**Title:** A meta-analysis of life cycle assessments on environmental footprints of five representative finishing swine diets – **NPB#17-159**

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**Industry Summary:**

High feed cost and environmental footprint are two major challenges for the US pork industry. Feed costs play a major role in determining the profitability of a swine enterprise. Energy and protein are the main nutrient components in swine diet. Energy represents the largest cost contribution to the finished diet followed by protein. Energy from corn has been a very economical source for swine diets. The complementary way in which corn and soybean blend to produce a well-balanced diet makes this combination a standard for supplying energy and protein. In cases of limited supplies and high prices of corn or soybean, producers are encouraged to evaluate alternative sources of energy and protein, including other grains, byproducts of feed and food industry, and make "what if" comparisons in a changing global and local market.

In the same time, as livestock production is one of the major causes of the world's environmental impacts including agricultural land use, water depletion, and climate change, researchers are looking for alternative diets that will lower environmental footprints of swine production. Life cycle assessment (LCA) is a tool to evaluate environmental footprints of a product or process throughout the entire life cycle. The use and impacts on land, air, water, and greenhouse gases all make up the environmental footprints of swine production. This project aims to provide robust estimations on environmental footprints of swine diets through LCA analysis. The goal is to gather solid information in literature to address the two major challenges for the swine industry: high feed cost and large environmental footprint, and to assist the US swine industry to look for realistic low cost and environmentally sustainable feeding strategies, and to highlight opportunities for potential change or innovation. The objective of the project is to quantify the carbon, water and land footprint of a standard corn-soybean finishing swine diet and four alternative diets.

From literature and survey, we identified the following five representative diets in the USA: Corn-Soybean meal, Corn-Soybean meal-low DDGS, Corn-Soybean meal-high DDGS, Corn-Soybean meal-

DDGS-Bakery-Middlings, and Sorghum-Soybean meal. The environmental footprints of major feed ingredients including corn, soybean meal, DDGS, sorgum, wheat-middlings, and amino acids were estimated through a synthetic LCA. The environmental footprints of the five representative diets at the feed production stage on a per pound live weight were calculated and summarized in one table. Introducing DDGS into the standard Corn-SBM diet will generally reduce the environmental footprints in global warming, land use, and water consumption at the feed production stage. Since the global warming footprint at the feed production stage and at the management or animal production stage are almost equally important in the overall global warming footprint of swine production. When DDGS is used in swine diet, the benefit of reducing global warming footprint at the feed production stage may be offset by the potential increasing global warming footprint at the management or animal production stage. Among the identified five representative diets, the Sorghum-SBM diet has the highest global warming and land use footprint, followed by the Corn-SBM-DDGS-Bakery-Middlings diet. Nevertheless, the Sorghum-SBM diet has the lowest water consumption footprint, while the standard Corn-SBM diet has the highest water consumption footprint.

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**Keywords:** Life cycle assessment, environmental footprint, swine, pork, diet, global warming, water consumption, land use, feed production

**Scientific Abstract:**

The objective of this project is to quantify the carbon, water and land footprint of a standard corn-soybean finishing swine diet and four alternative diets through a systematic review of related LCA studies, as well as a synthetic LCA. From literature and survey, we have identified the following five representative diets in the USA: Corn-Soybean meal, Corn-Soybean meal-low DDGS, Corn-Soybean meal-high DDGS, Corn-Soybean meal-DDGS-Bakery-Middlings, and Sorghum-Soybean meal. The global warming footprint of corn production in USA is estimated to be 0.311 kg $CO_2$ eq./kg in 2017, as comparing with 0.2 to 0.53 kg $CO_2$ eq./kg in literature. Estimation of the environmental footprints of soybean meal, DDGS, and wheat middling are greatly affected by the allocation methods used. Using the economical allocation method usually result in less environmental footprints of these feed ingredients, comparing with the mass allocation method, because more environmental footprints are allocated to more valuable co-products, such as crude soy oil, ethanol, or, wheat bran. The global warming footprint of DDGS in USA is only 0.242 kg $CO_2$ eq./kg based on current price. Introducing DDGS into the standard Corn-SBM diet will generally reduce the environmental footprints in global warming, land use, and water consumption at the feed production stage. Since the global warming footprint at the feed production stage and at the management are almost equally important in the overall global warming footprint of swine production. When DDGS is used in swine diet, the benefit of reducing global warming footprint at the feed production stage may be offset by the potential increasing global warming footprint at the management or animal production stage. The environmental footprints of the five representative diets at the feed production stage on a per pound live weight were calculated and summarized in one table. At the feed production stage, the global warming footprint of the five diets ranges from 0.782 to 1.474 kg $CO_2$ eq. per kg live weight; the land use footprint ranges from 2.086 to 5.729 $m^2$a crop eq. per kg live weight; the water consumption footprint ranges from 0.328 to 0.952 $m^3$ per kg live weight. Among the identified five representative diets, the Sorghum-SBM diet has the highest global warming and land use footprint, followed by the Corn-SBM-DDGS-Bakery-Middlings diet. Nevertheless, the Sorghum-SBM diet has the lowest water consumption footprint, while the standard Corn-SBM diet has the highest water consumption footprint.

## Introduction:

### *Alternative diets for finishing swine*

High feed cost and environmental footprint are two major challenges for the US pork industry. Feed costs play a major role in determining the profitability of a swine enterprise. Traditionally, the US producers use corn and soybean meal as a base for swine diets, and feed costs have represented 65 to 75% (Pork Checkoff, 2015) of the costs of swine production. This figure could be higher due to the volatility in the corn and soybean markets. The average swine finishing feed cost index for 2007-2016 was twice higher than the 2000-2006 index (Langemeier, 2016).

Energy and protein are the main nutrient components in swine diet. Energy represents the largest cost contribution to the finished diet followed by protein, or more specifically, the source of essential amino acids such as lysine (Harper, 2006). Energy from corn has been a very economical source for swine diets. The complementary way in which corn and soybean blend to produce a well-balanced diet makes this combination a standard for supplying energy and protein. Supplemental lysine is common and sometimes may replace soybean depending on relative prices of corn and soybean. In cases of limited supplies and high prices of corn or soybean, producers are encouraged to evaluate alternative sources of energy and protein, including other grains, byproducts of feed and food industry, and make "what if" comparisons in a changing global and local market.

Feed ingredients that could be used in swine diet are numerous and of various origins: production of grains and protein crops specifically to feed livestock (e.g., corn grain); by-product feeds from the production of human food and biofuel (e.g., corn meal and Dried Distillers Grains with Solubles (DDGS); and minerals, vitamins, and other additives from chemical production (Schenck and Huizenga, 2014). Small grains, such as barley, oats, and wheat can be useful feedstuffs. Small grains are higher in crude protein than corn and, more importantly, they are higher in lysine. When viewed in the context of an integrated crop and livestock system, addition of an extra crop to the corn-soybean rotation could be cost effective and reduce weather risks (Sullivan et al., 2005). DDGS are increasingly used in practice as a partial replacement for corn-soybean meal to reduce feed cost. Phosphate supplements represents the third most significant cost in swine diet, and feedstuffs that contribute more available phosphorus add value as less phosphate supplement is required (Harper, 2006). The maximum inclusion rates of various feed ingredients are based on limiting factors such as palatability, nutrient availability, protein quality, nutrient interrelationship, and the method of processing and feeding (NPB, 2008). To address high feed cost, producers should aggressively monitor ingredient prices and reformulate rations accordingly as ingredient prices change. The "least-cost formulation" principle is widely practiced to design alternative diets that meet nutritional requirements at the least cost.

In the same time, as livestock production is one of the major causes of the world's environmental impacts including agricultural land use, water depletion, and climate change, researchers are looking for alternative diets that will lower environmental footprints of swine production. Burek et al. (2015) used linear models to formulate multiple single-objective swine diets, and generated different preferred diets for different objectives. Their preliminary result showed that the least-cost diet includes wheat, sorghum, wheat middlings, and DDGS; the least-climate change impact diet includes wheat, wheat middlings, soybeans, soybean hulls, and DDGS; the least-water depletion diet includes wheat middlings, DDGS, and canola meal; the least-land use diet includes DDGS, wheat, rice bran, and corn gluten feed. It is anticipated that realistic low cost and environmentally sustainable feeding strategies should to be identified through combined analysis of both cost and environmental factors.

### *Life cycle assessment on environmental footprints*

Life cycle assessment (LCA) is a tool to evaluate environmental footprints of a product or process throughout the entire life cycle (Rebitzer et al., 2004), and is one of the best available tools used in EU for different production sectors including agriculture (European Commission, 2015). ISO 14040 and ISO 14044:2006 standards provide an internationally agreed method of conducting LCA (ISO, 2006). LCA was traditionally applied to analyze industrial systems, but has been adapted and progressed significantly over the past decade to assess the environmental effects of agriculture, and to improve agricultural sustainability. LCA for agricultural products begins with production of fertilizers, and then crop cultivation, and animal husbandry, through processing, use and disposal of wastes associated with its final use. LCA analyze all inputs and outputs that cross the system boundary, which largely depends on the goal of the study. The functional unit (FU) depends on the goal of the study and the system boundary, and are generally chosen to reflect the way each commodity is traded, such as one kg of product or live weight at the farm gate (Harris and Narayanaswamy, 2009).

Agricultural LCA studies typically examine a range of environmental impact categories, such as energy use, land use, pesticide use, acidification, eutrophication, climate change/global warming potential, etc. Agricultural LCA is often more complex than of industrial LCA. In addition to the main agricultural product, there are usually coproducts, so that appropriate environmental impacts need to be assigned to each product, a process known as allocation. Agricultural systems are interlinked and therefore changes to one system, e.g. arable crops used for animal feed, will have knock-on effects to other systems, e.g. the animal systems. Large uncertainty is widely acknowledged for on-field emissions from crops and animals. Impact of water use is a particularly complex issue and depends on how the system boundaries are defined in time (Harris and Narayanaswamy, 2009). The use of LCA software is recommended as a necessary criterion to ensure robustness, uncertainty analysis, and comprehensive coverage of processes and data volumes in agricultural LCA, as this would help with tracking changes and updating data. Agricultural LCA is a difficult and contentious task, as a result of the wide range of variables involved, but it could help to improve agricultural sustainability.

### *LCA types and goals*

There are mainly two types of LCA (Internal LCA and external LCA) (Pre consultant, 2018) widely used in determining the impact of a product on environment along its life cycle stages. Internal screening of LCA is usually made for a short time while using the available standard data and impact assessment. In the internal LCA sensitivity analysis is very important and ISO 14040, 14041 and 14042 are followed. On the other hand, for the external LCA all the prerequisites are similar to the internal type, in addition, it demands an external peer reviewing process besides the follow up process of ISO 14040.

Also, in the literature there are mostly two type of allocation have been studied widely. Of the two types, attributional life cycle assessment (ALCA) asses the direct impact of a product to the environment on a quo status situation (Hannah et al., 2018). For pork production, the environmental impacts arise from the utilization of raw materials and emissions of pollutants involved in per kg pork generation; for instance, the feed inclusion, energy or fuel for transport and heating for certain period. ALCA has been used commonly in pork production (McAuliffe et al., 2016), with a limitation in quantifying the impacts of variation of feed ingredients in the diets. For instance, the co-products or locally produced by-product which could be used for protein source doesn't cover the land use needed for it and thus require system expansion approach.

On the other hand, increasing demand for co-products or byproducts shifting the LCA method from direct impact analysis to indirect system of what is known as consequential life cycle assessment (CLCA). In CLCA, how the changes of a particular parameter drive/influence to the environment or processes in or outside the production cycle of a product presents a better reflection (Ekvall and Weidema, 2004). Moreover, in CLCA, of co-product allocation, mainly handled through system expansion. System expansion refers all the inputs and outputs related to the product of interest and the co-products are included by an expansion of the product system (Dalgaard et al., 2007). For example, if one feed ingredient is replaced with another feed ingredient, the whole diet composition will change to meet the nutritional requirements of the animal. If, for example, soybean meal (SBM) is replaced with RSM based on crude protein content, the net energy content per kilogram of feed will decrease. Meaning that if one aims to maintain the same growth performance of the animal, an increase in an energy-rich ingredient such as animal's fat (having a high GWP and EU) is required. Thus, this CLCA method would be able to quantify the changes to the system.

Goals of LCA studies usually are to inform the designers about the dominant aspects that determine the environmental load in the life cycle of a product system. A special attention is the feasibility of a selective take back and disassembly system (Pre Consultant, 2018).

***System boundaries for LCA of animal feed***

The system boundaries for LCA of animal feed ingredients have been defined by Schenck et al. (2014) as in Fig. 1. The main animal feed nutrient content data were obtained from the NRC (2012). Feed ingredient prices were collected from various feed market data sources, including Feedstuffs (2014), a weekly newspaper for agribusiness as well as from feed mills, pork industry representative and firms engaged in the production of feed additives. The animal feed cost values were provided from the Department of Agricultural Economics & Agribusiness at the University of Arkansas (Popp 2014). The main environmental footprint data (40%) for swine feeds was obtained from the US agricultural and product LCA models built in SimaPro 7.3.3 (PRé Consultants 2011). These models are a result of several years of work on fluid milk, poultry, cheese, peanuts, and swine LCA projects at the University of Arkansas (Van Loo et al. 2011; Mccarty et al. 2012; Thoma et al. 2013b; Kim et al. 2013; Adom et al. 2013; Nutter et al. 2013; Thoma et al. 2013a; Thoma et al. 2013c; Thoma et al. 2013d). Standard LCI databases were used (4%): US-EI v2.2 (EarthShift 2011) and US Input-Output database (Mongelli et al. 2005). Direct LCIA results from published papers (Tan et al.; Nielsen and Wenzel 2007; Mosnier et al. 2011) represent less than 10% of data sources. Approximately 7% of data uses surrogate LCI which are used to bridge data gaps for animal feed ingredients.

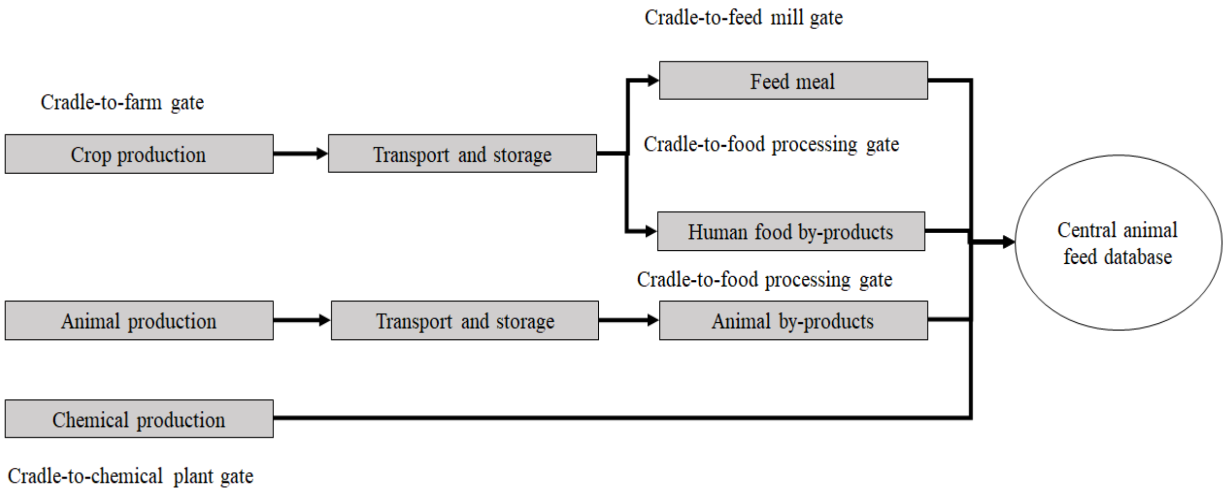


**Fig 1. System boundary for feed ingredient production (adapted from Schenck et al., 2014)**

A comprehensive system and subsystem boundary definition for pig production has been brought by a European research group in France Garcia-Launay et al. (2014). In their studies, they defined the boundary from the process of pig production including production and transport of feed ingredients, feed production at the feed factory, transport to the farm, piglet production, post-weaning and fattening, manure storage, transport and spreading (Fig.2). LCI data were collected from EcoInvent (version 2.0) (Nemecek and Kagi, 2007) database for the resource reuse and associated emission with the crop production and inputs for crop production (fertilizers, pesticides, tractor fuel and agricultural machinery).

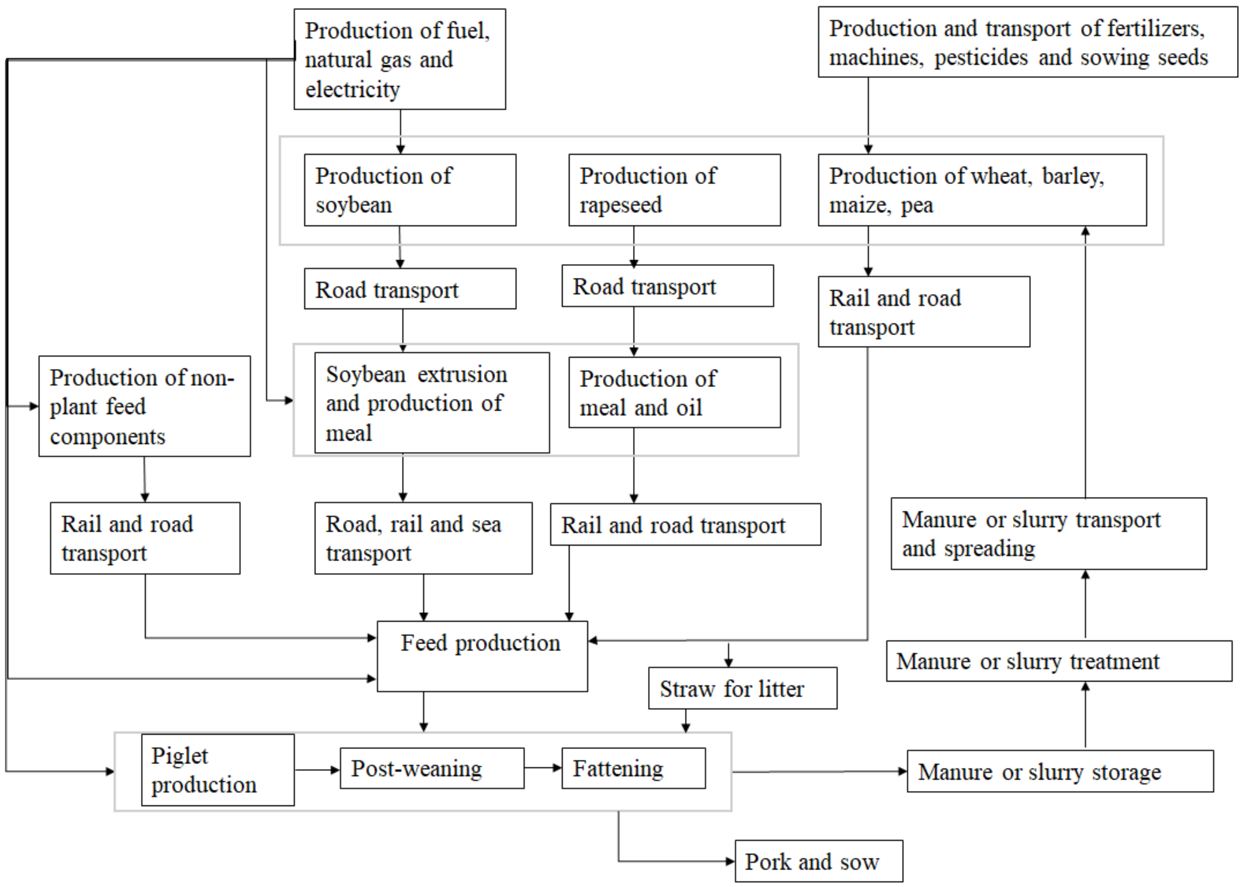


**Fig 2. System and subsystem boundaries for pig production (adapted from Faria-Launay et al., *2014)***

***Life cycle impact assessment (LCIA)***

Life cycle impact assessment (LCIA) of a product system helps in the interpretation of LCA studies by translating the emissions from large number of substances and resource extraction into a finite number of environmental impact scores (Hauschild and Huijbregts, 2015). The process of scoring these environmental impacts is termed as characterization which indicate the environmental impact per unit of stressor (e.g. per kg of resource used or emission released).

ReCiPe 2016 midpoint method, Hierarchist version (1.02) has been applied. This is the default ReCiPe midpoint method. Global warming differ from the 100a time horizon in IPCC 2013 because climate-carbon feedback for non-$CO_2$ GHGs is included. The update of ReCiPe provides characterization factors that are representative for the global scale, instead of the European scale, while maintaining the possibility for a number of impact categories to implement characterization factors at a country and continental scale.

Assessing environmental impact categories at midpoint level are global warming, stratospheric ozone depletion, ionizing radiation, fine particulate matter formation, ozone formation (human health), ozone formation (terrestrial ecosystem), terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, land use, mineral resource scarcity, fossil resource scarcity and water consumption.

***Meta-analysis and goal of this study***

Meta-analysis is a quantitative statistical analysis of a large collection of analysis results from individual previous studies for the purpose of integrating the findings. Results from a meta-analysis usually are more precise than any individual study contributing to the pooled analysis because of improved statistical power (Hunter and Schmidt, 1990). Studies have been conducted in assessing the environmental impacts on changing livestock diets (Mogensen et al. 2010; Nguyen et al. 2013) and pig diet (particularly in Netherlands) (Hannah et al., 2018), The recent progress of LCA studies and database (USDA, 2018) on swine production makes the conduct of a meta-analysis of these LCA studies feasible and desirable.

The use and impacts on land, air, water, and greenhouse gases all make up the environmental footprints of swine production. In order to address challenges in feed cost and environmental footprints, a combined analysis of both cost and environmental factors is required. This project conducted a systematic review of related LCA studies, as well as a synthetic LCA on environmental footprints of five representative diets based on conditions and trends of the US market, and the "least cost formulation" principles. By determining the midpoint environmental impacts (global warming, water consumption and land use) of the feed ingredients used in diet formulation, and then comparing the environmental impact of different diets, the project aims to provide robust estimations on environmental footprints of swine diets. The goal is to gather solid information in literature to address the two major challenges for the swine industry: high feed cost and large environmental footprint, and to assist the US swine industry to look for realistic low cost and environmentally sustainable feeding strategies, and to highlight opportunities for potential change or innovation.

**Objectives:**

The objective of the project is to quantify the carbon, water and land footprint of a standard corn-soybean finishing swine diet and four alternative diets through a systematic review of related LCA studies, as well as a synthetic LCA based on meta-analysis of all existing data and a compiled database. Specific objectives include:

(1) Identify four alternative diets that are representative based on conditions and trends of the US market in addition to standard corn-soybean diets, generate diet formulations based on "least cost formulation" principles, and evaluate cost differences among the five diets on a cost per pound live weight and per pig at the farm gate basis.

(2) Quantify the carbon, water and land footprint of each of the major feed ingredients included in the standard corn-soybean diet and the identified four alternative diets at the feed production stage through a systematic review of existing LCAs as well as a synthetic LCA, and then provide a ranging of results on the carbon, water and land footprint of each of the five representative diets on a per pound live weight and per pig at the farm gate basis, with main sources of uncertainty identified.

(3) Compare the environmental footprint differences between the standard corn-soybean finishing diet and the four alternative diets at the live animal production stage based on meta-analysis and estimation of excess nutrients and feed efficiency for each of the five diets.

**Materials & Methods:**

**Selection of representative swine diets**

Literature review and email survey among extension and industry experts were conducted in order to select four alternative diets that are representative based on conditions and trends of the US market. The basis for our alternative swine diet selection was driven by the factors involved in rearing finishing swine for instance, availability of the feed ingredients for a diet, nutrient availability, protein quality, palatability, anti-nutritional factors, storage life etc. For the selection of diet in swine production, it is important to bear in mind the feed essentially supplies all the composition needed for its growth and development. Generally, feed ingredients divided into five groups that comprises of energy, protein, minerals, vitamins and antibiotics (Luce, 2016). Energy supplying groups broadly consist of carbohydrates of cereal grains such as corn, sorghum grain, wheat and barley, supply most of the energy in swine rations while a part of this energy group provides protein to rations, however the protein from this cereals source is poor in quality due to lack of essential amino acids such as lysine. Therefore, additional protein is necessary to supply in the rations from the source like soybean meal, peanut milk, milk byproducts, meat and bone meal. Majority of the swine diets need supplemental sources of minerals while formulating a ration. Available cereal grains are low in calcium and phosphorus (Luce, 2016). Thus, a soybean and corn-based swine formulation requires the supplementation of calcium and phosphorus. Vitamins and antibiotics are also supplied to the swine formulation in order to increase the swine growth rate, improving feed efficiency and controlling many diseases.

The growing-finishing pig can be fed alternate energy sources such as grain sorghum, barley, wheat, triticale, fat and a variety of by-products feedstuffs. Alternative swine diets could be cost effective and useful for swine diets when produced in the industries that are involved in grain milling, baking, distilling, packing, rendering, fruit and vegetables processing, vegetable oil refining, dairying, egg and poultry processing. Various byproducts of these mills could potentially be the substitution of the existing feed diets since they provide the nutrients and would reduce the cost of swine production potentially (NPB, 2008).

In addition to the feed ingredients of standard corn-soybean diet (83.5% corn, 14% soybean, and 2.5% premix of minerals and trace elements-Dunn et al. 2013), we have identified the following 18 potential ingredients for alternative diets formulation from literature.

1. Corn
2. Distillers dried grains with soluble (DDGS)
3. Barley
4. Oats
5. Sorghum
6. Triticale
7. Wheat-soft white winter variety
8. Wheat-soft red winter variety
9. Wheat, hard red spring
10. Wheat, hard red winter
11. Wheat middlings
12. Soybean meal
13. Meat and bone meal
14. Canola meal
15. Sunflower meal

16. Peas
17. Synthetic amino acids
18. Animal fat or vegetable oil

It is noted that that these diets were further passed and verified through a cascade processes of large survey throughout different states in the US and least-cost formulating procedure to a representative number for our meta-LCA analysis.

With a view to select the representative alternative swine diets in US, a second round of survey among the swine nutrition specialists in universities, extension personnel and industry were conducted through their e-mail contacts and the customize survey questionnaire (See Appendix 1) to get the feedback from the respondents.

**Least cost formulation technique**

After the survey process the least–cost formulation technique was applied in consultation with expert nutritionists and linear programming based on "least cost formulation principles" to find the most suitable and representative alternative swine diets in the US. Nutrient requirement of the animal was obtained from NRC (2012). Up-to-date feed ingredient costs and nutrient analysis was collected from various feed market data sources, including feed mills, pork industry, and Feedstuffs, a weekly newspaper for agribusiness. Availability of the nutrient to the animal and minimum-maximum restrictions on levels was evaluated from literature review. Suitable ingredients was selected to make the ration nutritionally balanced, palatable, safe, and economical. The necessary fixed amount of certain ingredients (minerals and vitamins) was determined and then grains relative to protein supplements were estimated. As the most limiting indispensable amino acid, lysine was used to balance diets initially.

For each ingredient used, the price range was estimated in which the ingredient was economical. Feed intake per finishing pig, feed to gain ratio, average live weight at sale, cost per pig produced, and cost per pound live weight (2017 prices) for the standard corn-soybean diet and the four alternative diets was estimated from both model calculation and literature review, and the results was compared among the five representative diets. The cost comparison was considered on factors such as transportation, processing and storage needs.

**Quantification of the environmental footprint of the diets at feed production stage**

An exhaustive information and literature search was undertaken in the public domain, including international journals, the internet and industry reports, in order to collect information on environmental footprints of each of the major feed ingredients included in the standard corn and soybean diet and the identified four alternative diets. An iterative process was used to refine the search strategy in database such as Web of Science, Scopus, CAB Abstracts and Google Scholar. Manual search was carried out on the references that were cited in the identified studies. The search was targeted to all the existing LCA studies on these feed ingredients and all data that could contribute to the Life Cycle Inventory (LCI) for these feed ingredients. Two strategies were used to quantify the environmental footprints of the feed ingredients.

In the first strategy, a critical review on existing LCA studies was conducted, including the US agricultural and product LCA models built in SimaPro 7.3.3. Types of LCA methodology and allocation method used, the scope, scale and system boundary defined were summarized. LCA case studies with comparable system boundaries and assessment methods were compared and meta-analyzed. This may involve recalculation of the results of the available impact categories to one common FU.

In the second strategy, a synthetic LCA was conducted to evaluate the average and range of environmental footprints of each of these feed ingredients based on of all existing data. Standard LCI databases such as EarthShift (http://www.earthshift.com/) US-EI database v.2.2, the USLCI database (http://www.nrel.gov/lci/), Agri-footprint v1.0 database (Blonk Consultant, http://www.agri-footprint.com/), ecoinvent v3.3 database (Weidema et al. 2013) and US Input-Output database (Mongelli et al. 2005) based on national economic and environmental statistics were used as baseline. LCA case studies weree selected in which inventory data were available on the foreground processes. LCIs for the feed ingredients available in the literature were brought together and reanalyzed in selected LCA softwares including SimaPro (www.simapro.com). A transparent LCA model for calculating environmental footprints of swine production at the feed production stage was established.

After environmental footprints (carbon, water, land) of each feed ingredient is determined from the systematic review and the synthetic LCA, the environmental footprint of each of the five diets at the feed production stage was calculated on a per pound live weight and per pig at the farm gate basis.

**System boundary of LCA**

System boundary for existing LCA studies was reviewed by a thorough searching process of different databases, which would cover the major key words to find out the needed LCA studies for this research. For instance, searching information, literature and report through web of science, science citation index, science direct, scopous, google scholar etc. Identified major LCA studies were brought to focus on our synthetic LCA, drawing particular emphasis of the LCA studies carried out in USA.

For all the grain feed ingredients unit is the 'kg' production at farm gate while for processed feed ingredient is 'kg' feed ingredient at factory/millgate. For amino acids, the functional unit is 'kg' synthetic produced amino acid (Lysine.HCl, Threonine 98% pure crystalline threonine containing 2% water and 100% D,L-methionine), at the gate of the production site in the USA.

The agricultural production system includes the cultivation (winter wheat, corn, soybean, sorghum) in the United States of America (USA) and milling the produced grain at factory in the USA. Functional unit of LCA study is 1 kg of feed (winter wheat middling, corn, soybean meal, DDGS, sorghum and amino acids) production at factory/mill gate in the USA.

The system boundaries of grains milling process are from receiving of grains (wheat, corn, soybean. Sorghum) to delivery of products (wheat flour, corn meal, soybean oil) and other co-products at the dry milling factory gate. Considered activities include inputs of grains (wheat, corn, soybean, sorghum from USA), transport inputs, water, and heat from combustion of natural gas and electricity and an output of wastewater to waste water treatment. Capital goods are not included.

Milling process typically consists of several processing steps including receiving of dried/wet grains (wheat, soybean, corn, sorghum), and multiple grinding and sieving steps. In Agri-footprint, these process steps are aggregated into a single process for grains (wheat, corn, soybean, sorghum) dry/wet milling. The price information used to determine the allocation could be found in "Agri-Footprint - Part 2 - Description of data" – Appendix B (Blonk Agri-footprint BV, 2014).

For the dry milling of wheat Bechtel et al. (1999) was the only source with a quite complete dataset for the mass balance. This mass balance is underpinned with data from other, less complete sources. The energy requirements for the dry milling of wheat were from Eijk & Koot (2005) which was conducted by a Dutch consultant (KWA Bedrijfsadviseurs) to explore energy saving options for the members of the NVM (Dutch flour producers). The Dutch data for energy use of wheat milling were assumed representative for the other European countries and in the USA. For wheat middling LCA, it should be noted that attributional mass allocation was followed, based on dry matter of the products (for processing of the crop) and the mass of straw was not included in the system boundary, since it is generally used as left over in the crop land after harvesting the crop.

Similar to wheat-middling, attributional LCA approach is also applied to measure the environmental impacts of corn, soybean meal, and sorghum life cycle.

**Allocation methods in LCA**

According to the Pre Consultant (2018) there are 6 different types of allocation for LCA studies which are as follows:

1. Allocation default, unit processes
2. Allocation default, system processes
3. Allocation recycled content, unit processes
4. Allocation recycled content, system processes
5. Consequential, unit processes &
6. Consequential, system processes

Based on the inflow of the inputs and their corresponding outputs to the environment, there three types of allocation are practiced in the LCA studies- mass, economic and system expansion.

Attributional allocation system based on mass (dry matter) is applied in this study, since it facilitates to know the environmental impact of the product and the hotspots in its life cycle. Attributional approach further assist in comparing the environmental impacts of two products with same functional unit. This process describes the production of products and co-products (wheat flour, wheat bran, wheat middlings and feed and wheat germ, soybean oil, soybean meal, corn and sorghum) from a dry/wet milling process, in the United States. According to FAO Livestock Environmental Assessment and Performance Partnership recommendations (FAO, 2014) economic allocation should use as the methodology for co-product allocation throughout the feed supply chain. In the corn grain ethanol production, how the by-product DDGS would be allocated for fair and comparable environmental assessment is always the tricky and complex part. To overcome this allocation for a better understanding of the allocation for environmental impact assessment, LCA allocation decision can be drawn from ISO 14041 (1998) and ISO 14044 (2006). As to follow the ISO guidelines, allocation for different products of a process should be avoided if possible. Thus, the use of distiller's grain (DG) as animal feed does not achieve the goal. In order to resolve the crossing of system boundary issue, a system expansion (allocation by physical or economic relationships) approach is thus applied to capture the environmental burdens of DG in corn grain ethanol production process (Kraatz et al., 2014). Milling of wheat results in the production of wheat flour used for human consumption (the determining product) and wheat middlings (the co-product). The production volume of wheat middlings, therefore, is determined by the demand for wheat flour (van Zanten et al., 2014).

Physical relation is established based on mass among the produced products and co-products during the product system. Due to the unavailability of LCA on dry milling of wheat grain in the USA, a process of wheat grain dry milling based on mass in France from SimaPro (Version 8.5.2.0) is used as template to assess the environmental impacts of the wheat middling product system in the USA. Similar equation is applied for the determination of allocation co-efficient of other feed ingredients in this study.

The environmental impacts of a by-product or a waste material, i, can be expressed by the following equation: (Hossain et al., 2018)

$B_i = [A_x.I_p + (SP_i+T_i)]$……………………………………………………**eq. (1)**

Where, $B_i$ is the environmental impacts of the by-products *i*, *A* is the allocation coefficient (allocation coefficient refers to the fraction derived from the ratio of the main product and by-products according to their mass or economic value), x is the type of allocation, $I_p$ is the total environmental impact of the final process products and co-products, $SP_i$ is the environmental impacts of the secondary process (further processing to reuse) of by-product i, and $T_i$ is the environmental impacts due to the transport of the by-product 'i' for final use.

Two types of allocation (mass and economic) were considered in our study. For mass allocation co-efficient or fraction of the product or co-product was the amount of product and co-product produced after the dry milling of 1 kg grain. Assuming the fraction of products and co-products are the same for 1kg of grain dry milling in USA. Results for both mass and economic allocation of the product and co-products are presented in Appendix 3 attached with this report.

Mass and economic allocation percentage were calculated from the following equations based on their mass fraction of the grain milling process.

$W_i = [\frac{Mass_i}{Mass_{mp} + Mass_i}]$ ……………………………**eq. (2)**

Where, $Mass_i$ is the mass fraction of the by-product i, $Mass_P$ is the unit mass of the product and co-products P. The environmental impact of the byproduct 'i' can be derived by:

$B_{imass} = [W_i.I_p]$ ……………………………………………**eq. (3)**

In case of economic allocation, value of the products and co or by-products has been considered for their contribution to the environmental impacts. Economic allocation fraction of co-efficient of the product or co-product can be calculated by the following equation:

$E_i = \frac{Mass_i \times \$i}{(Mass_{mp} \times \$_{mp}) + (Massi \times \$_i)}$ ……………………………………**eq. (4)**

where $\$i$ is the unit price of by-product i, $\$_P$ is the unit price of the product and co-products. The environmental impact for economic allocation of by-product i can then be expressed by:

$B_{iecon} = [E_i.I_p]$ ……………………………………………………**eq. (5)**

**LCIA methods**

Hierarchist perspective method of Recipe midpoints 2016 v1.06 was applied based on scientific consensus with regard to the period (100 years) and plausibility of impact mechanism. Among all the categories, four impact categories were highlighted for all the feed (wheat middling, corn, soybean meal, sorghum, DDGS and amino acids) LCA studies, which are, global warming, land use, fossil resources and water consumption.

The midpoint characterization factor for climate change is the widely used Global Warming Potential (GWP). The GWP expresses the amount of additional radiative forcing integrated over 100 years' time period caused by an emission of 1kg of GHG relative to the additional radiative forcing integrated over that same time horizon caused by the release of 1 kg of $CO_2$. The amount of radiative forcing integrated over time caused by the emission of 1 kg of GHG is called the Absolute Global Warming Potential (AGWP) and is expressed in the unit W $m^{-2}$ yr $kg^{-1}$.

The midpoint characterization factor of any GHG (x) and any time horizon (TH) can be calculated as follows:

$$GWP_{X,\ TH} = \frac{AGWP_{x,TH}}{AGWP_{CO2,\ TH}} \qquad \text{……………………………………………………….. eq. (6)}$$

For water consumption, the characterization factor (CF) at midpoint level is $m^3$ of water consumed per $m^3$ of water extracted. Water extraction is the withdrawal of water from surface water bodies or the abstraction of groundwater from aquifer. It is the total amount of water withdrawn, irrespective of return flows to the water bodies or water use efficiencies. Water consumption, on the other hand is the amount of water that the watershed of origin is losing.

$$CF_{mid} = \begin{cases} 1 & if\ inventory\ in\ \ m^3\ consumed \\ water\ requirement\ ratio & if inventory\ in\ \ m^3\ withdrawn \end{cases} \qquad \text{………… eq. (7)}$$

Thus, for flows that are already given as consumptive water flows, the midpoint indicator coincides with the inventory.

In the case of land use, which covers the process of land transformation, land occupation and land relaxation that eventually turn to the relative species losses. CFs for the impact of land transformation and occupation are based on relative species losses calculated by De Baan et al. (2013) and Elshout et al. (2014).

Firstly, the midpoint characterization factor (in annual crop equivalents) for land transformation/occupation $CFm_{occ}$ is based on the relative species loss $S_{rel}$ caused by land use type x, proportionate to the relative species loss resulting from annual crop production:

$$S_{rel,\ x} = \frac{S_{rel,\ x}}{S_{rel,\ annualcrop}} \qquad \text{……………………………….eq. (8)}$$

$S_{rel}$ is calculated by comparing field data on local species richness in specific types of natural and human-made land covers, using the linear relationship described by Köllner et al. (2008):

$$S_{ref,\ i} = 1 - \frac{S_{LU,\ x,\ i}}{S_{ref,\ i}} \qquad \text{……………………….eq. (9)}$$

Whereby, $S_{LU}$ and $S_{ref}$ are the observed species richness (number of species) under land use type x and the observed species richness of the reference land cover in region i, respectively. Equation 4 yields outcomes between -∞ and +1, whereby a negative value means a positive effect of land occupation (i.e. a larger species richness), and the maximum of one represents a hundred per cent loss of species richness. Secondly, the midpoint characterization factor for land relaxation to a (semi-)natural state $CFm_{relax}$ (in annual crop equivalent·yr) is directly related to $CFm_{occ}$, using the following equation from Köllner et al. (2008):

$CFm_{relax,x} = CF_{occ,x} \times 0.5 \times t_{rel}$ ………………………………………………….**eq. (10)**

Whereby, $t_{rel}$ is the recovery time (years) for species richness. We assume a passive recovery towards a (semi-)natural, old-growth habitat based on average recovery times from Curran et al. (2014). They distinguish between forested and non-forested (open) ecosystems, as these natural vegetation types show different recovery rates.

In the LCA for different feed ingredients both primary and secondary data are used in the modeling where primary data ensure the highest quality while secondary data has limitations. However, for each unit process, it is very difficult to gather the real data and hence secondary data is necessary in LCI. Generally, secondary data have been applied to production of material inputs, production and combustions of fuels used for process energy, and transportation energy throughout the life cycle (The United Soybean Board, 2010).

Results of the feed ingredients LCA studies were used to estimate the environmental impacts of the representative diets. Feed ingredients such as bakery meal, vitamin premix with phytase and trace mineral premix environmental impacts data have been taken from SimaPro process library (Version 8.5.2.0), and available literature (scientific articles, reports).

**Background processes and assumptions**

Background processes available in the professional life cycle inventory databases in the SimaPro (Version 8.5.2.0) that further included land transformation, fertilizer and seed production, machineries, transportation, electricity generation, infrastructure building and chemicals production. In particular, the background processes included the product system of material inputs (e.g. fuel, chemicals, and agro-machineries) and their supply to the foreground processes. Agricultural input data for the grains (wheat, corn, soybean, sorghum) production were collected from the USDA-NASS survey (2017 to 2022), Ecoinvent 3, and from Agri-footprint database in the SimaPro software (Version 8.5.2.0) unless and otherwise stated in the text. It is noted that all the necessary data for the feed (wheat middling, corn, soybean meal, sorghum, DDGS and amino acids) production correspond to the grains and relevant products system in the United States unless and otherwise stated in the text. Foreground processes also includes some available inventory data from the SimaPro process library (Version 8.5.2.0) which comprises tillage, sowing, combine harvesting.

Necessary material inputs and assumptions for the related emissions at the foreground level is presented in the appendix section of this report**.** Yield of grains, fertilizer and pesticides data are three years average data (2015, 2016 and 2017) in the United States for their production. Synthetic fertilizers (N, P, K and Sulphur), pesticides processes are at regional storehouse in the USA and US-EI U database was followed from the SimaPro (version 8.5.2.0). Waste water treatment process was selected from ELCD database 3 following Agri-footprint mass allocation.

Respective crop production system in the USA was considered for the corresponding product system for the LCA studies in this report. For instance, crop production region 3 in the USA was applied for the winter wheat and corn. The production cycle for grains (e.g. winter wheat, corn, soybean and sorghum) is assumed to be one-year. Frequencies of fertilizer application for grains are considered according to their cultivation process along the year. Diesel combusted data for the industrial equipment for this study is taken from USLCI database (SimaPro 8.5.2.0). For the gasoline consumption and emissions, consumption data from Euro 3 has been applied from the SimaPro software version 8.5.2.0. In the case of energy required for cradle to mill gate feed production electricity at grid, Western US NREL/US U, electricity-low voltage at grid, 2015/US US-EI U for grain production and electricity, at grid, US/US System - copied from USLCI, electricity, diesel, at power plant/US U System - copied from USLCI for feed production are applied.

For amino acids LCA most of the raw materials and inputs are collected from the study by BLONK, MILIEUADVIES, 2010, Netherlands and assumed to be a same production process in the USA. Processes for raw materials and chemicals used for production, transport of materials to manufacturing plant, emissions to air and water from production, estimation of energy demand and infrastructure of the plant (approximation) have been followed as acrylic acid production model at plant in the USA (SimaPro 8.5.2.0). Methionine as amino acid source for lysine production via bio-synthetic process is considered for Lysine production, while for Threonine production Lysine is applied in the biosynthetic process. Sources of sugar syrup is take from sugar cane syrup in the USA (based on mass).

**Scenario analysis**

Two different scenarios have been considered for LCA studies of feed production. Scenario 1 study includes the agricultural inputs for grain production from the year 2015 to 2017 data (for some grains input data only for the year 2017) that are collected from USDA-NASS survey and Scenario 2 study consists of grains production inputs for a projected period of 2022 ( 5 years projection). Both scenarios are aimed to assess the environmental impacts under the midpoint categories in the USA. How the assumptions of the agricultural inputs for all the grains production affect the environmental impacts is also clarified with uncertainty analysis using the Monte Carlo uncertainty analysis in the SimaPro (Version 8.5.2.0).

**Sensitivity analysis**

Sensitivity analysis was conducted to identify the influential factors associated with different parameters, inputs, allocations, system boundaries and assumptions applied for each feed product systems with a view to know the effect on the final LCA results. Variation or fluctuation of environmental impacts of different feed production life cycle based on mass or economy over time (2015, 2016 and 2017 agricultural input data with their price and five years projected data until 2022) was brought to focus for case sensitive studies in the USA. Price of the desired co-products was also considered for sensitivity analysis.

**Environmental footprint at the live animal production stage**

It is expected that water and land footprint differences between various diets at the live animal production stage are negligible. Analysis at this stage will focus on excess nutrient excretion and carbon footprint due to barn emissions, and they will be estimated using two strategies. The first strategy is to estimate the excess nutrients based on feed efficiency and calculated nutrient balance of each of the five diets. A second strategy is to conduct a meta-analysis on published studies on measured air emissions and nutrient excretion from finishing swine production for diets that are comparable with the five diets in the project.

**Results:**

## Literature review

### *General principles of diet selection*

A single feed ingredient cannot be practically used to supply the animal's requirement for nutrients, since a particular ingredient may be excess of one or more nutrients and be deficient in others. Hence, it is always a combination of different ingredients, which make up a swine diet (Velayudhan et al. 2015). Generally to formulate a diet using different ingredients, supply of energy, protein and essential amino acids for the growth and development of the swine are considered. Energy and protein are the main nutrient components in swine diet. Energy represents the largest cost contribution to the finished diet followed by protein, or more specifically, the source of essential amino acids such as lysine (Harper, 2006).

Carbohydrates supply majority of the pig's caloric needs and fats present in the feed. Pigs have a relatively simple digestive system, which makes them inefficient to utilize vast quantities of hay, silage, or pasture grasses. Therefore, swine rations are made up primarily of grains, along with protein supplements and other vitamins and minerals. Cereal grains make up to 50% to 85% of the ingredients in swine rations, which in turn provide much of the energy to the animal (Myer and Brendemuhl, 2013).

Energy from corn has been a very economical source for swine diets. The complementary way in which corn and soybean blend to produce a well-balanced diet makes this combination a standard for supplying energy and protein. Supplemental lysine is common and sometimes may replace soybean depending on relative prices of corn and soybean. In cases of limited supplies and high prices of corn or soybean, producers are encouraged to evaluate alternative sources of energy and protein, including other grains, byproducts of feed and food industry, and make "what if" comparisons in a changing global and local market.

Cereals are fed to the swine to supply energy in the diets. On many occasions, pigs fed balanced small grain-based (cereals) diets can perform well compared with those fed corn-based diets (Sullivan et al., 2005). Corn grain is among the leading cereal used in the swine feed industry; which has a greater energy density than other cereal grains. Because of its abundance and high-energy concentration, corn is the base to which other cereal grains are compared. Small grains, such as barley, wheat, oats, rye, and triticale form other practical ingredients in swine feeding programs. Nutritionally, small grains are comparable to corn in some aspects, but there are variations depending on the grain. The crude protein (CP) in small grains are higher than that in corn especially the lysine which is the first limiting amino acid in cereal grain-based swine diets (Sullivan et al., 2005). In addition, small grains have a higher digestible phosphorus level than corn, but tend to be lower in energy content.

Protein feeds are generally used to supply the amino acids needed for the pig growth. Several co-products from different grain processing industries supply this essential protein source to the swine industry. With the rise of the ethanol industry, the quantity and availability of grain processing co-products have increased in recent years. Corn distiller dried grains with solubles (DDGS) from the fuel ethanol industry is a major co-product used in swine feed (Stein and Shurson, 2009). Corn gluten feed and corn gluten meals are co-products of the corn wet-milling industry. The wheat milling co-products include bran and middlings. The nutrient composition of these co-products differs from the original grain source (NRC, 1998). Soybean meal is the most available ingredient that provides the essential amino acids for the pig production. Alternatives such as soybeans, field peas, alfalfa meal, canola meal, linseed meal, sunflower meal, whey, fishmeal, plasma protein and meat and bone meal exist. However, many local markets have the limitation in using the fishmeal or animal tissue as protein providing feedstuffs for swine production (Lammers et al, 2007). Several protein supplying ingredients such as field peas, canola meal and linseed meal are not available for diet in the Midwest part swine production (Lammers et al 2007). Moreover, characteristics of these feedstuffs are not as well known as soybean meal. Whole soybean when used as protein ingredients must be well cooked or extruded to make the amino acids available for the pig. Whey protein is commonly used for young pig diet; however, its cost limits the application for other diets. Other alternatives such as dried distilleries grain with solubles (DDGS), corn gluten contains amino acids, and however, their availability is limited to some extent in the diet (Lammers et al, 2007). While corn gluten often provides some amino acids, their low content of critical amino acid lysine limits its use or needed an additional source of lysine supplementation in the diet.

Crystalline forms of some amino acid are also often feeding to the pigs with relatively more expense than the soybean meal in order to allow precise diet formulation for the swine production. Thus, it can reduce the bulk feeding of crude protein, which often are not used by the pig and excreted in the urine (Lammers et al, 2007).

Phosphate supplements represents the third most significant cost in swine diet, and feedstuffs that contribute more available phosphorus add value as less phosphate supplement is required (Harper, 2006).

***Feed Ingredients***

The appropriate amount of the ingredients in a swine diet largely depends on many factors, such as cost, nutrient availability (digestibility), quality of protein, amino acid profile, palatability, presence of anti-nutritional factors, storage life, age of the pigs, regional production of different ingredients.

Cost is one of the most difficult and major factors for the selection of alternative feeds. Hog farmers and industries must take into account the amount of nutrients supplied by the replacement feed. Variation of nutrient contents in the ingredients attributed to the difficulties in the comparison of feed cost from one to another. Therefore, relative values are quite useful for comparison purposes. However, other determinants such as transportation, special processing needs and storage can change the ultimate cost of any diet. This is particularly important when evaluating high moisture products such as liquid whey, distillers' grains and high moisture corn. The value of alternative ingredients should be based on their actual contribution of digestible energy and nutrients available to the diet. Historically, rations were least-cost balanced based on protein levels because protein was the most expensive nutrient in the diet. However, in many current economic environments, energy may now be more expensive per unit than protein. Rations should be reformulated to recognize this scenario and reformulated often as feed ingredient costs change.

The relative value of a feed ingredient is used to compare the value of that feed to the price of the industry standard energy and protein supplying ingredients delivered to the farm. They reflect the value of the ingredient as it relates to the three most expensive nutrients in a swine ration - energy, lysine and phosphorus. Note that these relative values do not consider the suggested limits on inclusion rates that are listed. The values are based purely on a comparison between the nutrient levels in the alternative feed and the nutrient standards - corn, soybean meal and dicalcium phosphate - and their respective costs.

Protein quality defines to the amino acid concentration and balance of the feed ingredient. Because lysine usually is the most limiting indispensable amino acid in corn-soybean meal-based diets, it is important to consider lysine when valuing alternative ingredients. For instance, corn gluten and wheat middlings have a high concentration of protein relative to the amount of lysine. If a diet was prepared with these ingredients based solely on the protein concentration, the pigs would not be provided sufficient lysine to support optimum performance. Diets for swine should be balanced according to the level of lysine instead of crude protein (NPB 2008). However, because the pig has a need for all indispensable amino acids, deficiency of one amino acid in a concentration lower than its requirement the performance of the pig will be hindered. Diets should therefore, be formulated based on all indispensable amino acids.

Energy and nutrient digestibility is a measure of the availability of energy and nutrients in a feed ingredient. In all practical feed ingredients, only a portion of the energy and nutrients are absorbed from the intestinal tract of the pig, whereas some of the energy and the nutrients are excreted in its feces. Only the part that is absorbed from the intestinal tract is available for utilization by the pig. This part is called the digestible part of the feed and is described by digestibility values or digestibility coefficients for energy and each nutrient. Digestibility values for energy and nutrients can vary considerably among feed ingredients and should be taken into account when a feed ingredient is valued. In general, the greater the concentration of fiber in a feed ingredient is, the lower is the digestibility of energy and most nutrients. As an example, the digestibility of energy and most nutrients is much greater in dehulled soybean meal than in alfalfa meal, because alfalfa meal has a much higher concentration of fiber than soybean meal.

Anti-nutritional factors are factors in a feed ingredient that interfere with nutrient digestibility and utilization. These include trypsin inhibitors, tannins, lectins, glucosinolates and others. For example, raw whole soybeans contain a trypsin inhibitor. As a result, they must be heat-processed or they will cause a decrease in performance due to decreased protein digestibility and absorption.

Palatability is the term used to describe the extent to which a pig likes to eat a feed ingredient or ration. As pigs grow older flavor preferences change just as they do in humans. Pigs, in fact, have more taste buds than humans (15,000 vs 9,000) so flavors, or off-flavors, can have an impact on what feed alternatives are feasible. In pig rations, for example, dried whole milk is very palatable while triticale has poor palatability at high inclusion levels.

Inclusion rate will vary for ingredients depending on palatability, nutrient availability, protein quality, nutrient interrelationship, and the method of processing and feeding. The maximum inclusion rates vary for each class of pigs and are based on limiting factors. If the ingredient is fed above the maximum suggested inclusion rate, animal performance and pork quality can be compromised.

According to the NRC report (NRC, 2012), there are more than 180 feeds which could be used for swine diet in the US. Moreover, US animal feed database also provides information on the necessary that could be utilized for hog production and management practices: phytase, ractopamine, and antibiotics. In general, the feed ingredients in US would vary from one part to other depending on the geographic region, cropping season, availability and price of the ingredients. Pig diets around the globe, continues to demonstrate its ability to utilize a broad list of ingredients - from corn, sorghum, soybean meal and lupines, to sunflower meal, canola meal, tapioca and bakery byproducts. Corn-soybean meal diets will remain a staple for the foreseeable future, but adoption of co-products will be essential to trim higher feed costs (Patience, 2010). For diets and feed ingredients, energy content can be expressed as calories (cal), kilocalories (kcal), or megacalories (Mcal) of gross energy (GE), digestible energy (DE), metabolizable energy (ME), or net energy (NE) (NRC, 1998). There has been an intensive effort to quantitatively depict the energy value of the vast array of feed ingredients available for selection in practical swine diets. List of existing ingredients for swine diets are shown in Table 7-1 (NPB,2008).

**Table 1. Alternative energy and protein ingredients in finishing swine diets (NPB, 2008)**

| Feed ingredient | Digestible energy, kcal/kg | Protein, % | Lysine, % | Max inclusion rate for finishing swine, % | Relative Value |
|---|---|---|---|---|---|
| **Energy ingredients** | | | | | |
| Corn | 3961 | 9.3 | 0.29 | 80 | 100 |
| Oats | 3112 | 12.9 | 0.45 | 20 | 85-90 |
| Sorghum | 3380 | 9.2 | 0.22 | 80 | 95-98 |
| Barley | 3427 | 12.7 | 0.46 | 80 | 95-105 |
| DDGS | 3441 | 29.8 | 0.67 | 20 | 100-110 |
| Wheat middlings | 3455 | 17.9 | 0.64 | 40 | 110-130 |
| Alfalfa meal | 1989 | 18.5 | 0.8 | 10 | 80-90 |
| Bakery waste, dried | 4330 | 11.9 | 0.30 | 40 | 100-110 |
| Beet pulp, dried | 3148 | 9.5 | 0.57 | 10 | 90-100 |
| Brewer's grain, dried | 2283 | 28.8 | 1.17 | 10 | 110-120 |
| Corn, high moisture | 3961 | 9.3 | 0.29 | 40 | 80-90 |
| Corn distillers, dried solubles | 3614 | 29.0 | 0.89 | 20 | 135-145 |
| Corn gluten feed | 3322 | 23.9 | 0.7 | 25 | 110-130 |
| Corn gluten meal | 4694 | 66.9 | 1.13 | 5 | 150-160 |
| Corn hominy | 3728 | 11.4 | 0.42 | 80 | 100-110 |
| Fats and oils | 8000 | 0 | 0 | 6 | 175-210 |
| Flax | 3400 | 37.3 | 1.38 | 5 | 150-155 |
| Oats, hulless | 4047 | 19.9 | 0.55 | 95 | 110-115 |
| Potato chips | 5833 | 7.2 | 0.34 | 25/10 | 125-150 |
| Rye | 3716 | 13.4 | 0.43 | 40/77 | 100-105 |
| Sucrose | 3833 | 0.0 | 0.0 | 33 | 85-95 |
| Soybean hulls | 1025 | 14.0 | 0.98 | 10 | 60-70 |
| Triticale | 3689 | 13.9 | 0.43 | 77 | 90-105 |
| Wheat, hard red spring | 3864 | 16.0 | 0.43 | 80 | 105-115 |
| Wheat, soft white winter | 3820 | 13.3 | 0.37 | 80 | 100-105 |
| Wheat bran | 2719 | 17.6 | 0.72 | 10 | 110-120 |
| Wheat, shorts | 3392 | 18.2 | 0.80 | 40 | 120-125 |
| Whey, dried | 3474 | 12.6 | 0.94 | 15 | 130-140 |
| Whey, liquid | 3571 | 12.9 | 1.17 | 30 | 140-150 |
| **Protein ingredients** | | | | | |
| Soybean meal, 44% protein | 3921 | 49.2 | 3.18 | 35 | 100 |
| Soybean meal, 48% protein | 4094 | 52.8 | 3.36 | 35 | 100-105 |
| Canola meal | 3206 | 39.6 | 2.31 | 15 | 75-85 |
| DDGS | 3441 | 29.8 | 0.67 | 20 | 55-60 |
| Peas | 3860 | 25.6 | 1.69 | 35 | 65-75 |
| Sunflower meal | 2010 | 26.8 | 1.01 | 20 | 50-60 |
| Beans cull | 360 | 26.4 | 1.45 | 12 | 55-65 |
| Brewer's grains, dried | 2283 | 28.8 | 1.17 | 10 | 40-50 |
| Corn distillers, dried solubles | 3614 | 29.0 | 0.89 | 20 | 55-60 |
| Corn gluten feed | 3322 | 23.9 | 0.70 | 25 | 45-55 |
| Corn gluten meal | 4694 | 66.9 | 1.13 | 5 | 55-70 |
| Fababeans | 3730 | 29.2 | 1.86 | 20 | 65-75 |
| Fish meal, menhaden | 4098 | 67.7 | 5.23 | 5 | 160-170 |
| Flax | 3400 | 37.3 | 1.38 | 5 | 60-65 |
| Lupins, sweet white | 3876 | 39.2 | 1.73 | 20 | 70-80 |
| Meat meal | 2867 | 57.4 | 3.27 | 5 | 120-130 |
| Meat and bone meal | 2440 | 51.5 | 2.51 | 7.5 | 120-130 |
| Milk, skim (dried) | 4146 | 36.0 | 2.98 | 10 | 100-110 |
| Milk, whole (dried) | 5667 | 27.5 | 2.50 | 10 | 100-105 |
| Soybeans, roasted | 4600 | 39.1 | 2.47 | 10 | 90-100 |

### *Corn*

Corn is sometimes referred to as maize, and related products (such as corn gluten meal) have been popular ingredients in swine diets for many years. Patience et al in (2002) stated that although alternatives feed ingredients in the diet can achieve the equivalent growth performance in different parts of the world, however, corn is fed as the main feed ingredient in diets for millions of pigs and will continue to be a major feed ingredient in the future. Similar statement was reported by Hans Stein, University of Illinois (Kevin Schulz, 2016) where he mentioned 'Nobody goes away from corn and soybean meal unless they can save money'. Examples of corn as a feed ingredient in swine diet is shown as in the following table.

**Table 2. Corn as a feed ingredient in swine diet**

| References | Diet | Information |
|---|---|---|
| Patience et al, 2002 | 1. Corn (48%), barley (20.87%), soymeal (26.61%)<br>2. Wheat (72.93%), soymeal (22.61%) | 1. Composition-<br>• Digestible energy (3550 kcal/kg)<br>• Metabolizable energy (3360 kcal/kg)<br>• Crude protein (8.50%)<br>• Lysine (0.26%)<br>• Digestible Lysine (0.17%)<br>• Digestible threonine (0.21%)<br>• Digestible tryptophan (0.04%)<br>• Calcium (0.02%)<br>• Phosphorus (0.25%)<br>2. Corn test weight does not significantly affect pig growth until it drops below 45 lbs/bu<br>3. Lysine and tryptophan are the first and second limiting amino acids for swine |
| Lampe et al, 2006 | 1. Corn (78.15%), Soybean (17.65%)<br>2. Barley (83.4%), soybean (12.55%) | 1. Different corns (white and yellow color) were tested on meat and fat quality of swine production<br>2. Loins of from pigs fed diets containing barley or white corn as the primary energy source do not have an advantage in meat quality over loins from pigs fed yellow corn diets. |

### *Soybean*

Soybeans is an important crop in the United States and are primarily used for animal feed, human food, and production of biofuels. Soybean meal (SBM) and other soy products contribute high-quality protein to diets fed to pigs because soy protein is rich in the limiting amino acids lysine, threonine, and tryptophan that are present in relatively low concentrations in the most commonly fed cereal grains. Soy products are also a significant source of energy in diets fed to pigs and soybean meal contains as much digestible and metabolizable energy as corn. Although soy is usually fed to pigs in the form of soybean meal, full fat soybeans may be included in the diets to increase the energy density of the diet. Examples of soybean as a feed ingredient in swine diet is shown as in the following table.

**Table 3. Soybean as a feed ingredient in swine diet**

| References | Diet | Information |
|---|---|---|
| Stein et al ,2012 | Generally, the inclusion rate ranges between 15 to 20 % (NPB, 2008) | 1. Composition (Dehulled SBM-NRC 2012)<br>• Dry matter (89.98%)<br>• Crude protein (47.73%)<br>• Ether extract (1.52%)<br>• Carbohydrates and lignin (34.46%<br>• Ash (6.27%)<br>• Digestible energy (3619 kcal/kg)<br>• Metabolizable energy (3294 kcal/kg)<br>2. Soybean meal is the premier source of digestible amino acids in diets fed to pigs<br>3. Soybean protein has a better balance of indispensable limiting amino acids than other plant proteins<br>4. Palatable |

### *Wheat*

Generally, wheat is produced for human consumption over the decades. Utilization of wheat as swine feed ingredients is limited to times when wheat is competitively priced with corn or other grains. Price-hiking of corn increased the discussion about the potential use of other grains, like wheat, in swine feeds. It is important to understand some of the limitations of using wheat in swine diets in order to make proper feeding decisions when it is economically advantageous to use wheat. There are two type of wheat typically available to swine producers: hard red winter wheat and soft red winter wheat. Pennsylvania, Ohio, Illinois, and Indiana are leading producers of soft red winter wheat varieties, while Central and Great Plains states like Kansas, Oklahoma, Texas, and Nebraska, produce hard red winter wheat. Examples of wheat as a feed ingredient in swine diet is shown as in the following table.

**Table 4. Wheat as feed ingredient in swine diet**

<table>
<tr><th>References</th><th>Diet</th><th colspan="3">Information</th></tr>
<tr><td rowspan="9">Wenger feeds, 2018</td><td rowspan="9">Maximum inclusion in the diet 80%</td><td colspan="3">1. Composition-</td></tr>
<tr><td>Items</td><td>Hard red wheat</td><td>Soft red wheat</td></tr>
<tr><td>Crude protein (%)</td><td>13.1</td><td>10.6</td></tr>
<tr><td>Lysine (%)</td><td>0.43</td><td>0.35</td></tr>
<tr><td>Crude fat (%)</td><td>1.9</td><td>1.7</td></tr>
<tr><td>ME (Kcal/lb)</td><td>1,455</td><td>1,490</td></tr>
<tr><td>Calcium (%)</td><td>0.05</td><td>0.05</td></tr>
<tr><td>Phosphorus (%)</td><td>0.41</td><td>0.30</td></tr>
<tr><td colspan="3">2. Wheat contains less energy but more protein and lysine than corn.<br>3. Hard red winter wheat contains more phosphorus than corn, and both wheat types contain more available phosphorus than corn.<br>4. Formulate diets containing wheat for lysine rather than protein.</td></tr>
</table>

### *Sorghum*

Grain sorghum often called milo is a feedstuff with an excellent nutritional value for swine. Numerous feeding trials with nursery and finishing pigs and gestating and lactating sows in the last 20 years have demonstrated the feeding value of sorghum relative to corn and other grains. The research has demonstrated that sorghum grain contains 96 percent the energy content of corn. However, recent data shows when processed correctly and balanced for digestible amino acid and available phosphorus concentrations, grain sorghum has a feeding value greater than the 96 percent value of corn. Recent research on sorghum grain and sorghum derived DDGS as feed ingredients indicated a similar growth rate of swine can be achieved with diets containing sorghum DDGS as diets containing corn DDGS or corn-soybean meal diets without DDGS (Tokach et al, 2016). Grain sorghum can totally replace all the corn, wheat or barley in all swine diets. An important consideration when using grain sorghum-based diets is its slightly lower energy and lysine content relative to corn. While grain sorghum is frequently substituted on an equal weight basis with corn, slight adjustment of the soybean meal or synthetic amino acids and supplemental phosphorus can be made to take full advantage of grain sorghum's nutrient composition. Examples of grain sorghum as a feed ingredient in swine diet is shown as in the following table.

**Table 5. Sorghum as a feed ingredient in swine diet**

| References | Diet | Information |
|---|---|---|
| Tokach et al, 2016 | 1. Sorghum (76.41%), soybean meal (21.16%)<br>2. Sorghum (80.7%), soybena (16.54%)<br>3. Sorghum (78.59%), soybean (17.36%) | 1. Composition-<br>• Dry matter (89%)<br>• Digestible energy (1,533 kcal/lb)<br>• Metabolizable energy (1,515)<br>• Crude protein (9.2%)<br>• Calcium (0.03%)<br>• Phosphorus (0.29%)<br>• Crude fat (2.9%)<br>• Total amino acids (3.1%)<br>2. Sorghum contains more of the limiting amino acid tryptophan than corn.<br>3. 1 to 2 percent poorer feed efficiency than those fed corn due to low energy content<br>4. Reduced particle size of 500 to 600 microns improve the feed efficiency |

### *Field Peas*

Field peas can be an exception alternative that compromise the price volatility of corn and soybean meal for the pork producers in USA. Field peas are grown in central South Dakota, the western US and Canada and tend to be dry-weather crop. The nutrient composition of field peas is between that of corn and soybean meal (SBM), and when used in swine diets, they can reduce the amounts of both corn and soybean in the diets. Examples of field peas as a feed ingredient in swine diet is shown as in the following table.

**Table 6. Field peas as a feed ingredient in swine diet**

| References | Diet | Information |
|---|---|---|
| Bob Thaler, 2012 | Field peas (40% to the growing-finishing pigs) | 1. Composition-<br>• Protein (23%)<br>• Lysine (1.64%)<br>• Fat (1.4%)<br>• Energy<br>2. Lower in methionine and thereby needed methionine supplementation<br>3. Unlike soybean field peas contains little or no anti-growth factor,<br>4. Palatability is not a concern |
| Hans Stein, 2006 | Field peas (36%), corn and soybean meal | 1. In diets fed to growing and finishing pigs, field peas may be included at levels sufficient to replace all of the protein supplied by soybean meal in the diets.<br>2. Inclusion rate does not influence feed intake, average daily gain, or the gain to feed ratio.<br>3. Lower carcass drip losses and a more desirable color of the longissimus muscle have been reported for pigs fed diets containing field peas, but other carcass characteristics have not been influenced by field peas in the diets<br>4. Maximum inclusion rate can be 36-45% for growing-finishing swine |

***Oats***

Oats can also be included as feed ingredients in the swine diets, but can be used effectively with certain limitations. Oats are highly palatable to all classes and ages of swine, and higher in protein and lysine content than corn. Examples of oats as a feed ingredient in swine diet is shown as in the following table.

**Table 7. Oats as a feed ingredient in swine diet**

| References | Diet | Information |
|---|---|---|
| Myer, 2008 | Oats (30%), Corn (57%), Soybean meal (11%) | 1. Compositions-<br>• Crude fiber (12.0%)<br>• Crude protein (11.5%)<br>• Lysine (0.4%)<br>• Calcium (0.07%)<br>• Phosphorus (0.31%)<br>• Metabolizable energy Kcal/lb- (1230)<br>• The average energy value of oats is given as 80 per cent of the energy value of corn.<br>2. Oats are high in fiber (10 to 15 per cent) and are too bulky to constitute a major portion of the diet for most classes of swine, especially for young, growing pigs.<br>3. Oats should be ground or rolled for use in swine diets. |

*Amino acids*

As the building blocks of protein, amino acids play multiple roles in pig health and performance. The amino acids needed to support an immune response are similar to those necessary for growth. This means amino acids are diverted away from growth when a pig's immune system is challenged. The proteins of corn and other cereal grains are deficient in certain essential amino acids for swine. Thus, protein supplements or sources are used in combination with cereal grains to correct the amino acid deficiencies. For example, the correct combination of grain and soybean meal provides a good balance of amino acids. Soybean meal is often the most economical source of amino acids for pigs throughout the United States. However, economic conditions can change making alternative plant-based amino acid sources (cottonseed meal, canola meal, sunflower meal, and peanut meal), animal co-products (meat and bone meal, fish meal, spray-dried egg, blood co-products, poultry meal), grain co-products (dried distillers, and corn gluten meal) or synthetic amino acids attractive for use in pig feed. Soybean meal is the only plant protein that compares with animal protein in terms of quality of amino acid content and can be used as the sole protein-based ingredient in most swine diets. Therefore, there is generally no nutritional need to have both animal and plant protein sources in a swine diet, with the exception of early nursery diets (K-STATE Swine Nutrition Guide, 2007 and Nebraska Cooperative Extension EC 95-273. 2000).

The concept of an ideal protein or ideal amino acid balance is to provide a perfect pattern of essential and nonessential amino acids in the diet without any excesses or deficiencies. This pattern is supposed to reflect the exact amino acid requirements of the pig for maintenance and growth. Therefore, an ideal protein provides exactly 100% of the recommended level of each amino acid. Although standard diets are usually formulated to meet the pig's requirement for lysine (the most limiting amino acid), excesses of many other amino acids exist. Two practical methods can be used to provide a more ideal balance of amino acids in pig feed. They are to use a combination of supplemental protein sources or to formulate the diet with crystalline amino acids (Kim et al., 2009; Knowles et al., 1998; Lenis et al., 1999; NRC, 1998 and PIC Nutrient Specifications, 2008). Examples of amino acids as a feed ingredient in swine diet is shown as in the following table.

**Table 8 Amino acids as a feed ingredient in swine diet**

| **Reference** | **Amino acid in diet** | **Information** |
|---|---|---|
| DeCamp et al. 2001, Gaines et al., 2004 | Appropriate amount of amino acid addition with lower crude protein and ractopamine hydrochloride (RAC) | 1. Good growth performance, without compromising carcass composition<br>2. However, maximum level of CP reduction, in conjunction with the optimum AA inclusion rate, has not been sufficiently determined for widespread acceptance by the swine industry. |
| Apple et al., 2017 | Crystalline amino acids-Lys (0.758%), Thr (0.15%), Met (0.039%),), Trp (0.04%), crude protein CP (12.78%), Corn (74.28%), soybean meal (1.25%), DDGS (20%) | 1. Reducing dietary CP, while meeting the SID requirements for Lys, Thr, Trp, Met, Ile, and Val with crystalline AA, decreased finishing pig performance<br>2. Ammonia emissions can be reduced by between 14.0 to 41.5% by the reductions in dietary CP<br>3. Modest reductions in dietary CP and inclusion of the crystalline AA to meet minimum SID requirements for the first 6 rate limiting AA may be an effective nutritional strategy to reduce nitrogen excretion with minimal to no effects on pig performance and pork carcass characteristics |

***By-products as feed ingredients***

By-products from different sources can also be considered as potential feed ingredients for swine diets and are classified based on their primary products origin:

A. By-products from grain sources
    I. Distilling by-products/co-products
    II. Brewing by-products
    III. Milling by-products
    IV. Baking by-products
B. Animal
    I. Milk by-products
    II. Meat by-products
    III. Egg by-products
C. Vegetables
    I. Potato by-products
    II. Cull beans
    III. Field peas
D. Sugar and starch production
    I. Cane, beet and corn molasses
    II. Salvage candy

Among the different by-products stated above the potential by-products that are commonly used considering economic and availability in swine growing regions in US will be discussed in following section.

***Distilling by-products-Distiller dried grains with soluble (DDGS)***

Major by-products/co-products of the brewing and distilling industries that are useful in swine diets, are brewers dried grains from the beer brewing industry, distillers dried grains from the commercial ethanol industry, and stillage from on-the-farm alcohol production (Thaler and Holden, 2001). Among all the by-products, distillers dried grains are common and mostly occurred feed ingredients in US pork industry. Distillers dried grains is the residue remaining after the removal of alcohol and water from a yeast fermented grain mash.

DDGS provides lysine, phosphorus, and energy, and replaces soybean meal, dicalcium phosphate, and corn in swine diets. It is approximately equal to corn as an energy source, and although DDGS is quite high in protein (27%) it retains the poor amino acid balance of grains and is particularly limiting in lysine (0.7%) (Thaler and Holden, 2001). Also, it appears that the amino acids in DDGS are less available than those from SBM. However, by supplementing swine diets with synthetic amino acids, DDGS can work well in swine diets. Also, DDGS does contain a relatively large amount of available phosphorus (.71%) (Thaler and Holden, 2001). Examples of DDGS as a feed ingredient in swine diet is shown as in the following table.

**Table 9. DDGS as a feed ingredient in swine diet**

| References | Diet | Information |
|---|---|---|
| Hans Stein, 2007 | DDGS (10%) reduced the corn meal by 5.7%, and soybean meal by 4.25% | 1. Composition-<br>• Digestible energy (4140 kcal.kg)<br>• Metabolizable energy (3897 kcal/kg)<br>• Total Phosphorus (0.61%)<br>• Crude protein (27.5%)<br>• Lysine (0.78%)<br>2. The inclusion of DDGS in diets fed to nursery and growing pigs may improve intestinal health and reduce problems with ileitis (Whitney et al., 2006a).<br>3. Greater digestibility of phosphorus in DDGS than in corn and soybean meal will reduce the need for adding inorganic phosphates to the diets<br>4. The fat in DDGS has a relatively high concentration of unsaturated fatty acids, which may cause increased belly softness of pigs fed diets containing DDGS (Whitney et al., 2006b).<br>5. Sources of DDGS that have a lysine to crude protein ration that is lower than 2.80 should not be used in diets fed to swine. |
| Ron Plain, 2006 | DDGS (10%) with limestones reduced the corn meal by 8.85% and soybean meal by 1.3% | 1. Composition-<br>• Dry matter (88-92%)<br>• Fat (9-10%)<br>• Fiber (8-9%)<br>• Crude protein 29-30%)<br>• Lysine (0.6-0.9%)<br>• Calcium (0.1-0.3%)<br>• Phosphorus (0.8-1.0%)<br>• Energy (1700 kcal/lb)<br>2. Ration palatability tends to decline as DGS content increases, resulting in reduced feed intake and slower rates of gain.<br>3. No change in feed conversion as the DDGS content of swine grow-finish diets is increased from 0% to 30%, but a decline in average daily feed intake (ADFI) and average daily gain (ADG) resulting in reduced carcass weights (Car Wt). |
| Malachy Young, 2011 | Growing-finishing swine (20%) is recommended | 1. Composition- nutritional compositions are within the similar range as obtained by Ron Plan and Hans Stein.<br>2. Assurances be sought for the absence of mycotoxins in DDGS before it is purchased. |

### *Wheat middlings*

By-products of milling wheat for flour consist primarily of the bran and aleurone layers of the kernel and the germ. Wheat flour by-products are generally identified by their fiber level. A wheat milling byproduct with more than 9.5% fiber is wheat bran; that with less than 9.5% fiber may be classified as wheat middlings; if fiber is less than 7%, it's wheat shorts; and that with less than 4% fiber is red dog. Examples of wheat middlings as a feed ingredient in swine diet is shown as in the following table.

**Table 10. Wheat-middling as feed ingredient in swine diet**

| References | Diet | Information |
|---|---|---|
| Thaler and Holden, 2001 | Wheat middlings (30%) can constitutes up yo 10 % of corn-soybean meal | 1. Compositions-<br>• Metabolizable energy (1300-1400 kcal/lb)<br>• Protein (16%)<br>• Lysine (0.6%)<br>• Tryptophan (0.18%)<br>• Phosphorus (0.9%)<br>2. Good pellet binding properties and are used extensively in commercially-pelleted swine feeds. |
| Prairie swine center, 2003 | Wheat middlings (26%), soybean meal, corn meal | 1. Improved feed conversion efficiency during the finisher period |
| Casas et al., 2018 | Wheat middlings (39.40%), corn (39%), soybean (19.5%) | 1. Wheat middlings had low bulk density compared with the bulk density of corn, which may result in difficulties when handling and storing wheat middlings, and it is possible that special equipment and bins are required to handle wheat middlings.<br>2. Concentrations of DE and ME in wheat middlings are lower than in red dog. |

### *Bakery*

Bakery is a by-product of the baking and cereal industries. Bakery varies on nutrient profile depending on source (i.e. cookies, pasta, cereal fines etc.). Therefore, nutrient analyses are necessary to optimize use in feed formulation. Bakery by-products should be as fresh as possible, challenge since bakery is manufactured from products designated as either off spec or "not fresh'. Most bakery by-products are in high fat and subject to oxidative rancidity. They can also become moldy if stored too long or not dried properly. Over-drying may lead to decrease in lysine availability. Examples of bakery as a feed ingredient in swine diet is shown as in the following table.

**Table 11. Bakery as a feed ingredient in swine diet**

| References | Diet | Information |
|---|---|---|
| AKEY, 2003 | Bakery by-products (maximum 20% for grow-finish swine), Corn meal, soybean meal | 2. Composition-<br>• Metabolizable energy (1600 kcal/lb)<br>• Crude protein (11%)<br>• Available lysine (0.24%)<br>• Fat (10%)<br>• Sodium (0.8%)<br>3. The sodium content of bakery as well as feed form (pellet vs. meal) dictates bakery inclusion rate<br>4. Dried bakery product may replace up to one-half of the corn in corn-soybean meal growing-finishing swine (Thaler and Holden, 2001) |

## 7.2 Identification of five representative swine diets in the USA

The five representative swine diets is identified as in table 12. Costs of the five representative swine diets are estimated based on current price of feed ingredients.

**Table 12. Five representative swine diets in the USA**

| Items | Standard diet | Alternative Diet #1 | Alternative Diet #2 | Alternative Diet #3 | Alternative Diet #4 |
|---|---|---|---|---|---|
| **Ingredient use, lb/pig (from 50 to 280 lb body weight)** | **Corn-SBM** | **Corn-SBM-low DDGS** | **Corn-SBM-high DDGS** | **Corn-SBM-DDGS-bakery-middlings** | **Sorghum-SBM** |
| Corn | 520.1 | 452.5 | 301.0 | 364.6 | 0 |
| Soybean meal | 119.7 | 95.8 | 70.4 | 91.4 | 120.4 |
| Corn DDGS, 7.5% Oil | | 96.4 | 190.9 | 66.3 | |
| Sorghum | | | | | 540.1 |
| Bakery meal | | | | 57.6 | |
| Wheat-middlings | | | | 68.7 | |
| Calcium carbonate | 5.45 | 6.14 | 7.01 | 6.73 | 5.81 |
| Calcium phosphate (monocalcium) | 2.94 | 1.27 | 0.35 | 0.41 | 2.46 |
| Sodium Chloride | 3.28 | 3.30 | 3.32 | 3.31 | 3.39 |
| L-Lys-HCl | 1.82 | 2.23 | 2.59 | 2.02 | 2.23 |
| DL-Met | 0.18 | 0.07 | | 0.05 | 0.47 |
| L-Thr | 0.44 | 0.23 | 0.12 | 0.29 | 0.44 |
| L-Trp | 0.05 | 0.07 | 0.10 | 0.00 | 0.04 |
| Vitamin premix with phytase | 0.76 | 0.77 | 0.77 | 0.77 | 0.79 |
| Trace mineral premix | 0.76 | 0.77 | 0.77 | 0.77 | 0.79 |
| **Estimated cost per pig** | $63 | $58 | $45 | $104 | $70 |

Note: SBM=Soybean Meal; DDGS=Distillers dried grain with solubles.

An e-mail survey was conducted over 119 respondents who have expertise in animal nutrition around the USA to confirm and validate the consulted alternative swine diets with their comments and suggestions. Out of the 23 respondents to our consulted alternative diets, only one respondent replied negatively. Most of the respondents supported the inclusion of DDGS, sorghum and amino acids in the alternative diets. Many experts suggested corn, soybean meal, DDGS, Sorghum, wheat middling's, synthetic amino acids and animal fat or vegetable oil for swine diet. One specifically commented that "My preference long term would be diets #3 & #4 as they rely less on corn DDGS which seems to follow corn markets and DDGS branding. DDGS is a great alternative but has enough fluctuation in supply and subsequent pricing that it does not lend itself as nicely to a constant inclusion. Long term I think DDGS will find a permanent use somewhere, which may or may not be as a livestock feed source. If or when that happens it will certainly drive feed costs up".

**LCA of individual feed ingredients**

***Corn***

Data for the material and energy requirements and process emissions for the growing, harvesting and transporting of 1 pound of corn grain in Region 3 includes emissions associated with production of fertilizers (nitrogen, phosphorous, potassium and lime) as well as production of pesticides (insecticides, herbisides, fungicides).

Grain maize or corn is one of the ideal feed ingredients in the diets for swine production around the globe. From the database survey in web of science on key words ‘corn LCA’ there are only 268 studies could be obtained which further directly not related to the corn LCA. With the similar key word in science direct, there have 1,988 research articles. A similar search resulted 274 results in science direct search option. However, in science direct, the search engine did not provide the actual research results only on corn LCA studies. Thus, there were different key searching options on corn LCA have been explored to get the most available resources and data on corn LCA worldwide through different database search engines. Since most of the database search options does not provide the scope to refine search according to the actual need except the web of science. Thus, the web of science was considered as the base search option for other feed ingredients as well with the recent published research items and data or available research inputs. There were 85 research items obtained from the key term search ‘corn LCA>USA’. Based on the available information in database the following section has been overviewed with recent data on corn and corn related LCA studies in USA only. Corn impacts from existing LCA studies in literature are presented in Table 13.

**Table 13. Corn impacts from existing LCA studies in literature**

| GWP (kg $CO^2$ eq./kg) | LU ($m^2$a crop eq./kg) | WC ($m^3$) | FR (kg oil eq./kg) | Reference |
|---|---|---|---|---|
| 0.2 | - | - | - | Joel Tallaksen (2017) |
| 0.53 | - | - | - | Kraatz et al., 2013 |
| 0.389 | - | - | - | Smith et al., 2017 |
| 0.342 | - | - | - | Pelton, 2019 |

There have been researches on maize production applying different techniques of LCA in the United States to quantify the energy consumption and GHG emissions. System boundary for most of the studies relate the cradle to farm-gate analysis (for instance system boundary for maize and biopolymer includes cradle to farm-gate; Kim et al., 2014) and their impact assessment. The system boundary for maize grain production involves the life cycle from cradle to the drying plant-exit gate (Fig. 3), including all agricultural processes required to produce dried grain maize and all auxiliary processes such as agro-chemicals production, maintenance of vehicles, etc. in analogy to previous studies (Fedele et al., 2014)

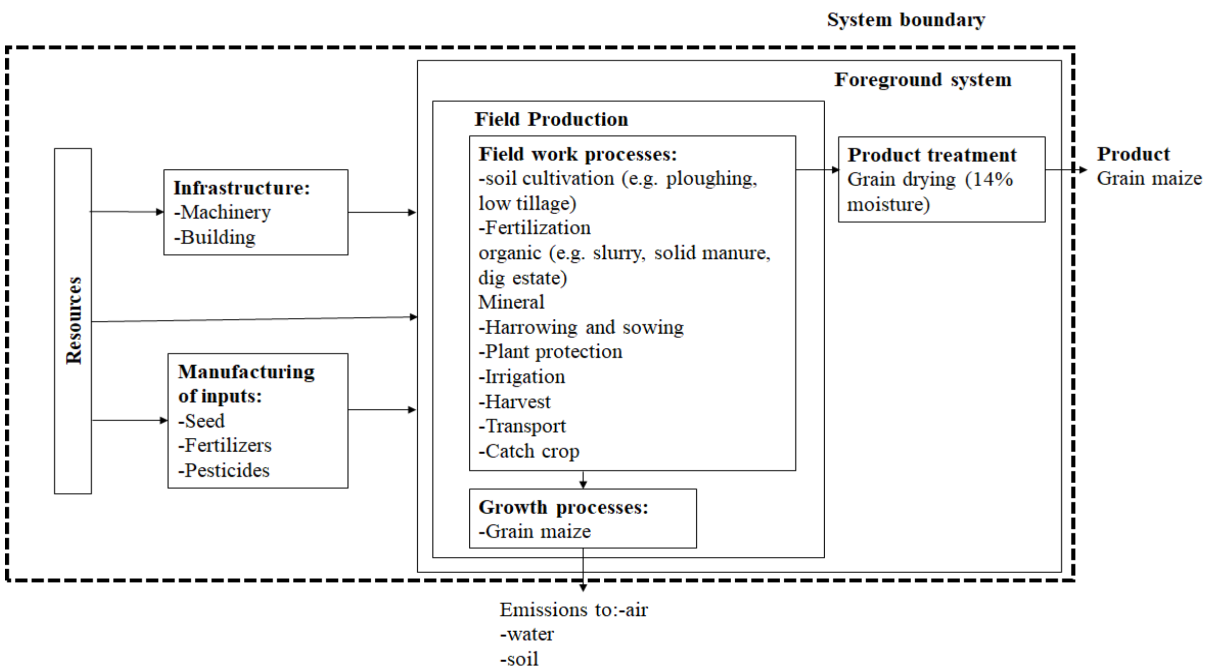


**Fig 3. System boundary for maize grain production (Adapted from Boone et al., 2016)**

In our study, we would apply a similar process of system boundary for corn as feed ingredients in the growing-finishing swine diets life cycle assessment study. The inputs for corn grain production are listed in Appendix2.1. Results from the attribution LCA studies of corn grain production (Cradle-to-farmgate) in the USA are presented in Table 14, Fig. 4 and Fig. 5.

**Table 14. Impact assessment of corn production in USA for the year of 2017 and 2022**

| Impact categories | Unit | 2017 | 2022 |
|---|---|---|---|
| Global warming | kg $CO_2$ eq./kg | 0.311 | 0.315 |
| Land use | $m^2$a crop eq./kg | 1.01 | 1.01 |
| Water consumption | $m^3$/kg | 0.394 | 0.404 |
| Fossil resources | Kg oil eq./kg | 0.054 | 0.056 |

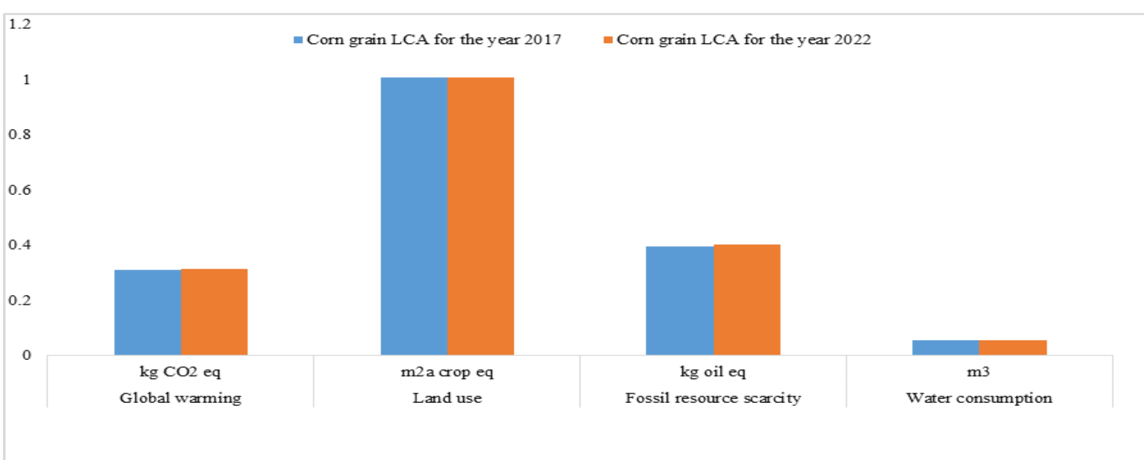


**Fig 4. Environmental impact of corn grain production in the USA (per kg corn production)**

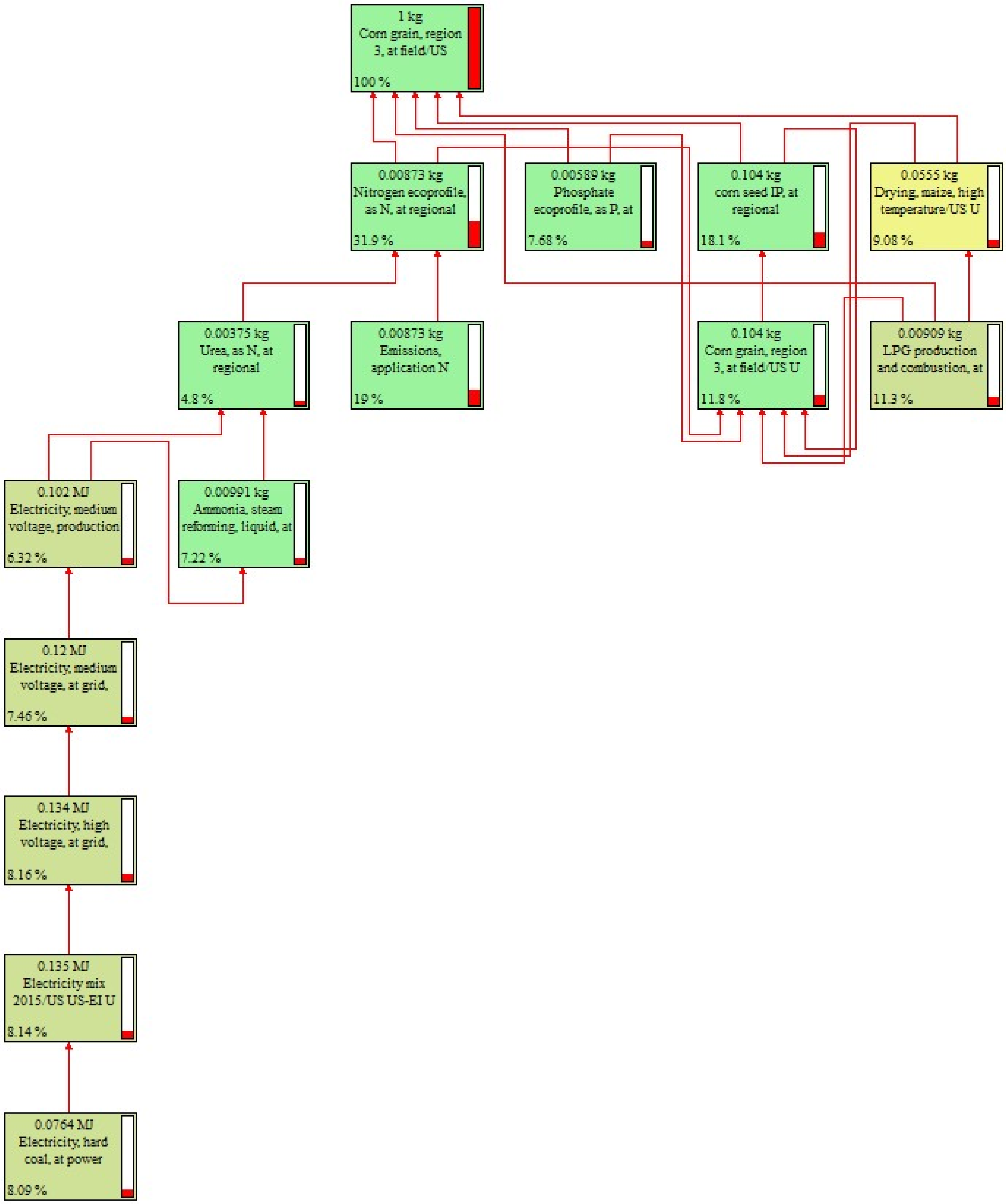


**Fig 5. Network (15 nodes out of 2191 visible nodes in the system with 7% cut-off) of global warming potential of corn grain production in the USA in 2017**

As can be seen in Figure 5, major global warming potential (about 32%) arises from the inflow of nitrogen ecoprofile as N at regional storehouse and its associated emissions (19%) in the production system. Among other inflows, intensive production of corn seed at region (IP) causes about 18% of the total global warming potential and drying of maize at high temperature also produces a significant amount (about 8%) of global warming impact in the production system.

In the fossil resources utilization impact, major contribution come from the intensive corn production (21%) at regional, nitrogen ecoprofile at regional (15.3%), high temperature maize drying (14.1%), transportation by lorry (11.1%) and from phosphate ecoprofile at regional (10.1%).

In case of water consumption in the corn grain production, most water consumption brought up by intensive corn seed production at regional, phosphate ecoprofile at regional and high temperature drying maize (18%, 9.19% & 8.06 % respectively).

Thus, from the results derived from the attributional LCA study of corn grain production in the USA, it can be said that major impact in all considered categories contributed by intensive corn seed production, nitrogen ecoprofile at regional, and maize drying in the production system.

It is observed that there is no land use change impact for the projected period of corn grain production assuming production related inputs, raw materials and processes are same. Exception was the yield and their corresponding agricultural inputs for the corn grain production. Other impact categories (global warming, fossil resources scarcity and water consumption) considered for the corn grain LCA increases by 1%, 2.5% and 3.7% respectively from the year 2017 to the projected year 2022.

Sensitivity analysis of the corn farming for 20% increase in corn yield with corresponding N,P,K, corn seed, water and fuel inputs shows that, global warming impact will increase by 12% from 0.311 to 0.351 kg $CO_2$ eq., fossil resources impact will increase by 13% from 0.054 to 0.061 kg oil eq., and water consumption impact will increase by 15% from 0.394 to 0.455 $m^3$/kg corn grain.

***Soybean meal***

For a goal and scope definition of soybean meal it's crucial to identify the environmental hot spots in the product chain of soybean meal. Studies or reports on life cycle assessment on soybean and soybean meal as feed ingredients was searched comprehensively in Web of Science database. From the database search using the key word 'Life cycle assessment soybean' we obtained 3 relevant research articles and other related findings with soybean life cycle assessment have been included into soybean LCA studies. Further refined with soybean and soybean feed to match our desired reports and studies was also carried out. In the following paragraph, reports related to the soybean production and their impact assessment on environment and soybean as animal feed are broadly represented with their system boundary. Soybean meal impacts from existing LCA studies in literature are presented in Table 15.

**Table 15. Soybean meal impacts from existing LCA studies in literature**

| GWP (kg $CO_2$ eq./kg) | LU ($m^2$a crop eq./kg) | WC ($m^3$) | FR (kg oil eq./kg) | References |
|---|---|---|---|---|
| 0.726 | - | - | - | Dalgaard et al., 2008 (economic alloc.) mix with palm oil processing |
| 0.901 | - | - | - | Dalgaard et al., 2008 (mass alloc.) mix with palm oil processing |
| 0.730 | - | - | - | Eriksson et al. (2004) (Economic alloc.) |
| 0.507 | - | - | - | Ecoinvent Centre (2004) (Economic alloc.) |
| 0.730 | - | 0.0048 | - | Omni tech International (2010) |
| 0.480 | 1.76 | - | - | Reckman et al., 2016 |
| 0.310 | - | - | - | Cheng et al., 2018 (hexane extraction for soy oil) |
| 0.52 | - | 0.1 | - | Quantis New Earth AGECO, 2016 |
| 0.150 | - | - | - | Mackenzie et al., 2016 |

Life cycle assessment for soybean and soybean meal production has been explored previously by researches around the world. For instance, the LCA studies conducted by Stone et al. (2012) defines the system boundary for soymeal from agricultural production of soybean to the soymeal as animal feed (Fig. 6).

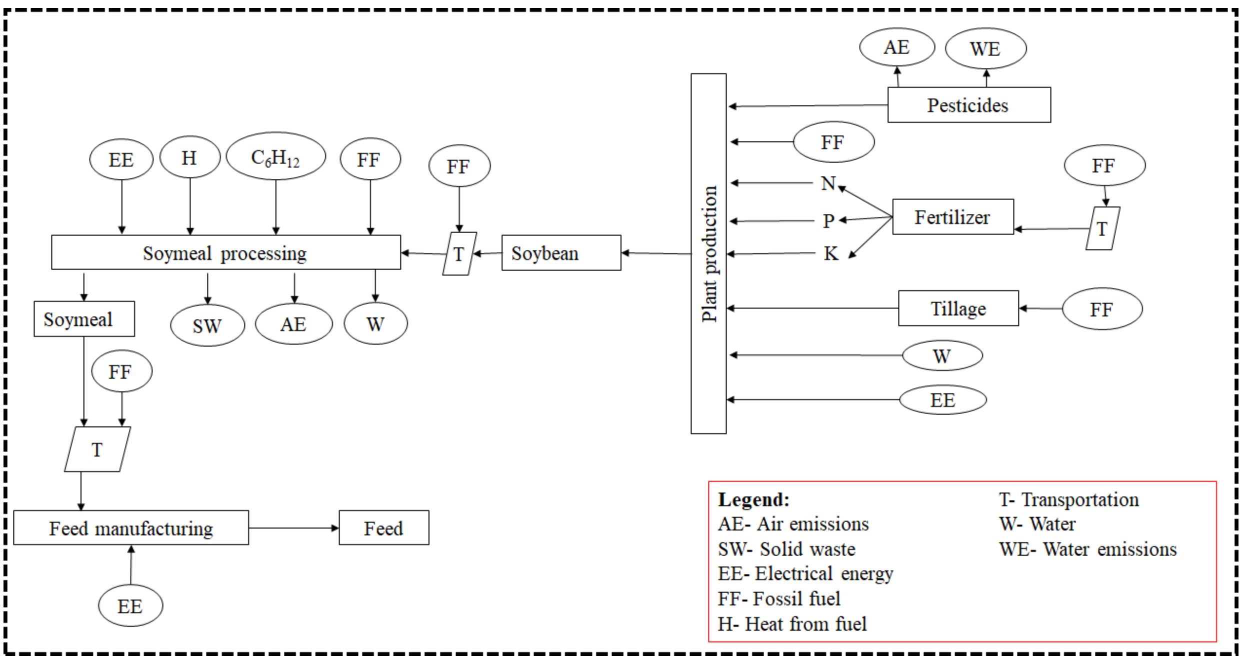


**Fig 6. System boundary for soybean meal feed production and manufacturing in the USA (Adapted from Stone et al., 2012)**

In this study of soybean meal LCA, we applied a similar approach of soybean meal production using the inputs data from 2017 to 2022 for the projection, which is mainly taken from the USDA-NASS survey, and other processes are assumed unchanged over the projection period. The inputs for soybean agricultural production and crushing for oil and soybean meal production are listed in Appendix2.2. Results from the attribution LCA studies of soybean production (Cradle-to-farmgate) in the USA are presented in Table 16. Impact assessment of soybean meal production from the produced soybean at plant (assuming the plant is nearby the farm which indicates no transportation for the soybean carrying to the plant) are presented in Table 17 and Fig. 7.

**Table 16**. **Impact assessment of soybean production in USA for the year of 2017 and 2022 (Crop production region 3)**

| Impact categories | Unit | 2017 | 2022 |
|---|---|---|---|
| Global warming | kg $CO_2$ eq./kg | 0.522 | 0.536 |
| Land use | $m^2$a crop eq./kg | 1.77 | 1.77 |
| Water consumption | $m^3$/kg | 0.816 | 0.798 |
| Fossil resources | Kg oil eq./kg | 0.0943 | 0.0908 |

**Table 17. Impact assessment of soybean Soybean meal by mass and economic allocation in USA for the year of 2017 and 2022**

| Impact categories | Unit | Soybean meal allocation | | | | | |
|---|---|---|---|---|---|---|---|
| 2017 | | | | | | | |
| | | Mass based allocation | | | Economic based allocation | | |
| | | Crude oil | Soy hulls | Soybean meal (SBM) | Crude oil | Soy hulls | Soybean meal (SBM) |
| Global warming | kg $CO_2$ eq./kg | 0.136 | 0.053 | 0.504 | 0.120 | 0.047 | 0.448 |
| Land use | $m^2$a crop eq./kg | 0.339 | 0.132 | 1.26 | 0.300 | 0.117 | 1.115 |
| Water consumption | $m^3$/kg | 0.157 | 0.060 | 0.578 | 0.138 | 0.054 | 0.514 |
| Fossil resources | Kg oil eq./kg | 0.028 | 0.010 | 0.102 | 0.025 | 0.01 | 0.091 |
| 2022 | | | | | | | |
| | | Mass based allocation | | | Economic based allocation | | |
| | | Crude oil | Soy hulls | Soybean meal (SBM) | Crude oil | Soy hulls | Soybean meal (SBM) |
| Global warming | kg $CO_2$ eq./kg | 0.133 | 0.052 | 0.494 | 0.118 | 0.046 | 0.439 |
| Land use | $m^2$a crop eq./kg | 0.338 | 0.132 | 1.257 | 0.300 | 0.117 | 1.115 |
| Water consumption | $m^3$/kg | 0.152 | 0.059 | 0.566 | 0.135 | 0.053 | 0.503 |
| Fossil resources | Kg oil eq./kg | 0.027 | 0.010 | 0.10 | 0.023 | 0.01 | 0.09 |

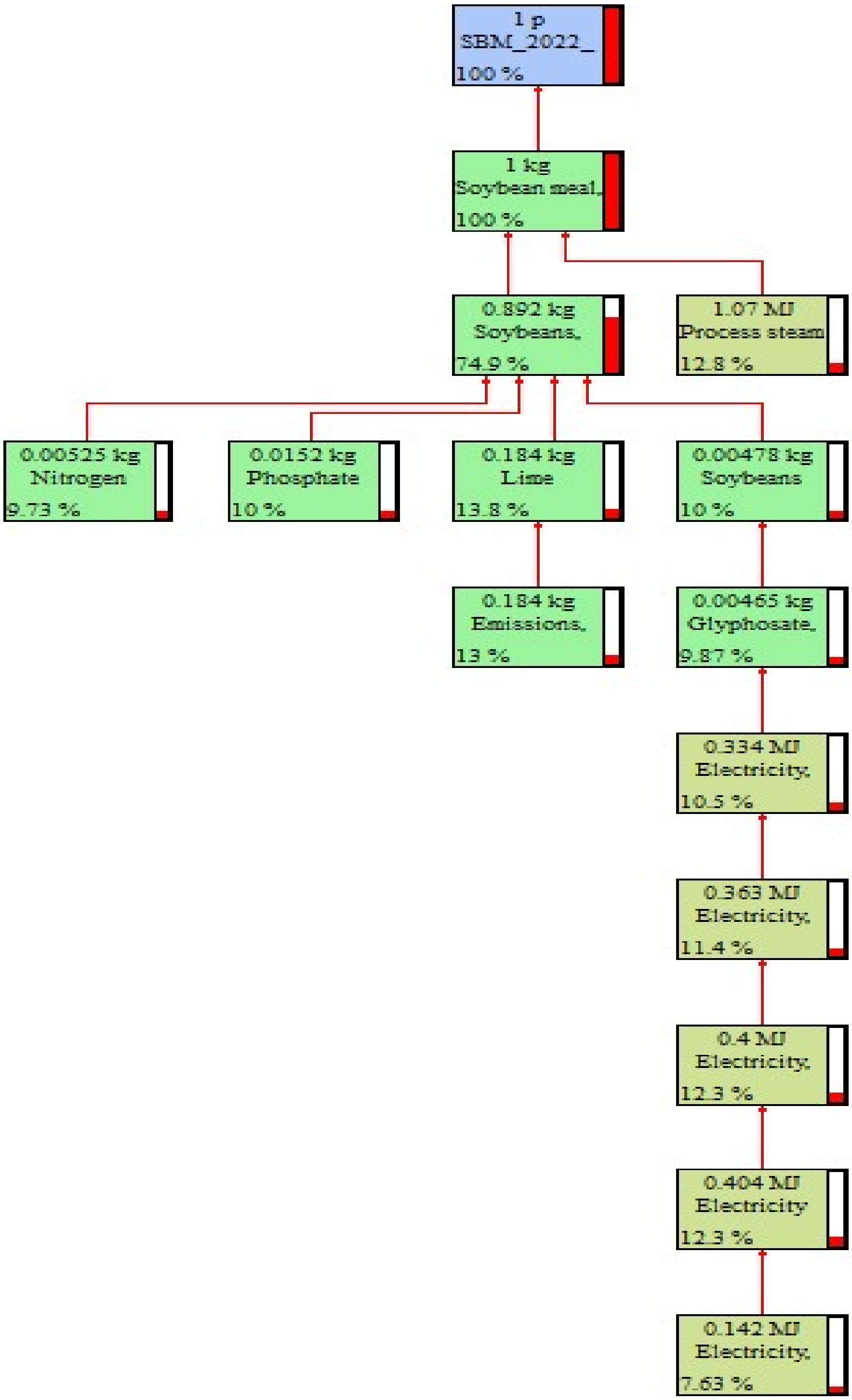


**Fig 7. Network (15 nodes out of 2191 visible nodes in the system with 7% cut-off) of global warming potential of soybean meal in the USA in 2017**

As can be seen in Fig.7, main global warming impact for soybean meal production comes from the lime application and its processing, which causes about 13.8 % of the total global warming impacts (GW). Major fertilizers (such as nitrogen & phosphate) and herbicides also contributed equally to the GW impact, which turn about 10% each. Energy usage for raw materials processing causes 10.5% of direct GW impact from diesel combustion in the industrial equipment. Process steam in the plant generated over 12% of the total gobal warming for soybean production in the USA.

Impacts on fossil resources scarcity mostly causes by electricity mix (about 11%) and process steam (about 22.5%) at plant. Diesel, electricity and natural gas usage contributes to about 10.1%, 13.6% &6.56% respectively during fertilizer, pesticides production and application, drying and equipment needed for the soybean production.

Major water consumption impact influenced by the fertilizer (phosphate & lime) and herbicides application and turns about 15%, 20.3% & 21.8% respectively. Other required raw materials and their processes added up to 100% of the GW during the soybean production system in the USA.

Thus, from the agricultural production of soybean meal LCA study, it can be said that lime, herbicides and phosphate fertilizer are the major influential factor for the environmental impacts considered in this study.

It is observed that land use for soybean meal production over the projected period is not changed. It is because the assumption that acreage of land for soybean cultivation remains unchanged. Due to yield changes for the projection when other inputs, processes and materials are assumed to be remained unchanged, impacts on global warming, fossil resources scarcity and water consumption decline by about 1.89%, 2.32% & 2.19 % respectively based on economic allocation. Economic allocation reduces the environmental impact by about 12% in all categories compare to the mass based LCA of soymeal production in USA.

A sensitivity test for the SBM production is also conducted. Major contributing factors in the production process are unavoidable and can merely be changed over the period. On the contrary, energy consumption from different sources (natural gas, electricity by diesel or hydropower or other sources) related to the processes involved in each stage of the life cycle study can have significant influence. Thus, a sensitivity test of using electricity from hydropower in the US is applied for the processes. Results indicate that replacement of process steam from natural gas, by hydropower electricity in the consumption mix causes almost double the global warming potential and land use (0.762 kg $CO_2$ eq & 2.21 m2 crop area eq. per kg SBM respectively) (Table 18), almost 14 times higher water consumption (9.18 $m^3$ per kg SBM). Thus, it is recommended to use the process steam run by the natural gas in the production plant for SBM production in USA. Land use is higher because hydroelectric plants in flat areas requires much more land than those in hilly areas or canyons where deeper reservoir can hold more volume of water in less area (Union of concerned scientists, USA). Similar group estimated the life-cycle emissions of hydroelectric plants in USA can be over 0.5 lbs of $CO_2$ eq. per Kwh electricity.

**Table 18. Sensitivity results of SBM LCA with hydropower replacing the process steam energy supply in the processes**

| Economic allocation | | With process steam energy supply | | | With hydropower energy supply | | |
|---|---|---|---|---|---|---|---|
| | | **SBM** | **Soybean hulls** | **Soy crude oil** | **SBM** | **Soybean hulls** | **Soy crude oil** |
| Global warming | kg $CO_2$ eq./kg | 0.439 | 0.046 | 0.118 | 0.762 | 0.08 | 0.205 |
| Land use | $m^2a$ crop eq./kg | 1.115 | 0.117 | 0.300 | 2.217 | 0.232 | 0.597 |
| Water consumption | $m^3$/kg | 0.503 | 0.053 | 0.135 | 9.813 | 1.029 | 2.641 |
| Fossil resources | Kg oil eq./kg | 0.10 | 0.010 | 0.027 | 0.137 | 0.014 | 0.037 |

***Distiller dried grain with soluble (DDGS)***

LCA studies, reports and related literature were searched thoroughly in different database search options. With the key word 'Life cycle assessment' there are more than 56 thousand research materials obtained in the web of science database searching option. Searching was further refined with corn and soybean separately, which showed over 2000 and 1000 respectively research materials including research articles, book, conference, meetings, proceedings etc. In order to bring the coverage only on DDGS, searching was further refined with 'DDGS' which eventually showed 10 research items. Thus, the final searching process could be showed as Life cycle assessment>corn>DDGS=10.

**Table 19. DDGS impacts from existing LCA studies in literature**

| GWP (kg $CO_2$ eq./kg) | LU ($m^2a$ crop eq./kg) | WC ($m^3$) | FR (kg oil eq./kg) | Reference |
|---|---|---|---|---|
| 0.85 | - | - | - | Kraatz et al., 2013 (economic alloc.) |
| 0.914 | 0.03 | - | - | K. Reckmann et al., 2016 |
| 0.780 | - | - | - | Mackenzie et al., 2016 |
| 1.19 | - | - | - | Kraatz et al., 2013 (mass alloc.) |
| 0.426 | | | | Thoma et al., 2011 |

System boundary for DDGS LCA study is formulated from corn grain production at farm in the crop production region 3 to the ethanol plant for ethanol production, and assuming the corn ethanol plant nearby the farm. The unit for the impact assessment for DDGS thus, determined by per unit production. The overall process and the system boundary with allocation for DDGS from corn grain ethanol is depicted in Fig. 8.

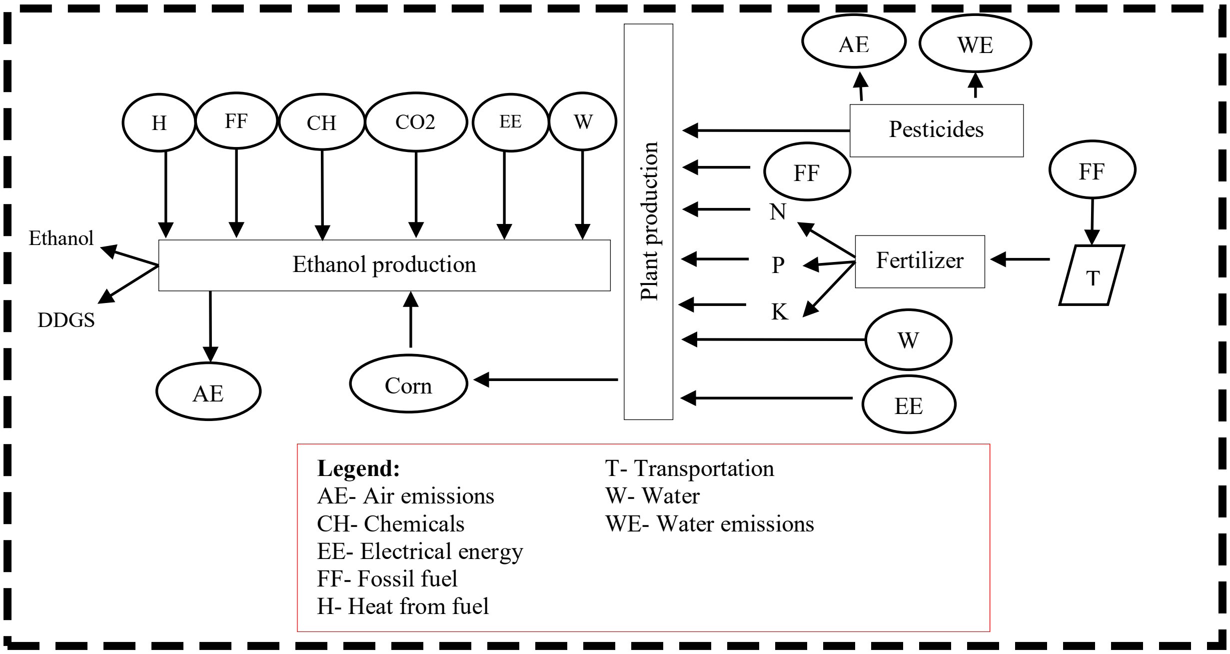


**Fig 8. System boundary for DDGS production from corn grain (crop production region 3) in the USA**

Results from the mass and economic LCA studies of DDGS production (Cradle-to-factory) in the USA are presented in Table 20, Fig. 9 and Fig. 10.

**Table 20. Environmental impacts of DDGS from corn grain in USA for the year of 2017 and 2022**

| Impact categories | Unit | DDGS allocation | | | |
|---|---|---|---|---|---|
| **2017** | | | | | |
| | | **Mass based allocation** | | **Economic based allocation** | |
| | | **DDGS** | **Ethanol** | **DDGS** | **Ethanol** |
| Global warming | kg $CO_2$ eq./kg | 0.738 | 0.704 | 0.242 | 1.2 |
| Land use | $m^2$a crop eq./kg | 0.571 | 0.549 | 0.187 | 0.932 |
| Water consumption | $m^3$/kg | 0.328 | 0.315 | 0.108 | 0.535 |
| Fossil resources | Kg oil eq./kg | 0.201 | 0.193 | 0.066 | 0.328 |
| **2022** | | | | | |
| | | **Mass based allocation** | | **Economic based allocation** | |
| | | **DDGS** | **Ethanol** | **DDGS** | **Ethanol** |
| Global warming | kg $CO_2$ eq. | 0.739 | 0.710 | 0.243 | 1.21 |
| Land use | $m^2$a crop eq./kg | 0.110 | 0.106 | 0.188 | 0.932 |
| Water consumption | $m^3$/kg | 0.332 | 0.319 | 0.109 | 0.542 |
| Fossil resources | Kg oil eq. | 0.202 | 0.194 | 0.0663 | 0.330 |

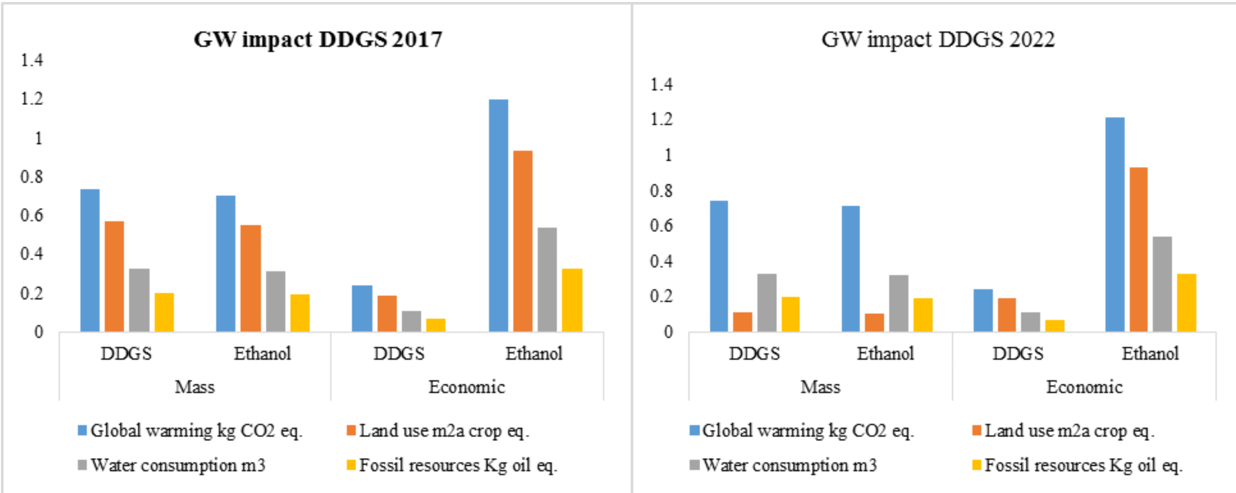


**Fig 9. Environmental impact of DDGS production in the USA for 2017 and 2022 in mass and economic allocation approach**

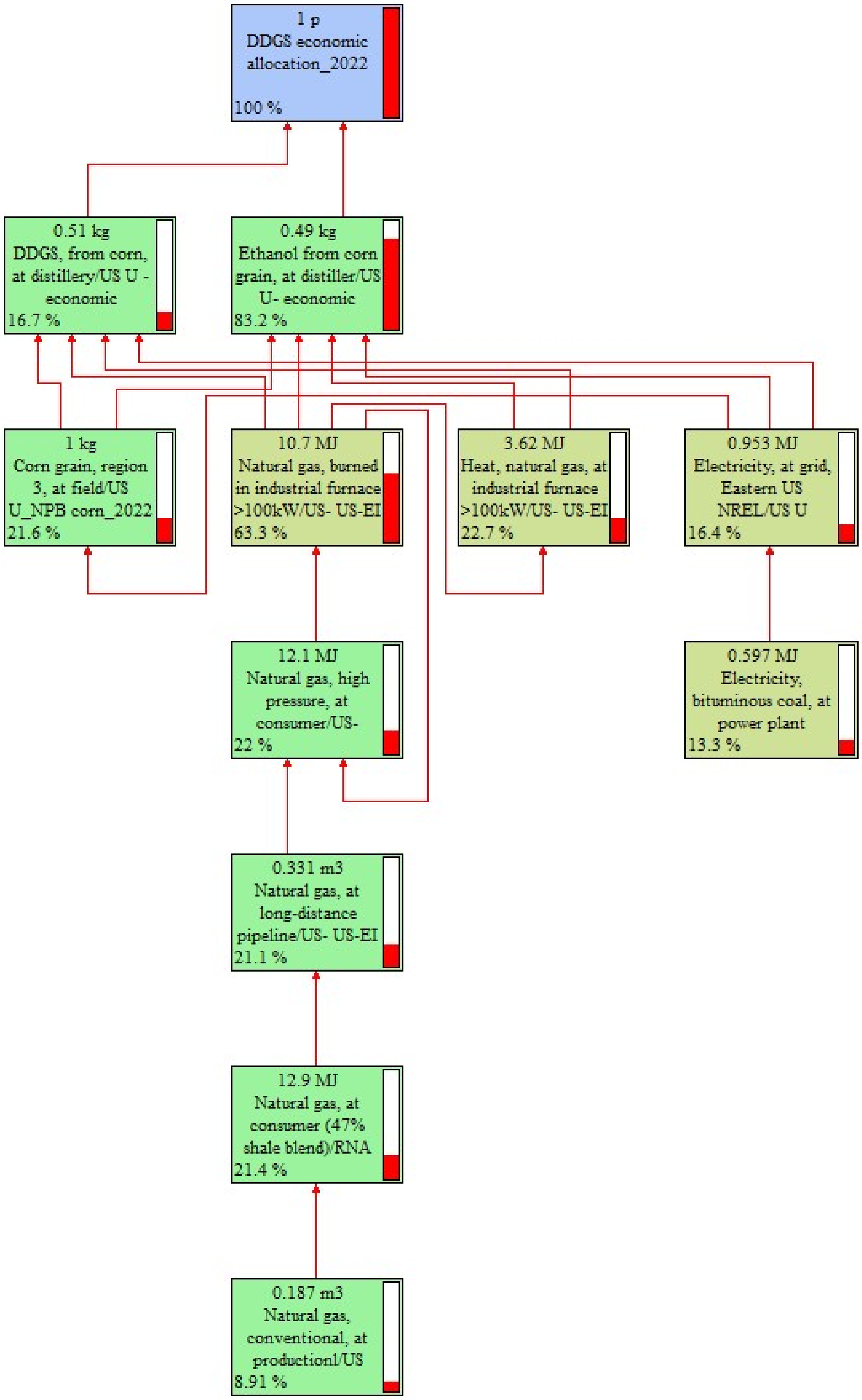


**Fig 10. Network (12 nodes out of 2194 visible nodes in the system with 7% cut-off) of global warming potential of DDGS production (economic allocation) in the USA in 2017**

As can be seen in Fig. 10, main global warming impact for DDGS co-production comes from ethanol distillation and its processing, which causes more than 80 % of the total global warming impacts (GW).

About 16% of the global warming impact comes from the DDGS production in the ethanol plant. Natural gas and electricity indirectly causes about 86% and 14% of GW impact respectively for ethanol and DDGS co-production at plant in the USA.

Impacts on fossil resources scarcity mostly causes by un-processed natural gas (about 74%) and bituminous coal (about 14%) at mine for energy supply in the processes involved for ethanol DDGS co-production respectively at the plant. Other contributors for the fossil resource scarcity related to the corn intensive production (maize drying by LPG), transport of fertilizer, corn grain and other raw materials to the plant and cumulatively causes about 1-2% of the total in this category.

Major water consumption impact influenced by the corn grain production, electricity at grid, natural gas at industrial furnace and sulphuric acid liquid at plant which contribute to 61.8%, 30.6%, 8.05% & 2 % respectively. Seed production, phosphate fertilizer and drying are the major role player for most water consumption at grain production stage, while run-of-river power causes the most part of water consumption by electricity.

Thus, from the DDGS LCA study, it can be said that natural gas, electricity at grid, intensive corn seed production (phosphate, nitrogen fertilizer and maize drying) are the major influential factors for the environmental impacts considered in this study.

As the price of the DDGS varies with demand, supply and consumption of the ethanol fuel and the combine protein and fat content of the co-produced DDGS, therefore, a sensitivity test of the DDGS is also carried out. A 20% increase of the current price is considered for the produced DDGS (assuming 35% combined protein-fat content) and the subsequent impact is quantified as in Table 21. It can be seen that an increase in the price of the DDGS will increase the environmental impact to the category global warming, land use, water consumption and fossil resources by 16.05%, 15.96%, 14.17%, & 16.67 % respectively.

**Table 21. Sensitivity test of the DDGS with 20% price increase from current price**

| **Economic allocation** | | **Based on current price** | | **20% increase of current price (only DDGS)** | |
|---|---|---|---|---|---|
| | | **DDGS** | **Ethanol** | **DDGS** | **Ethanol** |
| Global warming | kg $CO_2$ eq. | 0.243 | 1.21 | 0.282 | 1.17 |
| Land use | $m^2$a crop eq. | 0.188 | 0.932 | 0.218 | 0.902 |
| Water consumption | $m^3$ | 0.109 | 0.542 | 0.127 | 0.525 |
| Fossil resources | Kg oil eq. | 0.0663 | 0.330 | 0.077 | 0.319 |

***Sorghum or milo***

Forage sorghum, both grain and forage, is an important feedstuff for livestock. It is a summer crop, commonly in warm climates all over the world, especially where maize cannot be cultivated due to its high-water requirements. According to USDA, 2015 report the highest sorghum producing states in USA was Kansas, which produced about 280 million bushels of sorghum followed by Texas and Arkansas with a production amount of 150 and 43 million bushels respectively. These figures denote the production concentration area of sorghum in USA. By searching the key term “life cycle analysis sorghum’ there is 203 research items obtained and majority of which are not directly related to the sorghum LCA. Thus, refinement of searching carried out in several ways, which could be shown below with the number of research items obtained:

Life cycle analysis sorghum>USA>animal feed = 6 research items
LCA sorghum>animal feed>USA = 2 research items
Sorghum milo swine feed>>USA = 17
Sorghum milo swine feed>>USA>LCA = 0 research items

Sorghum impacts from existing LCA studies in literature presented in Table 22.

**Table 22. Sorghum impacts from existing LCA studies in literature**

| GWP (kg $CO_2$ eq./kg) | LU ($m^2a$ crop eq./kg) | WC ($m^3$) | FR (kg oil eq./kg) | Reference |
|---|---|---|---|---|
| 0.390 | - | - | - | Monti et al., 2009; Krohn and Fripp, 2012 (Seed production) |
| 0.232 | 0.505 | 0.257 | 0.0462 | Garcia et al., 2016 (double cropping barley+sorghum) |
| 0.490 | - | - | - | Moussa et al., 2016 |

Very few research items found in the database search on complete LCA of sorghum as single grain crop nor as animal feed in the United States. Therefore, the system boundary for sorghum is taken from other countries (for instance from Europe or South America) as representative for United States, assuming the production techniques of sorghum same like another countries.

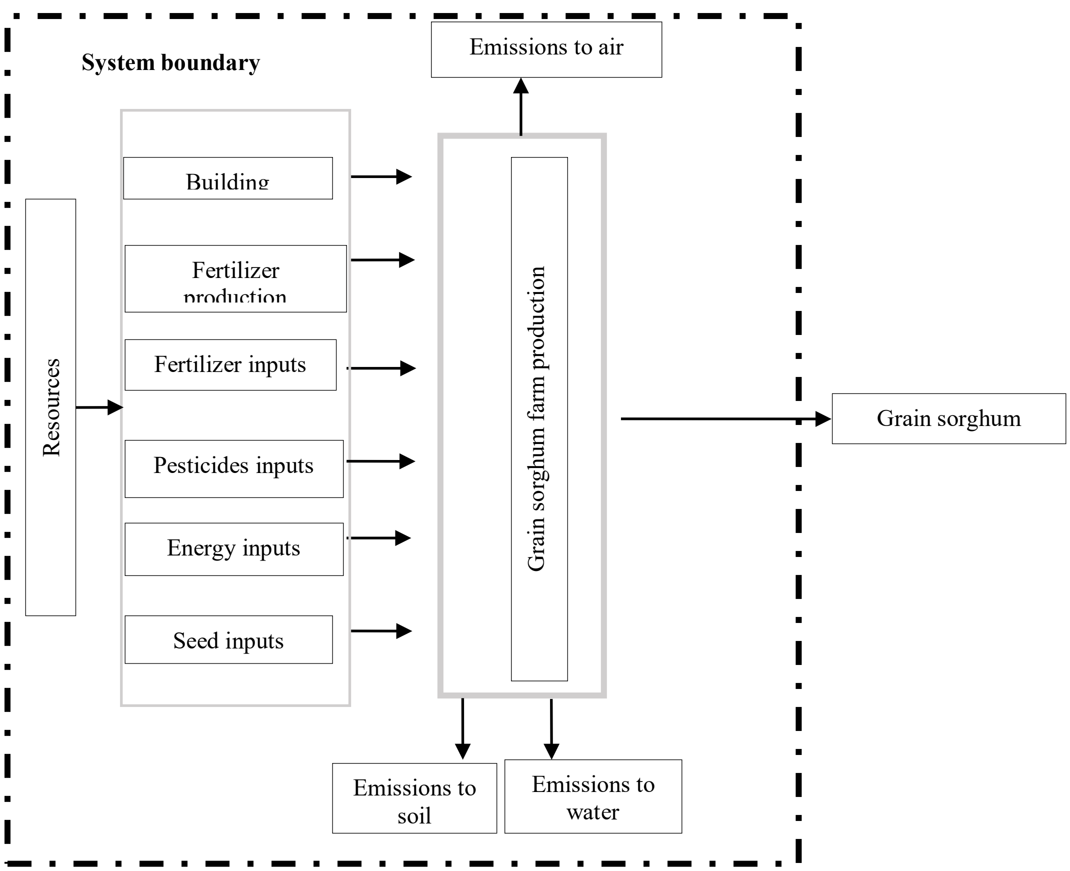


**Fig. 11. System boundary for grain sorghum LCA at farm gate**

There are some LCA studies on sorghum as relay and double cropping system in US can be brought to assess its environmental impacts. For instance, the life cycle inventory of inputs for sorghum cultivation can be shown in Table 23.

**Table 23. Inputs of sorghum cultivation as relay and double cropping in the agricultural phase (Berti et al., 2017)**

| Cropping sequence | Rate (kg ha$^{-1}$) | | | Herbicide (kg ha$^{-1}$) | Insecticide | Seed | Diesel (kg ha$^{-1}$) | Electricity (L ha$^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| | N | P | K | | | | | |
| WCFSR | 100 | 30 | 30 | 5.1+0.05+1.29 | 0 | 52 | 88 | 7.3 |
| WCFSD | 100 | 30 | 30 | 5.1+0.05+1.29 | 0 | 52 | 88 | 7.3 |
| FSNSD | 100 | 30 | 30 | 5.1+0.05+1.29+2.8 | 0 | 45 | 63 | 0 |
| FSDSD | 30 | 30 | 30 | 5.1+0.05+1.29+2.8 | 0 | 45 | 63 | 0 |

WCFSR = WC-forage sorghum (FS) in relay cropping (R); WCFSD = WC-FS in double cropping (D); FSNSD =FS in normal seeding date (NSD); FSDSD = FS sown at the time of double seeding date (DSD)

The inputs for life cycle inventory of sorghum or milo LCA study is extracted from the agrifootprint library projects in SimaPro 8.5.2.0. The inventory is for the per hectare production of sorghum as a mono-cropping system (As listed in Appendix2.3). Results from the mass and economic allocation based LCA studies of sorghum production (Cradle-to-farm gate) in the USA is presented in Table 24 and Fig. 12.

**Table 24. Environmental impacts (mass and economic based allocation) of sorghum in USA for the year of 2017 and 2022**

| Impact categories | Unit | Sorghum allocation | |
|---|---|---|---|
| **2017** | | | |
| | | **Mass based allocation** | **Economic based allocation** |
| Global warming | kg $CO_2$ eq. | 0.614 | 0.615 |
| Land use | m$^2$a crop eq. | 2.62 | 2.62 |
| Water consumption | m$^3$ | 0.0697 | 0.0697 |
| Fossil resources | Kg oil eq. | 0.0986 | 0.0998 |
| **2022** | | | |
| | | **Mass based allocation** | **Economic based allocation** |
| Global warming | kg $CO_2$ eq. | 0.658 | 0.659 |
| Land use | m$^2$a crop eq. | 2.8 | 2.79 |
| Water consumption | m$^3$ | 0.0746 | 0.0746 |
| Fossil resources | Kg oil eq. | 0.106 | 0.107 |

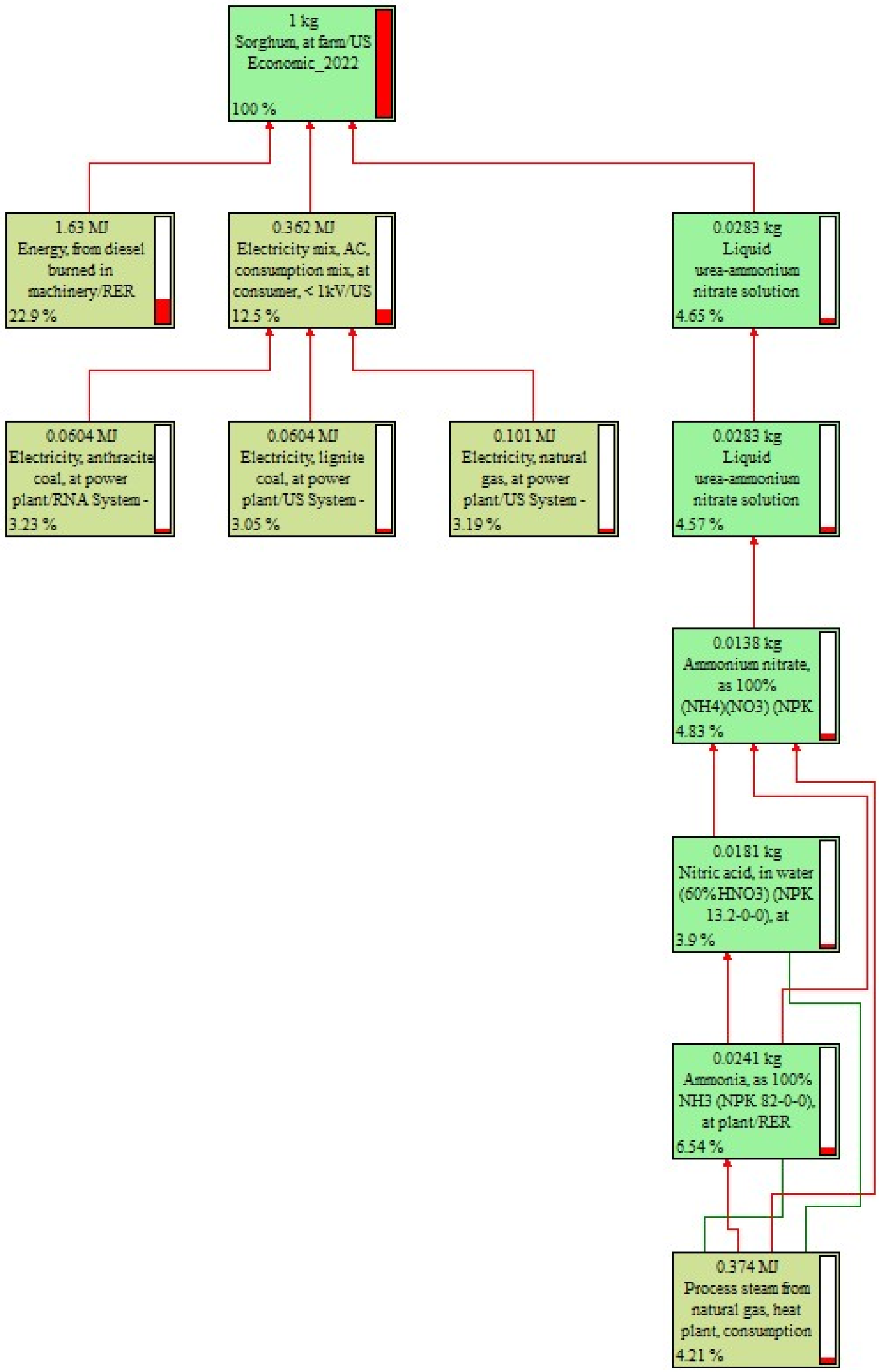


**Fig 12. Network (12 nodes out of 128 visible nodes in the system with 3% cut-off) of global warming potential of sorghum production (economic allocation) in the USA in 2017**

As can be seen in Fig 12, main global warming impact for sorghum production comes from energy consumption by machineries (22.9%), electricity at grid (12.5%) and liquid urea application fertilizer along the with the processes associated with these inputs over the projection to 2022..

Impacts on fossil resources scarcity mostly causes by diesel from electricity from crude oil (about 39%), electricity from coal and natural gas (7.43% & 7.25% respectively). Process steam from natural gas (9.2%) and natural gas from onshore and offshore production plant (14.8%) that are used for the urea fertilizer production in the grain production.

Major water consumption impact influenced by the sorghum grain production itself that account for 100% of the water consumption along the production stage. Energy burned in the equipment, lime fertilizer and process steam from light fuel oil causes about 0.18, 0.15 & 0.12% of the total water consumption in the grain product system.

Thus, from the sorghum grain LCA study, it can be said that energy from diesel burned in the machinery cost major of the global warming (about 12% out of 50% in this category), sorghum grain at farm production. Emissions associated with carbondioxide from fossil 40%, carbon dioxide in air 13% and nitrogen monoxide from the fertilizer production, application and evaporation (about 44%) ) are the major influential factors for the environmental impacts considered in this study.

Due to yield changes for the projection when other inputs, processes and materials are assumed to be remained unchanged, impacts on global warming, fossil resources scarcity and water consumption will increase by about 7.15%, 7.21% & 7.03 % respectively. Less acreage with almost similar yield over the projection (2022) causes the same usage of all raw materials needed for the grain production, which ultimately results slight higher environmental impacts than the year 2017.

Approximately 50-60% of the plant dry matter of grain sorghum remains in the field after harvest (http://www.sorghumcheckoff.com/news-and-media/newsroom/2017/10/30/utilizing-sorghum-stalks-for-grazing/). Since this study only consider the grain yield as feed production, raw materials and environmental burdens have not considered for the stover yield of grain sorghum plant. Thus, in the sensitivity analysis, stover yield is also considered. Price of the stover and grain is considered for the sensitivity analysis. A 20% price increase is examined to estimate the environmental burdens from the current price. Results of the sensitivity test is presented in Table 25. The results show that 20% price increase in the grain overall does not changes the environmental burdens in all categories. However, a 6-7% global warming impacts increase for the grain production, while a reduction of 12-13% appears in the stover production during the sorghum life cycle study in the USA.

**Table 25. Sensitivity test of the sorghum with 20% price increase**

| Economic allocation | | Based on current price | | 20% increase of current price (only grain) | |
|---|---|---|---|---|---|
| | | Grain | Stover | Grain | Stover |
| Global warming | kg $CO_2$ eq. | 0.211 | 0.118 | 0.225 | 0.105 |
| Land use | $m^2$a crop eq. | 0.889 | 0.502 | 0.956 | 0.445 |
| Water consumption | $m^3$ | 0.0239 | 0.0134 | 0.0255 | 0.0118 |
| Fossil resources | Kg oil eq. | 0.0343 | 0.0192 | 0.0365 | 0.017 |

***Wheat-shorts/middlings***

In order to cover major LCA studies related to middlings the search term initially set as "wheat LCA" and with it there are 478 research items can be found in the web of science online database. Further search refinement was carried out with the terms "USA" and "middling" and the figure obtained were 23 and 1 respectively. Although, a lot of the items obtained in the search with key term "wheat LCA" are not directly related to the wheat life cycle assessment, however, the relevant information for environmental impact assessment of wheat and associated products of wheat have been brought into these studies.

Two stages that are involved in wheat middling production consist of wheat grain and middling production by milling of wheat grain of which wheat grain stage causes the major environmental impact due to the implication of different inputs, raw materials, production processes and natural resources. Therefore, the assessment of environmental impacts/burdens needs to conduct throughout its product system. Wheat-shorts/middlings impacts from existing LCA studies in literature are presented in Table 26.

**Table 26. Wheat-shorts/middlings impacts from existing LCA studies in literature**

| GWP (kg $CO_2$ eq./kg) (economic alloc.) | LU ($m^2a$ crop eq./kg) | WC ($m^3$) | FR (kg oil eq./kg) | Reference |
|---|---|---|---|---|
| 0.330 | - | - | - | Mackenzie et al., 2016 |
| 0.329 | 1.16 | - | - | Hannah et al., 2014 |

The aim of our study is thereby to quantify the environmental impacts of wheat middling production and identify the hotspots in the production system. System boundary of the whole production system of wheat middling is depicted in Fig 13.

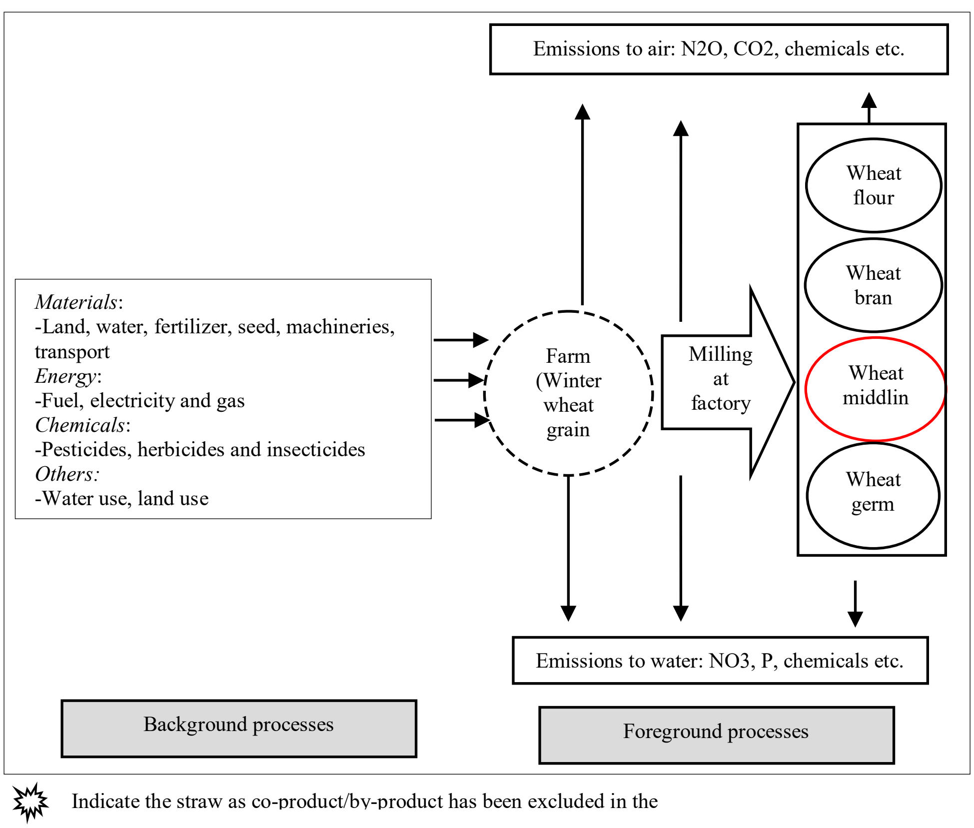

**Fig 13. Factory gate system boundary for wheat middling production in the USA.**

Raw materials for winter wheat grain middling is derived from the agricultural production. This stage of wheat grain production causes the major environmental burden or impacts, no matter which allocation is considered for ultimate products or co-products LCA analysis. Unit process of winter wheat grain production LCA is performed following attributional allocation and the straw yield as co-product is avoided (agreeing the ISO 14044:2006 rule-where allocation can be avoided). Straw yield is usually left over the field after harvest as the straw is as low valued. The inputs for the winter wheat grain production are listed in Appendix2.4. In the grain production stage the emissions of $CO_2$ accounts for 612 g per kg (Table 27) grain production of which nitrogen fertilizer added the most (around 47%).

**Table 27. Environmental impacts of wheat grain production with the average agricultural input data from 2015, 16 &17**

| Impact categories | Unit | Winter wheat grain |
|---|---|---|
| Global warming | kg $CO_2$ eq. | 0.612 |
| Land use | $m^2$a crop eq. | 1.12 |
| Water consumption | $m^3$ | 0.502 |
| Fossil resources | Kg oil eq. | 0.103 |

Results of the environmental impacts of mass and economic allocation based LCA studies of wheat grain middling in the USA with products and co-products is presented in Table 28, Fig. 14, Fig. 15, and Fig. 16.

**Table 28. Environmental impacts of wheat grain dry middling in USA for the year of 2017 and 2022**

| Impact categories | Unit | Sorghum allocation | |
|---|---|---|---|
| **2017** | | | |
| | | **Mass based allocation** | **Economic based allocation** |
| Global warming | kg $CO_2$ eq. | 0.737 | 0.690 |
| Land use | $m^2$a crop eq. | 1.113 | 1.042 |
| Water consumption | $m^3$ | 0.501 | 0.468 |
| Fossil resources | Kg oil eq. | 0.140 | 0.131 |
| **2022** | | | |
| | | **Mass based allocation** | **Economic based allocation** |
| Global warming | kg $CO_2$ eq. | 0.691 | 0.698 |
| Land use | $m^2$a crop eq. | 1.11 | 1.04 |
| Water consumption | $m^3$ | 0.508 | 0.475 |
| Fossil resources | Kg oil eq. | 0.125 | 0.132 |

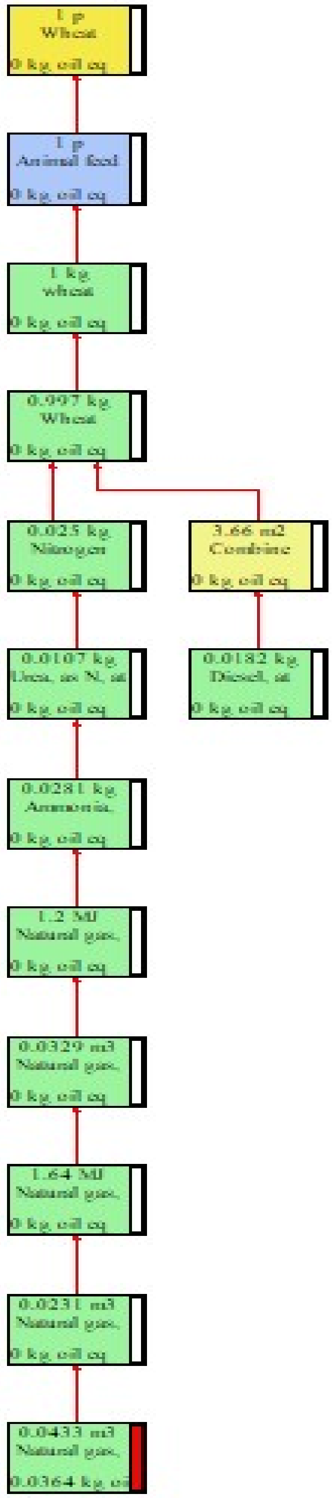


**Fig 14. Network (13 nodes out of 128 visible nodes in the system with 2.43% cut-off) of global warming potential of amino (L-Lysine-HCl) in the USA in 2017**

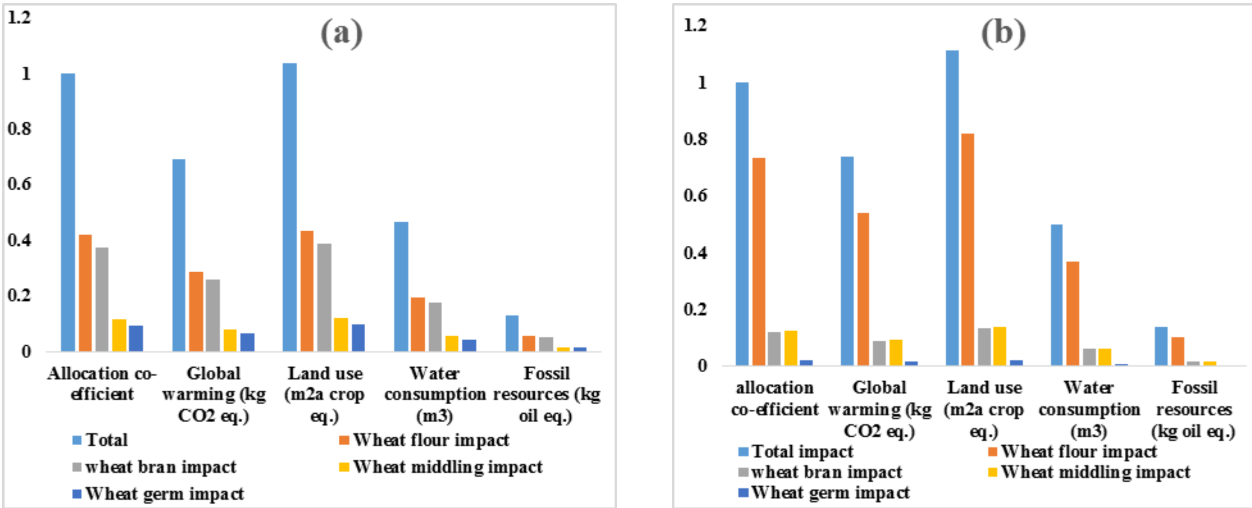


**Fig 15. Environmental impact of winter wheat middling LCA at mill gate in USA for the year of 2017: (a) LCA by economic allocation & (b) LCA by mass allocation**

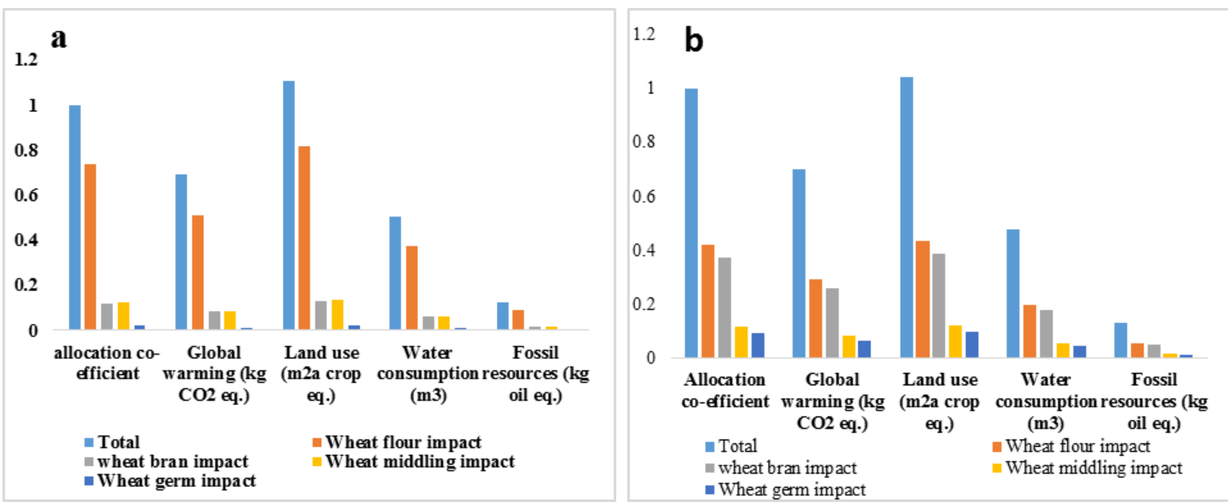


**Fig 16. Environmental impact of winter wheat middling LCA at mill gate in USA for the year of 2022 (USDA-NASS survey): (a) LCA by mass allocation & (b) LCA by economic allocation**

Final environmental impact results of the aimed co-product wheat middling was calculated using eq. 3 & 5 for the mass and economic allocation respectively. Results from the LCA studies of wheat middling by mass and economic basis shows the total environmental impacts are lesser by 5-7%. In all categories when economic allocation applied. Major portion of the impacts for all the considered categories goes to the products wheat flour and bran in both allocation system, which accounts for more than 80% of the total considered impact categories. Our desired products (wheat-middling) LCA liable for an environmental impacts generation of around 12% of the counted impact categories under both allocation system. In terms of global warming potential economic allocation reduced, the impact by 15% (from 92 g to 80 g of $CO_2$ emission per kg middling production) compare to the LCA studies by mass allocation. Reduction of environmental loads between the allocation systems is because of the distribution of the processes and their corresponding raw materials application (which came up from sub-unit processes) along the grain production stage to middling production at mill gate accumulated or counted by mass and price. It is noted that, market price of the products and co-products are always volatile based on their demand and supply situation. Thus, the current result of middling LCA study by economic allocation can also vary with price volatility.

Overall from the results of wheat middling LCA study with winter wheat in the USA, it can be said that economic allocation reduces the environmental burden by about 12.5% under the global warming category when price estimation and agricultural input taken from the year 2017. It is noted that the main product from the grain middling is considered as wheat flour which is more than 73% by mass and it's corresponding global warming impact also decline by 46% compare to the allocation by mass during the LCA study.

It is noted that the yield for the projected period decline to 2756 kg compare to the yield for the year 2017 which is 2821 kg/ha. Thus, the variation in the environmental impact under global warming category accounts for the resources extraction and processes related to the agricultural production of wheat grain. Similar agricultural production impact to other environmental categories distributed based on their resource utilization corresponding to the final products in the life cycle analysis. Global warming impact to the wheat middling LCA for the projected period reduces by 5.5% under the economic allocation system compare to the LCA by mass allocation. Other impact categories (Land use, water consumption and fossil resources) do not changes significantly for the winter wheat middling LCA over the projected period.

Overall, economic allocation provides less environmental impact in all the considered categories for the two scenarios applied for winter wheat middling LCA in the USA. It is noted that assumptive agricultural inputs and the price would be the major playing factors for LCA studies. Fluctuation of price of the produced products in a process and their LCA vary in different allocation system. Thus, how the price can manipulate the LCA results in economic allocation compare to the mass based allocation with a 10% increase in the products price is also conducted as a sensitivity analysis study for the winter wheat middling in USA.

Economic allocation for environmental impacts assessment from the winter wheat middling LCA in the USA is further carried out for a price sensitivity test. A 10% increase in the price of the desired co-product wheat middling is account for price elasticity, while other products price assuming unchanged over the projected period until 2022. The result is presented in Fig. 17. From the calcualted results for the price increase LCA analysis of wheat middling, it is observed that overall global warming potential increases about 8% (from 0.698 to 0.761 kg $CO_2$ eq.) compare to the assuming unchanged current price over the period. Price increase by 10% results about 16% global warming (from 0.081 to 0.096 kg $CO_2$) compare to the assumed unchanged price for the same time period. Nevertheless, price increase by 10% in wheat-middling also bring inccreasing global warming impacts from other products in the life cycle system. Other categories of impact also rises up to 8% from the price increase of wheat-middling LCA stuy.

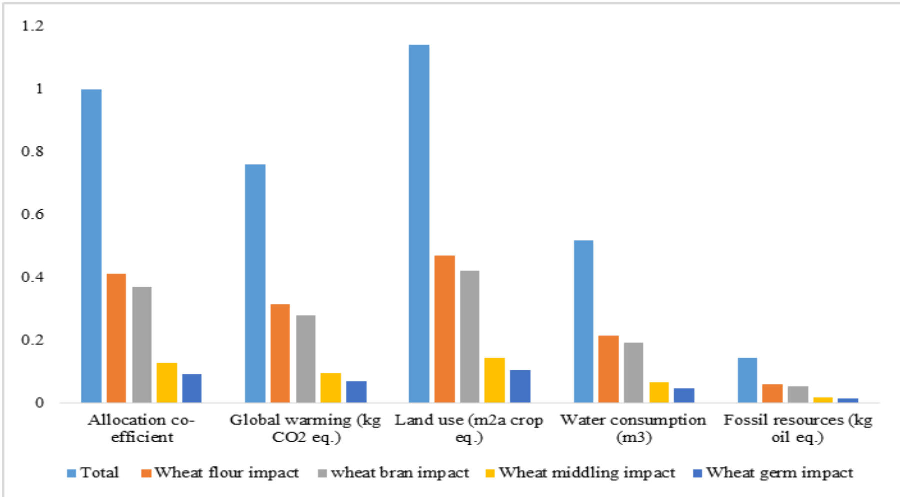


**Fig 17. Environmental impact of winter wheat middling LCA at mill gate in the USA, assuming a 10% price increase of the wheat middling**

### *Amino acids*

The system studied concerns the cradle to gate production of the amino acids. Whereas the production of components used in the production process represents the cradle, the starting point and the amino acids ready to leave the production site as end point of the studied system. The use of the considered amino acids is beyond the system boundary defined in this inventory (Fig. 18) .

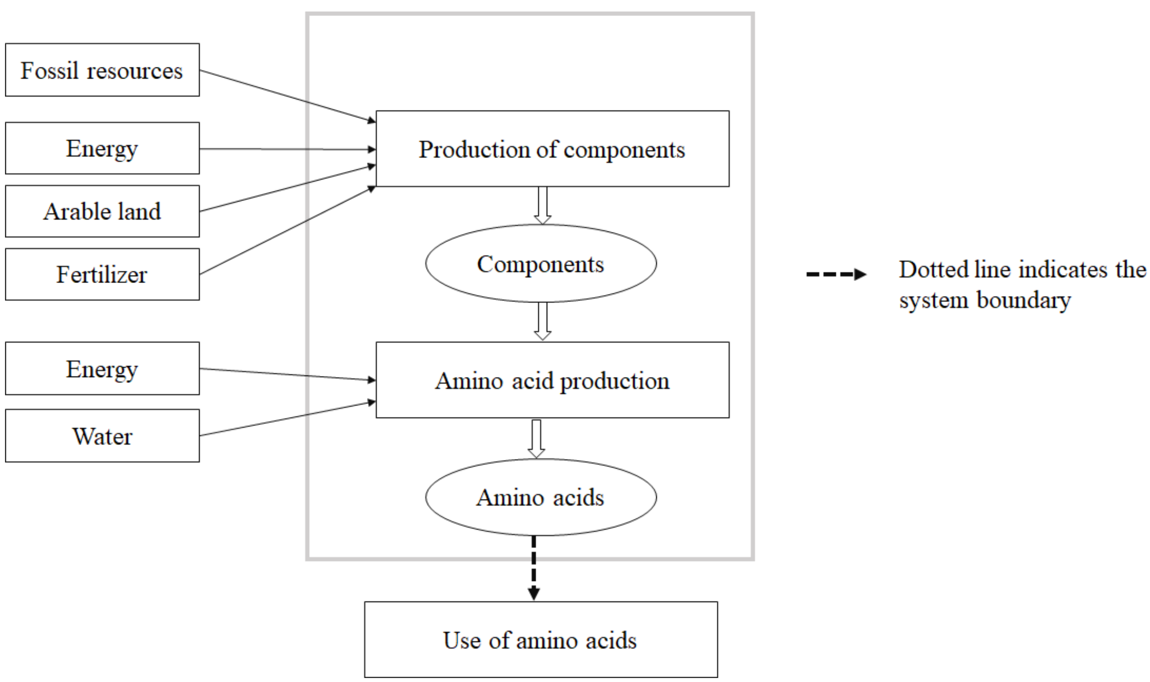


**Fig. 18. Schematic process map for the production of amino acids considered in this inventory, the dotted line represents the systemboundary**

The production site of amino acids is located in USA. In the life cycle assessment we excluded capital goods and office services (The exclusion of capital goods and office services is according the carbon footprint protocol PAS2050). Components used in minor quantities for the production of L-lysine and L-threonine as vitamins, amino acids, salts, antibiotics, and nitric acid for cleaning are excluded from the inventory because the expected share to the impact is very small relative to the effort to inventory the impacts (See Appendix 2.5). Searhcing through databases like Web of science , science direct, scopus and gogole scholar; very few studies obtained on amino acids LCA around the globe. With web of science searching there are 2 sceintific items obtained on amin acids LCA. Existing LCA study results on envrionmental impacts can be presented as below:

**Table 29. Amino acids impacts from existing LCA studies in literature**

| Amino acids impacts | GWP (kg $CO_2$ eq./kg) (economic alloc.) | LU ($m^2$a crop eq./kg) | WC ($m^3$) | FR (kg oil eq./kg) | Reference |
|---|---|---|---|---|---|
| Lysine | 4.940 | 0.2 | - | - | K. Reckmann et al., 2016 |
| Threonine | 4.940 | 0.2 | - | - | |
| Methionine | 2.890 | 0.01 | - | - | |
| HCL-Lysine | 4.81 | - | - | - | Mackenzie et al., 2016 |
| L-Threonine | 4.81 | - | - | - | |
| FU-Methionine | 2.95 | - | - | - | |
| L-Tryptophan | 9.62 | - | - | - | |
| L-Lysine | 4.294 | - | - | - | Mosnier et al., 2011 |
| L-Threonine | 4.294 | - | - | - | |
| FU-Methionine | 2.96 | - | - | - | |

The inputs for amino acids (L-Lysine-HCl, Methionine and Threonine) production are listed in Appendix2.5. The functional unit is 1 kg synthetic produced amino acid (Lysine.HCl, T hreonine 98% pure crystalline threonine containing 2% water and 100% D,L-methionine), at the gate of the production site (Marinussen and Kool, 2010). Our results from amino acids LCA including L-Lysine-HCl, Methionine, and threonine (Cradle-to-factorygate) in the USA are presented in Table 30, and Fig. 19.

**Table 30. Environmental impact of amino acids (attributional approach) in the USA**

| Impact categories | Unit | L-Lysine-HCl | Methionine | Threonine |
|---|---|---|---|---|
| Global warming | kg $CO_2$ eq./kg | 4.06 | 9.06 | 8.14 |
| Land use | $m^2$a crop eq./kg | 3.34 | 0.728 | 5.07 |
| Water consumption | $m^3$/kg | 1.49 | 4.93 | 2.90 |
| Fossil resources | Kg oil eq./kg | 0.757 | 2.94 | 2.00 |

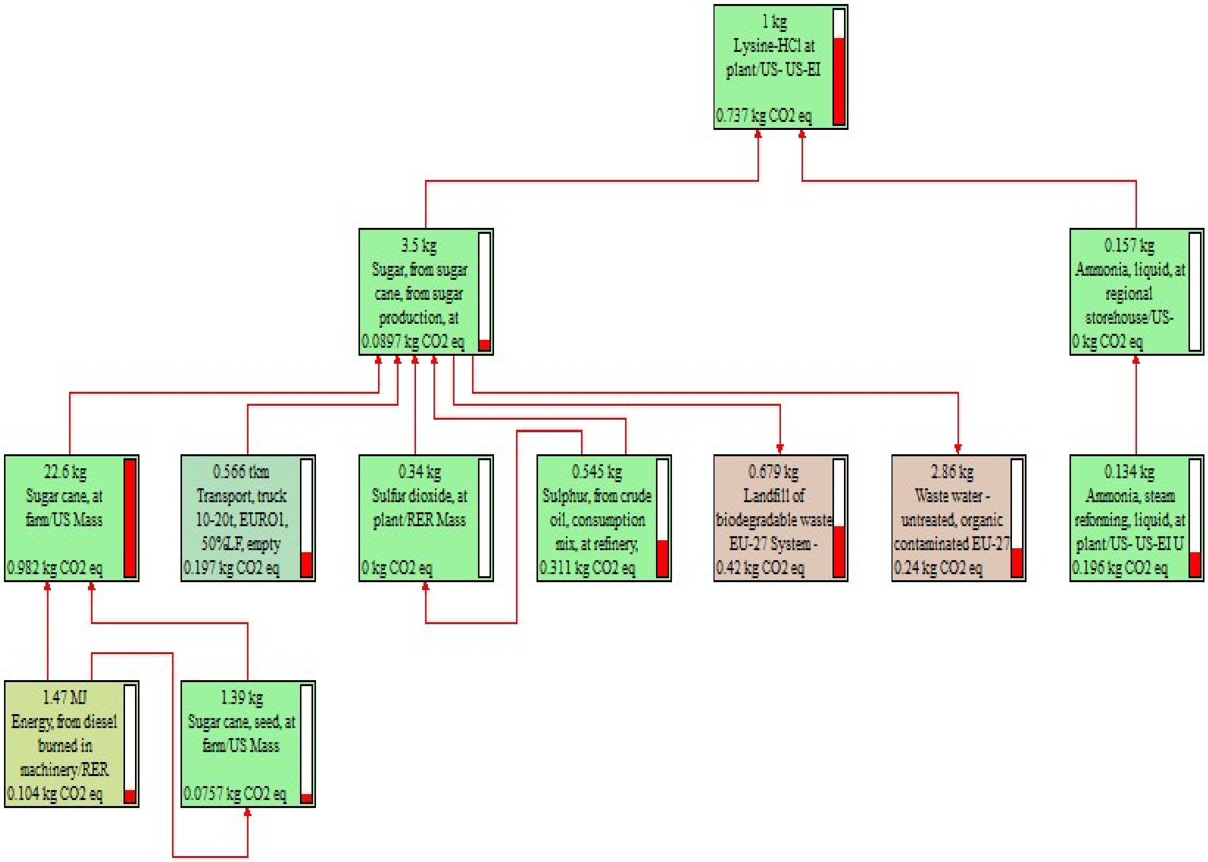


**Fig 19. Network (12 nodes out of 128 visible nodes in the system with 2.43% cut-off) of global warming potential of amino acid (L-Lysine-HCl) in the USA**

As can be seen in Fig. 30, main global warming impact for L-Lysine-HCl, Methione and Threonine comes from sugar syrup (64%), ammonium bicarbonate & electricity by natural gas (40% & 26%) and glucose from corn & ammonia liquid at regional storehouse (53% & 20%) respectively.

Impacts on fossil resources scarcity mostly causes by crude oil and natural gas about 70% (for sugar production and ammonia liquid at storehouse to the L-Lysine product system. For threonine, natural gas for ammonia liquid and medium voltage electricity for raw material glucose processes in the product system cumulatively causes 80% of fossil resource scarcity. In case of methionine production, electricity by natural gas causes the most, which constitute 53% of the total fossil resource scarcity.

Major water consumption impact influenced by organic chemicals and sugar production from sugarcane in the product system cumulatively causes more than 70% of the water consumption for L-Lysine-HCl. For threonine production most of the water consumption arises from the caustic input process (more than 66%), while for methionine production ammonium bi-carbonate input process constitute the largest portion (more than 84%).

For the production of amino acids, agricultural production of material inputs and their related process contributes the most except for methionine, which is produced chemically with agricultural input requirement in the product system. For threonine and lysine, sugar from sugarcane and cornstarch processing are the major contributing factor while acrylic acid input in the methionine production is major ruling factor in the amino acid product system.

It is observed that land use requirement for methionine production is the lowest (0.728 $m^2$a crop eq.) among three different amino acids LCA mentioned here. The reason is that methionine production requires no agricultural inputs or raw materials for which mass land utilization is needed (except land required for plant establishment), while for L-Lysine-HCl and threonine cane sugar, corn starch and corn steep liquor are essential inputs which requires huge land area for agricultural production. For L-Lysine-HCl more than 95% land use arises from the sugar supply from sugarcane production to the production process, while a 90% land use from glucose production from corn starch to the product system of Threonine.

### 7.4 Environmental footprint of the five representative diets at the feed production stage

Impact assessment of different feed ingredients based on economic allocation in USA for the year 2017 and 2022 are summarized in Table 31.

**Table 31. Impact assessment of different feed ingredients based on economic allocation in the USA (Impact per kg feed ingredients)**

| Feed ingredient | Global warming (kg $CO_2$ eq.) | | Land use ($m^2$a crop eq.) | | Water consumption ($m^3$) | | Fossil resources scarcity (Kg oil eq.) | |
|---|---|---|---|---|---|---|---|---|
| | 2017 | 2022 | 2017 | 2022 | 2017 | 2022 | 2017 | 2022 |
| Corn | 0.311 | 0.315 | 1.01 | 1.01 | 0.394 | 0.404 | 0.054 | 0.056 |
| Soybean meal | 0.448 | 0.439 | 1.115 | 1.115 | 0.514 | 0.503 | 0.091 | 0.090 |
| DDGS | 0.242 | 0.243 | 0.187 | 0.188 | 0.108 | 0.109 | 0.066 | 0.066 |
| Sorghum | 0.615 | 0.659 | 2.62 | 2.79 | 0.0697 | 0.0746 | 0.0998 | 0.107 |
| Wheat grain dry milling | 0.690 | 0.698 | 1.042 | 1.040 | 0.468 | 0.475 | 0.131 | 0.132 |
| L-Lysine-HCl | 4.06 | - | 3.34 | - | 1.49 | - | 0.757 | - |
| Methionine | 9.06 | - | 0.728 | - | 4.93 | - | 2.94 | - |
| Threonine | 8.14 | - | 5.07 | - | 2.90 | - | 2.00 | - |

Results of the environmental footprint of the five representative diets based on economic allocation in the USA at the feed production stage presented in Table 32 and Table 33.

**Table 32. Environmental impacts of the five representative swine diets based on economic allocation in the USA (Impact per kg diet)**

| Diet | Global warming (kg $CO_2$ eq.) | | Land use ($m^2a$ crop eq.) | | Water consumption ($m^3$) | | Fossil resources scarcity (Kg oil eq.) | |
|---|---|---|---|---|---|---|---|---|
| | 2017 | 2022 | 2017 | 2022 | 2017 | 2022 | 2017 | 2022 |
| Corn-SBM | 0.350 | 0.352 | 1.010 | 1.014 | 0.407 | 0.410 | 0.060 | 0.062 |
| Corn-SBM-low DDGS | 0.332 | 0.334 | 0.888 | 0.889 | 0.360 | 0.367 | 0.0611 | 0.062 |
| Corn-SBM-high DDGS | 0.340 | 0.342 | 0.930 | 0.930 | 0.375 | 0.382 | 0.0612 | 0.0626 |
| Corn-SBM-DDGS-Bakery-middlings | 0.386 | 0.388 | 0.881 | 0.882 | 0.363 | 0.369 | 0.0673 | 0.068 |
| Sorghum-SBM | 0.610 | 0.646 | 2.370 | 2.514 | 0.136 | 0.138 | 0.100 | 0.106 |

**Table 33. Environmental impacts of the five representative swine diets based on economic allocation in the USA (Impact per kg live weight)**

| Diet | Global warming (kg $CO_2$ eq.) | | Land use ($m^2a$ crop eq.) | | Water consumption ($m^3$) | | Fossil resources scarcity (Kg oil eq.) | |
|---|---|---|---|---|---|---|---|---|
| | 2017 | 2022 | 2017 | 2022 | 2017 | 2022 | 2017 | 2022 |
| Corn-SBM | 0.819 | 0.824 | 2.364 | 2.373 | 0.952 | 0.959 | 0.140 | 0.145 |
| Corn-SBM-low DDGS | 0.782 | 0.786 | 2.087 | 2.088 | 0.848 | 0.862 | 0.143 | 0.146 |
| Corn-SBM-high DDGS | 0.756 | 0.761 | 2.205 | 2.206 | 0.758 | 0.770 | 0.147 | 0.150 |
| Corn-SBM-DDGS-Bakery-Middlings | 0.913 | 0.918 | 2.086 | 2.087 | 0.859 | 0.873 | 0.159 | 0.161 |
| Sorghum-SBM | 1.474 | 1.561 | 5.729 | 6.077 | 0.328 | 0.333 | 0.241 | 0.256 |

**Environmental footprint at the live animal production stage**

***Effect of synthetic amino acids on excretion and gas emissions***

It is well documented that using synthetic amino acids and phytase in swine and broiler diets are effective for improving nutrient utilization effciency, reducing diet cost, reducing nitrogen and phosphorus excretion in manure as well as gas emissions.

Reducing dietary crude protein (CP) content can result in reduced excretion of excess nutrients such as nitrogen (Lenis, 1993), and thus can reduce $NH_3$ (Leek et al., 2005; Powers et al., 2007) and odor (Hayes et al., 2004; Le et al., 2005) emissions from manure. A reduced CP diet can be used without effects on animal performance by supplementing with synthetic amino acids to provide the limiting nutrients in the diet (Lenis and Schutte, 1990; Botermans et al., 2010). Up to 40% reduction in swine nitrogen excretion has been reported by reducing dietary CP content and supplementing AA (Sutton et al., 1999; Portejoie et al., 2004; Powers et al., 2007; Le et al., 2009). Reduced nitrogen excretion due to reduced dietary CP content was found mainly through the reduction in urinary nitrogen, and thus resulted in a lower ratio of urinary nitrogen to fecal nitrogen. (Gatel and Grosjean, 1992; Canh et al., 1998). Reduced dietary CP content was also found to be associated with reduced manure pH (Portejoie et al., 2004; Hanni et al., 2007; Le et al., 2008). Reduction in urinary nitrogen and manure pH both favor reduction in $NH_3$ emissions. Reducing dietary CP content and supplementing synthetic amino acids have been shown to be effective in reducing $NH_3$ emissions from swine operations, but the effectiveness of these adjustments in reducing odor was not significant in most studies

Kebreab et al. (2016) compared the impact of adding crystalline amino acids and phytase to swine and poultry diets without these supplements in Europe, North America and South America. Their results showed that using these supplements in pig and broiler diets reduced greenhouse gas emissions by 56% and 54 % in Europe, 17% and 15% in North America and 33% and 19% in South America, respectively, compared with feeding diets without supplemental synthetic amino acids and phytase.

The identified four alternative diets all included relatively higher level of synthetic amino acids as comparing with the standard corn-SBM diet. The supplemental synthetic amino acids may help to reduce excretion and greenhouse gas emissions during the live animal production stage. However, for the Corn-SBM-high DDGS diet, the benefit of synthetic amino acids may be offset by negetive effects of DDGS on gas emissions.

***Effect of DDGS on gas emissions***

It has been reported that increased DDGS content in the diets can result in increased production of volatile fatty acids and increased odor, $NH_3$, and $H_2S$ emissions (Powers and Angel, 2008; Pepple et al., 2010; Li et al., 2011). Yoon et al. (2010) and Gralapp et al. (2002) showed adding 5% to 15% DDGS had no negative effects on odor emissions. In the Corn-SBM-low DDGS diet, DDGS content is less than 15%, while in the Corn-SBM-high DDGS, DDGS content is around 30%. The Corn-SBM-high DDGS diet may result in higher gas emissions during the live animal production stage. Quantified information is lacking in literature.

**Discussion:**

**Selection of five representative swine diets**

Representative diets selection through the process of e-mail survey is the starting point for impact assessment study of swine diets in the USA in this report. Selected diets are widely accepted by the respondents around the USA from their expertise points of view. Decisions to change diets from the typical corn-soybean meal-based feeds depends on comparative cost of grain, availability of alternative feeds, effects on carcass quality and special feed handlings consideration. Economic feasibility of each by-product is also brought for justification. Several important points are taken for diet formulation, for instance growth stage of the swine, nutrition requirement at corresponding, transportation and handling cost. Similar criteria was also pointed out by Jones (2017), for instance the level of calcium should not exceed 1.5 times the level of Phosphorus, which would lead to reduction in feed conversion and eventually reduced gains. Similarly, the salt level should not exceed 5% of the diet. Another consideration in diet selection is to take account the fiber content. Generally, higher fiber contents refer to low energy supply in the diet and thereby fiber addition in the diet limit to maximum 5% for growing-finishing swine (Jones, 2017). All these points are caught to generate the list of probable ingredients available in the USA. Based on the available literature, scientific reports and expertise comments and suggestions from the survey, our synthesized diets are supported to be representative in the USA for swine production.

**LCA of individual feed ingredients**

Existing LCA analysis of individual feed ingredients for swine diet formulation are considered based on the available resources to synthesize a new LCA and system boundary for each ingredient used in the diets. Wide and vast searching with different databases and search engines, extrapolated to form a synthetic LCA presenting the major pros and cons from the existing LCA studies.

***Corn***

Synthesized LCA study of feed ingredient Corn brought up factors enhancing the environmental footprint. Intensive corn production demands more inputs and thus exerts high impacts eventually. For instance, according to US Fertilizer Institute (analysis based on fertilizer application rate and corn production and acreage data reported by USDA-NASS), farmers grew 6.64 billion bushels of corn using 3.2 pounds of nutrients (nitrogen, phosphorous and potassium) for each bushel and in 2014 they grew 14.22 billion bushels using less than 1.6 pounds of nutrients per bushel produced. This study indicates the necessity of intensive corn farming to meet up the national demand for food, feed and fuel supply. This consequence of high demand on corn farming resultant to high impacts on environment. For instance, news reported by University of Minnesota, corn as feed to US pork produced about 10.19 kg $CO_2$ eq. per bushels in the year 2012, which required 4.5 times less water (1.6 $m^3$/bushel) than corn to fed beef production (See web reference). Study reported by Wang (2007) indicates that since 1970s, per acre corn yield increase was due to the better seed variety, better farming practices, and other agricultural measures. Among the farming practices that causes most contribution to the corn yield was nitrogen fertilizer increased by 22% for yield increase of 90% (from 1970 to 2005) (Wang et al., 2007). GREET (Argone national Laboratory study reported that during the nitrification and denitrification process of the nitrogen fertilizer by the corn crop 2% of the nitrogen fertilizer converted into greenhouse gases N2O that corresponds to an emissions of about 28.84 kg $CO_2$/per kg of nitrogen fertilizer. According to the study conducted by Wang et al. (2003), per kg corn production causes about 0.01 kg CO2 eq./ kg of direct fuel used in the farming, while it increases to 0.05 kg CO2 eq./kg fuel used for corn farming in this study which in line with the above agreement of intensive corn farming increase the environmental impacts. Sensitivity analysis of the corn farming for the increase amount of fertilizer, seed, water and fuel of up to 20% increases the impact while the similar amount reduction of these inputs can decline the environmental impacts proportionately indicating the farming improvement can reduce the environmental impact in the US corn production.

Our review for corn LCA indicated that environmental impacts varies for corn agricultural production system from 0.2 to 0.53 kg $CO_2$ eq. per kg corn production and the variation caused by factors such as transportation, water requirement, fertilizer, source of energy supply. For instance, corn mobility causes typically higher $CO_2$ emission in Illinois and Indiana; Nebraska is a high producing, exporting state of irrigated corn while Minnersota is a high producing, and exporting state of low $CO_2$ eq. intensity with no irrigated corn (Smith et al., 2017).

Grain drying is the largest single use energy consuming process in the corn production system which accounted for 42.3% of total energy consumption (Tallaksen et al., 2017), finding from our study also indicated similar contribution. Finding of fertilizer production indirectly causes substantial $CO_2$ emissions in the corn product system (31%) and this is an identical agreement with research by Tallaksen (2017).

***Soybean meal (SBM)***

The carbon footprint of soybean meal in literature ranged from 0.15 to 0.90 kg $CO_2$ eq. per kg, when land use change is not considered (Dalgaard et al. 2008; De Boer at al. 2014 and Zgola et al. 2016). More than half of the carbon footprint of soybean meal is from field emission. The water footprint of soybean meal in US was estimated to be 0.11 $m^3$ per kg (Zgola et al. 2016). Study conducted by Dalgaard et al. (2008) on the soybean meal LCA drawn the environmental impacts results taking palm oil as marginal oil while producing soy oil and other co-products. The characteristics impact results were 0.7211 kg $CO_2$ eq. for global warming potential, average area per kg soybean meal consumed was 3.6 $m^2$year. This study shows global warming potential lesser (0.439 kg $CO_2$ eq per kg soybean production) and land use (1.77 $m^2$ year per kg soybean) than report by Dalgaard et al. (2008).

Guinee et al. (2004) applied the economic allocation to allocate environmental impacts between the main product and co-products for products providing more than one output (for instance, soybean processing provides oil, meal and hulls). They further defined the economic allocation is the allocation of environmental impact among the main product and co-products based on their relative economic values. Processing of 1 ton of soybean generates 706 kg SBM, 74 kg soybean hulls and 190 kg soybean oil (Vellinga et al., 2013). Using 2009-2013 average prices of US$411.6 per ton SBM and US$1008.4 per ton soybean oil (FOP prices, www.anec.com.br) and assuming that the price of soybean hulls is half of the price of SBM (206 US$/kg), SBM and soybean hulls account for 58.4% and 3.1% of the environmental impacts, respectively. This study is conducted following the similar mass fraction in the plant for assessing the environmental impacts. Based on current price (https://www.ams.usda.gov/mnreports/gx_gr117.txt) of the soybean meal, soy hulls and crude oil (29.3 cents/kg, 150$/ton & 295 $/ton respectively), it is found that SBM contributes to 63% of the total environmental impacts.

Another study conducted on soybean meal production as animal feed ingredient by Reckmann et al. (2016) found the global warming potential (GWP), eutrophication potential (EP), acidification potential (AP), and land use (LU) of feed ingredient-soybean meal (per kilogram of ingredient), GWP originating from direct (dLUC) and total (total LUC) land use change 0.480-kg$CO_2$-eq, 0.0016-kg$PO_4$-eq, 0.0012-kg$SO_2$-eq, 1.76-m2$yr^{-1}$, 0.520-kg$CO_2$-eq, and 0.252-kg$CO_2$-eq respectively. Results from our study indicates almost similar global warming potential.

Stating cultivation, transport (geographical location of the produced products and related inputs) are the influential factors. The far variation of the results is originated due to geographic location and availability of raw materials. For instance, if the plant location for SBM production and inputs are from the same area of a country and agricultural inputs are collected from the nearby vicinity, thereby it reduces the environmental impacts for transport energy and part of process energy required in the plant. Our synthesized LCA results showed a reduced environmental impacts and this is due to the agricultural inputs and other associated inputs for fertilizer, energy processing are assumed to be available at point of farming system.

***DDGS***

Mackenzie et al. (2016) conducted a study on co-products as feed for swine where he explained the functional unit as 1 kg expected carcass weight and the environmental impact (GWP) of producing 1 kg DDGS as feed from corn grain is 0.780 kg $CO_2$ eq. that is line with our LCA study for DDGS production.

DDGS generally comes as a by-product/co-product in the corn ethanol production process. Thus, the environmental impact or life cycle assessment of DDGS calculation are based on the recent development of ethanol production. A recent calculation of the corn grain ethanol production and its co-product's environmental impact assessment has been made in Wisconsin, USA by Kraatz et al. (2013). Characteristics of corn grain ethanol production can be presented in Table 34.

**Table 34. Ethanol plant structure and basic assumptions of the ethanol production system (Kraatz et al., 2013).**

| Inputs/Characteristics | Values used in the study | References |
|---|---|---|
| Location | Wisconsin, United States | |
| Ethanol production | 147,739,0000 ethanol refinery$^{-1}$ year$^{-1}$ | Sinistore and Bland (2010) |
| Ethanol/gasoline mixture | 95%/5% | |
| Corn grain yield | 9298 kg ha$^{-1}$ | USDA (2009) |
| Higher heating value | 29.6 MJ kg$^{-1}$ ethanol | Patzek (2004) |
| Density | 0.79 g cm$^{-3}$ ethanol | US NIST (2010) |
| Ethanol plant | Dry million system | |
| Conversion rate | 3.25 kg corn kg$^{-1}$ ethanol | According to Sinistore (2008) |

It is assumed that the production of corn grain for animal feed employs the same cultivation practices and site conditions as the corn grain produced for ethanol production. EIP and GHG emissions avoided using DDGS instead of corn grain in the dairy diet were calculated assuming that 1.1 kg of DDGS substitutes 1 kg of corn grain based on the NREL of the feed ( Kirchgeßner, 2004). Other literature sources suggest different substitution ratios, but these ratios are based on the entire balanced dairy diet (Kaiser 2008), which is not considered here. The 1.1 to 1 ratio considered in this study results in a substitution of an EI of 1.77 MJ per kg DDGS and of a GWP of 0.14 kg $CO_2$-eq per kg DDGS.

The mass allocation ratio of the refinery products ethanol and DDGS is based on the outgoing mass of the process. Mass inputs in this process are 3.3 kg corn grain and 3.4 L water for the production of 1 kg ethanol, 1.03 kg DDGS, and 1 kg $CO_2$. The mass allocation ratio of the environmental burdens on the ethanol and DDGS is therefore 49%:51% (Kraatz et al., 2013). Following a similar mass allocation, our study exhibits a GWP of 0.738 kg $CO_2$ eq. while an economic allocation produces almost one-third GWP of mass allocation, which is about 0.242 kg CO2 eq.

Different scenarios of co-products allocation along with their environmental burdens have cumulative effect on environment from the existing LCA studies. For instance, whole stillage (WS) treatment from corn derived ethanol production processing plant has two different impacts. Firstly, WS used as animal feed by transforming it into dried distillers' grain with solubles and secondly recycles of WS with an anaerobic biodigester and a combined heat and power (CHP) plant to provide electricity and steam to the ethanol refinery and returns the residue to the land as fertilizer (Kraatz et al., 2013).

Although comparison of both scenarios exhibited WS into electricity, heat, and fertilizer process, is the most environmentally benign coproduct use by showing a lower EI and GWP impact of about 54% EI and

67% respectively than the processing of WS into DDGS (Kraatz et al., 2013). However, the LCA study of DDGS co-product use as animal feed where the price could be a driven assumption factor (economic allocation) for another different scenarios require further investigation to explore. Our study explore that economic allocation (considering the price assumption) reduces the environmental impact significantly to almost one third of the mass based allocation system.

Meta-analysis study revealed the range of global warming impacts between 0.42 to about 1.1 kg $CO_2$ eq. Some studies in the meta-analysis carried out based on mass of the DDGS in the feed ration which thus produce the impacts by mass and did not show the impacts on economic based. For instance, LCA conducted by Mackenzie et al. (2016) was based on Canadian LCI database and is not well explained about the allocation of DDGS during corn ethanol production, which resulted an impact of 0.780 kg $CO_2$ eq. This study based on mass allocation produced a similar impacts 0.738 kg $CO_2$ eq. Economic based DDGS LCA study in the USA by Thoma et al. (2011) exhibited a global warming impacts of 0.426 kg $CO_2$ eq. while our study showed an impact of about 0.243 kg $CO_2$ eq. which is almost half of the previous study.

***Sorghum***

Few research items or reports obtained of environmental impacts study on sorghum as single crop cultivation in United States or other countries. Lack of mono cropping of sorghum is perhaps due to climatic requirement, low economic importance and higher inputs compare with other economic crops. Moreover, mono cropping also discourages diversity of cropping which brings the negative environmental impacts in the US mid-west cropping system (Robertson et al., 2014).

González-García et al. (2016) compared the environmental performance of sorghum, barley and oat silage production for livestock feed and found that sorghum would be the best option due to the highest biomass yield, followed by barley and oat. GWP of sorghum relay and double cropping with winter camelina by Berti et al. (2017) studies from SimaPro analysis were 1141 and 1124 kg $CO_2$ e $ha^{-1}$ respectively and the GWP using normal and double seeding rate with same cropping system were 1014 and 665 kg $CO_2$ e $ha^{-1}$ respectively. Additional sowing and harvesting of the double- or relay-crop increased $CO_2$ emissions due to increased diesel use. Our study by mass and economic allocation generates about 0.615 kg CO2 eq per kg of sorghum grain. Sensitivity analysis test with current price (0.329 kg $CO_2$ eq per kg sorghum) and 20% price increase (0.330 kg $CO_2$ eq per kg sorghum) study generates almost similar results with Bert et al. (2017) indicating mono-cropping of sorghum does not produce more burdens compare with the relay and double cropping of sorghum. Similar sorghum mono cropping low impacts has been supported by Noya et al. (2018), where sorghum produces 40% lower impacts than double cropping with either barley or rye.

***Wheat-middlings/shorts***

No studies found in the literature for wheat middling environmental impact assessment under different categories (for instance-global warming potential, land use, water consumption, terrestrial eutrophication, acidification and so on). There are a few LCA studies (Wouter and Acker, 2015; Parajuli et al. 2017; Taki et al. 2018, Brendan Gleason O'Donnell, 2008) available in literature on wheat grain production, which are taken as a basis for the life cycle studies of wheat middling.

The production system of the desired co-product consists of the three other product and co-products which mostly constituted the major environmental impacts in all categories considered for this study.

In case of scenario 1 which comprises the agricultural inputs from the year 2015 to 2017 (USDA-NASS survey data) and other process data from the SimaPro 8.5.2.0, grain production stage causes the major impact share which is about 80% of the whole products life cycle system either by mass or economic allocation system. With all the agricultural inputs an LCA of winter wheat in the USA of crop production region 3 is also carried out following attributional system to know the impacts of the winter wheat grain production and the results for global warming potential is about 0.612 kg $CO_2$ eq per kg wheat production. Major impacts contributing input at grain stage is nitrogen fertilizer which accounts about 47% at farm gate which in line with previous LCA studies of wheat (Koga et al. 2003, Piringer and Steinberg 2006 & Narayanaswamy et al., 2004). Using Ecoinvent database 1.3 an emission to about 0.498 kg $CO_2$ per kg wheat was obtained in Swiss lowlands (O'Donnel, 2008) for a smilar unit production of wheat in attributional system. It is noted that grain cultivation of wheat in the US produces two products wheat grain and wheat straw and the percentage of winter wheat straw in USA is about 3 to 4% (O'Donnell, 2008), thus the whole allocation counts for only grain production in this study. For the production of wheat-middling from winter wheat grain dry milling process, different allocation approaches show the variation in the considered impact categories. Variation in the impact results is due to the differences in the mass fraction of the allocation system. Mass allocation of the co-generated products wheat-middling during the milling of grain produces an global impact of 0.086 kg $CO_2$ eq. per kg grain milling process while the economic allocation produces about 13% less emission (from 0.080 to 0.092 kg $CO_2$ eq.). This is because the price of the products applied to their mass fraction generated during to the milling process. Water consumption decrease to 6.5% (from 0.501 to 0.468 m3 per kg grain milling), while the land use decline to about 6% (from 1.11 to 1.04 m2a crop eq.) in the economic allocation system.

In the case of scenario 2, data of agricultural production of the winter wheat comprises USDA-NASS survey data for a projection untill 2022 and processes includes data from the SimaPro 8.5.2.0 and the inventory of the emissions corresponds to the processes inlcuded for the production system. Mass and economic allocation approach is applied for the produced products and co-products after the attributional unit production of winter wheat grain in the USA. Total global warming impacts increases in the economic allocation system by about 1% (from .691 to 0.698 kg $CO_2$ eq. per kg grain milling for the product system). This increase of global warming in the product system when the current price assumed to be unchanged and further it is noted that the yield decreases for the projection which ultimately affect the global warming potential in per unit production. Economic allocation also reduces the other considered impact categories such as land use, water consumption and fossil resources by about 12, 12.5 and 1% respectively compare to the mass based LCA study of winter-middling in the USA. This reduction in the impacts result from the unchanged price applied for the generated products for the projection in the production system. Among the economic allocation for the current (average of 2015, 2016 & 2017) and projection period (average of 2018 to 2022) the total global warming increases by about 1% (from 0.691 to 0.698 kg $CO_2$ eq.) while for the mass allocation it turns to decline by about 6% (from 0.737 to 0.691 kg $CO_2$ eq.).

Among the existing LCA study reported by Hannah et al. (2014), it is found that using wheat middling in the diets of dairy cattle instead of feed of pig can decreases of about 0.329 kg $CO_2$ eq and 0.169 $m^2$ of land per kg of feed. Hannah's study did not specify the allocation and precise information for global warming of wheat-middlings.

*Amino acids*

Bio-synthetic production process of lysine and threonine in this study generates less environmental impacts compared with similar process conducted in France by Marinussen & Kool, 2010 (Table 34).

**Table 34. Comparative environmental impacts of amino acids in USA and Europe (per kg amino acids)**

| | | **USA** (This study) | | | **Germany** (Marinussen & Kool, 2010) | | | **Denmark** (Marinussen & Kool, 2010) | | | **France** (Marinussen & Kool, 2010) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Impact categories** | **Unit** | **Lysine** | **Methionine** | **Threonine** | **Lysine** | **Methionine** | **Threonine** | **Lysine** | **Methionine** | **Threonine** | **Lysine** | **Methionine** | **Threonine** |
| Global warming | kg $CO_2$ eq. | 4.06 | 9.06 | 8.14 | 8.914 | 5.535 | 19.681 | 8.453 | 5.408 | 18.211 | 6.746 | 5.536 | 13.041 |
| Land use | $m^2a$ crop eq. | 3.34 | 0.728 | 5.07 | 5.711 | 0.069 | 6.467 | 5.767 | 0.069 | 6.637 | 5.682 | 0.069 | 6.378 |
| Water consumption | $m^3$ | 1.49 | 4.93 | 2.90 | - | - | - | - | - | - | - | - | - |
| Fossil resources | Kg oil eq. | 0.757 | 2.94 | 2.00 | 2.809 | 3.073 | 7.551 | 2.689 | 2.983 | 7.143 | 2.187 | 3.042 | 5.632 |

Lower impacts of the environmental categories in the USA is due to the lower prices and availability of the inputs for the product system. Some categories of impacts for amino acids production are different from country to country because of source of energy use, distances traveled for raw materials inputs, demands and supply. For instance, the impacts for the categories included in this inventory are significantly lower for France compared to Denmark and Germany. This is because the much higher share of nuclear power in the French production mix of electricity compared to Denmark and Germany (Marinussen & Kool, 2010).

Among the existing LCA reports on amino acids, study conducted by Reckmann et al. (2016) and Mackenzie ta l. (2016) showed global warming potential for Lysine, Threonine, Methionine and Tryptophan 4.94, 4.94, 2.89 kg $CO_2$ eq. and 4.81, 4.81, 2.95 & 9.62 kg $CO_2$ eq. respectively. Our study produced lower impacts (4.06 kg $CO_2$ eq.) for Lysine production, while impacts for Methionine and Threonine are higher (9.06 & 8.14 kg $CO_2$ eq. respectively) than the study conducted by Reckmann et al. (2016) and Mackenzie et al. (2016). Reason of higher impacts might be due to Methionine as amino acid source for lysine while for Threonine, Lysine is applied to the biosynthetic process. Lysine producing microorganism may not adapt with threonine (as amino acid source) in the medium for biosynthetic production and thus required laboratory experiment for future research development.

**Environmental footprint of the five representative diets**

By comparing the environmental footprints of the five representative diets on a per pound live weight at the feed production stage, it can be seen that, introducing DDGS into the standard Corn-SBM diet will generally reduce the environmental footprints in global warming, land use, and water consumption. On the other hand, the Sorghum-SBM diet has the highest global warming and land use footprint, followed by the Corn-SBM-DDGS-Bakery-Middlings diet. Nevertheless, the Sorghum-SBM diet has the lowest water consumption footprint, while the standard Corn-SBM diet has the highest water consumption footprint among the five representative diets.

A national LCA study estimated the global warming footprint of US swine production to be 9.9 kg $CO_2$e per kg of boneless pork consumption, and the contribution to the overall global warming footprint by supply chain was 62.1% for live animal production (9.6% for sow barn and 52.5% for nurse to finish), 5.6% for processing, 1.3% for packaging, 7.5% for retail, and 23.5% for consumers (refrigeration, cooking, and $CH_4$ from food waste in landfill) (Thoma et al., 2011). Feed production and manure management were two major contributors, accounting for 42% and 39%, respectively, for the global warming footprint in the live animal production phase. The global warming footprint at the feed production stage in their study is estimated to be 2.58 kg $CO_2$e per kg of boneless pork consumption, which is actually comparable with our estimation (0.782 to 1.474 kg $CO_2$ eq. per kg live weight), considering the different unit used. As a comparison, 3.9 to10 kg $CO_2$e per kg of pork product were reported in several European studies (De Vries and De Boer, 2010).

Since the global warming footprint at the feed production stage and at the management are almost equally important in the overall global warming footprint of swine production. When DDGS is used in swine diet, the benefit of reducing global warming footprint at the feed production stage may be offset by the potential increasing global warming footprint at the management or animal production stage.

**Conclusions**

- From literature and survey, we have identified the following five representative diets in the USA: Corn-Soybean meal, Corn-Soybean meal-low DDGS, Corn-Soybean meal-high DDGS, Corn-Soybean meal-DDGS-Bakery-Middlings, and Sorghum-Soybean meal.

- The environmental footprints of major feed ingredients including corn, soybean meal, DDGS, sorgum, wheat-middlings, and amino acids were estimated through a synthetic LCA based on meta-analysis of all existing data and a compiled database, and the results are summarized in one table.

- The global warming footprint of corn production in USA is estimated to be 0.311 kg $CO_2$ eq./kg in 2017, as comparing with 0.2 to 0.53 kg $CO_2$ eq./kg in literature. The variation are mainly caused by factors such as transportation, water requirement, fertilizer, and source of energy supply. The major impact in all considered environmental categories are contributed by intensive corn seed production, nitrogen ecoprofile at regional, and maize drying in the production system.

- Estimation of the environmental footprints of soybean meal, DDGS, and wheat middling are greatly affected by the allocation methods used. Using the economical allocation method usually result in less environmental footprints of these feed ingredients, comparing with the mass allocation method, because more environmental footprints are allocated to more valuable co-products, such as crude soy oil, ethanol, or, wheat bran. And the lower the price of the ingredients, the less environmental footprints of these feed ingredients estimated by the economical allocation method. Therefore, choosing lower price feed ingredients generally can help to lower environmental footprints of feed. For example, when the price of DDGS is reduced in relative to ethanol, the environmental footprints of DDGS is also reduced.

- The global warming footprint of soybean meal production in USA is estimated to be 0.448 kg $CO_2$ eq./kg in 2017 using the economical allocation method, as comparing with 0.15 to 0.90 kg $CO_2$ eq./kg in literature. The major impact in global warming footprint of soybean meal production comes from the lime application and its processing. More than half of the carbon footprint of soybean meal is from field emission. The energy consumption from different sources (natural gas, electricity by diesel or hydropower or other sources) related to the processes involved in each stage of the life cycle study can have significant influence and cause large variations. Large variation may also be caused by geographic location and availability of raw materials.

- The global warming footprint of DDGS in USA is only 0.242 kg $CO_2$ eq./kg in 2017 based on current price, using the economical allocation method, as comparing with 0.426 to 1.19 kg $CO_2$ eq./kg in literature. It should be noted that the environmental impact of DDGS are sensitive to price change and depend on the continuous development of ethanol production.

- The global warming and land use footprints of sorghum are generally larger than corn, soybean meal, or DDGS, but water consumption of sorghum is minimum. Main global warming impact for sorghum production comes from energy consumption by machineries, electricity at grid and liquid urea application fertilizer.

- The global warming and land use footprints of wheat middling are comparable and second to sorghum, except that wheat middling has higher water consumption.

- The global warming footprint of synthetic amino acids are 10 to 20 times larger than other common feed ingredients. However, due to the usually small inclusion rate, synthetic amino acids do not play an important role in determining the overall environmental footprints of the feed.

- High level of supplemental synthetic amino acids in the identified four alternative diets may help to reduce excretion and greenhouse gas emissions during the live animal production stage. However, for the Corn-SBM-high DDGS diet, the benefit of synthetic amino acids may be offset by negetive effects of DDGS on gas emissions.

- The environmental footprints of the five representative diets at the feed production stage on a per pound live weight were calculated and summarized in one table. At the feed production stage, the global warming footprint of the five diets ranges from 0.782 to 1.474 kg $CO_2$ eq. per kg live weight; the land use footprint ranges from 2.086 to 5.729 $m^2a$ crop eq. per kg live weight; the water consumption footprint ranges from 0.328 to 0.952 $m^3$ per kg live weight.

- Introducing DDGS into the standard Corn-SBM diet will generally reduce the environmental footprints in global warming, land use, and water consumption at the feed production stage. Since the global warming footprint at the feed production stage and at the management are almost equally important in the overall global warming footprint of swine production. When DDGS is used in swine diet, the benefit of reducing global warming footprint at the feed production stage may be offset by the potential increasing global warming footprint at the management or animal production stage.

- Among the identified five representative diets, the Sorghum-SBM diet has the highest global warming and land use footprint, followed by the Corn-SBM-DDGS-Bakery-Middlings diet. Nevertheless, the Sorghum-SBM diet has the lowest water consumption footprint, while the standard Corn-SBM diet has the highest water consumption footprint.

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## Appendix 1. Email survey questions
## Appendix 1.1 First round of Email survey

Dear XXX,
I am a post-doc researcher in the Department of Biological & Agricultural Engineering at Kansas State University. We are conducting a survey in order to identify representative alternative diets for US swine production for a research project funded by the National Pork Board, and we need your help to answer the following questions based on your expertise.

From the following list of ingredients, could you please select the ingredients that would likely be used, and the ingredients that would not likely be used by the swine producers in your state, for growing-finishing pig diets?

You may simply delete the ingredients that would not be used from the list. If you can, please provide a maximum inclusion percentage and a "typical" percentage after the selected ingredients that would likely be used. You are welcome to suggest other ingredients if they are not in the list.

1. Corn
2. Distillers dried grains with soluble (DDGS)
3. Barley
4. Oats
5. Sorghum
6. Triticale
7. Wheat-soft white winter variety
8. Wheat-soft red winter variety
9. Wheat, hard red spring
10. Wheat, hard red winter
11. Wheat middlings
12. Soybean meal
13. Meat and bone meal
14. Canola meal
15. Sunflower meal
16. Peas
17. Synthetic amino acids
18. Animal fat or vegetable oil

Your answer will be kept confidential and for research purpose only. If you know anybody who may have the expertise to answer the questions in our survey, please feel free to forward the email or recommend to us. Your help are highly appreciated.

Thanks for your time!

Sincerely,
Md Ariful Haque
Postdoctoral Research associate
Department of Biological and Agricultural Engineering
Kansas State University
037 Seaton Hall
Manhattan, KS, 66506

## Appendix 1.2 Second round of Email survey

Dear XXX,

I am a post-doc researcher in the Department of Biological & Agricultural Engineering at Kansas State University. We are conducting a survey in order to identify four representative alternative diets for US swine production for a research project funded by the National Pork Board, and we need your help to answer two questions based on your expertise.

In addition to standard corn-soybean diet, we have formulated four alternative growing-finishing swine diets as in the following Table, based on assumed F/G ratio at 2.85. We would like to seek your opinion on whether the assumption of F/G ratio at 2.85 is representative in US, and whether these four diets can be considered as representative alternative diets for US swine production. If not, could you provide your suggestions?

| | **Standard diet** | **Alternative diet #1** | **Alternative diet#2** | **Alternative diet#3** | **Alternative diet#4** |
|---|---|---|---|---|---|
| **Ingredient use, lb/pig (from 50 to 280 lb body weight)** | Corn-SBM | Corn-SBM-low DDGS | Corn-SBM-high DDGS | Corn-SBM-DDGS-bakery-midds | Sorghum-SBM |
| **Corn** | 520.1 | 452.5 | 387.6 | 364.6 | |
| **Soybean meal** | 119.7 | 95.8 | 70.4 | 91.4 | 120.4 |
| **Corn DDGS, 7.5% Oil** | | 96.4 | 190.9 | 66.3 | |
| **Sorghum** | | | | | 540.1 |
| **Bakery Meal** | | | | 57.6 | |
| **Wheat Middlings** | | | | 68.7 | |
| **Calcium carbonate** | 5.45 | 6.14 | 7.01 | 6.73 | 5.81 |
| **Calcium phosphate (monocalcium)** | 2.94 | 1.27 | 0.35 | 0.41 | 2.46 |
| **Sodium chloride** | 3.28 | 3.30 | 3.32 | 3.31 | 3.39 |
| **L-Lys-HCl** | 1.82 | 2.23 | 2.59 | 2.02 | 2.23 |
| **DL-Met** | 0.18 | 0.07 | | 0.05 | 0.47 |
| **L-Thr** | 0.44 | 0.23 | 0.12 | 0.29 | 0.44 |
| **L-Trp** | 0.05 | 0.07 | 0.10 | 0.00 | 0.04 |
| **Vitamin premix with phytase** | 0.76 | 0.77 | 0.77 | 0.77 | 0.79 |
| **Trace mineral premix** | 0.76 | 0.77 | 0.77 | 0.77 | 0.79 |

Note: SBM=Soybean Meal; DDGS=Distillers dried grain with solubles; Bakery-midds=bakery middlings; 1, 2, 3 & 4 refers to the proposed alternative diets

Your answer will be kept confidential and for research purpose only. If you know anybody who may have the expertise to answer the questions in our survey, please feel free to forward the email or recommend to us. Your help is highly appreciated.

Thanks for your time!

Sincerely,

Md Ariful Haque
Postdoctoral Research associate
Department of Biological and Agricultural Engineering
Kansas State University
037 Seaton Hall
Manhattan, KS, 66506

# Appendix 2. Input data for LCA of individual feed ingredients

## Appendix 2.1 Inputs for agricultural production of corn grain in the United States of America

| Particulars | Amount | |
|---|---|---|
| **Inputs from nature** | | |
| | 2017 | 2022 |
| [1]Yield (lb/acre) | 9699.2 | 10065.44 |
| *[2]Water, unspecified natural origin, US (l) | 77.5 | 77.5 |
| *[3]Occupation, annual crop (land-m2a) | 0.4047 | 0.4047 |
| **Inputs from technosphere: materials/fuels** | | |
| *[3]Corn seed IP, at regional storehouse/US U (lb) | 0.104020385 | |
| *[4]Nitrogen ecoprofile, as N, at regional storehouse/US U (lb) | 0.007423293 | 0.007423293 |
| *[4]Phosphate ecoprofile, as P, at regional storehouse/US U (lb) | 0.005464368 | 0.005464368 |
| *[3]Manure, fertilizer, as applied N, at field/US U (lb) | 0.001545702 | 0.001545702 |
| *[4]Potash ecoprofile, at regional storehouse/US U (lb) | 0.007320191 | 0.007320191 |
| *[3]Lime ecoprofile, at factory/US U (lb) | 0.000820022 | 0.000820022 |
| Boron, at factory/US U (lb) | 0 | 0 |
| *[4]Sulfur, at regional storehouse/US U(lb) | 0.001340317 | 0.001340317 |
| *[5]Corn herbicides, at regional storehouse/US U (lb) | 0.000409002 | 0.000409002 |
| *[5]Corn insecticides, at regional storehouse/US U (lb) | 0.000119708 | 0.000119708 |
| *[6]Diesel produced and combusted, at industrial boiler/US U (gal) | 0.00005480480 | 0.00005480480 |
| *[6]Gasoline produced and combusted, at equipment/US U (gal) | 0.000006094 | 0.000006094 |
| *[7]Fungicides, at regional storehouse/US- US-EI U (lb) | 0.000047322 | 0.000047322 |
| *[5]Corn pesticides from NASS (emissions only)/US U (m2) | 0.4047 | 0.4047 |
| *Corn air, soil and water emissions (PO4 +NO3)/US U (m2) | 0 | 0 |
| *Transport, lorry 16-32t, EURO3/US- US-EI U (kgkm) | 45 | 45 |
| **Inputs from technosphere: electricity/heat** | | |
| *[6]Natural gas produced and combusted, at industrial furnace/US U (cuft) | 0.000243589 | 0.000243589 |
| *[6]Electricity, at grid, Western US NREL/US U (kwh) | 0.00222624 | 0.00222624 |
| *[6]LPG production and combustion, at industrial boiler/US U_NPB_Wheat middling (lb) | 0.0024239 | 0.0024239 |

[1] Average yield of 2015,2016 & 2017 USDA-NASS survey. For projected period the yield data is from 2022.

[2] Ecoinvent V 2.2, SimaPro 8.5.2.0. Assuming the water consumption is data unchanged from 2017 to 2022.

[3] Corn seed rate, manure & lime fertilizer and occupation land data are taken from the US-EI U, SimaPro 8.5.2.0, assuming no change for the projected period

[4]Average N, P, K, & S fertilizer data from USDA-NASS survey (2017,2016 & 2015,). N, P, K, & S Ecoprofile at regional storehouse in the USA US-EI 2.2 (SimpaPro 8.5.2.0). Projected data is calculated from the yield of 2022 and collected from USDA-NASS survey.

[5]Corn herbicides, and insecticides data are collected from Camagro, 2013. Corn herbicides at regional storehouse in the USA US-EI 2.2 (SimaPro 8.5.2.0). Assuming data would be same for 2022 projection period.

[6]Diesel, natural gas, electricity and LPG data is taken from (SimaPro 8.5.2.0). Assuming the data is unchanged for the year 2017 to 2022 winter wheat production in the USA.

[7]Corn fungicides data collected from USDA-NASS survey, 2016. Corn fungicides at regional storehouse in the USA US-EI 2.2 (SimaPro 8.5.2.0). Assuming the fungicides data is unchanged for 2017 to 2022

*Refers to the processes and associated data are from (SimaPro 8.5.2.0). Assuming the data is unchanged for the year 2017 to 2022 winter wheat production in the USA

**Appendix 2.2 Inputs for agricultural production of soybean in the United States of America**

| **Particulars** | **Amount** | |
|---|---|---|
| Inputs from nature | | |
| | 2017 | 2022 |
| Yield (lb/acre) | 29582 | 3078.0 |
| *1Water, unspecified natural origin, US (l) | 79.5 | 79.5 |
| *2Occupation, annual crop (m2a) | 0.76056338 | 0.76056338 |
| Inputs from technosphere: materials/fuels | | |
| *1Soybean seed IP, at regional storehouse/US U (lb) | 0.03 | 0.03 |
| *3Nitrogen ecoprofile, as N, at regional storehouse/US U (lb) | 0.006085193 | 0.005847953 |
| *3Phosphate ecoprofile, as P, at regional storehouse/US U (lb) | 0.017579446 | 0.016894087 |
| *3Potash ecoprofile, at regional storehouse/US U (lb) | 0.03076403 | 0.029564652 |
| *1Lime ecoprofile, at factory/US U (lb) | 0.202713707 | 0.202713707 |
| Boron, at factory/US U (lb) | 0 | 0 |
| *3Sulfur, at regional storehouse/US U (lb) | 0.005070994 | 0.004873294 |
| *4Soybean herbicides, at regional storehouse/US U (lb) | 0.005551048 | 0.005334633 |
| *4Soybean insecticides, at regional storehouse/US U (lb) | 0.00053854 | 0.000517544 |
| *5Diesel produced and combusted, at industrial boiler/US U (gal) | 0.001680335 | 0.001614844 |
| *5Gasoline produced and combusted, at equipment/US U (gal) | 0.000418155 | 0.000401853 |
| *4Soybean fungicides, at regional storehouse/US- US-EI U (gal) | 0.000328938 | 0.000316114 |
| *6Soybeans pesticides from NASS (emissions only)/US U (m2) | 0.76056338 | 0.76056338 |
| Soybean air, soil and water emissions (PO4 +NO3)/US U (m2) | 0 | 0 |
| Inputs from technosphere: electricity/heat | | |
| *5Natural gas produced and combusted, at industrial furnace/US U (cuft) | 0.015668 | 0.015057 |
| *5Electricity, at grid, Eastern US NREL/US U (kwh) | 0.004321821 | 0.004153329 |
| *5LPG production and combustion, at industrial boiler/US U_NPB_Wheat middling (kg) | 0.000252827 | 0.00024297 |

* refers to the processes and their associated emissions are taken from the SimPro (version 8.5.2.0) process library

1 Ecoinvent V 2.2, SimaPro 8.5.2.0. Assuming the water consumption, lime is data unchanged from 2017 to 2022.

2 Land. USDA-NASS survey 2017 (Calculated from the total area harvested)

3N,P, K & S fertilizer data from USDA-NASS survey (2017). N,P & K ecoprofile at regional storehouse in the USA US-EI 2.2 (SimpaPro 8.5.2.0). N, P, K & S projected data is calculated from the yield of 2022 and collected from USDA-NASS survey.

4Soybean herbicides, insecticides and pesticides data collected from USDA-NASS survey, 2017. Soybean herbicides, pesticides and insecticides at regional storehouse in the USA US-EI 2.2 (SimaPro 8.5.2.0). Assuming all data would be same for 2022 projection period.

5 Diesel,gasoline, natural gas, electricity and LPG data (taking the lower heating value) collected from the GREET version 2018. Assuming all the data are unchanged for 2017 to 2022.

6 NASS Soybean pesticides emissions data at US-EI U (SimaPro 8.5.2.0). Assuming the emissions data is unchanged for the year 2017 to 2022.

**Appendix 2.3 Inputs for the sorghum grain production in the United States of America**

| **Particulars** | **Amount** | |
|---|---|---|
| | 2017 | 2022 |
| *Yield (Kg/ha data of USDA-NASS survey 2017 & 2022) | 3835.372 | 3580.36 |
| **Inputs from nature** | | |
| #Water, well, in ground, US (m3) | 0 | 0 |
| #Water, unspecified natural origin, US (m3) | 264.9 | 264.9 |
| #Occupation, annual crop (m2a-land) | 10000 | 10000 |
| **Inputs from technosphere: materials/fuels** | | |
| #Energy, from diesel burned in machinery/RER Mass (MJ) | 5751 | 5751 |
| *Electricity mix, AC, consumption mix, at consumer, < 1kV/US Mass (MJ) | 1293 | 1293 |
| #Manure, from pigs, at pig farm/RER Mass (kg) | 402.9 | 402.9 |
| #Manure, from poultry, at poultry farm/RER Mass (kg) | 361.1 | 361.1 |
| #Potassium chloride (NPK 0-0-60), at regional storehouse/RER Mass (kg) | 20.74 | 20.74 |
| #NPK compound (NPK 15-15-15), at regional storehouse/RER Mass (kg) | 20.48 | 20.48 |
| #PK compound (NPK 0-22-22), at regional storehouse/RER Mass (kg) | 0.3152 | 0.3152 |
| #Potassium sulphate (NPK 0-0-50), at regional storehouse/RER Mass (kg) | 0.8131 | 0.8131 |
| #Di ammonium phosphate, as 100% (NH3)2HPO4 (NPK 22-57-0), at regional storehouse/RER Mass (kg) | 34.28 | 34.28 |
| #Triple superphosphate, as 80% Ca(H2PO4)2 (NPK 0-48-0), at regional storehouse/RER Mass (kg) | 0.67 | 0.67 |
| #Ammonium sulphate, as 100% (NH4)2SO4 (NPK 21-0-0), at regional storehouse/RER Mass (kg) | 12.33 | 12.33 |
| #Ammonium nitrate, as 100% (NH4)(NO3) (NPK 35-0-0), at regional storehouse/RER Mass (kg) | 6.787 | 6.787 |
| #Liquid urea-ammonium nitrate solution (NPK 30-0-0), at regional storehouse/RER Mass (kg) | 101 | 101 |
| #Urea, as 100% CO(NH2)2 (NPK 46.6-0-0), at regional storehouse/RER Mass (kg) | 52 | 52 |
| #Lime fertilizer, at regional storehouse/RER Mass (kg) | 400 | 400 |
| #Basic infrastructure, at farm/GLO Mass (ha) | 1 | 1 |
| #2,4-D, at plant/RER Mass (kg) | 0.03286 | 0.03286 |
| #Aliphatic organothiophosphate insecticides, at plant/RER Mass (kg) | 0.04848 | 0.04848 |
| #Atrazine, at plant/RER Mass (kg) | 0.1797 | 0.1797 |
| #Dicamba, at plant/RER Mass (kg) | 0.4226 | 0.4226 |
| #Dinitroaniline herbicides, at plant/RER Mass (kg) | 0.2228 | 0.2228 |
| #Glyphosate, at plant/RER Mass (kg) | 0.4572 | 0.4572 |
| #Herbicide, at plant/RER Mass (kg) | 0.04418 | 0.04418 |
| #Insecticide, at plant/RER Mass (kg) | 0.00511 | 0.00511 |
| #Metolachlor, at plant/RER Mass (kg) | 0.6022 | 0.6022 |
| #Malathion, at plant/RER Mass (kg) | 0.1109 | 0.1109 |
| #Phenyl organothiophosphate insecticides, at plant/RER Mass (kg) | 0.4728 | 0.4728 |
| #Quaternary ammonium herbicides, at plant/RER Mass (kg) | 0.01069 | 0.01069 |
| #Transport, truck 10-20t, EURO4, 80%LF, empty return/GLO Mass (kg) | 32.6 | 32.6 |
| #Transport, truck 10-20t, EURO4, 80%LF, empty return/GLO Mass (kg) | 22.92 | 22.92 |
| #Sorghum, seed, at farm/US Mass (kg) | 9.332 | 9.332 |

* refers to the yield data that has taken from the USDA-NASS survey

# refers to the fertilizer, Lime and all pesticides, herbicides, transport data are taken from the SimaPro 8.5.2.0 Agrifootprint mass allocation process library. Assuming all the data are unchanged for the projection 2022

**Appendix 2.4 Inputs for the winter wheat grain production in the United States of America**

| Particulars | Amount | |
|---|---|---|
| **Inputs from nature** | | |
| | **2017** | **2022** |
| [1]Yield (kg/ha) | 2821.201 | 2756.576316 |
| *Water, well, in ground, US (m3) | 0 | 0 |
| *Water, unspecified natural origin, US (l) | 44.6 | 44.6 |
| *[2]Occupation, annual crop (land-m2) | 1.097734348 | 1.097734348 |
| **Inputs from technosphere: materials/fuels** | | |
| *Wheat seed IP, at regional storehouse/US US-EI U (kg) | 0 | |
| *[3]Nitrogen ecoprofile, as N, at regional storehouse/US U (kg) | 0.025041438 | 0.025628509 |
| *[3]Phosphate ecoprofile, as P, at regional storehouse/US U (kg) | 0.012321977 | 0.012610853 |
| *[3]Potash ecoprofile, at regional storehouse/US U (kg) | 0.015700584 | 0.016068668 |
| Lime ecoprofile, at factory/US U | 0 | 0 |
| Boron, at factory/US U (kg) | 0 | 0 |
| *[3]Sulfur, at regional storehouse/US U (kg) | 0.003974831 | 0.004068017 |
| *[4]Wheat winter herbicides, at regional storehouse/US U (kg) | 0.003916004 | 0.004007811 |
| *[4]Wheat winter insecticides, at regional storehouse/US U (kg) | 0.000216628 | 0.000221707 |
| *[4]Wheat winter fungicides, at regional storehouse/US U (kg) | 0.0003001 | 0.000307339 |
| *[5]Diesel produced and combusted, at industrial boiler/US U (gal) | 0.00121 | 0.00121 |
| *[5]Gasoline produced and combusted, at equipment/US U (gal) | 0.000276 | 0.000276 |
| *Wheat pesticides from NASS (emissions only)/US U (m2) | 1.097734348 | 1.097734348 |
| *Wheat grains air, soil water emissions EI at farm/US U (PO4 + NO3)_NPB (kg) | 1 | 1 |
| Sowing/US* US-EI U (ha) | 0.000200801 | 0.000200801 |
| *Tillage, ploughing/US US-EI U (ha) | 0.000200801 | 0.000200801 |
| *Transport, lorry >16t, fleet average/US- US-EI U (tkm) | 0.004917195 | 0.004917195 |
| *Combine harvesting US-EI U (ha) | 0.0003667 | 0.0003667 |
| **Inputs from technosphere: electricity/heat** | | |
| *[5]Natural gas produced and combusted, at industrial furnace/US U *(cuft) | 0.0000274 | 0.0000274000 |
| *[4]Electricity, at grid, Western US NREL/US U (kwh) | 0.00412 | 0.0041200000 |
| *[5]LPG production and combustion, at industrial boiler/US U_NPB_Wheat middling (kg) | 0.000472 | 0.000365345 |
| *Electricity, low voltage, at grid, 2015/US US-EI U (kwh) | 0 | 0 |

[1]Average yield of the year 2015,2016 & 2017. For 5 years projected period the yield is considered from 2018 to 2022 and the data has taken from USDA-NASS survey.
[2] SimaPro 8.5.2.0(US-EL 2.2 2009 data). Assuming the occupation land data is unchanged for 2017 to 2022.
[3]Average N, P, K, & S fertilizer data survey from USDA-NASS (2017,2015, & 2012). N, P, K, & S ecoprofile at regional storehouse in the USA US-EI 2.2 (SimaPro 8.5.2.0). Projected data is the data of 2022 and collected from USDA-NASS survey.
[4]Average winter wheat herbicides, pesticides and insecticides data is from USDA-NASS (2017 & 2015 survey). Winter wheat herbicides, pesticides and insecticides at regional storehouse in the USA US-EI 2.2 (SimaPro 8.5.2.0). Projected data is from 2022 and collected from USDA-NASS survey.
[5] Diesel, gasoline, natural gas, and electricity data is from SimaPro (version 8.5.2.0). Assuming the data is unchanged for the year 2017 to 2022 winter wheat production in the USA
* Refers to the processes and data have been taken from the SimaPro US-EL 2.2 database (version 8.5.2.0) process library and assumed that data would be same for the 2017 and until the projection for 2022.

**Appendix 2.5 Inputs for amino acids (L-Lysine-HCl, Methionine and Threonine) production in the United States of America**

| Particulars | Amount | | |
|---|---|---|---|
| Inputs from nature | | | |
| | Lysine | Methionine | Threonine |
| [1]Water, cooling, unspecified natural origin, US (m3) | 0.072 | 0.024 | 0.009 |
| [1]Water, unspecified natural origin, US (m3) | 0 | 0.00041 | 0 |
| Inputs from techno-sphere: materials/fuels | | | |
| [1]Glucose {GLO}\| market for glucose \| APOS, U (kg) | 0 | 0 | 3 |
| [1]Maize fibre/bran, wet, from wet milling (grinding and screening), at plant/US Economic (kg) | 0.3 | 0 | 1 |
| [1]Sugar, from sugar cane, from sugar production, at plant/US Mass | 3.5 | 0 | 0 |
| [1]Ammonia, liquid, at regional storehouse/US- US-EI U (kg) | 0.155 | 0 | 0.700 |
| [1]Sulfuric acid (98% H2SO4), at plant/RER Mass (kg) | 0.320 | 0 | 1.5 |
| [1]Phosphoric acid, industrial grade, 85% in H2O, at plant/US- US-EI U (kg) | 0.025 | 0 | 0.004 |
| [1]Manganese sulfate {GLO}\| production \| Cut-off, U as salt (kg) | 0.005 | 0 | 0.001 |
| [1]Sodium hydroxide, 50% in H2O, production mix, at plant/US- US-EI U as caustic (kg) | 0.0045 | 0 | 0.370 |
| [1]Water, deionised, at plant/US US-EI U for fermentation and cleaning (kg) | 0.0046 | 0 | 120 |
| [1]Nitric acid, 50% in H2O, at plant/US- US-EI U as cleaning agent (kg) | 0.0015 | 0 | 0.08 |
| [1]C16-18 fatty alcohol from palm oil (No. 13a - Matrix), at plant, 100% active substance/EU-27 as antifoam (kg) | 0.01 | 0 | 0 |
| [#]Methionine/US- US-EI U_NPB as source of amino acids (kg) | 0.04 | 0 | 0 |
| [#]Lysine-HCl at plant/US- US-EI U_NPB as amino acid source (kg) | 0 | 0 | 0.004 |
| [1]Transport, freight, rail/US- US-EI U (tkm) | 0.519 | 0.519 | 0.519 |
| [1]Transport, lorry >16t, fleet average/US- US-EI U (tkm) | 0.0865 | 0.0865 | 0.0865 |
| [1]Chemical plant, organics/US-/I US-EI U (p refers to 1 process) | 0.0000000004 | 0.0000000004 | 0.0000000004 |
| [1]Electricity, natural gas, at power plant NREL/US U (MJ) | 0.003935 | 16 | 0.012 |
| [1]Dummy process steam copied from USLCI (MJ) | 0.000678 | 0 | 0.0006 |
| [1]Acrylic acid {GLO}\| market for \| APOS, U (kg) | 0 | 0.376 | 0 |
| [1]Methanol, at regional storage/US* US-EI U (kg) | 0 | 0.228 | 0 |
| [1]Hydrogen sulfide {GLO}\| market for \| APOS, U (kg) | 0 | 0.215 | 0 |
| [1]Hydrogen cyanide {GLO}\| market for \| APOS, U (kg) | 0 | 0.181 | 0 |
| [1]Ammonium bicarbonate, at plant/US- US-EI U (kg) | 0 | 1.61 | 0 |

[1] refers to the processes available in the SimaPro process librarr (version 8.5.2.0)

[#] refers to the amino acids processes generated in this study and used as source for corresponding amino acid production

'GLO' refers to global

"APOS' stands for At point of substitution

'US-EI U' stands for the database process library at SimaPro (version 8.5.2.0)

# Appendix 3. Calculated allocations of feed ingredients in LCA

## Appendix 3.1. Wheat middling fractions

| Items | Unit Price ($/kg) | Fraction by mass (in 1 kg)-Mass allocation | Price per fraction in 1kg | Economic allocation (%) | Source |
|---|---|---|---|---|---|
| Wheat flour | 1.014116 | 0.73 | 0.74030468 | 41.7531862 | 1* |
| Wheat bran | 5.5115 | 0.12 | 0.66138 | 37.30183401 | 2* |
| Wheat middling | 1.65345 | 0.125 | 0.20668125 | 11.65682313 | 3* |
| Wheat germ | 8.234181 | 0.02 | 0.16468362 | 9.288156668 | 4* |

1* https://www.statista.com/statistics/236624/retail-price-of-white-flour-in-the-united-states/
2* https://www.amazon.com/Barry-Farm-Wheat-Bran-lb/dp/B00015HOWQ
3* http://agebb.missouri.edu/dairy/byprod/bplist.asp
4* https://www.amazon.com/Bobs-Red-Mill-Wheat-Germ/dp/B004M3IXZU?th=1
https://twin-cities.umn.edu/news-events/new-study-corns-environmental-impact-varies-greatly-across-us

## Appendix 3.2 DDGS fractions

| Items | Unit Price ($/kg) | Fraction by mass (in 1 kg)-Mass allocation | Price per fraction in 1kg | Economic allocation (%) | Source |
|---|---|---|---|---|---|
| Ethanol | 0.465684 | 0.49 | 0.22818547 | 82.2534 | A* |
| DDGS | 0.09 | 0.51 | 0.0459 | 16.7466 | B* |

A* https://grains.org/ethanol_report/ethanol-market-and-pricing-data-august-28-2018/
B* https://www.ams.usda.gov/mnreports/nw_gr115.txt

## Appendix 3.3. Sorghum fractions

| Items | Unit Price ($/kg) | Fraction by mass (in 1 kg)-Mass allocation | Price per fraction in 1kg | Economic allocation (%) | Source |
|---|---|---|---|---|---|
| Grain sorghum | 0.186114 | 0.5 | 0.093056786 | 68.25642184 | C* |
| Stover | 0.086555 | 0.5 | 0.043277325 | 31.74357816 | D* |

C* https://ageconsearch.umn.edu/record/236656/files/436-Williams.pdf
D* https://ageconsearch.umn.edu/record/236656/files/436-Williams.pdf

## Appendix 3.4. Soybean meal (SBM) fractions

| Items | Unit Price ($/kg) | Fraction by mass (in 1 kg)-Mass allocation | Price per fraction in 1kg | Economic allocation (%) | Source |
|---|---|---|---|---|---|
| Crude soy oil | 0.5967 | 0.33666959 | 0.200890744 | 49.18893 | E* |
| Soy hulls | 0.143300429 | 0.03356415 | 0.004809757 | 1.1177689 | F* |
| SBM | 0.321874811 | 0.629766261 | 0.202705896 | 49.63338 | G* |

E* https://markets.businessinsider.com/commodities/soybean-oil-price
F* http://agebb.missouri.edu/dairy/byprod/allcompanies.asp
G* http://agebb.missouri.edu/dairy/byprod/allcompanies.asp