CHAPTER 27

The Role of DDGS in Environmental Sustainability

Introduction

There are numerous research studies showing nutritional and economic benefits of using DDGS in animal feeds, but most nutritionists and animal producers are unaware of several environmental benefits that feeding DDGS can provide (Shurson, 2017). In recent years, environmental sustainability has become a new megatrend in agriculture around the world, and large multinational companies are beginning to source feed ingredients based not only on cost and nutritional value, but also on their environmental impact to reduce the overall carbon footprint of animal production systems. Kauffman (2015) described the characteristics of a low emission Chinese swine farm using a combination of nutrient, emission and waste management approaches. In China over four billion tons of manure is produced annually, much of which contributes to nutrient overloading in waterways and eutrophication and dead zones. As more land is converted to monocrop production of corn and soybeans, pesticides, herbicides and fertilizers pollute waterways, biodiversity declines, natural carbon sinks are destroyed due to direct and indirect land use change, and greenhouse gases are emitted in all stages of feed production and transport. As a result, Kaufmann (2015) recommended that the following practices be implemented to improve sustainable livestock production in China, but these practices can also be applied globally:

1. Determine the complete environmental costs of bioremediation of water, soil and air pollution including manure and agrochemical runoff and contamination as well as loss of livelihoods, costs associated with greenhouse gas emission and costs of loss of manure as a source of nutrients and organic matter for cropland and associated costs of using commercial fertilizers.
2. Exploit the full potential of reducing protein content in animal feeds by formulating swine and poultry diets based on standard ileal digestible amino acids, net energy and digestible or available phosphorus basis as well as use rumen protected amino acids for high performance lactating dairy cows.
3. Implement the use of methane digesters for biogas production and require large-scale commercial farms to build biogas facilities that use manure as the primary feedstock.

Food animal production contributes a portion (18 percent) of total greenhouse gas emissions (i.e. carbon dioxide, methane, nitrous oxide; Steinfeld et al., 2006) globally, which is primarily attributed to gastrointestinal fermentation of feed in animals and manure storage. Several multi-national integrated feed, animal production and food companies have begun implementing supply chain management strategies to reduce their carbon footprint by selecting feed ingredients that minimize the carbon footprint of food animal production. Furthermore, several researchers have begun conducting life cycle assessments of the environmental impacts of using various feed ingredients in animal feeds. However, the assumptions, breadth and scope of many of these assessments vary among studies and impact the results and their interpretation (Zilberman, 2017). In fact, many of the published studies do not include the economic impact of environmental assessments, use static instead of dynamic models and do not take into account the actual measured emission rates from feeding diets, which leads to misleading results.

In addition to increased global interest in reducing greenhouse gas emissions and the carbon footprint of animal agriculture, it is also essential to use precision animal feeding programs to improve caloric and nutritional efficiency of feeds to not only feed and production costs, but also reduce nutrient excretion in manure and reduce odor and gases from confinement animal facilities. Lu et al. (2017) summarized these major environmental concerns. High nitrogen, phosphorus and trace mineral concentrations in manure that is applied to cropland can cause soil concentrations of these nutrients to exceed crop removal rates. Nitrate can leach through soils and contaminate ground water supplies and is considered to be a major pollution concern on livestock and poultry farms. Methane and nitrous oxide produced in manure contribute to greenhouse gas emissions, and volatilization of ammonia causes acid rain that has detrimental effects on vegetation and trees. Furthermore, phosphorus can enter surface waters through soil erosion and increase growth of algae and other aquatic plants, which reduces dissolved oxygen that can cause fish death. In addition, soil accumulation of excessive trace minerals (e.g. copper and zinc) can increase the risk of toxicity of plants and microorganisms.

Lu et al. (2017) suggested several nutritional strategies that can be effective for minimizing excess nitrogen, phosphorus and trace mineral excretion in manure. First formulate diets to accurately meet dietary protein or amino acid, phosphorus and trace mineral requirements of animals. Dietary crude protein levels can be reduced by using supplemental synthetic amino acids or feed ingredients with high ruminally undegraded protein. Excess phosphorus excretion can be minimized by formulating swine and poultry diets on an available or digestible phosphorus basis and adding supplemental phytase. Using multiple phase-feeding programs to adjust diet formulations more frequently as nutrient requirements change during the various stages of production can substantially minimize excess nutrient excretion. Second, use high bioavailable sources of phosphorus and trace minerals and avoid excesses of these nutrients when formulating diets. Third, consider using effective feed additives such as enzymes, probiotics, prebiotics and others that improve nutrient utilization in animal feeds. By implementing all of these practices, it will not only reduce feed and production costs, but also minimize potential negative environmental impacts.

It is well documented that using crystalline amino acids and phytase in swine and broiler diets are effective for improving nutrient utilization efficiency, reducing diet cost, reducing nitrogen and phosphorus excretion in manure as well as emissions of gases such as ammonia. 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 percent and 54 percent in Europe, 17 percent and 15 percent in North America and 33 percent and 19 percent in South America, respectively, compared with feeding diets without supplemental synthetic amino acids and phytase. These are substantial reductions and it is interesting to note that the North American swine and broiler diets used in this comparison contained 14.6 and 6.4 percent DDGS, respectively, but DDGS was not included in European and South American diets. As a result, the use of DDGS in animal feeds can be part of the solution for minimizing the negative environmental impacts of food animal production. This chapter summarizes several studies for various animal species that have shown beneficial effects of feeding DDGS on the environment.

Aquaculture

The global aquaculture industry continues to grow at a rapid pace, especially in Asian countries. For example, the aquaculture industry in Indonesia has increased 25 percent annually over the past five years (Henriksson et al., 2017a). As a result, significant attention is being directed toward methods to reduce its environmental impact and sustain long-term growth. One of the major factors that determine environmental impact in commercial aquaculture systems is the selection and use of feed ingredients. In fact, of all ingredients used in aquaculture systems, the use of fish meal has been the most criticized because of its negative environmental impacts and limitations for sustaining its widespread use in aqua feeds.

To compare the environmental impact of using common feed ingredients in aqua feeds in Indonesia, Henriksson et al. (2017a) classified them based on global warming, acidification, eutrophication, land occupation and fresh water consumption using life cycle assessment methodologies (**Table 1**). Shrimp meal had the greatest detrimental environmental impacts in all categories, while cassava had the least, except for land occupation of which fish oil had the least impact. Environmental impacts for corn flour and DDGS were generally intermediate among ingredients. When adding an economic allocation in the sensitivity analysis, there was minimal change in the allocation of environmental factors for cassava, corn flour, fish oil, wheat flour and corn gluten meal, but fish meal, rice bran, poultry by-product meal DDGS, corn gluten feed and shrimp meal had much lower impacts. The major reason for the reduction in most of these by-product ingredients is that the feed industry is utilizing these by-products that would otherwise be a waste stream in aqua feeds.

Tilapia farming has increased more than 20-fold over the past 20 years in Egypt and is the third largest animal production sector, providing 77 percent of the fish produced (El-Sayed et al., 2015; FAO, 2016). However, Egyptian fish farms are challenged with limited fresh water and achieving profitability. As a result, Worldfish implemented the "*Improving Employment and Incomes through the Development of Egypt's Aquaculture Sector*" project. This project provided training on best management practices and provided an improved strain of Nile tilapia to more than 500 fish farms. As a result, Henriksson et al. (2017b) conducted a benchmarking study to determine the environmental performance of using best management practices and genetic improvements in Egyptian aquaculture using life cycle assessment. Because Egypt is heavily dependent on imported feed ingredients, these researchers evaluated imported fish meal, fish oil, soybean meal, soybean oil and guar meal, along with poultry by-product meal rapeseed cake, corn gluten meal, corn gluten feed, corn flour, rice bran, wheat bran and DDGS. Based on their assumptions, the feed ingredients with the greatest contributions to global warming were soybean meal, wheat bran rice bran and corn gluten feed. However, on a per kilogram of ingredient basis, the ingredients with the greatest impact on greenhouse gas emissions were poultry by-product meal, fish meal, fish oil, corn flour, DDGS, corn gluten feed and corn gluten meal. However, the high impact of corn and corn co-products was caused by large dinitrogen monoxide emissions from Egyptian agricultural fields where excess nitrogen fertilizers are applied and suboptimal climatic conditions.

Beef and Dairy Cattle

Feeding high amounts of DDGS to dairy and beef cattle can result in increased nitrogen (N) and phosphorus (P) excretion in manure because DDGS contains about three times the crude protein and phosphorus content compared with corn.

Table 1. Comparison of feed ingredients used in the commercial aquaculture industry in Indonesia on their relative environmental impacts[1] (adapted from Henriksson et al, 2017[a])

Ingredient	Global warming[2]	Eutrophication[3]	Acidification[4]	Land occupation[5]	Fresh water consumption[6]
Fish meal	H	M	M	L	L
Shrimp meal	H*	H*	H*	H*	H*
Poultry by-product meal	H	H	H	H	M
Soybean meal	M	L	L	M	M
Corn gluten meal	H	M	H	M	M
Corn gluten feed	H	M	H	M	M
DDGS	M	M	M	M	M
Cassava	L**	L**	L**	M	L**
Corn flour	L	M	M	M	M
Wheat flour	M	M	M	M	M
Wheat bran	M	M	M	M	M
Rice bran	L	H	L	M	H
Fish oil	L	M	L	L*	L
Soybean oil	L	L	L	M	M

[1] H = high; M = medium; L = low

[2] Global warming = greenhouse gas emissions/ton

[3] Eutrophication = phosphorus and nitrogen runoff potential/ton

[4] Acidification = sulfur dioxide and nitrogen oxide emissions/ton

[5] Land occupation = land resources required/ton produced

[6] Fresh water consumption = cubic meters of water required/ton produced

*Highest impact among ingredients

**Lowest impact among ingredients

Nitrogen and phosphorus use efficiency can be improved by increasing N and phosphorus retention, reducing excess N and phosphorus intake, or both. Supplementing cattle on pasture with DDGS can result in N fertilization because DDGS contains a relatively high concentration of crude protein (N), and excess N is excreted as urea in urine. However, when manure is properly managed and applied to cropland, it serves as a very valuable fertilizer for crop production. In addition, for cattle grazing pastures, greater N content in urine has been shown to significant increase grass forage production when applied to actively growing grasses (Ball and Ryden, 1984).

Nitrogen and phosphorus utilization efficiency

Greenquist et al. (2011) compared the effects of N fertilization of smooth bromegrass pasture with providing supplemental DDGS to yearling steers on smooth bromegrass pasture on N utilization efficiency of the whole system. Nitrogen retention per hectare was 30 and 98 percent greater supplemented with 2.3 kg of DDGS per steer daily compared with those on pasture fertilized with 90 kg of N/hectare and steers grazing bromegrass pasture that was not fertilized and no supplemental DDGS was provided. Nitrogen excretion was also greater for DDGS supplemented steers than those grazing fertilized bromegrass, and both grazing systems resulted in more N excretion than the control. Although animal N utilization efficiency was not different among grazing treatments, N utilization efficiency improved 144 percent when supplementing grazing cattle with DDGS compared with fertilized bromegrass pasture, which indicates that feeding DDGS can improve N utilization efficiency of the whole bromegrass grazing system.

Bernier et al. (2014) evaluated N and phosphorus utilization of beef cows fed poor quality forage with or without protein provided by a 50:50 blend of corn and wheat DDGS when exposed to thermal neutral and prolonged cold climate conditions. Feeding DDGS increased total N and phosphorus content of manure, as well as the chemical forms of N and phosphorus that have the potential to increase nutrient runoff when manure is applied to cropland. However, results from this study showed that cows exposed to cold conditions have different protein and phosphorus requirements and utilization than cows exposed to thermal neutral conditions.

Hao et al. (2011) determined the effects of adding condensed tannins to cattle diets containing corn DDGS, and using open windrow manure composting, on nitrogen content and greenhouse gas emissions from manure composting. Concentrations of total carbon, nitrogen and ammonia in the final compost were greater in manure from cattle fed 40 percent DDGS diets with 2.5 percent condensed tannins than for composted manure from cattle fed only DDGS or the control diet. Adding condensed tannins had no effect on carbon dioxide, methane or nitrous oxide emissions during composting. These results showed that feeding diets containing 40 percent DDGS and condensed tannins increase the fertilizer value of manure compost without increasing greenhouse gas emissions.

Methane emissions

Cropland and pasture used for food, fiber, and biofuels production emits about 13.5 percent of greenhouse gases globally, and agricultural activities account for about 85 percent of nitrous oxide and 50 percent of methane emissions, which comprise 70 percent of non-carbon dioxide emissions from agriculture (IPCC, 2007). Emissions of carbon dioxide, methane and nitrous oxide into the atmosphere have been increasing over the past several decades and have been considered to be a major cause of climate change. The increase in carbon dioxide emissions have been primarily attributed to burning of fossil fuels, but significant quantities of methane and nitrous oxide emissions are produced in agriculture (Smith et al., 2007). While most of the nitrous oxide emissions are derived from soil (resulting from fertilizer and manure), most of the methane produced is derived from gastrointestinal fermentation in livestock. Therefore, there is tremendous interest and need to implement feeding, housing and management practices to mitigate emissions of methane in livestock production systems (Beauchemin et al., 2011).

Ruminants are a major contributor to methane emissions. Hristov et al. (2014) reviewed various strategies to mitigate enteric methane emissions in livestock operations. Although the effects of feeding corn DDGS on methane emissions are inconsistent among species, emissions in ruminants can be reduced by feeding reduced-oil DDGS (Hristov et al., 2014), because dietary lipid content appears to affect methane emissions (Hunerberg et al., 2013). Hristov et al. (2014) suggested that increasing forage digestibility and digestible forage intake is one of the major strategies to reduce methane emissions in ruminants. They also suggested that supplementing ruminant diets with feed ingredients containing relatively high lipid content (i.e. DDGS) can significantly reduce methane emissions. In fact, several studies have shown that methane emissions in beef and dairy cattle are reduced when feeding diets containing DDGS.

Drehmel et al. (2016) showed that the addition of corn oil to neutral detergent fiber residues derived from DDGS reduced production of methane while adding cellulose to DDGS increased methane production using an in vitro gas production technique, which suggests that manipulating dietary components can be used to reduce methane emissions in ruminants. McGinn et al. (2009) reported that methane emissions were reduced by 16 to 24 percent when 35 percent DDGS replaced barley in a beef cattle backgrounding diet when additional 3 percent lipid was added to dry matter. Feeding corn DDGS to feedlot cattle reduced methane emissions compared with feeding wheat DDGS and control diets (Hunerberg et al., 2013). However, when DDGS is used as an energy source and fed at high dietary inclusion rates to beef feedlot cattle, cattle consume excess protein (nitrogen) which dramatically increases nitrogen excretion in manure (Hunerberg et al., 2013).

Feeding DDGS to dairy cows has also been shown to reduce enteric methane emissions while increasing the bioenergy potential (methane production) from anaerobic digestion of manure (Masse et al., 2014). Benchaar et al. (2013) evaluated the effects of replacing corn and soybean meal with 0, 10, 20 or 30 percent high-oil DDGS in lactating dairy cow diets on enteric methane emissions and ruminal fermentation characteristics of dairy cows. Increasing dietary DDGS levels increased dry matter intake and milk yield, and methane production decreased linearly (**Table 2**). The reduction in methane production was attributed to increased amounts of lipid provided by DDGS and its effects on rumen fiber degradation, acetate:propionate and protozoa numbers. Results from this study indicate that feeding reduced-oil DDGS to lactating dairy cows is effective in reducing methane emissions while also improving dry matter intake and milk yield.

Table 2. Effects of feeding increasing levels of reduced-oil DDGS to lactating dairy cows on dry matter intake, milk yield, rumen pH and protozoa, and methane production (adapted from Benchaar et al., 2013)

Measure	**0% DDGS**	**10% DDGS**	**20% DDGS**	**30% DDGS**
Dry matter intake, kg/day	24.2	24.6	24.4	25.3
Milk yield, kg/day	32.6	35.1	35.8	36.6
Energy-corrected milk yield, kg/day[1]	35.3	37.8	37.3	37.1
4% fat-corrected milk, kg/day[2]	32.1	34.5	34.1	33.7
Milk/dry matter intake	1.40	1.44	1.44	1.45
Energy-corrected milk/dry matter intake	1.51	1.55	1.50	1.46
Rumen pH				
Minimum	5.92	5.92	5.98	5.97
Maximum	6.56	6.59	6.64	6.55
Average	6.21	6.21	6.27	6.22
Protozoa ($\times 10^5$/mL)	5.12	5.28	5.42	4.48
Methane production				
g/day	495	490	477	475
g/kg dry matter intake	0.6	20.1	19.7	18.9
% of gross energy intake	6.09	5.80	5.61	5.23
% of digestible energy intake	8.75	8.39	8.17	7.74
g/kg milk	15.6	14.2	13.6	13.2
g/kg fat-corrected milk	15.7	14.3	14.3	14.4
g/kg energy-corrected milk	14.3	13.1	13.0	13.0
g/kg milk fat	396	363	372	390
g/kg milk protein	446	415	411	400

[1] Energy-corrected milk = 0.327 × milk yield (kg/day) + 12.95 × milk fat yield (kg/day) + 7.2 × protein yield (kg/day)

[2] 4 percent fat-corrected milk = 0.4 × milk yield (kg/day) + 15 × milk fat yield (kg/day)

Judy et al. (2016) conducted a study with lactating dairy cows to determine the effects of feeding 20 percent reduced-oil DDGS diets, with or without 1.4 percent added corn oil, and a 20 percent reduced-oil DDGS diet with 0.93 percent added calcium sulfate on methane emissions. Feeding the reduced-oil DDGS diet increased dry matter intake and milk yield compared with feeding the control diet with no DDGS. Feeding the 20 percent reduced-oil DDGS diet had no effect on methane emissions compared with the control diet. However, adding calcium sulfate to the 20 percent DDGS diet reduced total methane produced compared with cows fed the control diet, and adding corn oil to the reduced-oil DDGS diet tended to reduce methane production. Similarly, when methane production was expressed as per unit of fat-corrected milk or per unit of dry matter intake, adding calcium sulfate or corn oil to the reduced oil DDGS diet reduced methane production compared with cows fed the control diet. These results show that adding calcium sulfate or corn oil to reduced-oil DDGS diets is effective in reducing methane emissions without affecting milk production.

Hydrogen sulfide emissions

Feeding diets containing high amounts of sulfur (greater than 0.40 percent) can potentially be toxic to ruminants, and although sulfur content in DDGS is variable, some sources contain relatively high concentrations. In addition, dietary sulfur can contribute to hydrogen sulfide emissions from the rumen and manure, and can cause sudden death in animals and humans if it is present in the production facilities at high concentrations. Drewnoski et al. (2014) conducted a study to compare hydrogen sulfide emissions from feeding 42 percent DDGS (contributed 0.40 percent sulfur to the diet), 7 percent dry matter of corn condensed distillers solubles (contributed 0.19 percent sulfur to the diet), and diets containing 21 percent DDGS (contributed 0.19 percent sulfur to the diet) with either supplemental sulfuric acid, sodium sulfate or calcium sulfate contributing 0.17 percent of total sulfure to the diets. Results from this study showed that there was no difference in sulfur intake or ruminal hydrogen sulfide concentration among dietary treatments suggesting that there was no difference in toxicity or hydrogen sulfide concentrations in the rumen. In a subsequent study, Morine et al. (2014) fed steers diets containing increasing amounts of forage to provide increasing dietary levels of neutral detergent fiber from bromegrass hay, and DDGS and condensed distillers solubles providing 0.46 percent sulfur to the diet, on rumen hydrogen sulfide concentrations. Results from this study showed that increasing the amount of NDF supplied by forage in the diet helped maintain high ruminal pH and decreased hydrogen sulfide concentration. Using this diet formulation strategy may be effective in not only reducing the risk of sulfur toxicity when feeding high sulfur diets, but also reduce hydrogen sulfide emissions.

Biogas production for energy use

Aguirre-Villegas et al. (2015) evaluated the effects of supplementing nutritionally balanced lactating dairy cow rations with varying amounts of DDGS, soybean meal and forage types, and integrating dairy and bioenergy production systems (manure anaerobic digesters) on land use, net energy intensity and greenhouse gas emissions. Within the integrated dairy and manure anaerobic digester system, maximizing the use of DDGS in the diets resulted in the greatest reduction in greenhouse gas emissions and net energy intensity, but increased land use compared to the reference system. These results indicated that implementing the use of anaerobic digesters on dairy farms can result in a 65 percent reduction in net energy intensity and reduce greenhouse gas emissions by 77 percent. Therefore, feeding DDGS diets has a significant positive impact on reducing energy use and greenhouse gas emissions on dairy farms using anaerobic digesters.

Poultry

Poultry manure contains significant nitrogen content, which if not properly managed can cause nitrate or nitrite contamination of water supplies, eutrophication, ammonia volatilization and increased nitrous oxide emissions. If diets contain excess protein above the bird's requirement, it is excreted as uric acid in manure where it is converted to ammonia by manure microbes (Pineda et al., 2008).

Nitrogen and phosphorus utilization efficiency

Feeding increasing dietary levels (up to 20 percent) of DDGS to broilers had no effect on dry matter and N excretion, but reduced P excretion when diets were formulated on a digestible amino acid basis and available phosphorus basis (Deniz et al., 2013). Similarly, Abd El-Hack and Mahgoub (2015) showed that N excretion in manure decreased by 8.6 and 4.3 percent in laying hens fed 5 or 10 percent DDGS diets, respectively, and phosphorus excretion was reduced by 3.3, 7.2 and 10.6 percent in laying hens fed 5, 10 or 15 percent DDGS diets compared with hens fed the control diet.

Martinez-Amezcua et al. (2006) conducted three experiments to evaluate the effectiveness of adding OptiPhos® phytase and citric acid to broiler diets for improving phosphorus availability in DDGS. In one of the experiments, they used a slope-ratio chick growth and tibia ash assay and determined that the bioavailability of phosphorus in DDGS was 67 percent. In another experiment, supplemental phytatse and citric acid released from 0.04 to 0.07 percent more phosphorus from DDGS, which suggests that both OptiPhos® phytase and citric acid supplementation can be used to increase the availability of phosphorus in DDGS for poultry. Therefore, the use of supplemental phytase and citric acid can increase the bioavailability of phosphorus in DDGS from 62 to 72 percent and reduce P excretion in poultry manure. Furthermore, Masa'deh (2011) reported that phosphorus excretion decreased linearly as dietary DDGS content increased.

Ammonia and hydrogen sulfide emissions

Feeding 20 percent DDGS diets to laying hens reduced emissions of ammonia by 24 percent and hydrogen sulfide by 58 percent compared to feeding a corn-soybean meal diet, with no effect on egg production and egg quality (Wu-Haan et al., 2010). The reduction in ammonia observed in this study is consistent with results reported by Roberts et al. (2007) and Li et al. (2012). This was confirmed in a subsequent study conducted by Li et al. (2014) which showed that feeding DDGS diets to laying hens decreased ammonia, but increased methane emissions without affecting other gases (Li et al., 2014). The reduction in hydrogen sulfide emissions reported by Wu-Haan et al. (2010) occurred despite greater sulfide concentrations in the litter and manure crusting was not reported. Undigested fiber in DDGS is fermented in the lower gastrointestinal tract of birds, resulting in the production of short chain fatty acids, which can reduce the pH of manure. Manure with low pH reduces the production of ammonium, which is non-volatile form of N, resulting in a less harmful effect on air quality (Babcock et al., 2008; Bregendahl et al., 2008). Therefore feeding DDGS not only reduces ammonia emissions, but it also increases the amount of N present in manure which increases its fertilizer value when applied to cropland. The fertilizer value of manure from an 800,000 laying hen operation fed 16 percent DDGS diets compared with no DDGS increased by $5,000/year on a N basis, and $47,000/year on a four-year P basis (Regassa et al., 2008)

Results from these studies indicate that feeding DDGS diets to layers and broilers can have a significant impact on reducing N and phosphorus excretion in manure, as well as reducing ammonia and hydrogen sulfide emissions.

Swine

Swine diets containing DDGS contain higher fiber, crude protein and sulfur compared to traditional corn-soybean meal diets (Kerr et al., 2008; Zhang, 2010), which affects nutrient digestibility and excretion (Kerr et al., 2003; Degen et al., 2007; Kil et al., 2010; Anderson et al., 2012). Due to the relatively high fiber content of DDGS, dry matter excretion is increased when feeding DDGS compared to corn-soybean meal diets without DDGS (Almeida and Stein, 2012). This results in increased manure volume produced, which may increase the need for greater manure storage capacity or more frequent manure removal from swine production facilities.

Nitrogen and phosphorus utilization efficiency

McDonnell et al. (2011) evaluated the effects of adding 0, 10, 20 or 30 percent corn DDGS to replace wheat in wheat and barley based diets, formulated on a net energy, ileal digestible amino acid, and digestible phosphorus basis, on N and phosphorus balance of growing-finishing pigs. As expected, N intake and urinary and total N excretion linearly increased with increasing DDGS levels in the diets (**Table 3**). This was due to feeding excess N from DDGS relative to pig requirements, resulting in increased deamination of excess amino acids and increased urinary excretion. Nitrogen retention was not affected by feeding the 10 and 20 percent DDGS diets, but feeding the 30 percent DDGS diet decreased N retention relative to nitrogen intake. The increased N excretion commonly observed by feeding DDGS diets to swine can be minimized by using synthetic amino acids to reduce the amount of excess protein (N) in the diet. In contrast, phosphorus intake linearly increased with increasing dietary DDGS levels, but there was no effect on P excretion or retention. These results indicate that feeding diets containing up to 30 percent DDGS increases N excretion but has no effect on phosphorus excretion in growing-finishing pigs when diets are formulated on a digestible amino acid and phosphorus basis.

Baker et al. (2013) compared the phosphorus balance and digestibility between dicalcium phosphate and DDGS for growing pigs and showed that although the standardized total tract digestibility of phosphorus from DDGS was less than dicalcium phosphate, it was quite high (93.1 and 63.1 percent, respectively), and did result in greater fecal excretion than dicalcium phosphate (**Table 4**). However, dicalcium phosphate is a much more expensive source of phosphorus in animal feeds and global supplies of inorganic phosphate reserves are rapidly declining, which makes DDGS an excellent and more sustainable alternative phosphorus source in swine diets.

Table 3. Effects of adding increasing levels of corn DDGS to wheat and barley based diets on nitrogen and phosphorus balance in growing-finishing pigs (McDonnell et al., 2011)

Measure	0% DDGS	10% DDGS	20% DDGS	30% DDGS
Nitrogen, g/day				
Intake[1]	52.7	57.2	57.9	62.8
Fecal excretion	7.3	6.2	7.4	8.0
Urine excretion[1]	15.0	18.0	17.2	20.8
Total excretion[1]	22.3	24.2	24.6	28.7
Retention	30.5	33.0	33.3	34.1
Retained/Intake[2]	0.58	0.58	0.58	0.54
Phosphorus, g/day				
Intake	9.7	9.6	9.1	8.9
Fecal excertion	3.7	3.7	3.3	3.3
Urine excretion	0.69	0.56	0.62	0.94
Total excretion	4.4	4.3	3.1	4.2
Retention	5.3	5.3	5.0	4.7

[1] Linear increase to increasing dietary DDGS levels (P less than 0.01)

[2] Quadratic response to increasing dietary DDGS levels (P less than 0.05)

Table 4. Comparison of phosphorus intake, excretion and digestibility between dicalcium phosphate and DDGS (adapted from Baker et al., 2013)

Measure	Dicalcium phosphate	DDGS
Feed intake, g/day	1,023	925
Phosphorus intake, g/day	2.5	3.8
Fecal phosphorus excretion, g/day	0.3	1.6
Apparent total tract digestibility of phosphorus %	86.1	58.5
Standardized total tract digestibility of phosphorus %	93.1	63.1

The addition of microbial phytase to swine diets has become a common practice to improve phosphorus digestibility, reduce phosphorus excretion in manure, and reduce diet cost by reducing the amount of inorganic phosphate required in the diet. Almeida and Stein (2012) added increasing levels of microbial phytase (0, 500, 1,000 or 1,599 phytase units) to corn or 50 percent DDGS diets and showed a linear improvement in standardized total tract digestibility of phosphorus in corn (40.9, 67.5, 64.5 and 74.9 percent, respectively), and tended to increase phosphorus digestibility in DDGS (76.9, 82.9, 82.5 and 83.0 percent, respectively). However, the magnitude of improvement in phosphorus digestibility by adding phytase to DDGS diets was much less than observed for corn and may not justify the additional cost of adding high amounts of phytase to swine diets.

Rojas et al. (2013) compared the phosphorus balance and digestibility of corn, DDGS and corn gluten meal, with and without 600 FTU/kg diet of supplemental phytase, when fed to growing pigs. Total phosphorus excretion was greatest for pigs fed the corn diet without phytase supplementation but was reduced by 50 percent when phytase was added (**Table 5**). However, feeding DDGS without phytase resulted in 40 percent less phosphorus excretion than feeding corn without phytase, and feeding corn gluten meal without phytase resulted in a 60 percent reduction in phosphorus excretion compared to feeding corn. Adding phytase to the corn diet had the greatest magnitude of improvement on reducing phosphorus excretion, with no benefit in the DDGS diets, and some improvement when phyatse was added to the corn gluten meal diet. As a result, adding phytase to corn and corn gluten meal diets improves standardized total tract digestibility of corn and corn gluten meal, but not DDGS. This lack of response to adding phytase to DDGS diets is a result of the already high phosphorus digestibility that occurs from the degradation of phytate during the fermentation process in dry-grind ethanol plants. Therefore, formulating DDGS diets on a digestible phosphorus basis for swine can dramatically reduce phosphorus excretion in manure compared with feeding corn based diets.

Table 5. Effect of microbial phytase supplementation (600 phytase units/kg) on fecal phosphorus concentration, excretion, and digestibility of corn, DDGS, and corn gluten meal (adapted from Rojas et al., 2013)

Measure	Corn		DDGS		Corn gluten meal	
	- Phytase	+ Phytase	- Phytase	+ Phytase	- Phytase	+ Phytase
Feed intake, g dry matter/day	481	456	463	471	475	482
P intake, g/day	1.6^{b}	1.1^{c}	2.2^{a}	2.2^{a}	1.0^{c}	1.0^{c}
P in feces %	2.0^{b}	1.1^{d}	0.9^{de}	0.7^{e}	2.4^{a}	1.4^{c}
P excretion, g/day	1.0^{a}	0.5^{c}	0.6^{bc}	0.5^{c}	0.4^{c}	0.2^{d}
Apparent total tract digestibility of phosphorus %	36.4^{d}	56.1^{c}	72.2^{ab}	78.5^{a}	70.6^{ab}	77.6^{a}
Standardized total tract digestibility of phosphorus %	42.5^{d}	64.1^{c}	76.5^{b}	82.8^{ab}	75.2^{b}	87.4^{a}

^{a,b,c,d,e}Means with different superscripts within row are different (P less than 0.05)

Feeding high fiber diets to ruminants and monogastric animals has been shown to increase the production of methane (Jarret et al., 2011; Klevenhusen et al., 2011). Furthermore, feeding diets containing DDGS may increase sulfur content which may cause an increase in hydrogen sulfide and other reduced-sulfur compounds and increase odor of swine manure (Blanes-Vidal et al., 2009; Feilberg et al., 2010; Trabue et al., 2011). Furthermore, the relatively high protein content relative to lysine content in DDGS results in increased protein and nitrogen content in animal feeds which can lead to increased nitrogen excretion and potentially ammonia production. Ammonia and hydrogen sulfide are two of the major gases produced from swine manure during storage.

Ammonia, hydrogen sulfide, methane and odor emissions

Several studies have been conducted to determine the effects of feeding DDGS to swine on gas and odor emissions from manure. Powers et al. (2009) measured air emissions of ammonia, hydrogen sulfide, methane and non-methane hydrocarbons when feeding diets containing 0 or 20 percent DDGS to growing-finishing pigs, with either supplemental inorganic or organic trace minerals. Although feeding the organic trace mineral sources reduced the increased hydrogen sulfide emissions resulting from feeding the 20 percent DDGS diet, ammonia, methane and non-methane hydrocarbon emission increased when feeding the DDGS diet. This is the only study that has shown an increase in ammonia and hydrogen sulfide emissions from feeding DDGS diets to pigs. Spiehs et al. (2012) observed no differences when feeding a 20 percent DDGS diet compared with a corn-soybean meal diet to growing pigs over a 10-week feeding period on total reduced sulfur, ammonia or odor concentrations.

Trabue et al. (2016) fed growing pigs diets containing 35 percent DDGS over a 42-day period and observed a reduction in manure pH and increased manure surface crust coverage, dry matter content, as well as increased concentrations of carbon, nitrogen and sulfur in manure compared with pigs fed a corn-soybean meal diet (**Table 6**). Warmer temperatures are often observed for manure with greater surface crusting or foam (van Weelden et al., 2015), and is associated with animals fed high fiber diets (Misselbrook et al., 2005; Lynch et al., 2007; Wood et al., 2012) and lower pH (Kerr et al., 2006). As a result, the increased crusting of manure (Wood et al. 2012), temperature (Blunden and Aneja, 2008; Blunden et al., 2008; Rumsey and Aneja, 2014) and reduced pH associated with feeding DDGS diets can reduce gas emissions. In fact, ammonia and hydrogen sulfide emissions from manure produced by pigs fed DDGS was less than from those fed a corn-soybean meal diet, but volatile fatty acid and phenolic compound concentrations were greater in manure from pigs fed the DDGS diet (**Table 6**). It is likely that the increased crusting of manure from pigs fed the DDGS diet reduced hydrogen sulfide emissions by acting as a barrier for emission to the air.

The emissions of various odor compounds from manure in the study conducted by Trabue et al. (2016) are shown in **Table 7**. These data were normalized for pig weight (animal unit) and nutrients consumed. Pigs fed the corn-soybean meal diet had greater ammonia (53 percent of N consumed) and hydrogen sulfide emissions (9 percent of sulfur consumed) than pigs fed the 35 percent DDGS diet (30 percent of N consumed and 2 percent of S consumed). These results are consistent with those from other studies where ammonia emissions were reduced from feeding DDGS diets to swine (Li et al., 2011) and poultry (Roberts et al., 2007; Wu-Haan et al., 2010; Li et al., 2012), which is likely due to reduced pH of manure (Roberts et al., 2007) and increased microbial activity from more carbon present in manure (Kerr et al, 2006; Ziemer et al., 2009). However, manure from pigs fed the 35 percent DDGS diet had greater volatile fatty acid and phenolic compound emissions, but no difference in indole emission than manure from pigs fed the corn-soybean meal diet (**Table 7**). These differences were relatively small compared with ammonia and hydrogen sulfide emissions because total volatile organic compound emissions represented less than 1 percent of the total carbon consumed from feeding both diets. Human panelists detected no differences in odor of compounds emitted from manure from pigs fed the two diets, but chemical analysis of individual odorous compounds showed greater hydrogen sulfide and ammonia, and less total volatile fatty acids and phenols in manure emissions from pigs fed the corn-soybean meal diet than those fed the DDGS diet. The majority (60 percent) of odorous compounds in swine manure were derived from ammonia and hydrogen sulfide. These data indicate that controlling nitrogen and sulfur excretion when feeding DDGS diets does not change ammonia and hydrogen sulfide emissions because the sulfur content in the DDGS diet was almost twice as high as in the corn-soybean meal diet (Trabue and Kerr, 2016), but manure hydrogen sulfide emissions from manure of pigs fed the DDGS diet was about 30 percent less than those fed the corn-soybean meal diet.

Table 6. Manure characteristics and air concentrations of odorous compounds from pigs fed corn-soybean meal and 35 percent DDGS diets (adapted from Trabue et al., 2016)

Measurement	**Corn-soybean meal diet**	**35% DDGS diet**
Manure characteristics		
Temperature, °C	14.1^{b}	14.5^{a}
Dry matter %	3.4^{b}	6.2^{a}
Crusting %	16.7^{b}	87.5^{a}
pH	8.42^{a}	7.61^{b}
Total ammoniacal nitrogen, μmol/g	480^{b}	628^{a}
Total sulfide sulfur, μmol/g	0.41^{b}	0.79^{a}
Air odorant concentrations, μg/m^{3}		
Ammonia	12,627^{a}	8,651^{b}
Hydrogen sulfide	189^{a}	129^{b}
Acetic acid	0.2^{9}b	21.3^{a}
Propanoic acid	0.50^{b}	20.0^{a}
2-methyl propanoic acid	0.49^{b}	17.9^{a}
Butanoic acid	0.67^{b}	32.1^{a}
3-methyl butanoic acid	0.36^{b}	17.7^{a}
Sum of volatile fatty acids ($C_5 – C_7$)	0.23	8.1
Phenol	33.3^{b}	54.6^{a}
4-methylphenol	12.4^{b}	24.1^{a}
4-ethylphenol	7.7^{b}	2.6^{a}
Indole	0.48	0.78
3-methylindole	1.06	0.57

^{a,b}Means with different superscripts within row are different (P less than 0.05)

Table 7. Emissions of odorous compounds from stored swine manure for pigs fed corn-soybean meal and 35 percent DDGS diets (adapted from Trabue et al., 2016)

Gas emission factor	Corn-soybean meal diet	35% DDGS diet
Ammonia, kg NH_3/day/animal unit	185.9^{a}	112.4^{b}
Ammonia, g N/kg N consumed	528.7^{a}	289.3^{b}
Hydrogen sulfide, kg H_2S/day/animal unit	1.80^{a}	0.87^{b}
Hydrogen sulfide, g S/kg S consumed	90.6^{a}	22.7^{b}
Total volatile fatty acids, mg VFA/day/animal unit	14.0^{b}	$1,752^{a}$
Total phenols, mg phenols/day/animal unit	554^{b}	960^{a}
Total indoles, mg indoles/day/animal unit	21.9	19.1
Total volatile organic compounds, g C/kg C consumed	0.31^{b}	0.74^{a}
Human odor panel[2]	772	700
Hydrogen sulfide[3]	576^{a}	287^{b}
Ammonia[3]	40.1^{a}	27.6^{b}
Total volatile fatty acids[3]	4.7^{b}	484^{a}
Total phenols[3]	212^{b}	485^{a}
Total indoles[3]	114	58
Total odor activity value[3]	862	948

[1] Animal unit = 500 kg body weight

[2] Values based on dilution thresholds and chemical analysis reported in odor activity values

[3] Values measured by human panels and chemical analysis normalized for live animal weight of 500 kg

[a,b] Means with different superscripts within row are different (P less than 0.05)

Carbon dioxide, methane and nitrous oxide are major greenhouse gases of concern in animal production systems. From the same study (Trabue et al., 2016), emissions of the major carbon, nitrogen and sulfur gasses were also determined (Trabue and Kerr, 2016). Results from this study showed that carbon dioxide, methane, and nitrous oxide emissions, expressed on an animal unit and amount of element consumed basis, were not different between the two diets (**Table 8**). However, as previously described, ammonia and hydrogen sulfide emission were reduced by feeding the DDGS diet. These results show that pigs fed DDGS diets have no greater greenhouse gas emissions from stored manure than those fed corn-soybean meal diets.

Manure foaming

In 2009, foaming manure became a widespread problem in the pork industry in the United States, causing decreased storage capacity in anaerobic manure pits and increased production of biogases, which created human and animal safety concerns. Although feeding DDGS diets was suggested as a potential contributing factor to this phenomenon, studies (Luo et al., 2015; van Weelden et al., 2016) have shown no direct evidence that feeding DDGS diets increases manure foaming. Results from these studies showed that foaming properties of manure were increased by larger particle size of feed and greater dietary fiber content, which reduce nutrient digestibility and increase dry matter excretion. Furthermore, Van Weelden et al. (2016) showed that manure from pigs fed coarse ground diets containing corn and soybean meal had the lowest methane production rate, and those fed corn-soybean meal-soybean hulls diets had the greatest methane production, with manure from pigs fed the 35 percent DDGS diet having an intermediate methane production rate. However, the biochemical methane production potential was greatest when feeding the 35 percent DDGS diet compared with corn-soybean meal or corn-soybean meal-soybean hulls diets. This suggests that for swine farms installing biogas production systems to capture energy from manure, feeding DDGS diets would provide manure with high amounts of carbon to generate higher amounts of methane.

Life cycle assessment

There is increasing interest in conducting life cycle assessments of the environmental impacts of using various feed ingredients in the swine industry. Lammers et al. (2010) conducted a partial life cycle assessment, which only included production and processing of feed ingredients used in Iowa swine diet formulations, including DDGS, and focused on non-solar energy use and global warming

Table 8. Emissions of major carbon, nitrogen, and sulfur gases in stored swine manure for pigs fed corn-soybean meal and 35 percent DDGS diets (adapted from Trabue and Kerr, 2016)

Gas emission factor	Corn-soybean meal diet	35% DDGS diet
Carbon dioxide, kg CO_2/day/animal unit[1]	3.89	3.71
Carbon dioxide, g C/kg C consumed	285.6	252.5
Methane, kg CH_4/day/animal unit	18.5	21.9
Methane, g C/kg C consumed	5.2	5.6
Ammonia, kg NH_3/day/animal unit	185.9[a]	112.4[b]
Ammonia, g N/kg N consumed	528.7[a]	289.3[b]
Nitrous oxide, kg N_2O/day/animal unit	7.9	7.5
Nitrous oxide, g N/kg N consumed	20.7	19.0
Hydrogen sulfide, kg H_2S/day/animal unit	1.80[a]	0.87[b]
Hydrogen sulfide, g S/kg S consumed	90.6[a]	22.7[b]

[1] Animal unit = 500 kg body weight

[a,b] Means with different superscripts within row are different (P less than 0.05)

potential. Unfortunately, economic analyses of diets were not considered in this study which provided misleading results. In another study by Thoma et al. (2011), there was about a 6 percent increase in the overall carbon footprint of pork production (production to consumption) when DDGS was included in swine diets, which was attributed to the additional energy consumed during processing of corn during the ethanol and co-product production process compared with corn grain and soybean meal.

The environmental impacts of using co-products from human food and biofuels supply chains in pig diets in Canadian pork production systems were determined in a life cycle assessment by Mackenzie et al. (2016). As shown in **Table 9**, feeding corn DDGS at maximum diet inclusion rates increase non-renewable resource use by 71 percent, non-renewable energy use by 68 percent, and global warming potential by 30 percent compared with the control corn-soybean meal diets, on a per kg of feed basis. However, including corn DDGS in the diets reduced acidification potential by 20 percent and eutrophication potential by 22 percent compared with the corn-soybean meal control and all other co-product diets. When environmental impacts were expressed on a kg of carcass weight basis, the impacts were less dramatic but in the same direction as when expressed on a per kg of feed basis.

Table 9. Average environmental impact per kg of feed of Canadian grower-finisher diets when co-product ingredients are included at maximum inclusion rates compared with a corn-soybean meal control diets. (adapted from Mackenzie et al. 2016)

Environmental factor	Control	Meat meal[1]	Bakery meal[1]	Corn DDGS[3]	Wheat shorts[4]
Non-renewable resource use, g Sb eq.	1.90	1.81	1.82	3.25	1.57
Acidification potential, g SO_2 eq.	5.71	5.30	5.32	4.46	5.03
Eutrophication potential, g PO_4 ep.	1.22	1.14	1.16	0.98	1.08
Global warming potential, kg CO_2 eq.	0.40	0.38	0.38	0.52	0.33
Non-renewable energy use, MJ	4.49	4.27	4.27	7.32	3.70

[1] Grower, finisher, and late finisher diets contained 5.0, 7.5, and 7.5 percent meat meal, respectively

[2] Grower, finisher, and late finisher diets contained 7.5, 10.0, and 10.0 percent bakery meal, respectively

[3] Grower, finisher, and late finisher diets contained 30.0, 30.0, and 20.0 percent corn DDGS, respectively

[4] Grower, finisher, and late finisher diets contained 30.0, 40.0, and 20.0 percent wheat shorts, respectively

Conclusions

The use of DDGS in diets for all food producing animals can contribute to improved environmental sustainability when using net energy and digestible nutrients when formulating precision animal feeds, which is essential to minimize excess excretion of nitrogen and phosphorus in animal manure. Although DDGS is relatively high in protein and low in lysine and other amino acids relative to the animal's requirements (swine, poultry and aquaculture), the widespread availability and cost effectiveness of synthetic amino acids allow nutritionists to reduce diet crude protein levels, meet all of the essential amino acid requirements and reduce nitrogen excretion in manure. For grazing ruminants, studies have shown that feeding DDGS not only improves growth and lactation performance, but also the urine and feces excreted from these animals can serve as an efficient and cost-effective way of providing nitrogen to growing pasture grasses and improve yields. One of the unique advantages of corn DDGS compared with other grains and grain-based ingredients is its relatively high total and digestible phosphorus content. Formulating swine and poultry diets on a digestible phosphorus basis and using phytase can significantly reduce manure phosphorus excretion. Furthermore, several studies have shown that feeding DDGS diets reduce methane emissions in ruminants, and ammonia and hydrogen sulfide emissions from swine and poultry manure. Initial studies comparing DDGS with other co-product or by-product ingredients indicate some additional advantages to minimize environmental impact of animal diets.

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