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Assessing the Environmental Footprint of Distiller-Dried Grains with Soluble Diet as a Substitute for Standard Corn–Soybean for Swine Production in the United States of America

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Abstract: The swine diet formulation in the United States of America (U.S.A.) is entering a new era of decision making to promote low-carbon pork production systems. As a part of the decision-making process, the precision nutrition approaches to customize diet and alternative feeding options that are economically viable and environmentally sustainable are given priority. Hence, the objective of this study is to identify an alternative diet over a standard corn–soybean meal diet. The byproducts from the supply chain of human food and biofuels, i.e., distiller-dried grain with solubles (DDGS), are chosen as an alternative option to formulate a swine diet. First, two alternative byproduct diets with low and high DDGS inclusion (10.1% and 28.8%, respectively) were formulated using the least-cost technique. Second, a life cycle inventory was created, followed by data collection from the key sources, including DATA SMART-2017, USDA, RIA-GREET 2018, and the relevant literature. Third, in SimaPro 8.5.2.0 (PRé Sustainability: LE Amersfoort, The Netherlands), the ReCiPe 2016, the midpoint method by economic allocation was used to investigate the environmental footprint of the formulated diets to inform sustainability decisions of swine-farm managers. The considered functional unit is the ‘lb diet’, and the system boundary is the farm gate that considers only the feed production stage. The observed results include global warming potential, land use, water consumption, fossil resources scarcity, and terrestrial ecotoxicity. The comparative results of a 28.8% DDGS diet over the standard corn–soybean meal diet for the displacement ratio of 0.69 show an approximate global warming potential saving of 0.04 kg CO_2 eq. per lb DDGS feed at the feed production stage. Moreover, the DDGS displacement ratio of 0.69 does not significantly impact water consumption and fossil resources; however, it can reduce land use by 26% and terrestrial ecotoxicity by 8% compared to the standard diet. Overall, the quantified environmental footprint results of the byproduct DDGS diets indicate that the footprints of DDGS diets were lower than the standard diet.

Keywords: DDGS; alternative diet for swine; byproduct diet; global warming potential; standard corn–soybean meal

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1. Introduction

Byproducts from bioprocesses that are often discarded as waste can be placed under circular bioeconomy practices. Such practices enable increased resource efficiency, which is believed to accelerate Sustainable Development Goals (SDGs) [1]. Resource utilization under circular bioeconomy principles also offers economic developments when implemented through the green technology planning decision model suggested by Ikram et al. [2]. Byproduct resources from various food, animal, vegetable, and sugar industries can be a potential animal food source. In swine diets, the major by-products from biobased industries are used. These include the distiller- and brewer-dried grains from ethanol and brewing industries. Moreover, there are many instances where the leftover stillage from on-farm alcohol fuel production units is used in swine diets [3]. Among all the byproducts, distiller-dried grains are common and mostly occur in feed ingredients in the pork industry in the U.S.A. More recently, the U.S.A. has seen the ethanol industry rising; as a result, the proportion and allocation of grain processing have increased. This resulted in a potential swine feed co-product, i.e., corn distiller-dried grains with solubles (DDGS) [4].

The appropriate amount of ingredients in a swine diet largely depends on many factors. These include protein quality, nutrients, palatability, storage life, cost, and amino acids. Apart from these, the age of the pigs to which the diet is to be fed, the ingredients' production environment, and sometimes the presence of anti-nutritional elements could also be an influence.

DDGS has added advantages of all these attributes and has been a very good alternative feed ingredient in the U.S.A. swine industry. DDGS substitutes soybean meal (SBM), di-calcium phosphate, and corn in swine diets, providing lysine, phosphorus, and energy. In DDGS, lysine is very restrictive to 0.7%, whereas phosphorus is relatively high (0.71%) [3]. In terms of energy, DDGS is approximately equal to corn, and the protein content in DDGS is relatively high at around 27%. As a result, amino acid balance is retained. Furthermore, the amino acids in DDGS appear to be less readily accessible than those in SBM. DDGS, on the other hand, can be used successfully in swine diets when supplemented with synthetic amino acids.

The rate of DDGS inclusion may vary depending on the nutrient quality in it and the growth stage of the swine. Stein (2007) reported that the inclusion of 30% DDGS on grow-finishing swine does not negatively affect swine growth performance; however, low lysine and high fiber content affect digestibility and pig performance [5]. For lactating sows, weanlings, and grow-finishing swine, inclusion of up to 30% can be made while for gestating sows the inclusion can be up to 50% depending on the quality of DDGS fed to the swine [5].

On the other hand, the variation of nutrient contents in the feed ingredients led to difficulties in the feed cost comparison. Therefore, relative values are quite useful for comparison purposes. To ease this complexity, Klashing (2012) defined the term displacement ratio as the amount of a feedstuff that is displaced when one unit of DDGS is added [6]. The unit addition of an alternative feedstuff, namely how much can replace the traditional corn and soybean from the diet, is not only important for cost calculation but also environmental sustainability. Indeed, the paper aimed to evaluate the environmental footprint of an alternative feed ingredient, DDGS, at different inclusion rates using the least-cost technique to formulate the diet. The life cycle assessment (LCA) method, as agreed upon by the ISO 14040 and ISO 14044:2006 standards, is used to evaluate the environmental footprint of a product or process throughout the entire life cycle. This method is rather popular and extensively used in the EU for different production sectors, including agriculture [7,8]. In LCA, the allocation has a significant impact on the environmental footprint. However, when allocation cannot be avoided, the hierarchy of allocation rules as per ISO 14044 was followed. As per ISO 14044, it should preferably be based on the physical relationship between the inputs and outputs [9].

According to the National Pork Board, the pork sector in the U.S.A. has achieved tremendous progress in terms of select environmental impact categories. Approximately 75.9% of the land, 25.1% of the water, and 7.0% of the energy use have been reduced during the last 55 years. However, this improvement is attributed only to the high productivity and efficiency in the pork production system [10]. To attain this high productivity, choosing a diet with lower environmental impacts, always ensures that the % of DDGS addition to the standard diet should not have a negative effect on swine growth. There are few research studies available for the environmental impact evaluation of feed ingredients in North American swine diets [11–14]. This study would thereby help facilitate an estimation of the environmental footprint of ingredients and diets as one of the baseline studies in the swine industry.

The novelty of this study will help the swine producer to choose a cost-effective and environmentally friendly diet. On a national level, the use of low-cost by-product DDGS in the diet will reduce the global warming potential (GWP), land use (LU), water consumption (WC), terrestrial ecotoxicity (TE), and fossil resources (FR).

2. Methods

2.1. Diet Formulation

All the major ingredients, including corn, SBM, and DDGS, used in this study are grown or produced in the US crop production region 3 and are assumed to be representative of the U.S.A. Formulations of the diets were based on surveys from experts and the least-cost formulation principles (Table 1). The nutrient budget of the diets was maintained according to the US national resources council nutrition requirement [15] and PIC nutritional requirement for finishing pigs [16]. Nutritional values were taken from the National Hog Farmer report published in 2020 as the second option [10]. Nutritional values other than those in the National Hog Farmer report were calculated with the help of the Animal Science Department, Kansas State University. An inclusion range of 10.1–28.8% DDGS was applied in the DDGS diets (see Table A1 in Appendix A).

Table 1. Growing finishing swine diets—control/standard and with different DDGS inclusion.

Ingredient Use	**Corn-SBM**	**Corn-SBM-10.1% DDGS**	**Corn-SBM-28.8% DDGS**
	lb/Pig (from 50 to 280 lb Body Weight)		
Corn	520.07	476.6	387.6
Soybean meal	119.75	99.1	70.4
Corn DDGS, 7.5% Oil	0.00	66.6	190.9
Calcium carbonate	5.45	6.1	7.01
Calcium phosphate (monocalcium)	2.94	1.3	0.35
Sodium chloride	3.28	3.3	3.32
L-Lys-HCl	1.82	2.2	2.59
DL-Met	0.18	0.1	0.0
L-Thr	0.44	0.2	0.12
L-Trp	0.05	0.1	0.10
Vitamin premix with phytase	0.76	0.8	0.77
Trace mineral premix	0.76	0.8	0.77

Note: SBM: Soybean meal; DDG: Distiller-dried grains with solubles.

2.2. System Boundary and Functional Unit

The system boundaries for the LCA model were cradle to farm-gate, and the functional unit was '1 lb diet' at the feed production stage. The environmental footprint calculation in this study was for grow-finish swine diets in the U.S.A. Figure 1 shows a simplified process flowchart of the ingredients with their system boundaries.

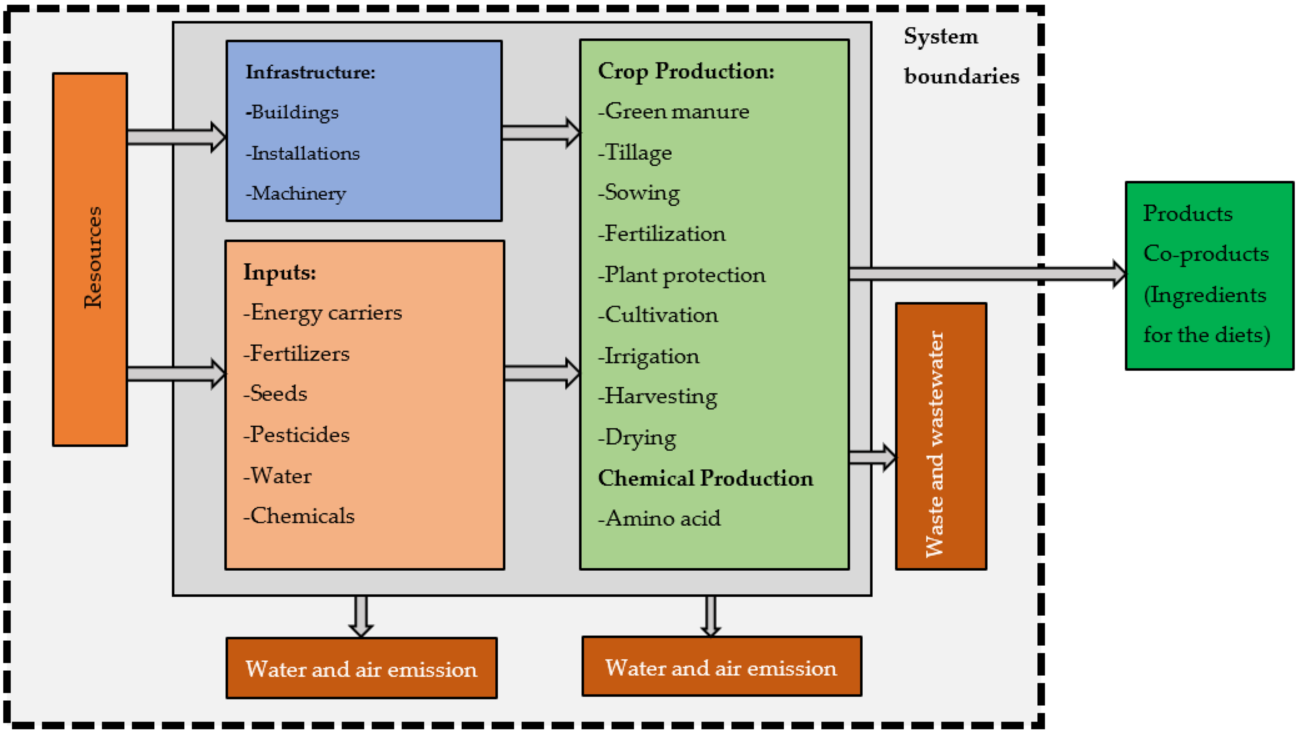

Figure 1. Process flowchart of the ingredients applied in the diets with their system boundary.

2.3. Life Cycle Inventory

Agricultural input data shown in Tables A2 and A3 in Appendix A for the grains (corn and soybean) production were from the USDA-NASS survey [17], Ecoinvent 3, and the Agri-footprint database (US EI 2.2) in SimaPro software version 8.5.2.0 unless otherwise stated [18]. It should be noted that necessary data for the feed ingredients' production correspond to the grains, and relevant product systems were within the United States unless otherwise stated. Both background and foreground processes included some available inventory data from the SimaPro Version 8.5.2.0 process library [18].

Foreground data including the yield of grains, fertilizer, and pesticide data were three-year-average data (2015, 2016, and 2017) in the United States. Synthetic fertilizers (N, P, K, and Sulphur) and pesticide processes were at the regional storehouse in the U.S.A., and the US-EI U database was followed from SimaPro version 8.5.2.0. The wastewater treatment process was selected from ELCD database 3 following Agri-footprint mass allocation.

The production cycle for corn and soybean was assumed to be one year, and the frequencies of fertilizer application were in accordance with the cultivation process throughout the year. All energy-consuming process data were from the USLCI database (DATASMART-2017, SimaPro 8.5.2.0). For LCA of amino acids, raw materials and inputs were collected from Marinussen and Kool [19], see Table A4 in Appendix A. The processing of raw materials and chemicals used for production, the transporting of materials to manufacturing plants, the emissions into the air and water from production, and the estimation of the energy demand and infrastructure of the plant (approximation) all followed the acrylic acid production model at the plant in the U.S.A. Methionine as an amino acid source for lysine production via the biosynthetic process was considered for Lysine production. For Threonine, Lysine was applied in the biosynthetic process.

2.4. Life Cycle Impact Assessment Method (LCIA)

An attributional LCA based on economic allocation was applied for all the ingredients and diets in this study (unless otherwise stated). The hierarchies perspective method of Recipe midpoints 2016 v1.06 was applied based on scientific consensus with regard to a 100-year period and the plausibility of the impact mechanism. Five impact categories, including

GWP, LU, WC, TE, and FR, were considered for the LCA studies. GWP was calculated as the CO_2 equivalent for a 100-year time scale; FR was from the higher heating value of fossil resources and expressed as kg oil-eq.; WC was expressed as m^3 water consumed; and LU was denoted as the relative species loss caused by a specified land-use type and expressed in m^2 annual crop eq.

2.5. Environmental Footprints by Mass and Economic Allocation

All the input data for feed ingredients (see Tables A2–A4 in Appendix A) and the processes associated with emissions were used for the LCA by SimaPro. The environmental footprint calculation by mass allocation was used according to their mass fractions, while for economic allocation, the economic fraction was derived using the following modified equation from Hossain et al. [20] (see Equation (1)).

$$B_i = P \times I \tag{1}$$

where B_i is the environmental impacts of the by-products i, P is the percent allocation, which refers to the fraction derived from the ratio of the main product and by-products according to their mass or economic value, and I is the total environmental impact of the final process products and co-products. When using economic allocation, the percent allocation for the products and co/by-products was estimated (Table 2) prior to the footprint calculation by SimaPro software using the following equation (see Equation (2)):

$$P = \frac{\text{Unit price of the product} \times \text{mass fraction of the product or byproducts} \times 100}{(\text{Unit price of product} \times \text{mass fraaction of the product}) + (\text{Unit price of the byproducts} \times \text{mass fraction of the byproducts})} \tag{2}$$

Table 2. The economic allocation of DDGS and SBM.

	Items	Unit Price ($/lb) [21–24]	Mass Allocation	Economic Allocation
DDGS	Ethanol	0.211	0.490	0.832
	DDGS	0.041	0.510	0.167
SBM	Crude soy oil	0.271	0.217	0.492
	Soy hulls	0.065	0.074	0.012
	SBM	0.146	0.709	0.496

Note: SBM: Soybean meal; DDG: Distiller-dried grains with solubles.

For all the ingredients, environmental footprint results were presented at a 1% cut-off, which meant the environmental load or contribution of a process less than 1% was discarded in the results.

3. Results and Discussion

3.1. Environmental Footprint of Individual Feed Ingredients

The environmental footprints of the byproduct DDGS by economic allocation was due to the relatively low prices of these byproducts. DDGS had the lowest environmental footprints compared to SBM and corn in all four categories of GWP, LU, WC, and FR, while SBM had the highest environmental footprints. The GWP, LU, and WC of DDGS via economic allocation were 22.1%, 81.4%, and 72.5% lower than that of corn, respectively (Table 3).

Table 3. Environmental footprints of SBM, DDGS, corn, bakery meal, and amino acids.

Ingredients		GWP kg CO_2 eq.	LU m^2 yr. Crop eq.	WC m^3	FR kg Oil eq.
SBM	Crude oil	0.390	0.346	0.160	0.028
	Soy hulls	0.054	0.135	0.062	0.010
	SBM	0.516	1.280	0.593	0.104
DDGS	DDGS	0.242	0.187	0.108	0.066
	Ethanol	1.200	0.932	0.535	0.328
Bakery meal		0.380 *	-	-	-
Corn		0.311	1.010	0.393	0.054
Amino acids					
L-Lysine-HCl		4.060	3.340	1.490	0.757
Methionine		9.060	0.728	4.930	2.940
Threonine		8.140	5.070	2.900	2.000
Tryptophan		9.620 *	-	-	-

Note: SBM: Soybean meal; DDG: Distiller-dried grains with solubles; GWP: Global warming potential; LU: Land use; WC: Water consumption; FR: Fossil resources. * ref. [10] (economic allocation).

The major contributors to the environmental footprints for individual feed ingredients are presented in Table 4. Fertilizer was the main contributor to GWP for corn and SBM. It accounted for 20% and 12.8%, respectively. The energy requirements for N fertilizer production ranged between 29 and 67 MJ/kg N, including values for both the low heating value and high heating value [25]. This energy mostly emanates from non-renewable energy and contributed to the dominant share of GWP to the corn and wheat middling. Non-renewable natural gas was the principal contributor to GWP for DDGS. For DDGS processing, when the non-renewable natural gas input energy was replaced with the renewable nuclear source, the GWP of DDGS could be further reduced by 39%, from 0.242 kg CO_2 eq. to 0.148 kg CO_2 eq. For amino acids, the production of raw materials (such as glucose) was the major contributor.

Table 4. Major contributors of environmental footprints for individual feed ingredients.

Ingredients	Major Contributing Factors	Contribution (%)			
		GWP	LU	WC	FR
Corn	Nitrogen ecoprofile at regional storehouse	19.7			
	Corn agricultural production		88.3	45.9	
	Natural gas, unprocessed, at extraction				26.9
SBM	Application lime ecoprofile at field	12.8			
	Soybean agricultural production at farm		94.3		
	Electricity, hydropower, at run-of river power plant			52.6	
	Natural gas, unprocessed, at extraction				22.6
DDGS	Natural gas burned at industrial furnace	41.3			
	Corn agricultural production at farm		79.7		
	Electricity, hydropower, at run-of river power plant			39.3	
	Natural gas, unprocessed, at extraction				74.0
Amino acid					
Lysine	Sugar, from sugar cane, from sugar production at plant	64.9	96.3	40.9	70.4
Methionine	Ammonium bicarbonate, at plant	26.1			38.8
	Electricity, natural gas, at power plant		71.0		
	Ammonia liquid at regional storehouse			84.6	
Threonine	Glucose global market for glucose at point of substitution unit process	54.0	92.3		50.2
	Ammonia, liquid, at regional storehouse			25.1	

Note: GWP: global warming potential; LU: land use; WC: water consumption; FR: fossil resources.

Between two DDGS diets, the displacement of the major ingredient, corn, was the highest with a 28.8% DDGS diet while for SBM it was a 10.1% DDGS diet (Table 5). DDGS inclusion in the diet did not only displace the major ingredients corn, SBM, and essential amino acids methionine and threonine, but also supplied a small amount of calcium carbonate and lysine in the diet. In the 28.8% DDGS diet, a unit of DDGS displaced 0.69 units of corn, which is higher than the national average by Arora et al. and RFA in refs. [26,27]. The per unit displacement of SBM by DDGS in all diets was within the range (0.2–0.3) reported in the literature.

Table 5. Displacement ratio for different DDGS inclusion in growing-finishing swine diet.

Ingredients	**10.1%**	**28.8%**
Corn	0.6532	0.6938
Soybean meal	0.31	0.2583
Calcium carbonate	−0.01	−0.0082
Calcium phosphate (monocalcium)	0.0252	0.0136
Sodium chloride	−0.0001	−0.0002
L-Lys-HCl	−0.006	−0.004
DL-Met	0.0017	0.0009
L-Thr	0.0031	0.0017
L-Trp	−0.0004	−0.0003
Vitamin premix with phytase	0.00	−0.0001
Trace mineral premix	0.00	−0.0001

Environmental footprint results from Table 6 demonstrated that GWP, LU, and TE were reduced with the increase in DDGS inclusion in the diets, while FR showed a trend of decline as compared with the standard diet. The highest environmental footprint reduction was attained with a 28.8% DDGS diet, which was 9.69% GWP, 22.97% LU, 2.36% WC, 20.3% TE, and 1.74% FR lower than the standard diet. A high FR footprint was attributed to the high energy requirement for the drying process of DDGS.

Table 6. Environmental footprint of growing-finishing swine diets—control/standard and with different DDGS inclusion for per kg diet at feed production stage.

Diet	**GWP (kg CO_2 eq.)**	**LU (m^2 Area Crop eq.)**	**WC (m^3)**	**TE (kg 1,4-DCB)**	**FR (kg Oil eq.)**
Standard (0% DDGS)	0.390	0.975	0.394	0.544	0.063
10.1% DDGS	0.374	0.898	0.365	0.502	0.063
28.8% DDGS	0.352	0.751	0.385	0.434	0.065

Note: GWP: Global warming potential; LU: Land use; WC: Water consumption; TE: Terrestrial Ecotoxicity FR: Fossil resources.

3.2. Sensitivity of Environmental Footprint to DDGS and Ethanol Price

The price of DDGS and ethanol historically in the US market has fluctuated over the decades (Figures 2 and 3). The price variation of DDGS could have a significant effect both economically and environmentally. Thus, a sensitivity test was conducted with the average (1.642), minimum (0.908), and maximum (3.898) price ratio from the historic DDGS and ethanol price data (Figure 4). The price ratio was computed from the average, minimum, and maximum prices of DDGS and ethanol from the historic data.

Figure 2. Historic price of DDGS ($/ton). Data from ref. [28].

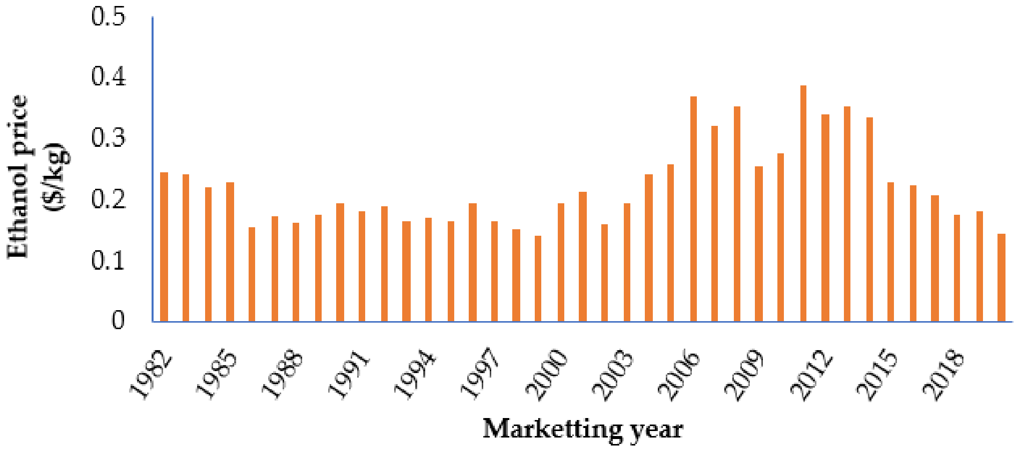

Figure 3. Historic ethanol price in the US market. Data from ref. [29].

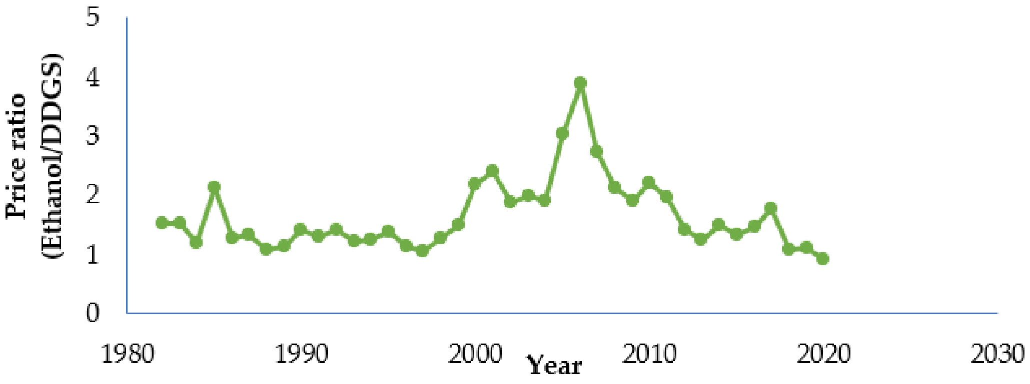

Figure 4. Historic price ratio of DDGS and ethanol in the U.S.A. market. Data from ref. [29].

Results from the DDGS and ethanol price sensitivity test demonstrated that with the historical average, minimum, and maximum price ratio between ethanol and DDGS, GWP and LU of the 28.8% DDGS diet is still below the standard diet. In contrast, the WC of the 28.8% DDGS diet is sensitive to the average, minimum, and maximum price ratios of ethanol and DDGS in comparison with the standard diet (Figure 5).

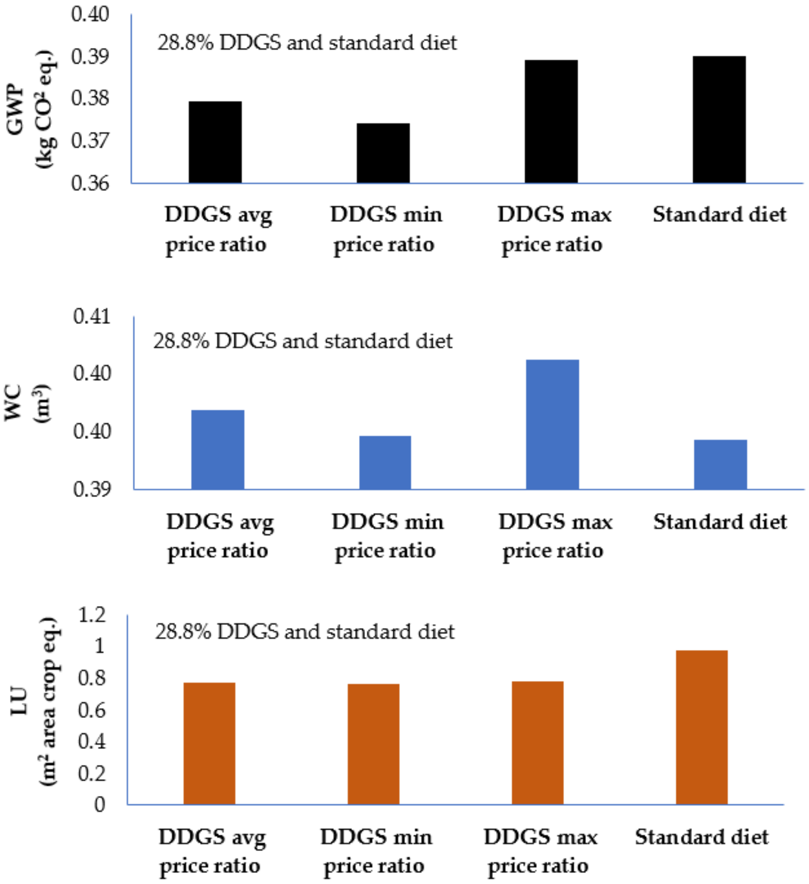

Figure 5. Sensitivity of environmental footprint in response to the price ratio of ethanol and DDGS.

3.3. Discussion

The displacement ratio of corn and SBM by DDGS reduced both the environmental footprint and the per dollar cost of the diet. The inclusion of DDGS compensated for a part of the amino acid requirement in the diet by providing an amino acid content three times greater than corn, thus playing a role in reducing the overall environmental footprint [4]. Besides amino acids, the addition of DDGS also supplies a portion of monocalcium phosphate in the diet. Another factor of the low environmental footprint of DDGS diets is that even with a high inclusion up to 28.8%, the low allocation to DDGS resulted in a low environmental footprint under economic allocation. Thus, from a check-and-balance observation, DDGS can reduce the overall environmental footprint in the diet as compared with the standard diet.

With an inclusion range of 10.1–28.8% of DDGS that corresponds to a corn displacement ratio range of 0.65–0.69 in the diet, we can save a GWP of 0.01–0.04 kg CO_2 eq. per lb feed at the feed production stage. In 2019, the total DDGS production in the US was 22.54 million metric tons, of which swine consumption was 3.6 million metric tons (16%) [27]. With the protein content of DDGS and corn of 28.15% and 8.24%, respectively, this amount of DDGS is equivalent to 12.33 million metric tons of protein equivalent of corn. Therefore, the current range of DDGS inclusion in the diet can save a GWP of up to 0.12–0.49 million metric tons of CO_2 eq. at the feed production stage on a national level. If the DDGS is not used for swine production, the crude protein and amino acid lysine content could be wasted. Based on the replacement ratio by Stein (2007), 28.8% DDGS inclusion can save 16.416% of corn and 12.24% of SBM [5]. This replacement can save the feed cost per pig by 28.65 $ and 3.88 $ for corn and SBM, respectively. Using such alternative diets, approximately 32.53 $ can be saved per pig, and this will reduce the overall swine production cost.

From the sensitivity results, with historical DDGS and ethanol price fluctuations from the base price, both 10.1% and 28.8% DDGS diets were demonstrated as environmentally benign diets compared to the standard diet. Although the 28.8% DDGS diet resulted in higher LU in comparison with the standard diet at the feed production stage, the discrepancy was, however, not too high at only 1.72%.

4. Conclusions and Limitations

An environmental footprint assessment was carried out on the DDGS diet as a substitute for standard corn–soybean for swine production in the U.S.A. Four impact categories, namely GWP, LU, WC, TE, and FR, are estimated for varying rates of DDGS inclusions (for instance, 10.1% and 28.8%) compared with the standard swine diet with 0% DDGS. Based on this assessment, the following conclusions were drawn:

- A DDGS displacement ratio of 0.65–0.69 can save a GWP of up to 0.12–0.49 million metric tons of CO_2 eq. at the feed production stage on a national level.
- Though the DDGS displacement ratio of 0.65–0.69 does not significantly impact WC and FR, it can save up to 26% LU and 8% TE.
- The historic price elasticity of DDGS and ethanol did not influence the diet's environmental footprint, indicating that the environmental footprint is not sensitive to the price of DDGS.
- With nutritional benefits and availability, DDGS remained one of the most important byproduct ingredients for the swine diet in the US.
- Although the amount of DDGS production is almost equal to the amount of ethanol in corn-based ethanol processing, with economic allocation, the environmental footprint of DDGS is lower than other ingredients in the diet.

The authors do acknowledge the current limitations of this study. For example, all the ingredients and diets were assumed to be produced in the geographic boundary of the U.S.A. The mass of the straw of the grain crops was not included in the system boundary. The industrial equipment's diesel and gasoline combustion data were attained from the USLCI database (SimaPro 8.5.2.0), and it may not be applicable to other parts of the world. We also acknowledge the uncertainties associated with this study due to the limited process data, such as methionine usage as an amino acid source for lysine fermentation. In contrast, for threonine, lysine is applied to the biosynthetic process. Lysine-producing microorganisms may not adapt to threonine (as amino acid source) in the medium for biosynthetic production.

Overall, from this study, we observed that DDGS inclusion in standard corn–soybean meal could potentially benefit the swine production sector and drive it towards being in line with sustainable standards. Furthermore, there has been a recent upward trend of DDGS use in the U.S.A. We believe it is high time to formulate policies that will accelerate the usage of DDGS at a massive level without compromising the growth performance of swine.

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Appendix A

Table A1. Nutrient budget of the diets at different phases of grow-finish swine in the U.S.A.

Nutrient Composition	**Standard Corn-SBM Diet**					**10.1% DDGS Diet**					**28.8% DDGS Diet**				
	Phase 1	**Phase 2**	**Phase 3**	**Phase 4**	**Phase 5**	**Phase 1**	**Phase 2**	**Phase 3**	**Phase 4**	**Phase 5**	**Phase 1**	**Phase 2**	**Phase 3**	**Phase 4**	**Phase 5**
	Weight Range (lb)					**Weight Range (lb)**					**Weight Range (lb)**				
	50–75	**75–140**	**140–195**	**195–240**	**240–280**	**50–75**	**75–140**	**140–195**	**195–240**	**240–280**	**50–75**	**75–140**	**140–195**	**195–240**	**240–280**
Gilt required SID Lys:NE Ratio	4.52	3.80	3.17	2.82	2.54	4.52	3.80	3.17	2.82	2.54	4.52	3.80	3.17	2.82	2.54
Calculated SID Lysine Required, %	1.10	0.94	0.80	0.72	0.65	1.10	0.94	0.80	0.71	0.65	1.09	0.93	0.79	0.70	0.65
PIC required SID Lys:NE Ratio	5.08	4.23	3.45	3.10	3.03	5.08	4.23	3.45	3.10	3.03	5.08	4.23	3.45	3.10	3.03
Calc. PIC SID Lysine Required, %	1.24	1.05	0.87	0.79	0.77	1.24	1.05	0.87	0.78	0.77	1.22	1.03	0.85	0.77	0.77
SID amino acids, %															
Lys	1.17	0.99	0.83	0.75	0.70	1.17	0.99	0.83	0.75	0.70	1.15	0.97	0.82	0.73	0.70
Ile:Lys	63	62	61	62	65	61	61	63	66	66	66	67	70	70	65
Leu:Lys	131	138	146	154	164	135	148	163	175	175	160	184	205	219	178
Met:Lys	32	31	30	28	30	31	29	29	31	32	29	33	36	38	32
Met & Cys:Lys	56	56	56	56	60	55	55	58	62	62	56	62	69	73	63
Thr:Lys	61	61	61	63	64	60	59	59	58	61	61	61	62	63	65
Trp:Lys	18.5	18.3	18.1	18.2	18.4	18.1	17.9	18.1	17.8	17.6	18.2	18.1	18.1	18.2	18.1
Val:Lys	69	69	70	72	76	68	70	74	78	78	76	80	86	89	78
His:Lys	42	42	43	44	47	41	42	44	47	47	45	47	50	51	47
Total Lys, %	1.31	1.11	0.94	0.85	0.80	1.32	1.13	0.96	0.87	0.81	1.34	1.15	0.99	0.89	0.81
ME, kcal/lb	1491	1497	1502	1506	1508	1490	1493	1500	1502	1506	1481	1483	1486	1488	1504
NE Noblet Grow/Finish, kcal/lb	1084	1107	1129	1138	1141	1007	987	1006	1011	1060	807	720	734	746	1032
NE Noblet Sow, kcal/lb	1125	1147	1167	1177	1179	1045	1022	1040	1045	1095	838	746	759	769	1066
DE NRC, kcal/lb	1554	1551	1549	1549	1550	1552	1548	1550	1549	1550	1551	1547	1544	1542	1548
NE NRC, kcal/lb	1103	1124	1144	1152	1155	1105	1123	1140	1146	1154	1092	1110	1122	1132	1152
SID Lys:NE, g/Mcal	4.81	3.99	3.29	2.95	2.75	4.80	4.00	3.30	2.97	2.75	4.78	3.97	3.32	2.92	2.76
CP, %	20.6	17.6	15.1	14.1	13.8	20.5	18.1	16.1	15.4	14.4	22.8	20.8	18.9	17.5	14.5
Ca, %	0.64	0.58	0.52	0.47	0.45	0.64	0.59	0.49	0.47	0.45	0.64	0.58	0.55	0.53	0.46
P, %	0.54	0.49	0.43	0.39	0.38	0.52	0.47	0.40	0.38	0.35	0.53	0.48	0.46	0.44	0.38
Available P w/o phytase, %	0.22	0.19	0.15	0.13	0.12	0.22	0.19	0.14	0.13	0.10	0.25	0.24	0.23	0.23	0.13
Available P, %	0.35	0.32	0.27	0.23	0.20	0.34	0.32	0.26	0.23	0.19	0.37	0.36	0.34	0.33	0.22
Avail P:calorie ratio g/mcal	1.05	0.96	0.81	0.70	0.62	1.05	0.96	0.78	0.71	0.56	1.14	1.10	1.05	1.00	0.67
Stand. Dig. P w/out phytase, %	0.30	0.26	0.21	0.19	0.18	0.28	0.24	0.19	0.18	0.15	0.29	0.26	0.24	0.23	0.18
Stand. Dig. P with phytase, %	0.40	0.37	0.31	0.28	0.26	0.39	0.35	0.29	0.27	0.23	0.40	0.36	0.34	0.33	0.26
STTD Ca, % without phytase	0.43	0.39	0.35	0.31	0.30	0.43	0.34	0.28	0.27	0.26	0.42	0.33	0.33	0.32	0.27
STTD Ca, % with phytase	0.47	0.43	0.38	0.34	0.33	0.47	0.43	0.35	0.34	0.32	0.46	0.41	0.39	0.37	0.33
Ca:P	1.17	1.18	1.22	1.19	1.18	1.23	1.26	1.22	1.22	1.26	1.20	1.20	1.20	1.20	1.21

Table A1. *Cont.*

Nutrient Composition	Standard Corn-SBM Diet					10.1% DDGS Diet					28.8% DDGS Diet				
	Phase 1	**Phase 2**	**Phase 3**	**Phase 4**	**Phase 5**	**Phase 1**	**Phase 2**	**Phase 3**	**Phase 4**	**Phase 5**	**Phase 1**	**Phase 2**	**Phase 3**	**Phase 4**	**Phase 5**
	Weight Range (lb)					**Weight Range (lb)**					**Weight Range (lb)**				
	50–75	**75–140**	**140–195**	**195–240**	**240–280**	**50–75**	**75–140**	**140–195**	**195–240**	**240–280**	**50–75**	**75–140**	**140–195**	**195–240**	**240–280**
STTD Ca:STTD P	1.17	1.16	1.22	1.22	1.28	1.21	1.22	1.21	1.25	1.38	1.17	1.13	1.13	1.15	1.29
Cost/ton	$194.04	$180.35	$167.03	$160.54	$156.90	$190.46	$175.40	$163.19	$156.48	$152.95	$183.73	$169.60	$159.41	$153.25	$154.60
Cost with processing	$206.04	$192.35	$179.03	$172.54	$168.90	$202.46	$187.40	$175.19	$168.48	$164.95	$195.73	$181.60	$171.41	$165.25	$166.60
Feed budget, lb/pig	50	155	158	148	145	50	155	158	149	145	51	157	161	150	146
Feed cost, $/pig	$5.17	$14.86	$14.13	$12.74	$12.27	$5.07	$14.49	$13.87	$12.52	$11.99	$4.96	$14.21	$13.79	$12.42	$12.13

SID = Standardized ileal digestible; STTD = Standardized total tract digestible; ME = Metabolizable energy; DE = Digestible energy; NE = Net energy.

Table A2. Inputs for agricultural production of corn grain in the U.S.A.

Inputs from Nature	
[1] Yield (lb/acre)	9699.2
[*,2] Water, unspecified natural origin, US (L)	77.5
[*,3] Occupation, annual crop (land-m^2a)	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
[*,4] Phosphate ecoprofile, as P, at regional storehouse/US U (lb)	0.005464368
[*,3] Manure, fertilizer, as applied N, at field/US U (lb)	0.001545702
[*,4] Potash ecoprofile, at regional storehouse/US U (lb)	0.007320191
[*,3] Lime ecoprofile, at factory/US U (lb)	0.000820022
Boron, at factory/US U (lb)	0
[*,4] Sulfur, at regional storehouse/US U(lb)	0.001340317
[*,5] Corn herbicides, at regional storehouse/US U (lb)	0.000409002
[*,5] Corn insecticides, at regional storehouse/US U (lb)	0.000119708
[*,6] Diesel produced and combusted, at industrial boiler/US U (gal)	0.00005480480
[*,6] Gasoline produced and combusted, at equipment/US U (gal)	0.000006094
[*,7] Fungicides, at regional storehouse/US- US-EI U (lb)	0.000047322
[*,5] Corn pesticides from NASS (emissions only)/US U (m^2)	0.4047
* Corn air, soil and water emissions (PO_4 + NO_3)/US U (m^2)	0
* Transport, lorry 16–32t, EURO3/US- US-EI U (kgkm)	45
Inputs from technosphere: electricity/heat	
[*,6] Natural gas produced and combusted, at industrial furnace/US U (cuft)	0.000243589
[*,6] Electricity, at grid, Western US NREL/US U (kwh)	0.00222624
[*,6] LPG production and combustion, at industrial boiler/US U_NPB_Wheat middling (lb)	0.0024239

[1] Average yield of 2015, 2016, and 2017 USDA-NASS survey. [2] Ecoinvent V 2.2, SimaPro 8.5.2.0. [3] Corn seed rate, manure and lime fertilizer, and occupation land data are taken from the US-EI U, SimaPro 8.5.2.0. [4] Average N, P, K, and S fertilizer data from USDA-NASS survey (2017, 2016, and 2015,). N, P, K, and S Ecoprofile at regional storehouse in the USA US-EI 2.2 (SimpaPro 8.5.2.0). [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). [6] Diesel, natural gas, electricity, and LPG data are taken from (SimaPro 8.5.2.0). [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). * Refers to the processes and associated data from (SimaPro 8.5.2.0).

Table A3. Inputs for agricultural production of soybean in the U.S.A.

Inputs from Nature	
Yield (lb/acre)	29,582
[*,1] Water, unspecified natural origin, US (L)	79.5
[*,2] Occupation, annual crop (m^2a)	0.76056338
Inputs from Technosphere: Materials/Fuels	
[*,1] Soybean seed IP, at regional storehouse/US U (lb)	0.03
[*,3] Nitrogen ecoprofile, as N, at regional storehouse/US U (lb)	0.006085193
[*,3] Phosphate ecoprofile, as P, at regional storehouse/US U (lb)	0.017579446
[*,3] Potash ecoprofile, at regional storehouse/US U (lb)	0.03076403
[*,1] Lime ecoprofile, at factory/US U (lb)	0.202713707
Boron, at factory/US U (lb)	0
[*,3] Sulfur, at regional storehouse/US U (lb)	0.005070994
[*,4] Soybean herbicides, at regional storehouse/US U (lb)	0.005551048
[*,4] Soybean insecticides, at regional storehouse/US U (lb)	0.00053854
[*,5] Diesel produced and combusted, at industrial boiler/US U (gal)	0.001680335
[*,5] Gasoline produced and combusted, at equipment/US U (gal)	0.000418155
[*,4] Soybean fungicides, at regional storehouse/US- US-EI U (gal)	0.000328938
[*,6] Soybeans pesticides from NASS (emissions only)/US U (m^2)	0.76056338
Soybean air, soil and water emissions (PO_4 +NO_3)/US U (m^2)	0

Table A3. *Cont.*

Inputs from Technosphere: Materials/Fuels	
Inputs from technosphere: electricity/heat	
[*,5] Natural gas produced and combusted, at industrial furnace/US U (cuft)	0.015668
[*,5] Electricity, at grid, Eastern US NREL/US U (kwh)	0.004321821
[*,5] LPG production and combustion, at industrial boiler/US U_NPB_Wheat middling (kg)	0.000252827

[*] 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. [2] Land. USDA-NASS survey 2017 (Calculated from the total area harvested). [3] N, P, K, and S fertilizer data from USDA-NASS survey (2017). N, P, and K ecoprofile at regional storehouse in the USA US-EI 2.2 (SimpaPro 8.5.2.0). [4] Soybean 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). [5] Diesel, gasoline, natural gas, electricity, and LPG data (taking the lower heating value) collected from the GREET version 2018. [6] NASS Soybean pesticides emissions data at US-EI U (SimaPro 8.5.2.0).

Table A4. Inputs for amino acids (L-Lysine-HCl, Methionine and Threonine) production in the U.S.A.

Inputs from Nature			
	Lysine	**Methionine**	**Threonine**
[1] Water, cooling, unspecified natural origin, US (m^3)	0.072	0.024	0.009
[1] Water, unspecified natural origin, US (m^3)	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% H_2SO_4), at plant/RER Mass (kg)	0.320	0	1.5
[1] Phosphoric acid, industrial grade, 85% in H_2O, 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 H_2O, production mix, at plant/US- US-EI U as caustic (kg)	0.0045	0	0.370
[1] Water, deionized, at plant/US US-EI U for fermentation and cleaning (kg)	0.0046	0	120
[1] Nitric acid, 50% in H_2O, 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 library (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).

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