Tropical Animal Health and Production (2022) 54:44
https://doi.org/10.1007/s11250-022-03045-6

REGULAR ARTICLES

# The environmental performance of different pork production scenarios: a life cycle assessment study

M. R. Villavicencio-Gutiérrez[1] · N. A. Rogers-Montoya[2] · R. Martínez-Campos[1] · G. Gómez-Tenorio[3] · F. E. Martínez-Castañeda[1]

Received: 29 July 2021 / Accepted: 4 January 2022

## Abstract

In order to evaluate the environmental performance generated by a “semi-technified” pig farm, as well as the comparison of different pig production scenarios, pig feed and animal production subsystems were evaluated considering both: (a) origin of feed ingredients and (b) variations in pig weight. Life cycle assessment methodology was used to evaluate the environmental performance, establishing 1 market pig as the functional unit (FU). Three ingredient origin distances (400, 950, and 1800 km) and three slaughter weights (110, 100, and 90 kg) were considered for the simulation analysis and comparison. The feed production subsystem was the main generator of environmental impacts, mainly caused by the cultivation of sorghum and the production of fat. The origin of the inputs represented the main increase in environmental impact for the feed production subsystem, mainly in the Fossil Depletion category, with a fivefold increase by acquiring inputs from 900 km and a ninefold increase at a distance of 1800 km. Producing lighter pigs resulted in the best environmental alternative, given the resultant 11% reduction in environmental impact.

**Keywords** Environmental profile · Feed ingredient origin · Pig weight · ReCiPe (midpoint approach)

## Introduction

Pig production is considered to be strategic all over the world in view of the economic and social benefits that it engenders, since pork is the world’s second most widely produced meat product (FAOSTAT 2020). However, pig farming is also held responsible, both directly and indirectly, at all the different stages of the supply chain, for causing environmental harm. According to Gerber et al. (2013), it is estimated that pig farming generates around 668 million tonnes of $CO_2$ equivalent ($CO_2$-eq) per annum, constituting 9% of all the emissions produced by the livestock sector. Greenhouse gases such as methane ($CH_4$), nitrous oxide ($N_2O$), and carbon dioxide ($CO_2$) not only have negative effects on the environment, but also result in losses of nitrogen, energy, and organic material that reduce the efficacy and productivity levels of pig production units (Gerber et al. 2013). Hence, pig farmers face the challenge of finding competitive solutions based on an environmental focus.

Life Cycle Analysis (LCA) has been used to identify the environmental burdens and critical points along the supply pig/pork chain to design strategies for reducing environmental impacts (Basset-Mens and Van der Werf 2005; Nguyen et al. 2011; Reckmann et al. 2013; González-García et al. 2015; Wang et al. 2015). McAuliffe et al. (2016) have classified LCA studies related to pork production published between 2005 and 2014 into three main processes: (a) feed production; (b) pig production throughout the cycle; and

✉ F. E. Martínez-Castañeda
femartinezc@uaemex.mx

M. R. Villavicencio-Gutiérrez
rossyvillavicencio@gmail.com

N. A. Rogers-Montoya
natchorogers@gmail.com

R. Martínez-Campos
armartinezc@uaemex.mx

G. Gómez-Tenorio
ggomezt@uaemex.mx

[1] Instituto de Ciencias Agropecuarias Y Rurales, Universidad Autónoma del Estado de Mexico, Instituto Literario 100, 50000 Centro, Toluca, Mexico

[2] Colegio de Postgraduados, Campus Montecillo, Texcoco, Mexico

[3] Centro Universitario UAEMex-Temascaltepec, Temascaltepec, Mexico

(c) waste management. These studies all evaluated potential acidification, global warming, and eutrophication, concluding that feed production was responsible for generating the biggest environmental impact. Other findings were the difficulty of making precise comparisons among the various LCA studies, due to the differences in their aims, the system limits established, the functional unit used, the life cycle impact evaluation methods adopted, and the different characteristics and productive parameters pertaining to each production unit.

Current LCA studies seek more precise information and focus on mitigating environmental impacts and promoting the efficient use of resources. The comparative analysis of different scenarios, variations in production technology, dietary options, pig housing, and dung management, among other things, has become a constant in current research. In Cuba, Alba et al. (2019) evaluated the environmental impact of 76 three pig production technologies — genetic farms, multiplier farms, and full-cycle farms — showing that genetic farms had the lowest environmental impact. In Greece, Anestis et al. (2020) determined the environmental impact associated with modifying the pig diet on a commercial pig farm and concluded that changes in diet can potentially increase feed efficiency, pig weight gain, and environmental performance.

Lamnatou et al. (2016) studied the environmental impacts for the following four scenarios: (1) animal feed only; (2) feed and drinking water; (3) feed, drinking water, and straw; and (4) feed, drinking water, straw, and transportation. They also adopted three different functional units: (1) 1 market pig; (2) 1 kg of live body weight (LW); and (3) 1 kg of meat carcass weight (CW). Environmental impact was evaluated based on (1) cumulative energy demand; (2) potential global warming; and (3) ReCipe with a Midpoint and Endpoint focus. Their results showed that the environmental impacts were highest for the scenario in which transportation was included, and where the functional unit used was 1 kg of meat CW. Moreover, they came up with different findings for each of the three evaluation methods, mainly regarding the contribution made by each feed ingredient to the total environmental impact of the implemented diet. Bava et al. (2017) studied the potential environmental impacts of heavy pig production in Italy, analyzing different systems for producing pigs with live weights of 168.7 ± 3.33 kg at slaughter. Their study showed that heavy pigs generated higher environmental impacts than light ones. For their part, in Ireland, McAuliffe et al. (2017) compared the respective environmental impacts of pig production units, increasing productive performance by 10% and 25% in comparison to the base scenario. They reported that herds with higher productive efficiency levels had higher feed conversion levels and potentially generated less global warming, acidification, and eutrophication. In a base scenario sensitivity analysis, they reported that high-protein diets resulted in a lower potential for global warming, but in a higher potential for acidification and eutrophication. They also reported that feed transportation distances did not significantly affect the environmental impacts.

Pérez (2001) has drawn attention to the water pollution problems associated with pig farming in Mexico, while Méndez et al. (2009) studied the potential contamination of freshwater generated by pig farms. However, they did not measure the environmental impact of such farms. Using LCA methodology, Olea (2009) studied the environmental profile of pig production in the UK and Mexico to identify hot spots where sustainability could be improved in different production systems. In general, he reported that the latter country has poor nutrient flow performance due to inefficient waste management and asserted that the said performance might be improved by recycling more manure via methane capturing and other agricultural practices.

Pig farm productivity levels in Mexico are measured using technical and productive indicators that vary even among production units that share the same technification level. Semi-technified pig farms usually adjust their slaughter weights and use both local and imported inputs. Huerta (2013) mentions that pigs are commercialized in accordance with the weight required by the market, which range from 90–110 kg to 120–125 kg (SNIIM 2020). The National Pig Farming Commission and the Mexican Pig-farming Council assert that around 85% of all pig feed consists of grains such as corn, wheat, and soy (OCDE 2019). Although these items are produced in Mexico, since the national supply of feed companies in that country is insufficient, there is a high level of dependency on imported grains (Rodríguez and Díaz 2013). The objectives of the study described here were to evaluate the environmental performance generated by a semi-technified pig farm, taking stock of activities that involve the manufacturing of pig feed for livestock and animal production and to analyze environmental impacts and comparison scenarios, indicating feed ingredient origins and variations in production weight per market pig.

## Material and methods

In this study, the LCA methodology was used to evaluate the environmental performance of a semi-technified pig farm, adhering to the ISO 14040 (2006) and ISO 14044 (2006) norms, which cover the following phases: (1) definition of the aim and scope; (2) description of the life cycle inventory; (3) evaluation of the life cycle impact; and (4) interpretation of the results and the environmental impact and comparison of different scenarios.

LCA is a technique developed to identify possible areas of improvement in terms of environmental performance of products along all the stages of its production chain (ISO 14044, 2006); LCA applied to livestock accounts for the potential environmental impact derived by the acquisition of inputs, animal breeding, manure management, slaughter, waste management in slaughterhouses, and the distribution and consumption of meat and processed meat products. LCA environmental implications are related directly with climate change, given that climate change is one of the 18 environmental categories that LCA analyzes. The results can aid decision-makers to design strategies focused on mitigating emissions generated by swine farms, based on a rational use of natural resources.

The environmental performance of a semi-technified pig farm was assessed with a base scenario and comparative scenarios considering (1) different pig finishing weights and (2) different feed sources. The system boundary was established using a cradle-to-farm-gate perspective (Fig. 1). The functional unit (FU) established for this study is 1 market pig, defined as a pig with the weight required by the market for slaughter. In this particular study, the weight established was 110 kg. According to different authors (McAuliffe et al. 2016; Lamnatou et al. 2016; Noya et al. 2017), the selected FU can be adopted within the framework of the LCA so as to apply to pig production.

## Definition of the study system

The evaluated farm was a semi-technified, farrow-to-finish one located in Central Mexico and covering an area of 0.51 ha. In Mexico, Rodríguez and Díaz (2013) identified three types of pig farming systems: (1) technified pig rearing (40% of total production); (2) semi-technified pig rearing (30% of total production); and (3) backyard pig farming (30% of total pig rearing). Technified farms are defined as a productive system that uses innovative technology to produce feed, with automatic feeding systems and strict biosecurity protocols. Some farms incorporate the industrialization process with private slaughterhouses and generally have herds up 1000 sows. In semi-technified pig farms, the levels of technology are variable, with less developed infrastructure and sanitary protocols. While some farms produce their feed, most tend to use brand feeds, thus increasing production costs. Industrialization generally takes place in private or municipal slaughterhouses that serve local and regional markets, as well as small urban areas and occasionally cities (SAGARPA 1998). Productivity is variable among these type of farms since the size of the herds ranges from 150 to 500 sows, with a strong dependency for out-farm genetics (ASERCA 1996). The herd consisted of 200 sows and 2 boars (used to detect estrus in the sows); reproduction was via artificial insemination. The sow cycle was 146 days (116 days' gestation, 23 days' lactation, and a

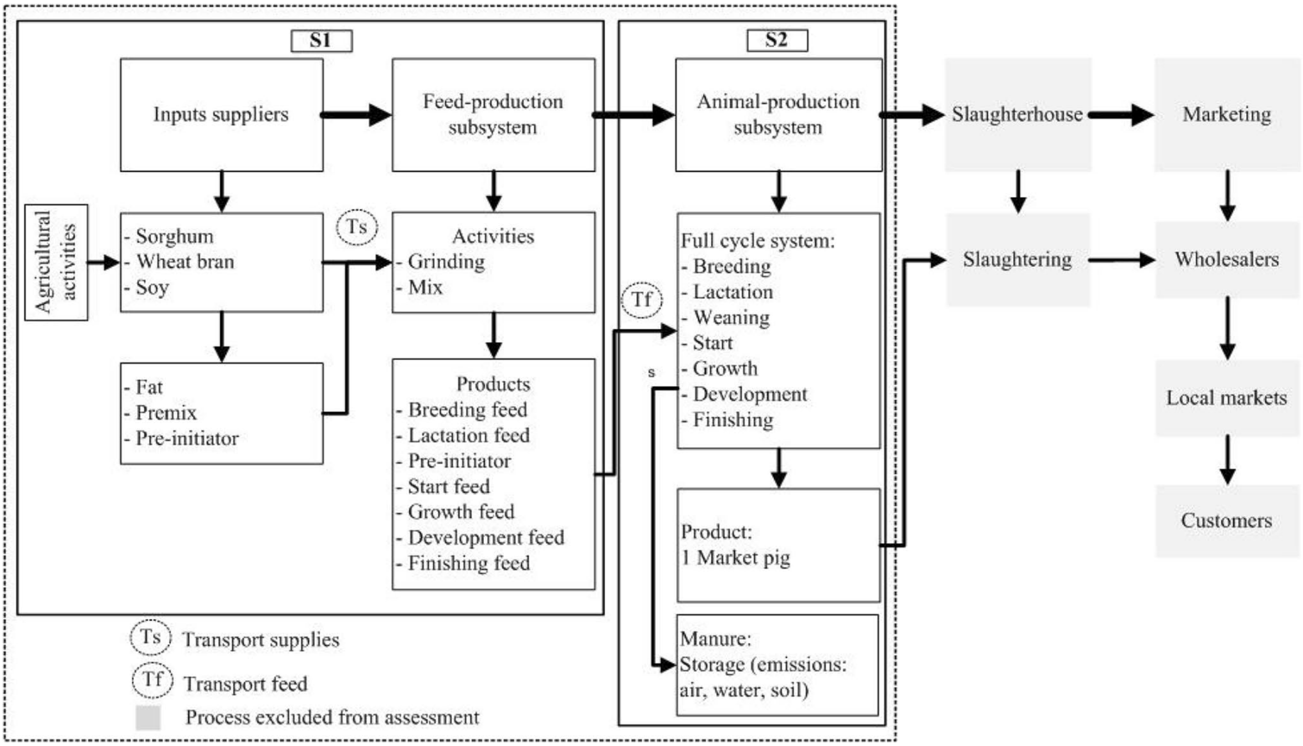

**Fig. 1** System boundary used on the studied farm

7-day weaning-to-first service interval), with 12.5 live born piglets per litter, a 16% mortality rate during lactation, and an average weight of 7.37 kg at weaning. The fattening phase was 130 days and the pigs were split up into pre-starting, starting, growth, development, and finishing groups, depending on their physiological stage, until they reach a weight of 110 kg live weight (LW).

The farm was connected to the electricity grid and its lactation and weaning areas were mechanically ventilated and heated by means of infrared lamps. The lactation barns were cleaned using a drag system and a high-pressure water system, with the manure being stored in an open-air collection ditch.

The farm also had its own feed factory, producing six different feed diets for each of the pigs' physiological stages: breeding, lactation, starting, growth, development, and finishing. The ingredients used to manufacture the different diets were sorghum, soy, wheat bran, fat, and premix consisting of vitamins and minerals. Table 1 shows the ingredients required to produce 1 kg of feed per production phase.

**Assumptions** Pig finishing weight plays a decisive role in determining the environmental impact of pork production (Bavia, 2017). The selling weight for pigs in Mexico depends on consumer requirements and the available farm infrastructure (Rebollar et al. 2007). The environmental impacts and comparison with the base scenario of 110 kg, LW referred to as High Weight (HW), were established as follows: (1) 100 kg, LW referred to as Medium Weight (MW), and (2) 90 kg, LW referred to as Low Weight (LoW), in accordance with the following criteria:

- HW = 130 days; MW = 117 days; and LoW = 111 days of production, respectively,

Reductions in the amount of fuel needed to transport the grains used to produce feed may result in the reduction of environmental burdens in the pig production system (Noya et al. 2017). Since feed inputs in Mexico are acquired from different regions, the following distance criteria were established for the study:

- Central Mexico: feed inputs are acquired from suppliers located less than 385 km away from the farm, and classified as "local inputs," since they are located in the same agri-food zone as the pig farm (SIAP 2013). These data pertain to the base scenario.
- Northeast Mexico: feed inputs are acquired in the states with the highest grain and oilseed production levels (SIAP 2018), located between 400 and 950 km away from the pig farm.
- Imported inputs: currently most of Mexico's grains and oil seeds are imported from the USA (SIAP 2018). Feed inputs from Galveston, TX, 1800 km away from the farm, were included in the analysis.

## Scenarios

The scenarios were established based on the finishing weight and the output source (Table 2).

## Life cycle inventory

Data entry sheets were used to gather the information for each process included within the limits of the system.

**Table 2** Scenarios established for purposes of environmental evaluation

| Scenario | Finishing weight | Origins of inputs |
|---|---|---|
| I* | HW | Central Mexico |
| II | MW | |
| III | LoW | |
| IV | HW | Northeast Mexico |
| V | MW | |
| VI | LoW | |
| VII | HW | Imported |
| VIII | MW | |
| IX | LoW | |

HW — 110 kg; MW — 100 kg; LoW — 90 kg

*Base scenario

**Table 1** Amounts of ingredients required per production phase to produce 1 kg of feed

| | Breeding feed | Lactation feed | Start feed | Growth feed | Development feed | Finishing feed | Unit |
|---|---|---|---|---|---|---|---|
| Sorghum | 0.710 | 0.610 | 0.650 | 0.745 | 0.730 | 0.700 | kg |
| Soy | 0.105 | 0.250 | 0.240 | 0.220 | 0.195 | 0.220 | kg |
| Fat | 0.005 | 0.015 | 0.030 | 0.005 | - | - | kg |
| Premix | 0.035 | 0.035 | 0.080 | 0.030 | 0.025 | 0.020 | kg |
| Wheat flour | 0.145 | 0.090 | - | - | 0.050 | 0.060 | kg |

### Inventory analysis for the feed production subsystem (S1)

The inventory analysis was integrated considering three main activities:

a. Feed ingredient production: Corresponded to agricultural activities related to the cultivation of the grains and oilseeds needed for diet formulation were considered. Data were obtained from the Agricultural and Food Database (AGRIBALYSE), Agency for Environment and Energy Management (ADEME 2016).
b. Transport activities: They considered the transportation of inputs to the feed factory. The number of liters of fuel per kg of feed produced was calculated based on the type of vehicle needed to transport the ingredients, fuel efficiency expressed in km/l, and load-bearing capacity, and then adjusted based on the FU.
c. Feed manufacturing: the amount of electricity consumed in order to grind and mix grains was considered. Power consumption was calculated considering the installed capacity of the feed factory and adjusted based on the FU.

### Inventory analysis for the animal production subsystem (S2)

**Land use** The farm covered an area of 0.51 ha, split up into different areas: service (insemination), gestation, lactation, breeding (weaning and starting), and fattening (growth, development, and feeding).

**Consumption of electric power** The total bimonthly consumption of electric power (1090 kWh) reported by the producer was considered and the consumption per FU was worked out based on the number of days per physiological stage that pigs spent in the area.

**Water consumption** Water consumption, including the water used to clean the premises, was calculated in accordance with the values stipulated in the literature (Boulanger 2011).

**Fuel consumption in S2** The amount of fuel needed to transport feed from the factory to the farm was calculated considering the 40 km.

**LW** The amount of feed consumed during the reproduction (i.e., service, gestation, and lactation) stages was considered, being calculated based on the FU. The amount of feed consumed between the weaning and finishing stages was considered, and weight gain was worked out for each stage.

**Manure** The amount of manure generated during each physiological stage was calculated based on the feed conversion rate (i.e., the amount of feed consumed divided by the amount of weight gained). The amount of nutrients (nitrogen [N], phosphorous [P], and potassium [K]) in the generated manure was calculated for each FU taking into account Mexican data (Domínguez et 210 al., 2014) and adjusted for the production periods established in each scenario.

The amounts of methane ($CH_4$), nitrous oxide ($N_2O$), and ammonia ($NH_3$) emitted due to enteric fermentation and manure management were taken into account, basing the calculation on the tables for calculating livestock sector gas emissions published by the Spanish Ministry of Agricultures, Fisheries and Food (2004).

The entry and exit inventory data for the FU (i.e., 1 market pig) are shown in Table 3 below.

The S1 fuel consumption for scenarios IV, V, and VI was adjusted to cover the acquisition of inputs in Northeast Mexico, while the amount of imported inputs was adjusted to cover scenarios VII, VIII, and IX.

## Life cycle impact assessment

Open LCA Version 1.8 software (OpenLCA, 2019) was used to model the system being studied. The environmental impacts were estimated for 18 midpoint categories considered by Lamnatou et al. (2016) The impact categories, agricultural land occupation (ALO), climate change (CC), fossil depletion (FD), freshwater ecotoxicity (FE), freshwater eutrophication (FEU), human toxicity (HT), ionizing radiation (IR), marine ecotoxicity (ME), marine eutrophication (MEU), metal depletion (MD), natural land transformation (NLT), ozone depletion (OD), particulate matter formation (PMF), photochemical oxidant formation (POF), terrestrial acidification (TA), terrestrial ecotoxicity (TE), urban land occupation (ULO), and water depletion (WD), were estimated for both the base scenario and the comparative scenarios.

In accordance with standardized LCA methodology, the classification and characterizations were carried out as per ISO 14040 (2006) norms.

# Results

## Characterization results for the base scenario

The environmental impacts for the base scenario I are shown in Table 4, where it can be seen that S1 is responsible for most of the overall impact, with percentages of over 73% in 11 categories (ALO, CC, FE, HT, ME, MEU, NLT, POF, TE, ULO, and WD), while the animal production subsystem exceeded 55% in six impact categories (PMF, TA, MD, IR, FD, and FEU).

**Table 3** Summarize data inventory for the pig production system per FU (1 market pig)

| Scenarios | I HW | II MW | III LoW | |
|---|---|---|---|---|
| Inputs/outputs | | Unit | | |
| Feed production subsystem (S1) | | | | |
| Inputs | | | | |
| Sorghum | 186.01 | 179.12 | 166.74 | kg |
| Soy | 53.99 | 51.83 | 48.14 | kg |
| Fat | 1.52 | 1.44 | 1.31 | kg |
| Premix | 8.61 | 8.26 | 7.57 | kg |
| Wheat flour | 12.83 | 12.45 | 12.10 | kg |
| Pre-initiator | 12.29 | 8.24 | 8.24 | kg |
| Electricity | 0.56 | 0.53 | 0.50 | kWh |
| Fuel (transportation)* | 1.09 | 0.57 | 0.54 | L |
| Outputs | | | | |
| Breeding feed | 27.65 | 27.65 | 27.65 | kg |
| Lactation feed | 9.86 | 9.00 | 12.00 | kg |
| Pre-initiator | 12.29 | 8.24 | 8.24 | kg |
| Start feed | 32.50 | 30.95 | 25.55 | kg |
| Growth feed | 49.92 | 48.00 | 44.16 | kg |
| Development feed | 65.00 | 62.50 | 57.50 | kg |
| Finishing feed | 78.00 | 75.00 | 69.00 | kg |
| Animal production subsystem (S2) | | | | |
| Inputs | | | | |
| Land used | 24.37 | 24.37 | 24.37 | $m^2$ |
| Total feed | 275.22 | 261.34 | 244.10 | kg |
| Water | 1135.87 | 1096.34 | 1044.76 | L |
| Fuel (transportation) | 1.76 | 1.66 | 1.55 | L |
| Electricity | 9.4 | 9.11 | 8.75 | kWh |
| Outputs | | | | |
| Pig (live weight) | 110.00 | 100.00 | 90.00 | kg |
| Manure | | | | |
| Mass | 137.60 | 132.18 | 120.71 | kg |
| Nitrogen | 3.36 | 3.21 | 3.05 | kg |
| Phosphorus | 1.11 | 1.06 | 1.01 | kg |
| Potassium | 2.2 | 2.09 | 1.99 | kg |
| Emissions | | | | |
| $CH_4$ | | | | |
| Enteric fermentation | 0.49 | 0.46 | 0.46 | kg |
| Manure management | 3.15 | 3.03 | 2.91 | kg |
| $N_2O$ (nitrous oxide) | 0.001 | 0.001 | 0.001 | kg |
| $NH_3$(ammonia) | 1.66 | 1.60 | 1.50 | kg |

HW — 110 kg; MW — 100 kg; LoW — 90 kg; *Source of inputs: Central Mexico

## Feed production subsystem (S1)

The activities involved in feed production are shown in Fig. 2 below. Feed ingredient production has been identified as critical, followed by transport activities, and lastly feed production, with minimal impact. The contributions made by transport activities were considerable in the fossil depletion (FD), ionizing radiation (IR), and metal depletion (MD) categories, with respective percentages of 81%, 75%, and 65%.

Figure 3 shows the contribution of feed inputs. Sorghum makes a significant contribution in eleven of the categories where S1 has the main impact, occupying nearly 50% of all the land needed to produce inputs (ALO). The agricultural practices involved in sorghum cultivation, which include the use of agrochemicals, generate 33% of all the $CO_2$-eq emissions in the climate change (CC) category, and 71% and 89% of the environmental burdens per kg of 1.4 DB eq in the freshwater ecotoxicity (FE) category and the terrestrial ecotoxicity (TE) category respectively. Likewise, sorghum cultivation generates 33% of all the nitrate and ammonia emissions in the freshwater eutrophication (MEU) category, 38% of all the photochemical oxidants (POF) that are generated, and 64% of all water depletion (WD).

Wheat cultivation generates from 6 to 28% of the total environmental load, while soy cultivation contributes in 5 categories. The highest impact was in the category of marine ecotoxicity (52%). Animal fat contributes to the environmental burdens in 11 categories, having a bigger impact in those of human toxicity (HT) and natural soil transformation (NLT), with respective percentages of 79% and 100% (Fig. 3), which is very relevant.

## Animal production subsystem (S2)

Animal production subsystem results are shown in Table 4. The main impacts were in the freshwater eutrophication (FEU) and the fossil depletion (FD) categories, with respective contributions of 92% and 70%. The FEU contributions have to do with the amount of phosphorous in the excreta, while the FD contributions are related to fossil depletion caused by the consumption of fuel when transporting feed to the farm, and activity that also impacts the ionizing radiation (IR) and metal depletion (MD) categories, with respective contributions of 68% and 65%.

The $NH_3$ and $N_2H$ emissions generated during the manure management process have respective negative impacts of 55% and 60% on the formation of particulate matter (PMF) and on terrestrial acidification.

Figure 4 shows the impact levels per physiological stage. The biggest contributions pertained to the finishing stage, with respective values of 28%, 32%, 29% 29%, 23%, and 23% in FD, FEU, IR, MD, PMF, and TA categories, followed by the growth stage, with respective contributions of 23%, 24%, 23%, 24%, 19%, and 19%, and the breeding stage, with important respective contributions of 21% and 19% in the PMF and TA categories.

**Table 4** ReCiPe midpoint impact per market pig

| Impact category | Total | Feed production subsystem (S1) | Animal production subsystem (S2) | Unit |
|---|---|---|---|---|
| ALO | 841.71 | 817.32 | 24.40 | $m^2*a$ |
| CC | 101.30 | 74.06 | 27.24 | kg $CO_2$-eq |
| FD | 2.95 | 0.88 | 2.07 | kg oil eq |
| FE | 3.92 | 3.9 | 0.0 | kg 1,4-DB eq |
| FEU | 1.21 | 0.1 | 1.1 | kg P eq |
| HT | 143.78 | 134.71 | 9.07 | kg 1,4-DB eq |
| IR | 0.18 | 0.06 | 0.12 | kg U235 eq |
| ME | 242.63 | 239.44 | 3.18 | kg 1,4-DB eq |
| MEU | 2.37 | 2.22 | 0.15 | kg N eq |
| MD | 0.15 | 0.05 | 0.10 | kg Fe eq |
| NLT | 0.41 | 0.4 | 0.00 | $m^2$ |
| PMF | 0.94 | 0.42 | 0.52 | kg PM10 eq |
| POF | 0.37 | 0.33 | 0.04 | kg NMVOC |
| TA | 7.72 | 3.07 | 4.65 | kg $SO_2$ eq |
| TE | 19.52 | 19.52 | 0.00 | kg 1,4-DB eq |
| ULO | 0.49 | 0.48 | 0.02 | $m^2*a$ |
| WD | 7.41 | 6.09 | 1.33 | $m^3$ |

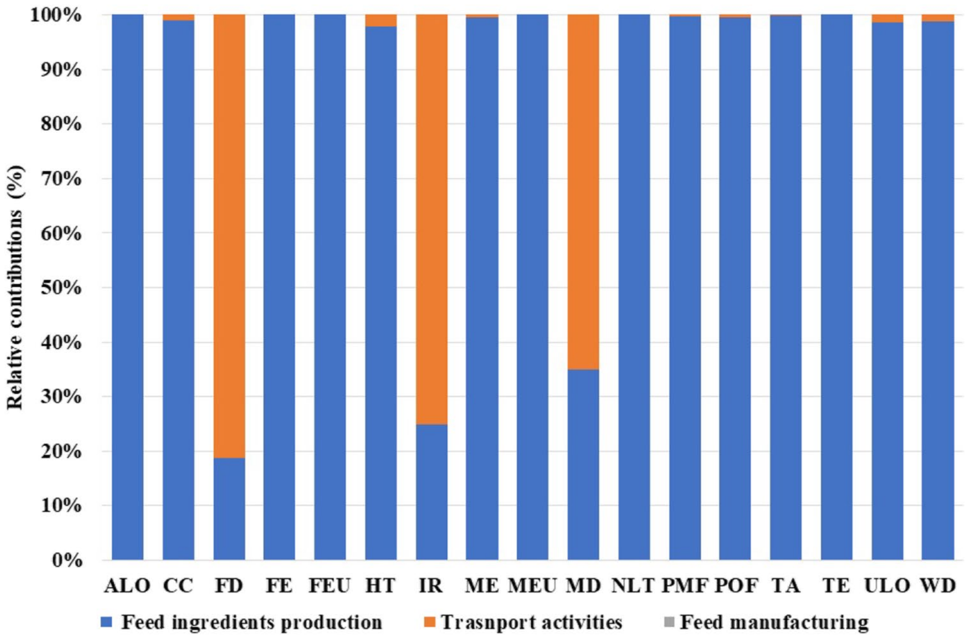

**Fig. 2** Relative contributions of the processes involved in the feed production subsystem

## Comparative results for the different scenarios

### Comparative analysis of the different scenarios for the feed production subsystem (S1)

The characterization results for the feed production subsystem in the base scenario and the comparative scenarios are summarized in Table 5.

When the base scenario finishing weight was reduced by 10 kg and 20 kg, respective average environmental impact reductions of 4% and 11% are observed in the impact categories studied. These differences in finishing weights were mainly due to the amounts of inputs required for feed production. In other words, since 275.22 kg of feed is needed to produce 1 HW pig, 261.34 kg of feed was needed to produce 1 MW pig and 244.10 kg for 1 LoW pig. Variations in feed production play a decisive role in determining the environmental burdens in S1, with the pertinent categories being occupation of agricultural land (ALO), climate change (CC), fossil depletion (FD),

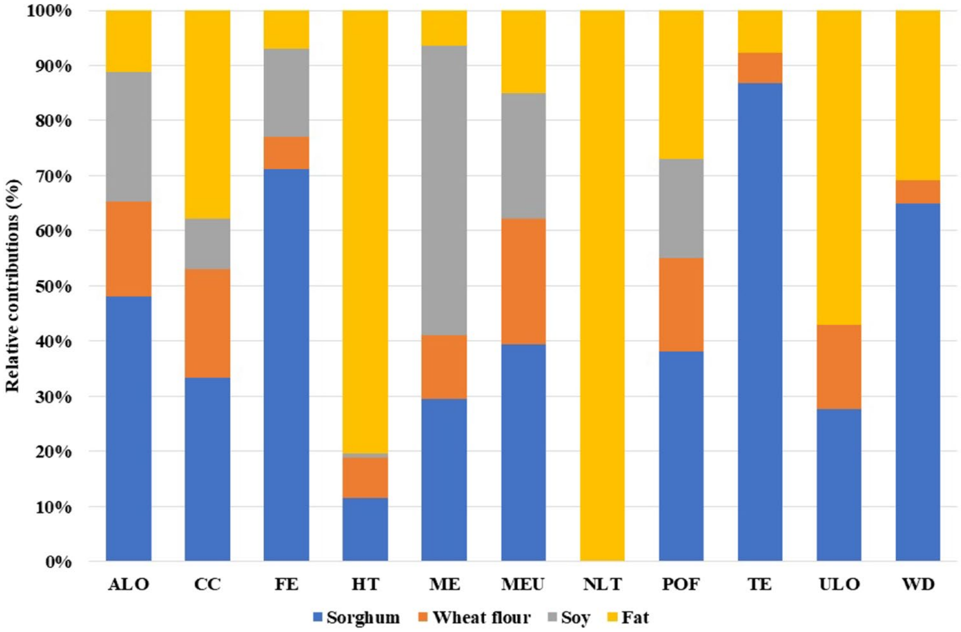

**Fig. 3** Distribution of environmental burdens generated by feed ingredient production

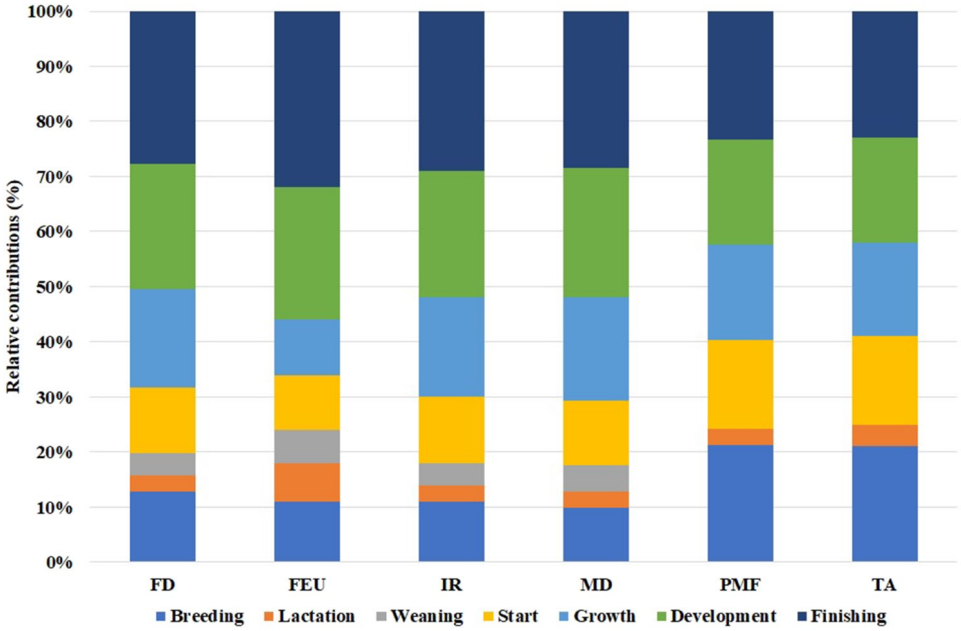

**Fig. 4** Distribution of environmental burdens generated in the different physiological stages

human toxicity (HT), marine ecotoxicity (ME), and water depletion (WD).

Besides being sensitive to variations in weight, the CC, FD, HT, ME, and WD categories were also sensitive to input origin variations (Fig. 5). The production of 1 HW pig using inputs acquired in Northwest Mexico (scenario IV) leads to a 2% environmental load increase for the ME category, a 5% environmental load increase for the CC category, 7% environmental load increase for the WD category, 12% environmental load increase for the HT category, and an environmental load increase of up to 500% for the FD category, while the production of the same pig using imported inputs leads to an environmental load increase of 5%, 11%, 13%, 24%, and 900% for the ME, CC, WD, HT, and FD categories, respectively.

## Comparative analysis of the scenarios for the animal production subsystem (S2)

Figure 6 only shows environmental burden variations according to pig weight in scenarios I, II, and III, given that no changes were observed in the other scenarios. The most

**Table 5** Characterization results for the feed production subsystem in the nine scenarios

| Impact category | I | II | III | IV | V | VI | VII | VIII | IX | Unit |
|---|---|---|---|---|---|---|---|---|---|---|
| ALO | 817.32 | 786.72 | 735.52 | 817.37 | 786.77 | 735.57 | 817.43 | 786.82 | 735.61 | $m^2$*a |
| CC | 74.06 | 71.14 | 66.14 | 78.32 | 75.23 | 69.92 | 82.32 | 78.96 | 73.48 | kg $CO_2$-eq |
| FD | 0.88 | 0.82 | 0.77 | 4.53 | 4.34 | 4.01 | 7.97 | 7.53 | 7.07 | kg oil eq |
| FE | 3.92 | 3.77 | 3.51 | 3.92 | 3.77 | 3.51 | 3.92 | 3.77 | 3.51 | kg 1,4-DB eq |
| FEU | 0.09 | 0.09 | 0.08 | 0.09 | 0.09 | 0.08 | 0.09 | 0.09 | 0.08 | kg P eq |
| HT | 134.71 | 128.79 | 117.77 | 151.33 | 144.76 | 132.54 | 166.96 | 159.30 | 146.42 | kg 1,4-DB eq |
| IR | 0.06 | 0.05 | 0.05 | 0.29 | 0.27 | 0.25 | 0.50 | 0.47 | 0.44 | kg U235 eq |
| ME | 239.44 | 230.25 | 214.83 | 245.02 | 235.60 | 219.78 | 250.25 | 240.47 | 224.43 | kg 1,4-DB eq |
| MEU | 2.22 | 2.13 | 2.00 | 2.22 | 2.14 | 2.00 | 2.22 | 2.14 | 2.00 | kg N eq |
| MD | 0.05 | 0.05 | 0.05 | 0.23 | 0.22 | 0.21 | 0.40 | 0.38 | 0.35 | kg Fe eq |
| NLT | 0.41 | 0.39 | 0.36 | 0.41 | 0.39 | 0.36 | 0.41 | 0.39 | 0.36 | $m^2$ |
| PMF | 0.42 | 0.41 | 0.38 | 0.43 | 0.41 | 0.38 | 0.43 | 0.42 | 0.39 | kg PM10 eq |
| POF | 0.33 | 0.32 | 0.30 | 0.34 | 0.33 | 0.31 | 0.35 | 0.34 | 0.32 | kg NMVOC |
| TA | 3.07 | 2.95 | 2.75 | 3.09 | 2.97 | 2.77 | 3.11 | 2.99 | 2.79 | kg $SO_2$ eq |
| TE | 19.52 | 18.79 | 17.50 | 19.52 | 18.79 | 17.50 | 19.52 | 18.79 | 17.50 | kg 1,4-DB eq |
| ULO | 0.48 | 0.46 | 0.42 | 0.51 | 0.49 | 0.45 | 0.54 | 0.51 | 0.48 | $m^2$*a |
| WD | 6.09 | 5.85 | 5.41 | 6.49 | 6.23 | 5.76 | 6.86 | 6.58 | 6.09 | $m^3$ |

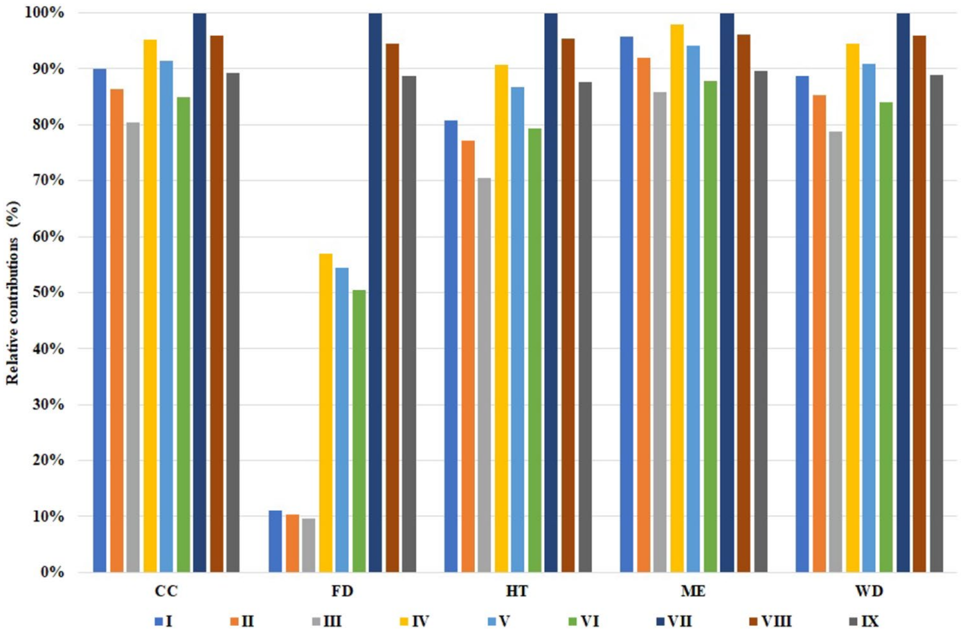

**Fig. 5** Percentage values for the impact categories that are sensitive to S1 variations in finishing weight and source distance

representative changes were in CC, FD, FEU, PMF, TA, and WD. These results were mainly due to a reduction in the amount of excreta per finishing weight generated on the farm.

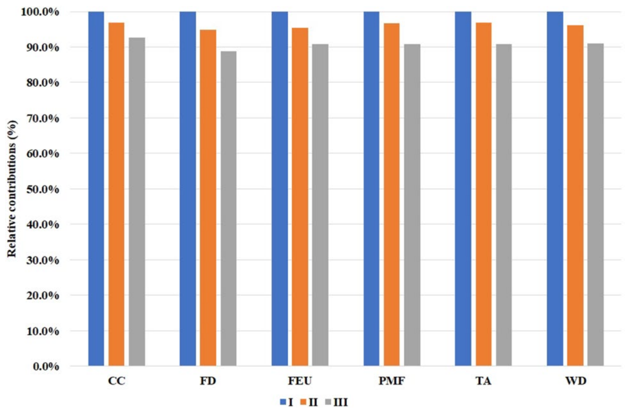

**Fig. 6** Percentage values for the impact categories that are sensitive to variations in S2 finishing weight

## Discussion

### Base scenario

#### Feed production subsystem (S1)

According to the base scenario environmental results, the biggest environmental burdens were generated in the feed production subsystem, with levels of over 73% in the impact categories pertaining to land occupation, climate change, toxicity, eutrophication, photochemical formation, and water depletion. These results are consistent with the findings of González-García et al. (2015), who studied the pig production chain in Portugal, where the environmental burdens for the aforesaid categories were over 70%. In both cases, the impacts were attributed to the production of pig feed ingredients. The Portuguese study indicates four ingredients, soy (oil and meal), grain maize, wheat (silage and grain), and barley (grain), as critical environmental points whose contributions range from 63 to 97%, depending on the category, while, in the case of Mexico, the critical points were primarily related to the cultivation of sorghum, wheat, and soy, whose contributions range from 61 to 93% depending on the categories. Animal fat production occupies second place, with contributions ranging from 30% for WD to 100% for NLT. According to Lamnatou et al. (2016), animal fat production is a by-product which has a big impact on the environment. The calculated contributions from animal fat production in this study was obtained from the Agrybalyse database (2020) that considers the production of Processed Animal Protein (PAP) made with broilers (OpenLCA, 2019). The environmental burdens of fat production integrate all processes related to slaughter and production of by-products such as sterilization, fat obtention, grinding, and drying. The inventory also takes into account the use of energy and water.

Although one of the limiting factors when comparing different life cycle studies is the environmental study method that was used, the results of the aforementioned studies, which used the ReCiPE Midpoint method, are consistent with those reported by McAuliffe et al. (2016), who, based on a thematic review of over 10 life cycle studies of pig production, with different aims and scopes, identified the feed production subsystem as the biggest contributor to environmental burdens in the pork supply chain, in terms of potential global warming, eutrophication, and acidification.

#### Animal production subsystem (S2)

In the study described here, it was determined that the animal production subsystem contributed to the FEU, TA, and PMF environmental impact categories, with respective values of 92%, 60%, and 55%, due to the $NH_3$, $N_2H$, $CH_4$, and $CO_2$ emissions generated by the enteric fermentation and manure storage processes. The results for the FEU and TA categories accord with the values reported by Alba et al. (2019), who studied three pig production technologies in Cuba, determining that the biggest contributors to the FEU category (89%) and the TA category (86%) were stable- and lake-based animal production. These results are at odds with the findings of González-García et al. (2015) and Lamnatou et al. (2016), who assert that the animal production subsystem is the one that generates the biggest environmental burdens, with eutrophication and acidification values of over 70%.While the PMF category was not been taken into consideration in prior studies of the environmental profile pertaining to pig production systems, the present study concludes that it plays a significant role in the generation of environmental burdens. The differences in the aforesaid results can be attributed to the fact that the Cuban study did not envisage the use of purines on farmland, while the study carried out in Portugal by González-García et al. (2015) did, indeed, cover purine use.

The biggest environmental burdens in S2 were generated during the growth, development, and finishing stages, which were jointly responsible for between 59 and 66% of the environmental impacts generated by this subsystem. According to Reckmann et al. (2012), the biggest environmental impacts occur during the pig finishing stage, since heavier pigs consume more feed and hence excrete more manure. They also mentioned a limitation in results because it only contemplated manure storage, notwithstanding which they consider it essential that manure management be studied. In his environmental profile of intensive pig production in Mexico, Olea (2009) found that the flow of nutrients was poor due to inefficient waste management, and suggested that the said systems be improved by increasing manure recycling and thus capturing more methane.

## Comparative analysis of the scenarios for the feed production subsystem (S1)

In the comparative profiles pertaining to the feed production subsystem, it was observed that the distance (i.e., input origins) played a decisive role in the environmental trends in scenario IV and scenario VII, with the main impact occurring in the FD category, where the environmental burdens increased fivefold and ninefold respectively.

In characterization terms, an average of 0.82 kg oil eq is needed to transport feed ingredients to the feed factory, with inputs from Central Mexico that reach a level of 4.29 kg oil eq when inputs from Northeast Mexico are also considered. The said level increases to oil eq when inputs from Galveston, TX, are included. McAuliffe et al. (2017) studied the environmental footprints of pig production in Ireland and found that replacing imported inputs with national ones (i.e., ones transported from distances of between 2000 and 5000 km) did not lead to any changes in LCA results. This finding was confirmed by Srnicek and Williams (2017), who stress that local consumption is no guarantee of lower environmental costs, since such local feed production is often still carried out using inefficient techniques.

The above findings are at odds with those of Noya et al. (2017), who stated that reductions in the amount of fuel used to transport the grains utilized to produce feed might lead to reduced environmental burdens. It bears pointing out that, in latter study, carried out in Galicia, Spain, the maize inputs were transported from Argentina, USA, and Ukraine, while the soy-meal ones came from Argentina, USA, and Brazil, being transported over distances ranging from around 7000 km to around 10,600 km. Unfortunately, there is a high level of dependency on maize and soy in Mexico. For example, in 2019, Mexico imported 15,376,673 tons of maize from the USA. Although the obvious environmental disadvantage occurs in the FD category, if the USA increased its maize production per Ha, the impact in the ALO category could theoretically be reduced.

## Comparative analysis of the scenarios for the animal production subsystem (S2)

In the comparative profiles pertaining to the animal production subsystem, the finishing weight variable played a decisive role in reducing environmental burdens only in scenarios II and III, since, in semi-technified systems that produce pigs with a finishing weight of 110 kg, as opposed to 100 kg, there is a 4% reduction in the environmental burdens for impact categories of CC, 384 FD, FEU, PMF, TA, and WD, while there is an 11% environmental load reduction when pigs with a finishing weight of 90 kg are produced. These results showed that the production of pigs with a finishing weight of 90 kg, in present conditions, generated smaller environmental burdens in the environmental profile pertaining to semi-technified pig production.

Soleimani et al. (2021) demonstrated that improving feed efficiency in swine farms is pivotal for achieving sustainability, since the main environmental impacts of such farms come from feed production, manure excretion, and gas emissions. However, not only diet contributes to such matter since it is also necessary to consider selection for feed efficiency and specific nutritional requirements for genetic lines to mitigate environmental impacts. The latter author found that compared to conventional diets, optimized diets for a high feed efficient genetic line and a low feed efficient genetic line reduced in average 4.2% and 3.8% environmental impacts, respectively.

While the main objective of the study was to determine the environmental burdens and not the economic impact or production costs, it is important to examine all aspects that can affect swine farms —— i.e., economic effect of selling lighter or heavier pigs. Rebollar et al. (2007) determined that the optimal weight for selling live pigs in a semi-technified farm in the state of Mexico was 142.7 kg, emphasizing that the maximum profit could only be obtained if the selling price was not altered; in such case, the producer would obtain the maximum profit with live weights between 95 and 115 kg. However, in a similar study that focused on pork cuts, Rebollar et al. (2014) demonstrated that selling heavier pigs did not necessarily mean a higher profit for the producer, given that a sensitivity analysis determined that growing pigs to a weight of 113.5 kg resulted in the technical optimum for selling carcasses, primal, sub-primal, and retail pork cuts.

As already mentioned in the introduction to this study, market requirements play a decisive role in the establishment of finishing weights. In Italy, for example, where the pork production sector focuses on the production of heavy pigs, Bava et al. (2017) studied the environmental impacts generated by producing such pigs, weighing 168.7 ± 3.33 kg, and ascertained that environmental impacts were generally bigger for lighter animals, enabling producers to continue growing heavy pigs for conversion into cured ham, they suggest studying examining different feed options, taking into account both protein supply and also the stringent requirements imposed on products with the DOP (i.e., *Denominazione di Origine Protetta* or "Protected Designation of Origin") label.

The major policy implications of this study are sustained in stimulating the production of feeds for livestock within the country, since such practice can contribute to carbon capture, preventing erosion of unproductive lands, generate carbon sinks, all with an efficient use of resources and recycling of water. Additionally, producing local feeds reduces energy used for transportation of inputs, generates a small circuit of commercialization, and in general, reduces governmental funds destined to mitigate environmental impacts. LCA in the pig production chain helps to find environmental issues to transform them in viable and sustainable solutions from a social, economic, and environmental perspective. The results obtained contribute to the development and restructuring of waste handling programs in Mexico, in order to have a clear regulation of such programs. Furthermore, LCA allows to establish the processes involved in livestock waste handling, from the origin, minimization, reutilization, and disposal or exploitation to produce energy.

## Conclusion

The results of the study described here indicate that the feed production subsystem is the main generator of environmental impacts mainly caused by the cultivation of sorghum and the production of fat. Unlike other studies that concluded that maize and soy are the main generators of environmental burdens, the present study finds that sorghum cultivation and fat production constitute critical points in the chain. These findings can serve as a basis for future LCA studies of pork production in Mexico, which require further environmental impact analyses, based on alternative feed scenarios that make it possible to reduce the system's environmental burdens while still yielding good profits.

Variations in input sources correlated with the main environmental impact variations for the feed production subsystem, doing so mainly in the FD category, where the acquisitions of inputs from a distance of 900 km resulted in a fivefold environmental load increase, while the acquisition of inputs from a distance of 1800 km resulted in a ninefold environmental load increase. The production of lighter pigs proved to be the best environmental alternative, given the resultant 11% reduction in environmental impact.

It bears stressing that it is necessary to include manure management and treatment —— which, in the present study, had repercussions on the freshwater eutrophication, terrestrial acidification, and particulate matter formation categories —— in the animal production subsystem in order to be able to determine which emissions are avoided within the said system.

Given the importance of Mexican pig production both in Mexico and in the rest of the world, this study provides important information about the environmental profile of a typical Mexican semi-technified pork production system, based on multiple pork production scenarios that represent 30% of all the pig production units in Mexico. It highlights pertinent factors that need to be considered in order to create models that result in reduced emissions and an improved environmental profile, or make it possible to develop effective environmental impact reduction protocols.

The present LCA study about the Mexican pig production chain serves as a foundation for future LCA studies with a cradle-to-cradle perspective, with reference towards reusing and properly handling waste, and utilization of by-products, in order to close natural cycles.

**Acknowledgements** The authors wish to thank the National Council for Science and Technology of Mexico for scholarship number 570063, granted to María del Rosario Villavicencio Gutiérrez for the purpose of carrying out her doctoral studies; the pork producer that kindly provided the information used in this study; and the UAEM 4219/2016SF research project.

**Author contribution** María del Rosario Villavicencio-Gutiérrez: investigation, formal analysis, writing — original draft, software; Nathaniel Alec Rogers-Montoya: writing — review and editing; Angel Roberto Martínez-Campos: validation; Germán Gómez-Tenorio: resources; Francisco Ernesto Martínez-Castañeda: data curation, conceptualization, methodology, supervision.

**Funding** This work was supported by the National Council for Science and Technology (Spanish abbreviation: CONACYT) with scholarship number 570063, granted to María del Rosario Villavicencio Gutiérrez for the purpose of carrying out her doctoral studies and The Autonomous University of the State of Mexico research project UAEM 4219/2016SF.

**Data availability** The datasets generated and analyzed during the current study are not publicly available because they are property of a commercial farm but are available from the corresponding author on reasonable request.

## Declarations

**Ethics approval** Not applicable.

**Consent to participate** Not applicable.

**Consent to publish** Not applicable.

**Competing interests** The authors declare no competing interests.

## References

ADEME. (2016). French Environment and Energy Management Agency, Agribalyse program V1.3.

Alba, Y., Barrera, E., Sarduy, A. Pérez, M., Hermida, O., Dewlf, J., 2019. Life cycle assessment for Cuban pig production: case study in Sancti Spiritus. Journal of Cleaner Production. 219, 99-109.

Anestis, V., Papanastasiou, D., Bartzanas, T., Giannenas, I., Skoufos, I., Kittas, C, 2020. Effect of a dietary modification for fattening pigs on the environmental performance of commercial pig production in Greece. Sustainable Production and Consumption. 22, 162-176.

ASERCA Apoyos y Servicios a la Comercialización Agropecuaria. 1996. Una visión de la porcicultura en México. Claridades Agropecuarias. 34. 40 p

Bava, L., Zucali, M., Sandricci, A., Tamburini, A, 2017. Environmental impact of the typical heavy pig production in Italy. Journal of Cleaner Production. 140, 685-691.

Basset-Mens, C., van der Werf, H, 2005. Scenario-based environmental assessment of farming systems: the case of pig production in France. Agriculture, Ecosystems and Environment. 105, 127-144.

Boulanger, A. 2011. El control de agua y su consumo en porcinos. Sitio Argentino de Producción Animal: http://www.produccionanimal.com.ar/agua_bebida/control_agua_y_consumo.pdf. Accessed 20 Jan 2021.

Domínguez, G., Galindo, A., Salazar, G., Barrera, G., & Sanchez, F. (2014). Las excretas porcinas como materia prima para procesos de reciclaje utilizados en actividades agropecuarias. Jalisco: SAGARPA-INIFAP.

FAOSTAT. 2020. https://www.fao.org/faostat/es/#home. Accessed 20 Jan 2021.

Gerber, P., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A., Tempio, G, 2013. Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations (FAO), Rome.

González, S., Belo, S., Dias, AC., Várzea, J., da Costa, R., Ferreira, A., Arroja, L, 2015. Life cycle assessment of pigmeat production: Portuguese case study and proposal of improvement options. Journal of Cleaner Production. 100, 126-139.

Huerta, O., 2013. Productividad y visión de negocio de las empresas porcinas, en Bobadilla, E., Martínez, F, E., (Eds.), Porcicultura Mexicana: Auge y crisis de un sector. Universidad Autónoma del Estado de México, Mexico, pp. 165–172.

ISO, 2006a. Environmental management-life cycle assessment-principles and framework.

ISO, 2006b. Environmental Management-Life Cycle Assessment-Requirements and Guidelines.

Lamnatou, C., Ezcurra, X., Chemisana, D., Plà, L, 2016. Environmental assessment of a pork-production system in North-East of Spain focusing on life-cycle swine nutrition. Journal of Cleaner Production. 137, 105-115.

Méndez, R., Castillo, E., Vázquez, E., Briceño, O., Coronado, V., Pat, R., & Garrido, P. 2009. Estimación del potencial contaminante de las granjas porcinas y avícolas del estado de Yucatán. Ingeniería. 13(2), 13-21.

McAuliffe, G., Chapman, D., Sage, C, 2016. A thematic review of life cycle assessment (LCA) applied to pig production. Environmental Impact Assessment Review. 56, 12-22.

McAuliffe, G., McAuliffe, Takahashi, T., Mogensen, L., Hermansen, J., Sage, C., Chapman, D., Lee, M., 2017. Environmental trade-offs of pig production systems under varied operational efficiencies. Journal of Cleaner Production. 165, 1163-1173.

Ministerio de Agricultura, Pesca y Alimentación. (2004). Cuadros de cálculo de emisiones del sector ganadero en relación con la directiva IPCC. Spain, Government of Spain.

Nguyen, T., Hermansen, J., Mogensen, L, 2011. Enviromental assessment of Danish pork. Aarhus University, Department of Agroecology, Denmark.

Noya, I., Villanueva, P., González, S., Fernández, M., Rodríguez, M., Moreira, M, 2017. Life Cycle Assessment of pig production: A case study in Galicia. Journal of Cleaner Production. 142, 4327- 4338.

OCDE. 2019. Exámenes de mercado en México. Estudio de Mercado de la carne de cerdo. https://www.oecd.org/daf/competition/examenes-de-mercado-en-mexico-estudio-de-caso-del478mercado-de-la-carne-de-cerdo.htm (consulted on May 3, 2020).

Olea, R. 2009. Analysis of Sustainability in the Pig Production Chain: Life Cycle Assessment of Contrasting Scenarios. Newcastle University (PhD).

Open LCA. (18 de 02 de 2019). *The open source Life Cycle and Sustainability Assessment software*. Obtenido de https://www.openlca.org/release-openlca-1-8/. Accessed 20 Jan 2021.

Pérez, R. 2001. Porcicultura y contaminación del agua en la Piedad, Michoacán, México. Revista Internacional de Contaminación Ambiental. 17(1), 5-13.

Rebollar, S., Gómez, G., Hernández, J., Rojo, R., de Jesús, F., Avilés, F. 2007. Determinación del óptimo técnico y económico en una granja porcícola de Temascaltepec, Estado de México. Ciencia Ergo Sum. 14 (3), 255-262.

Rebollar, S., Gómez, G., Callejas, N., Guzmán, E., Hernández, J. 2014. Óptimos técnicos y económicos en cortes de carne de cerdo en dos regiones de México. Agronomía Mesoamericana 25 (1), 161-168.

Reckmann, K., Traulsen, I., Krieter, J., 2012. Environmental Impact Assessment - methodology with special emphasis on European pork production. J. Environ. Manag. 107, 102 - 109.

Reckmann, K., Traulsen, I., Krieter, J., 2013. Life Cycle Assessment of pork production: A data inventory for the case of Germany. Livestock Science. 157, 586-596.

Rodríguez, G., Díaz, M., 2013. Situación de la porcicultura porcina en México, en Bobadilla, E., Martínez, F. E. (Eds.), Porcicultura mexicana: auge y crisis de un sector. Universidad Autónoma del Estado de México, Mexico, pp. 53–81.

SAGARPA Secretaria de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación. 1998. Situación actual y perspectivas de la producción de carne de porcino en México 1990-1998. México. 73 p.

SIAP. 2013. Regiones Agroalimentarias de México. https://www.gob.mx/siap/prensa/presenta-la-sagarpa496 serie-monografica-regional-agroalimentaria-38627 (consulted on May 3rd, 2020).

SIAP. 2018. Producción agrícola. Avances de siembras y cosechas, resumen nacional por estado. https://www.gob.mx/siap/acciones-y-programas/produccion-agricola-33119 (consulted on May 3rd, 2020).

SNIIM. 2020. Mercados Nacionales Pecuarios, Porcinos. http://www.economiasniim.gob.mx/nuevo/Home.aspx?opcion=/SNIIM-Pecuarios-Nacionales/MenPec.asp?var=Por (consulted on August 20th, 2020).

Soleimani, T., Gilbert, H. 2021. An approach to achieve overall farm feed efficiency in pig production: environmental evaluation through individual life cycle assessment. The International Journal of Life Cycle Assessment. 26, 445-469.

Srnicek, N., Williams, A. 2017. Inventar el Futuro. Poscapitalismo y un Mundo sin Trabajo. Malpaso Ediciones. Barcelona.

Wang, X., Dadouma, A., Chen, Y., Sui, P., Gao, W., Jia, L, 2015. Sustainability evaluation of the large-scale pig farming system in North China: an energy analysis based on life cycle assessment. Journal of Cleaner Production. 103, 144-164. https://doi.org/10.1016/j.jclepro.2015.04.071