 continued

	P18	P16	P15	P13
Zinc (kg)	0.0073	0.0074	0.0069	0.0076
Avoided fertilizer production				
From manure N	0.7432	0.7503	0.6968	0.7651
From manure P	0.6848	0.6914	0.6420	0.7049
From manure K	0.5996	0.6054	0.5622	0.6173

[a] Estimated values for a swine in finishing with 70 kg of initial weight to reach 100 kg of final weight, considering the feed conversion rate from Vidal et al. (2010)

[b] Values of *P* and *K* in manure were from Tavares (2012)

feed composition, with constant characteristics with values from Tavares (2012). In this sense, the volatile solids (VS) were 0.21 kg VS animal^{-1} day^{-1}, while values for nitrogen excretion are shown in Table 4.

Other emissions derived from the animal manure management system, such as ammonia, zinc and copper, were calculated based on emission factors according to Gac et al. (2006) and Tavares (2012). Avoided fertilizer was estimated using Eq. (1) and values from Table 4. Finally, for the main product, we assumed a transport distance to the slaughterhouse of 50 km with a diesel truck. LCI for the finishing swine stage are listed in Table 4.

2.3 Life cycle impact assessment

The impact assessment method was the CML-IA, using a midpoint approach to facilitate the understanding and identification of impact origins without adding subjectivity to the final values. Although the method allows the evaluation of up to 12 impact categories, we chose to assess only the global warming potential (GWP100), which identifies GHG emissions using the IPCC characterization model in kg CO_2 equivalent, also known as the CF. The characterization factors were according to the fifth report of IPCC (2013), considering 30 and 28 kg of CO_2 equivalent per kg of fossil and biogenic methane (CH_4), respectively, and 265 kg CO_2 equivalent per kg of nitrous oxide (N_2O).

3 Results and discussion

For interpretation, we first analyzed the CF of 1 kg of each feed composition and subsequently emissions from only enteric fermentation and waste management (animal production), which is known in this study as emissions from livestock during the finishing period (i.e., on-farm emissions); finally, we assessed the entire system (FU analysis) with a final comparison between the scenarios.

3.1 Feed carbon footprint

Analysis of the impact from the production of 1 kg of each feed indicates that the feed applied in P13 has the highest emission of GHG, while feed P18 showed the best environmental performance, decreasing by 9.3 % or 0.06 kilograms of CO_2 equivalent in comparison with P13, as shown in Fig. 2. In absolute value of CO_2 equivalent, 1 kg of feed

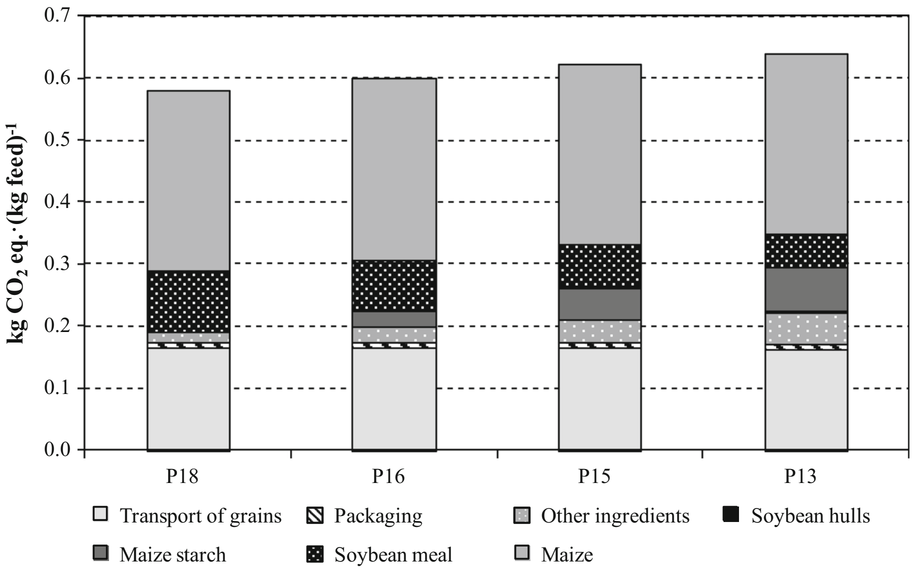

Fig. 2 Carbon footprint of 1 kg feed

P13 emits 0.64 kg after production and delivery on the farm (Concórdia), while P15, P16 and P18 emit 0.62, 0.60 and 0.58 kg, respectively.

Analysis of feed components indicates that maize is the main hotspot due to its high abundance in all compositions (Table 1), with a contribution of 0.293 kg CO_2 eq. per kg of feed for all evaluated scenarios, as it has the same proportion in all four diets. Soybean meal emits 0.097, 0.083, 0.068 and 0.054 kg CO_2 eq. for P18, P16, P15 and P13, respectively, following the share of soybean meal in the compositions: 26.7 % for P18, 22.9 % for P16, 18.9 % for P15 and 14.9 % for P13. Maize starch is the third largest source of the CF among the feed ingredients, equivalent to 0.025 kg of CO_2 in P16, 0.051 kg in P15 and 0.070 kg in P13; feed P18 does not contain maize starch. Synthetic amino acids and other ingredients have a CF of 0.018, 0.026, 0.039 and 0.053 kg of CO_2 eq. for P18, P16, P15 and P13, respectively.

The other two inputs of feeds are non-food components. Packaging showed little contribution, with 1.3 % of CO_2 eq. on average for the four diets. The same is not true for transport, which has a significant share in the CF, with 26.9 % on average per kilogram of feed. Thus, transport becomes the second largest source of GHG emissions in the feed after maize cultivation and processing (due to the large amount consumed).

Although scenario P18 uses a higher amount of soybean meal (3.8 % more than the second largest consumer of this ingredient, P16) and therefore results in higher GHG emissions, these are outweighed by the use of maize starch and SAA in the other scenarios. Eriksson et al. (2005), evaluating three different feed compositions, reported similar results, where the scenario utilizing synthetic amino acids (scenario SAA) represented slightly more GWP than the scenario with no amino acids and peas as an alternative to wheat (scenario PEA). The authors concluded that more GHG could be saved if amino acids were excluded. In our study, SAA represented an emission approximately 5.0 kg CO_2 eq. kg^{-1} of lysine, threonine, tryptophan and valine and 3.0 kg CO_2 eq. kg^{-1} of methionine, while in Eriksson et al. (2005), this value was 3.6 kg CO_2 eq. kg^{-1}. All values were very close despite the high level of uncertainly associated with the SAA data.

GHG emissions from grain and its derivatives are generated by fossil fuel usage in the agricultural phase and direct and indirect N_2O emissions due to the urea application as a nitrogen source used in maize production and its volatilization as NH_3 or NO_x and N leaching as NO_3^-, as noted by Prudêncio da Silva (2011) when assessing the feed used for the production of chickens in Brazil. The emission of CO_2 from fossil fuel combustion contributes an average of 68.6 % of the total CF for the production of one kilogram of feed, whereas N_2O is responsible for 27.0 %.

3.2 Livestock carbon footprint

Analyzing the CF of livestock during the finishing period, we highlight the greater contribution of CH_4 emissions from the enteric fermentation of animals and manure storage (Fig. 3).

Enteric fermentation contributes approximately 16.2 % on average (3.27 kg of CO_2 eq.) of total emissions in animal production (20.22 kg of CO_2 eq.). Manure storage is responsible for the largest share in this phase, reaching 73.7 % of total livestock emissions (13.45 kg on average for the scenarios, Table 5), considering CH_4 and N_2O emissions. Due to the period required to stabilize the organic matter in manure (120 days), manure storage in open tanks is primarily responsible for GHG emissions in this step. Eriksson et al. (2005) reached a similar conclusion, where the hotspot, apart from feed production, was manure storage, mainly due to methane emissions.

Soil application showed lower emission, with N_2O being the only source. Field emission participates with 10.1 % of the total emission in livestock or 2.04 kg CO_2 eq. (Fig. 3).

Livestock emission estimates were directly dependent on the amount of time that swine were housed in growing-finishing; therefore, the feed highly influences the estimates. As shown in Table 5 and Fig. 3, the swine in P13 are fed with feed that results in a lower daily weight gain (1.02 kg—Table 3), thereby requiring more time to reach the FU (29.41 days)

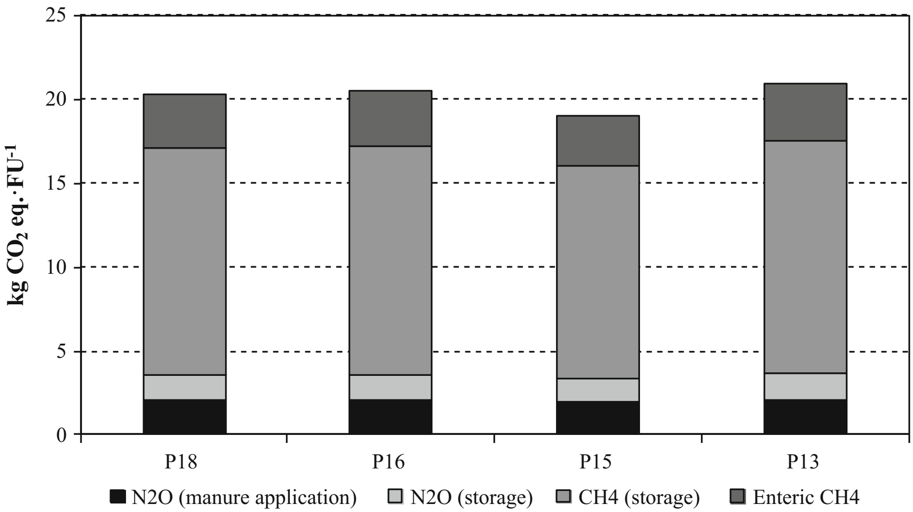

Fig. 3 Livestock carbon footprint (on-farm emissions)

Table 5 Carbon footprint of finishing swine stage (in kg CO_2 eq. FU^{-1})

Life cycle	P18	P16	P15	P13
Feed	52.45	48.92	51.60	57.46
Building construction	0.16	0.16	0.15	0.17
Transport–slaughter	0.96	0.96	0.96	0.96
Electricity	1.23	1.24	1.15	1.26
Livestock emissions (on-farm)	20.33	20.54	19.07	20.92
Enteric fermentation (CH_4)	3.29	3.32	3.08	3.38
Manure storage (CH_4)	13.52	13.66	12.68	13.92
Manure storage (N_2O)	1.47	1.49	1.38	1.51
Land application (N_2O)	2.05	2.07	1.93	2.11
Avoided fertilizer	−4.62	−4.67	−4.34	−4.75
Total	70.51	67.15	68.59	76.02

and resulting in higher emissions for enteric fermentation and manure management with 20.94 kg CO_2 eq. The swine fed with P15, however, have an average daily gain of 1.12 kg (highest of the four scenarios), requiring only 26.79 days to achieve FU. Therefore, P15 has the best environmental performance in animal rearing (total of 19.07 kg CO_2 eq. emitted).

3.3 Finishing carbon footprint

Evaluating the entire finishing step (including feed consumption, livestock emissions and other inputs) to increase in weight from 70.00 to 100.00 kg, all scenarios reveal that feed intake is the greatest contributor of CO_2 eq., with an average of 74.5 % of total emissions. Similar results were obtained by other authors (Basset-Mens and van der Werf 2005; Baumgartner et al. 2008; Dalgaard 2007; Eriksson et al. 2005; Kingston et al. 2009; Kool et al. 2009; Nguyen et al. 2011), all of whom highlighted the contribution of feed and emphasized this step as the most impactful on the swine production chain. The high impact of this step is associated with grain cultivation (mainly maize) and transport, as shown in Fig. 2.

Table 5 quantifies the total GHG emissions for each scenario. The results were directly influenced by the feed performance in terms of mass gain to swine (feed conversion rate and daily weight gain). Scenarios with higher feed consumption during the period also had higher emissions. P18 requires 90.30 kg of feed to meet the FU proposed, followed by P13 with 89.70 kg. These values converted into CO_2 equivalent emissions represent 52.45 and 57.46 kg for P18 and P13, respectively.

Despite the small difference in consumption between P18 and P13 (P18 consumes 0.6 kg more than P13), feed composition in P13 has 9.3 % more emissions than P18, as shown in the comparison for each feed kilogram (Fig. 2). Thus, P13 has the highest emissions associated with feed, although it is not the largest consumer among the scenarios.

The swine in P15 is the third largest feed consumer, with 82.80 kg, followed by P16, which is the scenario that requires the least amount of feed, 81.60 kg. Feed emissions associated with scenarios P15 and P16 are 51.60 and 48.92 kg of CO_2 eq., respectively. Both have lower GHG emissions than P18 and P13 due to their superior feed conversion rates. The difference in GHG emissions between P15 and P16 is due to the quantity and quality of each composition. P15 has a higher consumption (more than 1.20 kg) and a higher emission per kilogram of feed, 0.024 kg CO_2 eq.

Feed consumptions in P18 and P15 have nearly equal CF emissions (differing by 0.85 kg CO_2 eq.). Although P18's feed has a considerably lower CF per kg of feed than P15 (as displayed in Fig. 2), the higher consumption due to its high feed conversion rate makes both results similar when assessed over the whole system.

The second largest CF was from livestock, reaching an average of 28.7 % of the total GHG emitted and corresponding to 20.22 kg CO_2 eq. CH_4 emissions (enteric fermentation and manure management) are most responsible for the CF, with an average of 16.71 kg (23.7 % of total), while N_2O corresponds to 5.0 % of the total (3.50 kg of CO_2 eq. on average). Although N_2O has a higher GWP, CH_4 accounted for a much higher volume of CO_2 equivalent, due to the larger quantities emitted compared with N_2O in the manure management system.

Other emissions do not appear to be significant, as the sum of the impacts associated with feed and livestock achieved an average share of 96.9 % of the total. The buildings in which the animals were housed have an average CF of 0.16 kg of CO_2 eq. (Table 5), <0.2 % of the total emitted. The gases are mainly related to materials such as cement and limestone, which contribute approximately 52 % of the impact of the facility. Electricity consumption in animal housing was evaluated separately from construction, accounting on average for 1.7 % of GHG emissions. The difference in performance between the scenarios is related to the time of animal rearing, which is dependent on the feed conversion rate for each diet (Table 3).

Swine transport to slaughter is responsible for an emission of 0.96 kg CO_2 eq. for all scenarios. This amount corresponds to a small share of the total GHG emissions (approximately 1.4 %). Although the transport (truck) consumes diesel, the short distance and low amount of mass transported (related to FU) resulted in this small share.

The avoided impact by the application of manure as an organic fertilizer is shown as a positive impact in the results (or environmental benefits), attenuating the negative impacts on the balance. This application results in the 'non-use' of approximately 2.02 kg of chemical fertilizer. This non-consumption represents a positive impact of 6.5 % (average) of the total emission, as shown by the negative values of Table 5. This 'credit' is equivalent to 4.60 kg CO_2 eq. avoided on average for the scenarios evaluated. Slight differences in avoided fertilizer between the scenarios are explained by the different amounts of manure generated in each one.

3.4 Comparative assessment

The comparison of scenarios, simulating the consumption of four different diets in the same process (finishing swine), shows that P16 has the best environmental performance with respect to GHG emissions. Although the feed in this scenario does not have the lowest CF (status attributed to feed in P18, Fig. 2) and has the second largest CF associated with manure management (Fig. 3), P16 has the lowest CO_2 eq. This low amount is due to the high feed conversion rate in swine P16 that results in a lower amount of feed required to reach the 100.00 kg slaughter weight.

Swine in P15 showed similar values to those in P16. Although P15 is fed with a greater CO_2 eq. emitter, the shorter amount of time required to achieve 30.00 kg (26.8 days—Table 3) influences the amount of manure managed. This difference of almost 2 days generates less waste and hence a lower emission of CO_2 eq., as shown in Table 5.

Regarding the P18 scenario, although its diet composition had the lower CF per kg of feed, this scenario has the second highest emission of CO_2 eq. because of its low feed efficiency (3.01—Table 3), resulting in a higher daily feed and longer period of time needed to reach the final body weight.

Swine in the P13 scenario have the greatest final emission. In addition to consuming the worst performance diet (Fig. 2), they also have the lowest daily weight gain and therefore require a longer amount of time to reach the FU.

Improvement options for feed production were evaluated by Baumgartner et al. (2008) and Eriksson et al. (2005) in studies with different diet compositions for swine production in Germany and Sweden, respectively, by replacing the soybean meal (current practice) with European grain legumes (peas and faba beans), a feed with higher levels of SAA, or grain produced on the farm (Baumgartner et al. 2008). The results showed that feeding the swine with European grain legumes or SAA was able to reduce the GHG emissions per kg of swine by 5–6 %, respectively, when compared to current scenario with the use of soybean meal (Baumgartner et al. 2008). Eriksson et al. (2005) reached similar results by replacing a feed based on soybean meal with a feed containing peas, rapeseed meal and SAA, saving approximately 7 % of the GWP. Comparing to our results, swine fed with P13 (feed with high levels of SAA) showed the highest impacts when compared to the scenario with no use of SAA and a high content of CP (P18). Nevertheless, it is important to highlight that the slight reduction in the GHG emissions in SAA (Baumgartner et al. 2008; Eriksson et al. 2005) was associated with no use of soybeans from deforested areas, while in our study, this impact was not considered because we assumed the use of grains from southern Brazil (see Prudêncio da Silva et al. 2010). If we had considered these impacts in soybean production, the CF of P18 would probably have been increased. Using grain produced on farm (Baumgartner et al. 2008) resulted in a decrease in the CF due to less grain transportation, which represented on average 26.9 % of the total GHG from feed production in our study.

Similar to our results, Meul et al. (2012), evaluating four diets for fattening swine, found that by decreasing the CP content (N-LOW) and increasing the levels of SAA, it was not possible to reduce the CO_2 eq. emissions. However, the authors only evaluated the emissions per kg of feed produced. Although the diets were nutritionally equivalent with no expected consequences in the finishing stage (Meul et al. 2012), as we showed in our study, it is important to consider that the feed diet can change the performance in promoting daily weight gain, and the need for more feed consumption increases the environmental impact.

4 Conclusions

LCA can be used as a basis for evaluating various scenarios of animal production with the ability to specify paths for better environmental performance within the methodological specifications of the analysis. In this specific case study, P16 obtained a reduction in up to 11.7 % of the CF (global warming potential) compared with P13, with changes in only one of the stages of the swine life cycle (feed composition).

Due to the superior environmental performance through LCA of P16 and the technical feasibility of the diets described by Vidal et al. (2010), this scenario was shown to be the most favorable. Nevertheless, to ensure the complete viability of P16, further analysis is recommended to assess the economic factors and, especially with regard to the production and transport of feed. In addition, an uncertainty analysis should be conducted since the parameter uncertainties in LCA studies can be high. Moreover, it should further be considered that the LCA considers fractions of a day in animal rearing to estimate the net environmental impacts, while in practice farmers do not make use of such precision.

This study demonstrates that small changes in an already consolidated system, such as feed protein origin and variation of its content, may generate significant reductions in environmental impacts. Extrapolating these results, which are modeled around a FU of one swine, for annual production, for example, or values of a production region (such as the west of Santa Catarina), the reduction becomes much more significant, many times justifying a choice that otherwise would be discarded.

Due to the high impact generation related to feed production (73 % of the total emitted), this step is the main hotspot in the finishing stage of swine production and should therefore be the main focus of attention and improvement. Issues related to the efficiency and productivity of crops, feed conversion and transport of feed components become key parameters when the goal is the reduction in the CF of swine farming.

Finally, products should be analyzed in their overall context. As demonstrated in this study, the consumption of better performance feed does not necessarily mean less environmental impact because it may have inferior performance in promoting weight gain in finishing swine.

For further recommendations, we suggest conducting an LCA of Brazilian swine production considering the earlier steps of the swine supply chain, from piglet production to the end of the weaning-to-growing (25–70 kg) stage. In addition, the influence of CP content on manure characteristics and consequently on N_2O emissions should be evaluated. The use of food residues for animal feed is an alternative feed strategy that has not yet been studied by Brazilian researchers.

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