Preface and Acknowledgements

As technology in the U.S. ethanol industry continues to evolve, so does the development of new corn co-products with different nutritional profiles, characteristics, and feeding applications compared with conventional dried distillers grains with solubles (DDGS). Many of these new corn co-products are beginning to be produced in large quantities and are being used domestically and exported to customers in various countries around the world. Of these new corn co-products, corn fermented protein co-products containing at least 50% crude protein and spent yeast have become of interest to many aquaculture, poultry, and swine nutritionists and animal producers. However, there is limited information regarding the nutritional characteristics and feeding value of corn fermented protein co-products for various animal species. This has resulted in some confusion of how they differ from conventional DDGS sources and other types of high protein distillers dried grains (HP-DDG) co-products. Therefore, the purpose of this publication is to provide a concise summary of current research-based information on the use of corn fermented protein co-products and other new corn co-products in animal feeds. This will enable the U.S. Grains Council leadership and representatives to engage and educate current and prospective customers to help them achieve the greatest nutritional and economic benefits when using these co-products in diets for all animal species.

To achieve this goal, the U.S. Grains Council asked Dr. Gerald (Jerry) Shurson, Professor in Animal Nutrition in the Department of Animal Science at the University of Minnesota, to serve as the author of this “Use of Corn Fermented Protein and Other Novel Corn Co-Products in Animal Feeds Users Guide”. Dr. Shurson is a leading expert on the nutritional value and feeding applications of DDGS and these new corn co-products. He has led an active corn co-product research program for the past 24 years, has collaborated extensively with many other corn co-product researchers, and has served as a technical nutrition consultant for the U.S. Grains Council in all export market regions around the world since 1998.

This Novel Corn Co-Products Users Guide was written using all of the peer-reviewed scientific journal publications that are currently available. In addition, some industry technology providers and corn co-product marketers have provided unpublished research data and information for use in this U.S. Grains Council Users Guide. These entities have granted permission to use their data and have reviewed and approved its use in this publication. Special thanks to Drs. Ryan Mass, Mallorie Wilken, and Ms. Jackie Lissolo at ICM, Inc., Dr. Scott Tilton at The Andersons, Dr. Jennifer Aurandt and Mr. Trevin Kennedy at Marquis Energy, and Drs. Kevin Herrick, Melissa Jolly-Breithaupt, and Mr. Derek Balk at POET for graciously providing unpublished data and granting permission for its use in this publication.

Chapter 1
Nutritional Characteristics and Environmental Impacts of Corn Fermented Protein Co-Products

Introduction

Production of sustainable, nutritious, safe, and affordable food for an increasing global population is one of the great challenges faced by our global society today (Shurson, 2017). Feeding the world sustainably requires developing and adopting new innovations to improve nutritional efficiency of food production while managing arable land use, preserving water availability and quality, protecting ecosystems and biodiversity, and mitigating the effects of climate change (Shurson, 2017). Increased competition for grains and oilseeds between biofuels, food, and animal production has led to questions regarding the long-term sustainability of using these resources for production of biofuels (Shurson, 2017). However, using biofuels co-products in animal feeds can contribute to the environmental sustainability of food animal production because converting food crops into biofuels and co-products results in only a 1% to 2.5% loss in overall energy efficiency (Lywood and Pinkney, 2012). Because only the starch and other fermentable carbohydrate fraction of corn is converted to ethanol, the remaining crude protein (CP), oil, fiber, and ash is concentrated in co-products. Therefore, using corn co-products in animal feeds is an efficient way of conserving and utilizing these concentrated sources of energy and nutrients to economically produce meat, milk, and eggs in an environmentally sustainable manner.

Ethanol and co-product production in the United States has changed and increased dramatically over time. Corn co-product production began in the 19th century in the alcoholic beverage distilleries (e.g., whiskey distilleries) that used corn as a primary feedstock, with the resulting wet distillers grains being fed to dairy and beef cattle at nearby farms (Shurson et al., 2012). Up until the 1950s, wet distillers grains were considered to be mainly a protein ingredient and were used to partially replace other protein ingredients, almost exclusively in cattle feeds. In fact, very little corn distillers grains co-products were used in swine and poultry diets until the late 1990s (Shurson et al., 2012). Large wet milling facilities were built in the 1970s and 1980s to produce enough ethanol to consider using it as an additive in gasoline (Shurson et al., 2012). The wet milling process separates starch and corn oil for human food and other industrial applications, leaving behind the protein and fiber fractions. The resulting corn co-products from wet milling processes are corn gluten meal, corn gluten feed, and corn germ meal. Corn germ meal and corn gluten meal are dried and have become popular high protein ingredients in poultry diets, partly because of their concentrated pigments (xanthophylls) which provide natural coloration of egg yolks and broiler skin. In contrast, corn gluten feed has been generally marketed as a wet co-product to beef and dairy farms because these farm animal species were best able to utilize the high fiber content of this co-product. In contrast, during the 1990s to early 2000s, many farmer-owned dry grind ethanol plants were constructed to produce ethanol in larger quantities to meet increased market demands for ethanol use as an oxygenation agent in gasoline (Shurson et al., 2017). This led to the more than 200 dry grind ethanol plants producing about 38 million tons of distillers co-products today, which consist of wet and dried distillers grains without or with solubles, and corn distillers oil (CDO). Two major, and a few minor ethanol and co-product production process designs have been used and have resulted in different nutrient profiles of corn co-products. At the same time, a tremendous amount of animal nutrition research was conducted to expand the use of distillers dried grains with solubles (DDGS) into swine, poultry, and aquaculture diets in both the domestic and export markets. The ensuing educational efforts provided by leading DDGS researchers resulted in much greater DDGS use in U.S. swine and poultry diets, and nutrition consultants for the U.S. Grains Council were instrumental in helping build DDGS demand in the export market, where about 11 million tons of DDGS are exported annually to more than 60 countries.

Corn oil separation from thin stillage after fermentation began around 2005, which reduced the oil (crude fat) content of DDGS and substantially altered its nutrient profile. The reduction in DDGS oil content created concerns about continued use of DDGS in swine and poultry diets based on the assumption that the metabolizable energy (ME) content was reduced. To help DDGS users manage the increased variability in energy and digestible amino acid content among DDGS sources containing variable amounts (4 to 13%) of corn oil, poultry and swine nutrition researchers began developing ME and digestible amino acid prediction equations to accurately estimate these essential components in the specific DDGS source(s) used in feed formulations. Today, almost all U.S. ethanol plants produce DDGS with reduced oil, and the domestic and export markets continue to use DDGS in dairy, beef, swine, poultry, and aquaculture diets. The 4th edition of the U.S. Grains Council DDGS User's Handbook, published in 2018, provides an excellent summary of the feeding value of DDGS with reduced oil to all species of food-producing animals.

Optimization of the efficiency of converting starch to ethanol has resulted in several ethanol facilities following an evolution process similar to that of the wet milling and oilseed processing industries in which nutrients are concentrated in co-products to improve their nutritional value and use in animal feeds. These technologies involve separating corn fiber either prior to, or after fermentation, concentrating the protein and yeast, and removal of variable amounts of corn oil to produce new types of corn co-products called corn fermented protein (CFP). The three major providers of these new proprietary technologies to produce CFP co-products are ICM, Inc., Fluid Quip Technologies, and Marquis Energy. These CFP co-products are much higher in CP (> 50%) content than conventional DDGS with reduced oil (~ 27% CP), with an estimated content of 20 to 29% spent yeast. The energy and digestible nutrient profiles of CFP co-products are also substantially different from high protein distillers dried grains (HP-DDG; 36-48%CP) sources in the market. Corn protein concentrate (CPC) contains the greatest amount of CP (>67%) and least amount of oil (0.5%) of all corn co-products and is produced using distinctly different wet milling processes than those used in dry grind ethanol facilities to produce CFP and HP-DDG. Because of the many types of high protein corn co-products available in the domestic and export market today, it is no surprise that buyers of these co-products are often confused by the terminology and the different nutritional characteristics of these types of corn co-products. Therefore, the purpose of this chapter and Chapter 2, 3, 4, and 5 are to describe the nutritional value and feeding applications of corn fermented protein (CFP) co-products in aquaculture, poultry, swine, and dairy diets, respectively. Chapter 6 provides a summary of the nutritional composition and feeding applications of HP-DDG sources, while Chapter 7 is a summary of CPC feeding applications in aquaculture and poultry diets. Last, Chapter 8 is a summary of the nutritional profiles and feeding studies involving the use of other corn co-products including corn bran and solubles (CBS), deoiled DDGS, and CDO.

Understanding Crude Protein and Amino Acids in Corn Co-Products

On the surface, feed ingredients that contain high concentrations of CP are attractive for use in all animal feeds because CP (amino acids) is the second most expensive component of animal diets after energy, and relatively low amounts of high CP ingredients are often needed to meet an animal's amino acid requirements. However, although CP, crude fat, and crude fiber continue to be universally used in pricing and trading feed ingredients around the world, the actual nutritional and economic value of feed ingredients is not based on these nutritional measures. Instead, the metabolizable energy (ME) or net energy (NE), digestible amino acids, and digestible phosphorus content are the key determinants of actual nutritional and economic value. The CP content of a feed ingredient is determined by measuring the nitrogen content and multiplying this concentration by a constant factor of 6.25, which is the inverse of the weighted average nitrogen content of 16% in proteins (Shurson et al., 2021). Nitrogen is one of the chemical components that make up amino acids, which are building blocks of proteins, and is used as a proxy to estimate the protein content of ingredients. However, the accuracy of using this universal method for estimating the actual concentrations of intact proteins is not sufficient for achieving optimal amino acid (protein) utilization in animal feeds because amino acid profiles vary, and some ingredients contain relatively high concentrations of non-protein nitrogen compounds (e.g., nucleic acids and nucleotides, some vitamins, amines, amides, and urea) that are not proteins. In addition, CP provides no information about concentrations, proportions, digestibility, and bioavailability of amino acids which is required data used in diet formulations (Shurson et al., 2021).

Soybean meal (SBM) is typically used as a global reference or "gold standard" of high protein (44-48% CP) ingredients because it contains high concentrations of all essential (indispensable) amino acids that are highly digestible (85-95%) and in balanced proportions relative to the amino acid requirements of swine, poultry, and fish when combined with a grain-based energy source. Compared with soy protein, corn protein is relatively low in lysine (Lys) content and is considered the first limiting amino acid (most likely to be deficient) in diets for monogastric animals. The Lys to CP ratio in corn co-products (2.8 to 4.0) is much less than in SBM (6.2). As a result, when corn co-products (e.g., DDGS, HP-DDG, CFP) are added to swine, poultry, and aquaculture diets as partial replacements for SBM, supplemental crystalline L-Lys HCl and other synthetic amino acids are usually required to meet digestible amino acid requirements of monogastric animals. In addition, the digestibility of Lys in corn co-products (e.g., DDGS – 65%) is generally substantially less than in SBM (90%) for swine, poultry, and fish. Because swine and poultry diets are formulated on a digestible amino acid basis, ingredients containing lower amounts of digestible Lys (e.g., DDGS) must be either added in greater amounts to meet the digestible amino acid requirements of animals, or crystalline amino acids (e.g., L-Lys HCl), which are about 98% digestible, must be supplemented. The same principle applies to other essential amino acids such as threonine (Thr), tryptophan (Trp), methionine (Met), valine (Val), and isoleucine (Ile) which are generally less digestible in corn co-products (e.g., DDGS – 73-82%) than in SBM (85-91%) for monogastric animals.

Compared with SBM, corn co-products have much greater fiber content (neutral detergent fiber – NDF; total dietary fiber - TDF) which has been shown to increase intestinal mass and mucin secretion in the intestinal tract of pigs. Threonine is the primary amino acid that comprises intestinal epithelial cells and mucin, which leads to increased endogenous losses of Thr when high fiber diets are fed to pigs. Because mucin proteins are poorly digested and amino acids are not reabsorbed, synthetic L-Thr must be added to swine diets containing > 10% corn co-products to compensate for these increased Thr losses and optimize growth performance (Mathai et al., 2016; Wellington et al., 2018). It is unclear if these responses occur in poultry and fish, but it is likely that they do, and L-Thr supplementation may be necessary to optimize growth performance and carcass composition in poultry and fish diets containing moderately high diet inclusion rates of corn co-products.

Leucine (Leu) is the most abundant amino acid in both SBM (3.62%) and corn co-products (e.g., DDGS = 5.30%), but the proportion of Leu relative to Lys in corn protein is in great excess relative of the requirements of pigs, birds, and fish. The consequences of excess Leu become more significant as the diet inclusion rates of corn co-products increase. Excess Leu increases the catabolism of Ile and Val (two other branched-chain amino acids; BCAA) because BCAA have similar molecular structures and catabolic pathways. Therefore, as SBM is partially or completely replaced with the addition of more than 20% of high CP corn co-products in swine diets, synthetic L-Val and L-Ile must be added to compensate for the negative effects of excessive Leu (Cemin et al., 2019a,b; Kwon et al., 2019; Kwon et al., 2020; Siebert et al., 2021; Zheng et al., 2016). However, the optimal digestible Val to Lys and Ile to Lys ratios have not been well defined in pigs, poultry, or fish diets. Similar evidence exists for the need to manage BCAA balance in poultry diets (Waldroup et al., 2002; Peganova and Eder, 2003; Erwan et al., 2008; Ospina-Rojas et al., 2017; Soares et al., 2019), but little is known about the role of dietary excesses of leucine and BCAA balance in aquaculture diets.

In contrast to Leu, the Trp concentrations in corn co-products are lowest of all essential amino acids. Despite its relatively low requirement for swine and poultry, Trp plays several important physiological roles including protein synthesis of lean body tissue, regulation of immune responses, and is a precursor for serotonin which regulates appetite and stress. However, to support optimal serotonin production, adequate amounts of Trp must be transported across the blood-brain barrier. Unfortunately, Trp competes with large neutral amino acids (Ile, Leu, Phe, Tyr, and Val) for transport across the blood-brain barrier. Excess large neutral amino acids (i.e., Leu) decrease serotonin concentrations suggesting that supplementing swine diets with L-Trp may overcome feed intake reductions caused by excess Leu in swine diets resulting from increasing inclusion rates of high CP corn co-products (Salyer et al., 2013; Kwon et al., 2019; Cemin et al., 2020; Kerkaert et al., 2021; Clizer, 2021). Although the ideal digestible Trp to Lys ratio has not been defined in corn co-product diets for swine, research results suggest that this ratio is greater than current NRC (2012) recommendations. It is likely that similar considerations should be given toward increasing the Trp content in poultry and aquaculture diets containing high amounts of high CP corn co-products to optimize growth and carcass characteristics.

Yeast Content of Corn Co-Products

One of the distinguishing features of CFP co-products from other corn co-products is that they contain an estimated 20 to 29% spent yeast (*Saccharomyces cerevisiae*), which is substantially greater than the estimate of 7 to 10% spent yeast in conventional DDGS sources (Shurson, 2018).

However, it is important to note that the residual spent yeast in CFP is not in a viable form that allows it to function as a direct fed microbial (DFM) or probiotic in animal feeds like viable yeast products such as active dry yeast. However, the components of yeast cell walls (mannan oligosaccharides, nucleotides, and β-glucans) have been shown to provide health benefits when fed to animals in some studies (Shurson, 2018). Prohibiting the use of antibiotics for growth promotion in animal feeds in many countries has created tremendous interest in identifying "functional" ingredients that contain compounds that may provide health benefits to food-producing animals (Shurson et al., 2021). There has been an extensive amount of research conducted in recent years to evaluate the effectiveness, magnitude, and consistency of improved growth performance responses from adding various alternative non-antibiotic feed additives to animal feeds, including viable yeast (Vohra et al., 2016) as direct fed microbials (DFM; probiotics), and yeast cell wall derivatives including mannan oligosaccharides, nucleotides, and β-glucans (Shurson, 2018). Therefore, these yeast cell wall components represent one of the potential value-added features of using CFP co-products in animal feeds. Unfortunately, the efficacy and consistency of growth and health responses from adding concentrated forms of mannan oligosaccharides, nucleotides, and β-glucans in animal feeds has been disappointing.

Although summaries of results from more than 733 published trials that evaluated the effects of feeding mannan oligosaccharides to companion animals, horses, rabbits, poultry, pigs, calves, and various aquaculture species have generally shown improvements in growth rate and feed conversion along with reductions in mortality, the responses were not consistent (Spring et al., 2015). In poultry, Hooge (2004a, b) summarized responses (16 to 44 feeding trials) from feeding mannan oligosaccharides to broilers and turkeys and reported that while the magnitude of improvement in growth rate and feed conversion was relatively small and inconsistent, more than half of the studies showed significant reductions in mortality. Miguel et al. (2004) reported that the magnitude of improvement from adding mannan oligosaccharides to nursery pig diets was greater than the responses observed in the poultry studies reported by Hooge (2004a, b), but results were inconsistent. Similarly, Torrecillas et al. (2014) reported that while several studies showed improvements in survival, disease resistance, and growth performance in fish, other studies showed no change when mannan oligosaccharides were added to diets.

The β-glucan concentration in CFP co-products has been estimated to be about 8.2 to 8.4% using the Megazyme International Yeast β-glucan assay (Shurson, 2018). Beta-glucans are classified as prebiotics, but their molecular structure varies among sources and affects their physiological functions. Vetvicka et al. (2014) reviewed studies involving the addition of β-glucans to pig diets and reported improvements in growth and various types of immune responses. However, Vetvicka and Oliveira (2014) concluded that the inconsistent growth and health responses from dietary supplementation of β-glucans in pig diets may be due to differences in their molecular structure, molecular weight, and purity. Feeding yeast β-glucans to several species of fish has been shown to improve pathogen resistance, growth performance, and survival in several studies (Ringo et al., 2012). However, it is unlikely that the concentration of β-glucans in CFP co-products is great enough, at the relatively low dietary inclusion rates of CFP co-products used in aquaculture diets to provide these health benefits.

Yeast-derived nucleotides have been shown to improve intestinal morphology and function, immune response, composition in intestinal microbiota, liver function and morphology, and growth performance (Sauer et al., 2011). However, because yeast contains other bioactive metabolites and cell wall components, it is difficult to attribute improvements in growth and immune responses solely to nucleotides (Sauer et al., 2011). Results from a summary of responses from 15 studies showed consistent improvements in immune responses, pathogen resistance, growth performance and survival from feeding various sources of nucleotides to fish (Ringo et al., 2012). However, most of the responses from 16 studies reviewed by Sauer et al. (2011) that involved feeding various concentrations of *Saccharomyces cerevisiae*, yeast culture, and commercial nucleotide products to pigs showed no effect.

Although the estimated amount of spent yeast in CFP co-products is interesting and a potential value-added benefit beyond the nutritional value of these co-products, it should not be the primary reason for their use in animal feeds for several reasons. First, residual yeast is not in a viable to function as a probiotic. Second, the concentration of spent yeast only represents about 25% of the total mass of CFP co-products, which means that much lower concentrations of individual bioactive yeast cell wall components (mannan oligosaccharides, β-glucans, and nucleotides) are present. Finally, the effectiveness, magnitude, and consistency of growth and health improvements from the addition of concentrated yeast products and their derivatives has been disappointing. To put these points in perspective, Schweer et al. (2017) summarized growth performance responses from over 2,000 research trials with swine that evaluated various non-antibiotic feed additives including oligosaccharides, prebiotics, and yeast products, and reported that only about 30% of these trials showed improvements in growth performance. Among the product categories, direct fed microbials (39.9% of trials), pharmacological levels of zinc and copper (39.2% of trials), and organic acids (31.2%) were the most consistent in improving growth rate of pigs. Of the 98 trials that evaluated yeast products, only 23.5% reported increased growth rate, 12.2% reported increased feed intake, 11.2% showed improved gain efficiency, and only 1% reported reduced mortality. It is commonly believed that alternatives to growth promoting antibiotics may be more effective when animals are under a health challenge or stressful event. However, in this scientific literature review summary, only 8.6% of the trials reported some type of health challenge, and direct fed microbials (35%) and pharmacological levels of zinc and copper (30%) were more likely to provide growth improvements than other feed additives evaluated. These results indicate that while yeast products may provide some growth performance and health benefits to weaned pigs (and poultry and fish) under certain conditions, the likelihood of achieving a consistent positive response is relatively low and the conditions that lead to positive growth responses have not been well defined.

AAFCO Definitions of Corn Co-Products

Accurate and effective communication between sellers and buyers regarding the nutritional composition and feeding value of feed ingredients is essential to avoid unwanted surprises or disappointments. Unfortunately, one of the greatest communication challenges in the corn co-product market (and in the published scientific literature) is the lack of awareness and use of standardized American Association of Feed Control Officials (AAFCO) definitions of various corn co-products. In addition, the use of different brand names for several CFP co-products produced using the same technology has created confusion in the market. A summary of common names, brand names (if applicable), typical analysis, and the AAFCO definitions of various types of corn co-products is shown in **Table 1**. The common names and brand names (if applicable) provided in this table should be used by buyers when communicating with suppliers of various corn co-products to ensure that there is clear understanding of the type of co-product being considered. Marketers of corn co-products are also encouraged to avoid using ethanol industry jargon when communicating with ingredient buyers and nutritionists in the feed industry. For example, terms such as “condensed distillers solubles” should be used instead of “syrup” to help customers align their understanding of the type and characteristics of corn co-products with official AAFCO definitions and terminology. Another common terminology mistake that is frequently made, involves the description of the relative differences in corn oil content among types of DDGS. Terms such as “full-fat”, “reduced-oil”, and “de-oiled” DDGS are often intended to provide a relative indication of the crude fat content of DDGS, but unfortunately, too many times the term “deoiled” is misused when referring to “reduced-oil” DDGS. The only “de-oiled” corn co-product in the market today is produced by solvent extraction of corn oil which results in a DDGS co-product that contains less than 3% crude fat and is marketed under the brand name NovaMeal. Therefore, it is important to clearly define the minimum crude fat or oil content of DDGS sources during communications between buyers and sellers.

Perhaps the most confusing term among ethanol co-products is the use of “high protein” to describe corn co-products that contain more than the 25% to 30% CP found in conventional DDGS. Although HP-DDG (36% to 48% CP) is a distinctly different category of corn co-products than DDGS, it is often confused with CFP co-products, which contain CP concentrations that contain more than 48% CP. The processes used to produce CFP are substantially different than those used to produce HP-DDG and results in different nutritional profiles. This is the main point of differentiation between the two CFP categories is that the Fluid Quip Technologies and the ICM, Inc. processes do not use any additives and are listed in the CFP Mechanically Separated category. The Marquis ProCap™ process uses a flocculant and Harvesting Technologies uses a polymer in their process resulting in classifying these co-products in the Corn Fermented Protein category (without mechanical separation).

Similarly, CFP sources are also confused with CPC sources which are produced by very different wet milling processes resulting in substantially different nutritional profiles. Unfortunately, corn co-product producers, marketers, and researchers have often not carefully described and used appropriate terminology when communicating information about the different co-products in research publications, websites, presentations, technical brochures, and product specifications sheets. Therefore, nutritionists are cautioned to be aware of the significantly different nutrient profiles among various “high protein” corn co-products that have been produced and evaluated in animal feeding trials during the past 15 years when using data from various published research studies. One of the goals of this U.S. Grains Council Corn Co-Product Handbook is to summarize these differences to help ingredient purchasers and animal nutritionists understand the differences among this increasing portfolio of corn co-products.

Table 1. Common names, brand names, typical analysis, and American Association of Feed Control Officials (AAFCO) definitions of corn co-products

Common Name	Brand Name	Typical Analysis (As-Fed Basis)			AAFCO Identification	General Description
		Crude Protein, %	Crude Fat, %	Crude Fiber, %		

DDGS	None - commodity	25-30	6-9	<14	27.6, 27.8	Dried distillers grains with condensed distillers solubles are obtained after the removal of ethanol by distillation from yeast fermentation of a grain by condensing and drying at least ¾ of the solids of the resulting whole stillage and after a portion of oil is removed.
DDGS	Dakota Gold	24-29	4-5	<14	27.6, 27.8	Dried distillers grains with condensed distillers solubles are obtained after the removal of ethanol by distillation from yeast fermentation of a grain by condensing and drying at least ¾ of the solids of the resulting whole stillage and after a portion of oil is removed.
De-oiled DDGS	NovaMeal	26-36	<3	<14	27.9	Solvent-extracted DDGS resulting in a crude fat content of less than 3%.
Full Fat DDGS	None – commodity	25-32	10-14	<14	27.6, 27.8	Dried distillers grains with condensed distillers solubles are obtained after the removal of ethanol by distillation from yeast fermentation of a grain by condensing and drying at least ¾ of the solids of the resulting whole stillage with no oil removed.
DDGS with Bran	None – commodity	23-36	3-16	<14	27.6, 27.8, 48.2	DDGS mixed with bran separated by plant prior to fermentation. Can be in dry or wet form (dry form common analysis is provided here).
DDGS Mechanically Separated	Not commercially available	24-48	3-8	<14	27.6	Post-distillation residual whole stillage resulting from the mechanical separation of fiber and protein. Contains condensed distillers solubles. Can be in dry or wet form (dry form common analysis is provided here).
DDG	None – commodity	24-35	4-8	<14	27.5	Dried distillers grains without condensed distillers solubles is obtained after the removal of ethanol by distillation from yeast fermentation of a grain or grain mixture. May have a portion of oil removed.
High Protein DDG	ANDVantage™ 40Y and other unbranded sources using ICM, Inc. FST™	36-48	4-6	<12	27.5	Dried distillers grains with a portion of fiber and oil removed to concentrate the protein but contains no condensed distillers solubles.
Condensed distillers solubles (syrup)	None – commodity	5-25	3-23	0-4	27.7	Condensed distillers solubles is obtained after removal of ethanol after distillation by condensing the thin stillage fraction into a semi-solid.
Condensed distillers solubles (syrup)	SOLMAX™	19-21	2-7	<1	27.7	Condensed distillers solubles is obtained after removal of ethanol after distillation by condensing the thin stillage fraction into a semi-solid (approximately 50-75% solids).
Distillers Dried Yeast	ALTO YEAST PROPLEX DY	40-55	0-8	0-6	96.5	Dried, non-fermentative, inactive *Saccharomyces cerevisiae* yeast removed from the mash either before or after distillation and must contain more than 40% crude protein.
Hydrolyzed Yeast	ULTRAMAX™	40-45	6-10	3-5	96.12	Concentrated, non-extracted, partially soluble (accomplished by enzymatic hydrolysis), yeast digest.
Bran with Syrup	Solbran™ ANDVantage™ Bran Plus and other unbranded sources using ICM, Inc. FST™	18-28	4-9	15-20	48.2, 27.7	Bran separated from grain prior to fermentation and added to condensed distillers solubles after fermentation before drying. Can be in dry or wet form (dry form common analysis provided).
Fermented Fiber Mechanically Separated	Not commercially available	<24	2-7	10-20	27.6	Post-distillation mechanical separation of the whole stillage resulting in a concentration of fiber. Does not contain distillers solubles unless listed.
Corn Fermented Protein	None	>48	3-8	<8	27.5	Portions of fiber and oil removed by concentrating residual grain and yeast proteins by methods commonly used in the

						distilling industry. Contains concentrated spent yeast. Does not contain condensed distillers solubles unless listed
Corn Fermented Protein Mechanically Separated	A+ Pro BP 50 NexPro® AltiPro™ Still Pro 50™[1] ANDVantage™ 50Y PROTOMAX™ ProCap Gold™	>48	1-5	<8	27.5	Post-distillation separation of protein from the whole stillage, utilizing only mechanical separation. Will contain spent yeast products, no non-mechanical methods utilized post-distillation. Does not contain distillers solubles unless listed.

[1]Still Pro 50™ is no longer being sold under this name but is listed here because it is used in published scientific literature to describe corn fermented protein produced using Fluid Quip Technologies.

Corn distillers oil (CDO) is another major co-product available for use as a supplemental energy source in animal feeds and was not listed in Table 1 because it contains no CP or crude fiber. The process involves partially removing corn oil by centrifugation from the condensed distillers solubles stream or by solvent extraction of DDGS. Corn distillers oil contains more than 85% total fatty acids, less than 2.5% unsaponifiable matter, less than 1% insoluble impurities, and its fatty acid profile, metabolizable energy content and feeding applications for swine and poultry are described in Chapter 8 of this handbook.

Nutrient Profile of Corn Fermented Protein Co-Products

There are at least three different types of proprietary processing technologies used to produce corn fermented co-products. ICM's Advanced Processing Package™ (APP™) is used to produce PROTOMAX™, also sold by The Andersons, Inc. as ANDVantage 50Y. Fluid Quip Technologies' Maximized Stillage Co-Products Technology™ (MSC™) is used to produce CFP co-products with brand names of BP50, A+ Pro, NexPro®, and Altipro. Marquis ProCap™ Technology™ is used to produce a CFP co-product marketed under the brand name of ProCap Gold™. Although each of these types of technologies concentrate the protein and yeast in the final co-products, their nutritional profiles are different (**Table 2**). In addition, other new technologies are being commercialized and will produced new corn co-products that will enter the feed ingredient market in the near future.

On a dry matter (DM) basis, the gross energy content of CFP sources varies from 5,309 kcal/kg DM to 5,795 kcal/kg DM but is substantially greater than the 4,940 kcal/kg DM to 5,140 kcal/kg DM found in conventional DDGS sources (Yang et al., 2021). A few studies have determined and compared the ME content of some CFP sources with DDGS sources for swine (Chapter 6) and broilers (Chapter 5), and the ME content of CFP co-products are 1.2 to 1.5 times greater than in DDGS. The CP content of CFP co-products also varies but is generally greater than 53% (DM basis). Likewise, this wide range in CP content resulted in variable concentrations of many of the indispensable amino acids among CFP co-product sources (**Table 3**), especially for Lys (1.91% to 2.26%), Met (0.93% to 1.37%), Thr (1.86% to 2.15%), and Trp (0.39% to 0.62%).

Although different measures of lipid (ether extract and acid hydrolyzed ether extract) and fiber [neutral detergent fiber (NDF), acid detergent fiber (ADF), soluble dietary fiber, insoluble dietary fiber, and total dietary fiber TDF)] content have been reported in various published studies for different CFP co-products, the concentrations of the nutritional components also vary among sources (**Table 3**). Although the ash content of CFP sources ranges from 1.54% to 8.49%, the calcium and phosphorus concentrations are relatively similar among sources. Therefore, to optimize energy and nutritional efficiency when including any of these CFP co-products in swine and poultry diets, it is essential to use appropriate ME, digestible amino acid, and digestible phosphorus values during feed formulation, and currently available information is summarized in Chapters 5 and 6 of this Handbook.

Table 2. Comparison of the nutritional composition of various sources of corn fermented protein (dry matter basis)

Analyte	ANDVantage 50Y[1]	Still Pro 50[2]	A+ Pro[3]	NexPro[4]	ProCap Gold[5]
Dry matter, %	93.76	100.00	91.73	93.00	88.00
Gross energy, kcal/kg	5,636	NR	5,351	5,309	5,795
Crude protein, %	55.24	53.0	54.73	53.87	55.78
Lys:crude protein	3.46	4.19	3.96	3.95	3.93
Ether extract, %	NR*	5.1	5.0	NR	NR
Acid hydrolyzed ether extract, %	10.56	NR	NR	6.02	10.78
Neutral detergent fiber, %	30.56[6]	24.1	26.52	NR	NR
Acid detergent fiber, %	22.22[6]	4.83	5.27	NR	NR
Soluble dietary fiber, %	2.99	NR	NR	3.66	1.16
Insoluble dietary fiber, %	29.2	NR	NR	26.23	24.74
Total dietary fiber, %	31.14	NR	NR	29.89	25.90
Ash, %	1.54	5.49	5.98	8.49	8.39
Ca, %	0.02[6]	0.05	0.04	NR	0.05
P, %	0.70[6]	1.1	0.89	NR	0.88

*NR = not reported.
[1]Unpublished data from Lee and Stein (2021) obtained with permission from The Andersons, Inc.
[2]Published data obtained from Correy et al. (2019); Still Pro 50™ is no longer being sold under this name but is listed here because it was used in this study to describe corn fermented protein produced using Fluid Quip Technologies.
[3]Published data obtained from Yang et al. (2021).
[4]Published data obtained from Acosta et al. (2021).
[5]Published data obtained from Cristobal et al. (2020).
[6]Unpulished data obtained with permission from The Andersons, Inc.

Table 3. Comparison of amino acid profiles of corn fermented protein sources (dry matter basis)

Analyte	ANDVantage 50Y[1]	Still Pro 50[2]	A+ Pro[3]	NexPro[4]	ProCap Gold[5]
Dry matter, %	93.76	100.00	91.73	93.00	88.00
Crude protein, %	55.24	53.0	54.73	53.87	55.78
Indispensable amino acids, %					
Arg	2.53	2.49	2.57	2.48	2.81
His	1.22	1.41	1.57	1.43	1.59
Ile	2.14	2.24	2.46	2.35	2.31
Leu	6.87	5.80	6.87	6.11	6.33
Lys	1.91	2.22	2.17	2.13	2.15
Met	1.37	1.05	1.17	1.09	1.24
Phe	2.93	2.67	2.90	2.68	2.85
Thr	2.13	2.06	2.19	2.15	2.15
Trp	0.62	0.45	0.40	0.45	0.56
Val	2.71	3.08	3.21	3.04	3.23
Dispensable amino acids, %					
Ala	4.07	3.51	4.09	3.73	3.88

Asp	3.72	3.62	3.89	3.81	3.84
Cys	1.19	0.90	1.07	0.94	1.14
Glu	9.46	7.61	8.88	7.94	8.55
Gly	2.09	2.00	2.18	2.16	2.34
Pro	4.45	3.46	NR	3.76	4.00
Ser	2.55	2.25	2.47	2.33	2.50
Tyr	2.47	2.08	2.22	2.13	2.16

*NR = not reported.
[1]Unpublished data from Lee and Stein (2021) obtained with permission from The Andersons, Inc.
[2]Published data from Correy et al. (2019); Still Pro 50™ is no longer being sold under this name but is listed here because it was used in this study to describe corn fermented protein produced using Fluid Quip Technologies.
[3]Published data from Yang et al. (2021).
[4]Published data from Acosta et al. (2021).
[5]Published data from Cristobal et al. (2020).

Environmental Impacts of Corn Fermented Protein Co-Products

The future of the planet and human societies is dependent on our ability to create a regenerative, circular economy that reduces waste, carbon and nitrogen footprints, and climate change while improving efficiency of resource use to keep consumption within planetary boundaries with an ever-increasing global population of people. One of the most widely debated topics involving food security and sustainability is whether food animal production should continue to be a part of our global food system.

Animal agriculture is central to our global food system, economies, and society, and accounts for 40% of agricultural gross domestic product, employs 1.3 billion people, creates livelihoods for 1 billion poor people, provides 33% of dietary protein intake, and is a potential solution for overcoming undernourishment (Steinfeld et al., 2006). However, animal agriculture is a major contributor to many environmental problems including land degradation, climate change, air pollution, water shortage and pollution, and loss of biodiversity (Steinfeld et al., 2006).

Estimates of global greenhouse gas (GHG) emissions from livestock production have been reported to range from 8 to 51% which has created confusion among scientists and policy makers (Herrero et al., 2011). While this estimate has been highly debated, the current estimate is 14.5% (Gerber et al., 2013). Depending on animal species, type of production system, and geographic location, feed production contributes 50 to 85% of climate change impact, 64 to 97% of eutrophication potential, 70 to 96% of energy use, and about 100% of land occupation in monogastric animal production systems (Garcia-Launay et al., 2018). Therefore, because feed ingredients used in animal feed production have a large influence on environmental impact, one of the most effective strategies to reduce the environmental impact of food animal production is to use multi-objective diet formulation approaches including low environmental impact feed ingredients determined by LCA (Mackenzie et al., 2016b; Garcia-Launay et al., 2018; de Quelen et al., 2021; Méda et al., 2021; Soleimani and Gilbert, 2021). Life cycle assessment (LCA) is a compilation and evaluation of the inputs, outputs, and environmental impacts of a system used to produce a product throughout its life cycle (van Middelaar et al., 2019). Standardized methodology and guidelines have been established for determining various LCA environmental impact indicators (LEAP, 2015), but most of the limited number of LCA feed ingredient databases include feed ingredients used in the European Union, and LCA values are not directly applicable to ingredients used in the United States. However, the Global Feed LCA institute (GFLI; https://tools.blonkconsultants.nl/tool/16/) has developed the largest database (962 feed ingredients) with the most LCA indicator variables (n = 18; **Table 4**) and the most widespread global application (European Union, United States, and Canada).

Table 4. Global Feed LCA Institute environmental impact measures that have been applied to feed ingredients

Environmental impact measure	Unit	Description
Global warming with or without land use change	kg CO_2 equiv./kg product	Indicator of potential global warming due to emissions of greenhouse gases to the air, using carbon dioxide as a standard, with or without a change in land use
Stratospheric ozone depletion	kg CFC11 equiv./kg product	Indicator of emissions to air that cause destruction of the stratospheric ozone layer using chlorofluorocarbon-11 as a reference standard
Ionizing radiation	kBq Co-60 equiv./kg product	Impact on radiation as measured by kilobecquerels of cobalt-60 radioactive isotope as a reference standard
Ozone formation, human health	kg NOx equiv./kg product	Impact on nitrous oxide gases that affect the ozone and human health
Fine particulate matter formation	kg PM2.5 equiv./kg product	Impact on air quality as atmospheric particulate matter with particles having a diameter of less than 2.5 micrometers
Ozone formation, terrestrial ecosystems	kg NOx equiv./kg product	Impact on nitrous oxide gases that affect the ozone and human health
Terrestrial acidification	kg SO_2 equiv./kg product	Indicator of the potential acidification of soil and water due to the release of nitrogen oxide and sulfur oxide gases
Freshwater eutrophication	kg P equiv./kg product	Indicator of the potential for increased phosphorus emission to freshwater
Marine eutrophication	kg N equiv./kg product	Indicator of the potential for increased nitrogen emission to freshwater
Terrestrial ecotoxicity	kg 1,4-DCB/kg product	Impact of toxic substances emitted to the environment on land organisms using 1,4-dichlorobenzene as a standard
Freshwater ecotoxicity	kg 1,4-DCB/kg product	Impact of toxic substances emitted to the environment on freshwater organisms using 1,4-dichlorobenzene as a standard
Marine ecotoxicity	kg 1,4-DCB/kg product	Impact of toxic substances emitted to the environment on sea water organisms using 1,4-dichlorobenzene as a standard
Human carcinogenic toxicity	kg 1,4-DCB/kg product	Impact of carcinogenic toxic substances to the environment using 1,4-dichlorobenzene as a standard
Human non-carcinogenic toxicity	kg 1,4-DCB/kg product	Impact of non-carcinogenic toxic substances to the environment using 1,4-dichlorobenzene as a standard

Land use	m^2a crop equiv./kg product	Impact of converting non-agricultural land into agricultural use
Mineral resource scarcity	kg Cu equiv./kg product	Indicator of depletion of natural inorganic mineral resources using copper as a standard
Fossil resource scarcity	kg oil equiv./kg product	Indicator of the depletion of natural fossil fuel resources
Water consumption	m^3/kg product	Indicator of the amount of water (cubic meters) required to produce a kg of product

In addition to GHG emission and carbon footprint, the Food and Agriculture Organization of the United Nations recently initiated a new focus on improving nitrogen (N) utilization and reducing N waste by 50% by 2030. The global livestock industry contributes about one-third of human-induced N emissions (nitrates, ammonia, nitrous oxide, and other nitrogen oxides), poultry and pork supply chains contribute 29% of the total from food animals, and 68% of these N emissions are associated with feed production (Uwizeye et al., 2020). Nitrous oxide is a potent greenhouse gas, and ammonia and nitrogen oxides contribute to air pollution, cause acidification and eutrophication, and pose risks to human health (Galloway et al., 2008; Sutton et al., 2013). Nitrates and organic N have caused increased water pollution and biodiversity loss (Galloway et al., 2003; Hamilton et al., 2018; Ascott et al., 2017; Erisman et al., 2013). Globally only 20% of N is retained in useful products with 80% of various forms lost to the environment (Sutton et al., 2019). Therefore, there is a tremendous need to improve the protein-amino acid-nitrogen utilization of diets in food animal production, especially those that may provide a substantial amount of amino acids like CFP, toward meeting the daily requirements of efficient food animal species of fish, poultry, and pigs.

Phosphorus (P) is the third most expensive nutritional component of animal diets beyond energy and amino acids. Oster et al. (2018) identified several gaps that must be addressed to balance the agricultural P cycle and improve sustainability of pig and poultry production and suggested improving animal feeding strategies (adding phytase to diets), reusing and recycling (manure and slaughter waste), focusing on soil agroecosystems, improving farmer economic performance, and developing effective government policies and regulations (P quota, P tax). One important aspect missing from these strategies is the use of corn co-products such as CFP and DDGS which have relatively high concentrations of digestible P which can reduce reliance on inorganic P supplements and P excretion in manure. If corn co-products are not included in swine, poultry and aquaculture diets, the only other option to optimize P utilization when feeding diets containing plant-based ingredients with relatively high amounts of phytate to swine is to add exogenous phytase enzymes. By using phytase, the proportion of dietary P used by the animal is increased, the amount of P excretion in manure is reduced, and the antinutritional effects of phytate on digestibility of other nutrients are minimized (Shurson et al., 2021). In fact, several ethanol plants add phytase during the fermentation process which further increases the conversion of indigestible phytate to digestible phosphate (Reis et al., 2018). All of these benefits are provided by using CFP and other corn co-products because the amount of phytate in corn is naturally converted to digestible phosphates by yeast during the fermentation process. Therefore, achieving the goal of “phytate-free” nutrition proposed by Cowlieson et al. (2016) is possible if corn co-products and phytase are used strategically in monogastric diets.

Corn production uses large amounts of water, land, and other inputs that contribute to GHG emissions, climate change, fossil fuel depletion, air pollution, and local water scarcity (Smith et al., 2017). The U.S. ethanol industry and animal production are the primary consumers of corn and are becoming increasingly focused on assessing and improving environmental sustainability. While some studies (Kraatz et al., 2013) have suggested that converting whole stillage into electricity, heat, and fertilizer has 54% less energy intensity and 67% less global warming potential than processing it into DDGS, Smith et al. (2017) developed a model to account for country-level environmental impacts of using U.S. corn in animal production and ethanol supply chains and showed that these effects vary among location, industry sector, and environmental indicators evaluated. Several studies have evaluated various environmental impacts of feeding corn distillers' grains with solubles to beef cattle (Hünerberg et al., 2014; Leinonen et al., 2018; Asem-Hiablie et al., 2019; Werth et al., 2021), dairy cattle (Aguirre-Villegas et al., 2015), poultry (Kebreab et al., 2016; Benavides et al., 2020), swine (Stone et al., 2012; Meul et al., 2012; Kebreab et al., 2016; Mackenzie et al., 2016a,b; Benavides et al., 2020), and aquaculture (Henriksson et al., 2017; Cortés et al., 2021). Depending on the system boundaries being modeled, allocation method, and proportion of environmental impacts assigned to ethanol and DDGS, there are positive and negative environmental benefits of feeding DDGS to various animal species. However, this is not different than for most other feed ingredients.

Because of the tremendous need to reduce the carbon footprint in biofuels and co-product production, Marquis Energy was one of the first U.S. ethanol and co-product production facilities to become certified in the International Sustainability and Carbon Certification (ISCC) program in 2010. The ISCC was formed to meet the European Union directive of reducing GHG emissions by using renewable energy, and a low carbon intensity (CI) score is required to market biofuels in the European Union. In Japan, ISCC Plus is required for biofuels marketers. Although the ISCC was designed for assigning a CI score to biofuels, the program also assigns a CI score to corn co-products produced such as DDGS and CFP (ProCap Gold™). Unlike most LCA determinations, all CI inputs in the ISCC program are distributed to each product stream (including corn co-products) based on the energy content derived from each stream. This results in equal CI scores for ethanol and co-products at the ethanol plant gate. The current carbon intensity of DDGS in the U.S. ethanol industry is about 700 g of CO_2 equivalent/kg of DDGS. The DDGS and CFP (ProCap Gold™) produced by Marquis Energy has a CI score (https://www.iscc-system.org/certificates/valid-certificates/) that is only about 25% (175 g of CO_2 equivalent/kg of DDGS and ProCap Gold™) of the corn co-product sources in the industry. This dramatic reduction in carbon intensity has been achieved by strategically investing and implementing technology and practices that include carbon capture and sequestration. The ISCC measures CI using LCA at various steps throughout the entire ethanol and co-product supply chain beginning at the farm and ending with the end-user. Marquis Energy works closely with corn farmer suppliers to ensure through third party audits that low carbon practices (e.g., no conversion of virgin timber or prairie grassland into cropland, erosion control, responsible nutrient management, maintaining natural habitat) have been implemented and followed. Only corn produced by farmers who voluntarily participate in this ISCC program can be used to produce ISCC certified ethanol and corn co-products.

Corn fermented protein co-products are relatively new to the feed ingredient market, and much smaller quantities are produced and used in animal feeds compared with DDGS. Therefore, there is limited information on feeding CFP co-products to various animal species and their environmental impacts. However, a recent study conducted by Burton et al. (2021) estimated the dietary effects from feeding diets containing increasing amounts of CFP on GHG emissions per kg of body weight gain and kg of meat produced in broilers (**Table 6**), per kg of body weight gain in turkey poults, and per kg of feed and weight gain in Atlantic salmon (**Table 7**) using an economic allocation. Results from the feeding trials used in this study are provided and discussed in Chapter 2 (aquaculture) and Chapter 3 (poultry). The Global Food LCA Institute (GFLI) database was used to obtain data for feed ingredients in experimental diets to calculate the GHG emissions. However, because the GFLI database does not contain LCA data for CFP, these researchers used environmental impact data from Tallentire et al. (2018) for a different high protein corn co-product produced in the ethanol industry in the calculations. This assumption is questionable because different inputs and processes are used for producing different sources of CFP. Furthermore, CFP partially replaced some of the SBM in diets used in these feeding trials, but LCA data for SBM is highly variable based on country of origin and can have a significant effect on the results. Unfortunately, these details were not described in this study. Although these issues contribute to questionable results, it appears that increasing amounts of CFP in broiler diets reduced GHG emissions per kg of weight gain and per kg of meat produced (**Table 5**). Furthermore, although adding 10% CFP to broiler diets resulted in similar N retention compared with feeding the control diets with 0% CFP, N retention was improved by feeding 5% CFP diets. Feed formulations that improve N retention may also reduce N excretion which may be another beneficial environmental effect. Similarly, feeding diets containing 0%, 4%, and 8% CFP to turkey poults reduced GHG emissions (kg CO_2 equivalent per kg of body weight gain) from 3.96 (0%) to 3.77 and 3.40 kg CO_2 equiv, respectively. Likewise, the addition of increasing amounts of CFP to partially replace SBM in Atlantic salmon diets appears to reduce GHG emissions per kg of feed and per kg of weight gain (**Table 6**). Therefore, the use of CFP to replace SBM in salmon diets likely has a significant advantage for reducing the carbon footprint of salmon production, especially under European conditions where importation of SBM from deforested regions of South America is discouraged.

Table 5. Effects of feeding increasing dietary levels of corn fermented protein to broilers on nitrogen retention and estimated greenhouse gas emissions during a 42-day feeding period (adapted from Burton et al., 2021)

Measure	Dietary Corn Fermented Protein Inclusion Rate, %		
	0%	5%	10%
Nitrogen retention, %	29.4[b]	30.4[a]	28.7[b]
Greenhouse gas emissions, kg CO_2 equiv./kg body weight gain	2.48	2.21	2.01
Greenhouse gas emissions, kg CO_2 equiv./kg meat	5.85	5.03	4.57

[a,b]Means without common superscripts within rows are different ($P < 0.05$).

Table 6. Effects of feeding diets containing 0, 5, 10, 15, and 20% corn fermented protein as a partial replacement for soybean meal to Atlantic salmon (initial weight = 304 g) on estimated greenhouse gas emissions during a 12-week feeding period (adapted from Burton et al., 2021)

Measure	Dietary Corn Fermented Protein Inclusion Rate, %				
	0%	5%	10%	15%	20%
Greenhouse gas emissions, kg CO_2 equiv./kg feed[1]	1.64	1.55	1.47	1.39	1.30

Greenhouse gas emissions, kg CO_2 equiv./kg gain	1.59	1.44	1.37	1.36	1.27

[a,b]Means without common superscripts within rows are different ($P < 0.05$).

Conclusions

Corn fermented protein (CFP) co-products are produced using new technologies in dry grind ethanol facilities and contain high concentrations of energy, crude protein, and amino acids that have feeding applications primarily in aquaculture, broiler, and weaned pig diets, but can be broadly used in all animal feeds. The nutrient profiles and amino acid digestibility vary among sources of CFP which requires communicating with suppliers to apply appropriate metabolizable energy and amino acid digestibility coefficients to the specific CFP source used in feed formulations. The amino acid profile of corn protein is relatively low in lysine and tryptophan, but high in leucine which creates an amino acid imbalance with valine and isoleucine that requires supplementation of synthetic amino acids as dietary inclusion rates of CFO increase in monogastric diets to achieve satisfactory growth performance and carcass composition responses. These co-products also contain an estimated 20 to 29% spent yeast, which contributes to slightly improved amino acid profile relative to amino acid requirements and may provide animal health benefits depending on diet inclusion rates and health status of fish, pigs, and poultry.

Use of low environmental impact feed ingredients is an essential part of sustainable food animal production. Although several life cycle assessments of adding DDGS in animal feeds have shown an increase in greenhouse gas (GHG) emissions, several other environmental impacts are greatly reduced by feeding DDGS. A few U.S. ethanol plants have become certified in the International Sustainability and Carbon Certification program to meet the European Union directive of reducing GHG emissions by using renewable energy and a low carbon intensity score for ethanol and corn co-products. An initial study has been conducted to estimate the effects of feeding diets containing CFP to broilers, turkeys and Atlantic salmon on GHG emissions and showed substantial reductions.

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Chapter 2
Feeding Applications of Corn Fermented Protein Co-Products in Aquaculture Diets

Introduction

Although the use of corn fermented protein (CFP) co-products is extensively promoted in aquaculture diets, it is surprising that there have been only a few published studies. Corn fermented protein co-products are excellent energy and digestible amino acid sources for use in aquaculture diets and have been evaluated as complete or partial replacements for soybean meal and fish meal in diets for European seabass (*Dicentrarchus labrax*), Nile tilapia (*Oreochromis niloticus*), Pacific white shrimp (*Litopenaeus vannamei*), and Atlantic salmon (*Salmo salar*).

Comparison of the Nutrient Profile of Corn Fermented Protein with Common Protein Sources in Aquaculture Diets

Unlike swine and poultry diet formulations, the use of various "high protein" feed ingredients in aquaculture diets is frequently evaluated based on their relative capability of partially replacing common standards of fish meal (FM) and SBM. There are limited comparative energy and amino acid digestibility data for CFP sources relative to SBM and FM for various fish species, but Qui et al. (2017) compared the DM, energy, CP, and amino acid digestibility of a CFP source (NexPro) with SBM and FM fed to Pacific white shrimp (*L. vannamei*). As shown in **Table 1**, DM digestibility of CFP was greater, energy and amino acid digestibility was similar, and protein digestibility was less than FM. Soybean meal had greater DM, CP, energy and amino acid digestibility than CFP and FM. These results suggest that CFP is an acceptable replacement for FM but not SBM in Pacific white shrimp diets.

Table 1. Comparison of proximate analysis, amino acid composition and apparent digestibility of corn fermented protein (CFP) from NexPro, soybean meal (SBM), and fish meal (FM) for Pacific white shrimp (*L. vannamei*; adapted from Qiu et al., 2017)

Analyte, % (as-fed basis)	CFP	SBM	FM
Dry matter	94.77	89.03	92.01
Apparent DM digestibility, %	69.72	78.51	49.15, 49.45
Crude protein	49.20	44.89	62.78
Apparent digestibility of protein, %	60.58	97.03	67.07, 71.3
Crude fat	4.31	3.78	10.56
Crude fiber	4.29	3.20	0.00
Apparent energy digestibility, %	68.09	82.56	69.77, 67.78
Ash	4.87	6.67	18.75
Ala	3.26 (70)	2.04 (94)	3.91 (69)
Arg	3.26 (77)	3.35 (97)	3.68 (75)
Asp	4.05 (73)	5.10 (95)	5.34 (69)
Cys	0.82 (73)	0.62 (91)	0.47 (54)
Glu	7.49 (68)	8.24 (96)	7.47 (71)
Gly	1.54 (73)	2.04 (95)	4.88 (67)

His	1.42 (76)	1.20 (94)	1.63 (74)
Ile	2.18 (71)	2.17 (93)	2.42 (69)
Leu	5.64 (68)	3.57 (92)	4.21 (71)
Lys	2.14 (72)	3.06 (95)	4.67 (77)
Met	0.83 (74)	0.66 (95)	1.61 (71)
Phe	2.89 (69)	2.35 (93)	2.39 (65)
Pro	3.58 (68)	2.39 (95)	3.08 (67)
Ser	2.53 (75)	1.90 (93)	2.11 (58)
Thr	2.02 (73)	1.75 (92)	2.41 (66)
Trp	0.54 (80)	0.62 (95)	0.62 (80)
Tyr	2.34 (74)	1.64 (95)	1.67 (74)
Val	2.73 (72)	2.34 (91)	2.99 (67)

European Seabass (*Dicentrarchus labrax*)

Two studies have been published that evaluated feeding CFP to European seabass (Goda et al., 2019; 2020). In the first study, Goda et al. (2019) conducted an 8-week growth performance trial to determine if increasing levels (30, 40, and 50%) of CFP could be used to partially replace soybean meal in diets for *Dicentrarchus labrax* fingerlings with average initial body wight of 7.5 g/fish. Researchers initially referred to the CFP used in this study as a “high protein DDG source” but later correctly described it as NexPro in the conclusions. Experimental diets were formulated to contain the same crude protein (45%) and crude fat (13%) content. As shown in **Table 2**, fish fed the 30, 40, and 50% CFP diets had improved body weight gain, specific growth rate, and feed intake compared with fish fed the control diet. There was no mortality among dietary treatments and fish fed the 50% CFP diet had improved feed conversion compared with those fed the other treatments. Improvements in hematological, biochemical, total antioxidant capacity, and intestinal morphology measures were observed when fish were fed the CFP diets compared with those fed the control diets, and the authors suggested that these responses may be associated with yeast components present in CFP. Results from this study show that adding up to 50% CFP to partially replace soybean meal in diets for seabass juveniles improves growth performance and may positively affect fish health status.

Table 2. Effects of feeding increasing dietary levels of corn fermented protein (NexPro) to European seabass (*Dicentrarchus labrax*) on growth performance (adapted from Goda et al., 2019)

	Dietary Corn Fermented Protein Inclusion Rate, %			
Measure	**0%**	**30%**	**40%**	**50%**
Initial body weight, g/fish	7.47	7.50	7.50	7.53
Final body weight, g/fish	14.47^{b}	17.20^{a}	17.37^{a}	18.03^{a}
Weight gain, g/fish	7.00^{b}	9.70^{a}	9.87^{a}	10.50^{a}
Specific growth rate, %/day	0.87^{b}	1.39^{a}	1.41^{a}	1.70^{a}
Feed intake, g/fish	11.97^{b}	14.17^{a}	13.30^{a}	13.20^{a}
Feed conversion ratio[2]	1.71^{a}	1.45^{ab}	1.46^{ab}	1.26^{b}
Survival, %	100	100	100	100

[1]Specific growth rate = 100 × [(final body weight (g) – initial body weight (g)/duration of feeding (days)]

[2]Feed conversion ratio= live weight gain (g)/dry feed intake (g).

^{a,b}Means without common superscripts within rows are different ($P < 0.05$).

In a subsequent study, Goda et al. (2020) fed diets containing 30, 40, and 50% CFP to partially replace soybean meal (SBM), and supplemented with a commercial protease enzyme, to evaluate growth performance, physiological, and intestinal histology responses in juvenile European seabass. Feeding the 50% CFP diet resulted in increased final body weight, weight gain, specific growth rate, and feed conversion ratio compared with feeding the control, 30% and 40% CFP diets (**Table 3**). These improvements were a result of improved protein efficiency ratio, protein productive value, lipid retention, and energy retention in fish fed the 50% CFP diet compared with those fed the control diet, with improvements also observed in these nutritional efficiency measures when feeding the 30% and 40% CFP diets compared with the control diet (Table 3). There was no fish mortality observed in any of the treatments during the 70-day feeding trial. Similar to the results reported by Goda et al. (2019), feeding the CFP diets supplemented with protease enzyme improved measures of hematology, serum biochemistry, humeral immune responses, and intestinal morphology. These results support the addition of up to 50% CFP in juvenile seabass diets as a partial replacement of SBM to support optimal growth performance and health.

Table 3. Effects of feeding increasing dietary levels of corn fermented protein (NexPro) with protease enzyme supplementation to European seabass (*Dicentrarchus labrax*) on growth performance and nutritional efficiency (adapted from Goda et al., 2020)

	Dietary Corn Fermented Protein Inclusion Rate, %			
Measure	**0%**	**30%**	**40%**	**50%**
Initial body weight, g/fish	7.47	7.53	7.43	7.43
Final body weight, g/fish	15.57^{a}	16.80^{ab}	17.07^{ab}	19.28^{b}
Weight gain, g/fish	8.10^{a}	9.27^{ab}	9.63^{ab}	11.85^{b}
Specific growth rate, %/day	1.31^{a}	1.43^{ab}	1.48^{ab}	1.70^{b}
Feed intake, g/fish	16.93^{a}	15.57^{b}	14.47^{b}	13.07^{c}
Feed conversion ratio[2]	2.09^{a}	1.68^{ab}	1.47^{ab}	1.10^{b}
Survival, %	100	100	100	100
Protein efficiency ratio	1.07^{c}	1.33^{b}	1.48^{b}	1.94^{a}
Protein productive value, %	11.08^{c}	17.33^{b}	19.78^{b}	26.15^{a}
Lipid retention, %	22.42^{c}	26.94^{b}	35.69^{a}	27.82^{b}
Energy retention, %	6.72^{d}	7.80^{cd}	10.20^{a}	8.28^{b}

[1]Specific growth rate = 100 × [(final body weight (g) – initial body weight (g)/duration of feeding (days)]
[2]Feed conversion ratio= live weight gain (g)/dry feed intake (g).
[a,b,c,d]Means without common superscripts within rows are different ($P < 0.05$).

Nile Tilapia (*Oreochromis niloticus*)

There are limited data on the digestibility of various nutrients in CFP co-products for various aquaculture species. However, one study (unpublished) has been conducted to determine the organic matter, gross energy, crude protein, ether extract, and amino acid digestibility of CFP from ProCap Gold when fed to Nile tilapia (*Oreochromis niloticus*), and the digestibility coefficients are shown in **Table 4**.

Table 4. Apparent digestibility (%) of organic matter, gross energy, crude protein, ether extract, and amino acids of two samples of CFP fed to adult Nile tilapia (*O. niloticus*; unpublished data adapted with permission from Marquis ProCap)

Measure, %	**CFP**
Organic matter	60.6
Gross energy	83.1
Crude protein	83.1
Ether extract	52.9
Indispensable amino acids	
Arg	93
His	94
Ile	93
Leu	94
Lys	89
Met	89[a]
Phe	93
Thr	85
Val	92
Dispensable amino acids	
Ala	94
Asp	93
Glu	96
Gly	93[a]
Pro	95
Ser	92
Tyr	92

[a,b]Means without common superscripts within rows are different ($P < 0.05$).

Suehs and Gatlin (2022) conducted a study to determine the nutritional value of CFP (ProCap Gold) on growth performance, body composition, and immune responses of juvenile Nile tilapia (*Oreochromis niloticus*). In the first trial, the control diet was formulated to contain 36% crude protein provided by SBM, soy protein concentrate, and menhaden fish meal (FM). The experimental diets were formulated to partially replace SBM and FM with 7.5, 15, 22.5, 30, or 37.5% CFP, and were supplemented with soybean oil to provide 6% lipid in all diets. Each pelleted diet was fed to groups of 15 juvenile tilapia (10.6 g initial body weight) per aquarium to provide 3 replicates per dietary treatment during the 8-week feeding period. At the end of the 8-week feeding period, 3 fish from each aquarium were selected and humanely euthanized to measure hepatosomatic index, intraperitoneal fat ratio, fillet yield, and fillet composition. Blood samples were also collected to determine several non-specific immune responses including blood neutrophil oxidative radical production, intracellular and extracellular superoxide anion production, lysozyme, total protein, total immunoglobulins, and anti-protease activity. Results showed no differences in growth, gain efficiency, survival, fillet yield (**Table 5**), and body composition (**Table 6**) among dietary treatments. This was expected because all diets were formulated to contain the same protein and energy levels as increasing amounts of CFP was added to partially replace SBM and FM. Furthermore, feeding diets containing up to 37.5% CFP had no effect (data not shown) on any of the non-specific immune measures evaluated in this study.

Table 5. Effects of feeding diets containing 0, 7.5, 15, 22.5, 30, and 37.5% corn fermented protein (ProCap Gold) to juvenile Nile tilapia (*O. niloticus*; initial weight 0.25 g) on growth performance, fillet yield, hepatosomatic index, intraperitoneal fat, and survival during an 8-week feeding period (Suehs and Gatlin, 2022; adapted with permission from Marquis ProCap)

	Dietary Corn Fermented Protein Inclusion Rate, %					
Measure	**0%**	**7.5%**	**15%**	**22.5%**	**30%**	**37.5%**
Increase from initial weight[1], %	383	321	353	376	354	364
Gain:Feed[2]	0.85	0.79	0.82	0.87	0.81	0.83
Fillet yield[3], %	27.2	27.3	28.5	26.1	26.7	26.7
Hepatosomatic index[4], %	3.09	2.73	3.26	2.92	3.30	3.32
Intraperitoneal fat, %	1.10	1.33	0.99	1.13	0.94	1.40
Survival, %	100	97.8	91.1	100	88.9	95.6

[1]Weight gain = (final weight, g – initial weight, g) / initial weight,g × 100.
[2]Gain:Feed = weight gain, g / dry feed offered, g.
[3]Fillet yield = fillet weight, g / 100 g body weight.
[4]Hepatosomatic index = (100 × liver weight, g / body weight, g).
[5]Intraperitoneal fat, % = (intraperitoneal fat weight, g / body weight, g × 100).

Table 6. Whole body composition of juvenile Nile tilapia (*O. niloticus*) fed diets containing 0, 7.5, 15, 22.5, 30, and 37.5% corn fermented protein (ProCap Gold) after an 8-week feeding period (Suehs and Gatling, 2022; adapted with permission from Marquis ProCap)

	Dietary Corn Fermented Protein Inclusion Rate, %					
Measure	**0%**	**7.5%**	**15%**	**22.5**	**30%**	**37.5%**
Moisture, %	70.9	72.9	70.9	70.8	71.4	69.9
Protein, %	17.5	16.8	17.4	17.2	17.2	17.4
Lipid, %	7.4	6.5	7.4	7.8	7.0	8.3
Ash, %	3.8	3.7	3.7	3.9	3.9	3.9
Protein conversion efficiency, %	44.2	40.0	42.4	43.4	40.1	42.5

An unpublished study conducted at Auburn University evaluated the addition of CFP (NexPro) at increasing diet inclusion rates (0, 3.15, 6.30, 9.45, and 12.60%) as a partial replacement for corn protein concentrate (CPC) in diets for juvenile Nile tilapia (7.5 g initial body weight) on growth performance during a 9-week feeding period. There were no significant differences in weight gain, feed conversion, and survival, indicating that up to 12.6% CFP can effectively replace CPC in juvenile tilapia diets without compromising growth performance (**Table 7**).

Table 7. Effects of feeding diets containing 0, 3.15, 6.30, 9.45, and 12.60%) corn fermented protein (NexPro) to juvenile Nile tilapia (*O. niloticus*) on growth performance during a 9-week feeding period (adapted from unpublished research from Auburn University with permission from POET)

	Dietary Corn Fermented Protein Inclusion Rate, %				
Measure	**0%**	**3.15%**	**6.30%**	**9.45%**	**12.60%**
Final mean weight, g	80.4	73.1	79.8	79.5	79.5
Final biomass, g	1,446	1,405	1,436	1,447	1,447
Weight gain[1], %	965	880	953	954	936
Feed conversion ratio[2]	1.23	1.30	1.24	1.23	1.24

Survival, %	90.0	96.3	90.0	91.3	92.5

[1]Weight gain = (final weight – initial weight)/initial weight × 100.
[2]Feed conversion ratio = feed offered/ (final weight – initial weight).

Pacific White Shrimp (*Litopenaeus vannamei*)

Qui et al. (2017) conducted three growth performance trials to evaluate the addition of increasing amounts of CFP (NexPro) as a replacement for SBM or a combination of FM and SBM in practical diets for juvenile Pacific white shrimp (*Litopeneaus vannamei*). In trial 1, shrimp (0.18 g initial body weight; 10 shrimp/tank) were fed diets containing 0, 10, 20, or 30% CFP as a replacement for SBM during a 6-week feeding period. No significant differences in growth rate or feed conversion were observed among dietary treatments (**Table 8**). However, in trial 2, partially replacing portions of SBM and FM in the diets with the addition of 10, 20, or 30% CFP resulted in a reduction in final weight, weight gain, and poorer feed conversion when shrimp were fed the diets containing 20% and 30% CFP compared with those fed the control (0%) and 10% CFP diets (**Table 9**). As a result, a third trial was conducted to determine the maximum inclusion rate of CFP in diets for juvenile shrimp to support optimal growth performance (**Table 10**) and effects on whole body composition (Table 7). Based on these growth performance results, an upper limit of 18% CFP was recommended for juvenile shrimp diets due to reduced weight gain and feed conversion when 24% CFP diets were fed. The reduction in growth performance observed at the higher inclusion rates was likely due to lower energy (68%) and protein (61%) digestibility in CFP compared with SBM (83% and 97%, respectively), and lower in protein digestibility than FM (67 to 71%). In fact, apparent digestibility of several amino acids was lower in CFP compared with SBM (see details in Chapter 1). There were no differences in shrimp whole body composition for moisture, protein, lipid, ash, and macro and trace minerals except for increased iron and copper at the 18% and 24% diet inclusion rates compared to feeding the control diet (**Table 11**). These results suggest that the bioavailability of iron and copper in CFP is relatively high compared with other ingredients used in these diets.

In summary, the results of these three trials indicate that CFP is a good plant-based protein source that can be added up to 30% of juvenile Pacific white shrimp (*Litopeneaus vannamei*) diets to replace SBM, or up to 18% to replace a combination of SBM and FM without negatively affecting growth performance. However, energy and amino acid digestibility of the CFP source evaluated in this study was less than in SBM.

Table 8. Effects of feeding diets containing 0, 10, 20, and 30% corn fermented protein (NexPro) to juvenile shrimp (*L. vannamei*; initial weight 0.18 g) on growth performance during a 6-week feeding period in trial 1 (adapted from Qui et al., 2017)

	Dietary Corn Fermented Protein Inclusion Rate, %			
Measure	**0%**	**10%**	**20%**	**30%**
Final mean weight, g	3.4	3.5	3.1	3.1
Final biomass, g	28.0	31.7	29.0	29.4
Weight gain[1], %	1,724.4	1,894.9	1,679.8	1,827.8
Feed conversion ratio[2]	2.44	2.35	2.62	2.58
Survival, %	84.0	92.0	94.0	94.0

[1]Weight gain = (final weight – initial weight)/initial weight × 100%
[2]Feed conversion ratio = feed offered/ (final weight – initial weight).

Table 9. Effects of feeding diets containing 0, 10, 20, and 30% corn fermented protein (NexPro) to juvenile shrimp (*L. vannamei*; initial weight 1.24 g) on growth performance during a 7-week feeding period in trial 2 (adapted from Qui et al., 2017)

	Dietary Corn Fermented Protein Inclusion Rate, %			
Measure	**0%**	**10%**	**20%**	**30%**
Final mean weight, g	9.9[a]	9.2[a]	8.0[b]	7.7[b]
Final biomass, g	225.8	204.6	191.4	199.0
Weight gain[1], %	684.8[a]	644.7[ab]	554.9[bc]	519.4[c]
Feed conversion ratio[2]	1.61[a]	1.72[a]	2.05[b]	2.12[b]
Survival, %	76.7	73.3	80.0	85.8

[1]Weight gain = (final weight – initial weight)/initial weight × 100%

[2]Feed conversion ratio = feed offered/ (final weight – initial weight).

[a,b,c]Means without common superscripts within rows are different ($P < 0.05$).

Table 10. Effects of feeding diets containing 0, 6, 12, 18, and 24% corn fermented protein (NexPro) to juvenile shrimp (*L. vannamei*; initial weight 0.25 g) on growth performance during a 6-week feeding period in trial 3 (adapted from Qui et al., 2017)

	Dietary Corn Fermented Protein Inclusion Rate, %				
Measure	**0%**	**6%**	**12%**	**18%**	**24%**
Final mean weight, g	5.1[ab]	5.4[a]	5.1[a]	4.6[ab]	4.3[b]
Final biomass, g	41.9	46.8	46.2	41.5	37.6
Weight gain[1], %	1,837.7[ab]	2,065.7[a]	1,854,2[ab]	1,776.2[ab]	1,593.5[b]
Feed conversion ratio[2]	1.81[b]	1.67[b]	1.74[b]	1.94[ab]	2.14[a]
Survival, %	82.5	87.5	90.0	90.0	87.5

[1]Weight gain = (final weight – initial weight)/initial weight × 100%

[2]Feed conversion ratio = feed offered/ (final weight – initial weight).

[a,b]Means without common superscripts within rows are different ($P < 0.05$).

Table 11. Whole body composition of juvenile shrimp (*L. vannamei*; initial weight 0.25 g) fed diets containing 0, 6, 12, 18, and 24% corn fermented protein (NexPro) during a 6-week feeding period in trial 3 (adapted from Qui et al., 2017)

	Dietary Corn Fermented Protein Inclusion Rate, %				
Measure	**0%**	**6%**	**12%**	**18%**	**24%**
Moisture, %	77.98	77.45	77.40	76.64	75.90
Protein, %	75.18	73.00	72.60	73.90	73.90
Lipid, %	5.62	5.88	6.81	6.29	6.92
Ash, %	11.43	11.70	11.58	11.70	11.55
Calcium, %	2.97	3.33	3.09	3.41	3.40
Phosphorus, %	1.08	1.06	1.01	1.03	1.02
Sodium, %	1.06	1.15	1.10	1.10	1.09

Potassium, %	1.38	1.45	1.41	1.39	1.38
Sulfur, %	0.87	0.90	0.88	0.88	0.88
Magnesium, %	0.26	0.29	0.27	0.29	0.28
Iron, mg/kg	13.53[b]	16.40[ab]	16.05[ab]	15.70[ab]	18.68[a]
Copper, mg/kg	66.53[c]	69.68[bc]	73.93[abc]	84.85[a]	80.58[ab]
Zinc, mg/kg	73.28	76.13	74.18	75.13	75.48
Manganese, mg/kg	2.23	3.55	2.75	3.20	3.90

[a,b,c] Means without common superscripts within rows are different (P < 0.05).

Guo et al. (2019) also conducted a study to evaluate the addition of increasing dietary levels of CFP (NexPro) to replace CPC or FM in diets for juvenile Pacific white shrimp (initial weight = 0.36 g) for an 8-week growth performance trial. As shown in **Table 12**, there were no differences in mean weight, weight gain, feed:gain, and survival among all dietary treatments. However, replacing FM with 20% CFP reduced final biomass and reduced feed conversion compared with feeding diets containing 0 or 10% CFP. These results indicate that CFP is a good protein source for Pacific white shrimp and can replace up to 20% of CPC, or up to 15% FM without compromising growth performance.

Table 12. Growth performance and survival responses of juvenile Pacific white shrimp fed increasing dietary levels of corn fermented protein (CFP; NexPro) to partially replace corn protein concentrate (CPC) or fish meal (FM) during a 56-day feeding period (adapted from Guo et al., 2019)

Measure	Diet type							
	CPC	CPC	CPC	CPC	FM	FM	FM	FM
	0% CFP	10%CFP	15% CFP	20% CFP	0% CFP	10% CFP	15% CFP	20% CFP
Biomass, g	225	227	230	221	240[b]	235[b]	230[ab]	216[a]
Mean weight, g	7.49	7.64	7.88	7.50	8.05	7.90	7.88	7.38
Weight gain, g	7.13	7,28	7.52	7.14	7.68	7.54	7.52	7.02
Weight gain, %	1,997	2,032	2,106	1,996	2,104	2,093	2,106	1,920
Feed:gain	1.5	1.5	1.5	1.5	1.4[a]	1.4[a]	1.5[ab]	1.6[b]
Survival, %	100.0	99.2	97.5	98.3	99.2	99.2	97.5	97.5

[a,b]Means without common superscripts within rows are different (P < 0.05).

Atlantic Salmon (*Salmo salar*)

Burton et al. (2021) conducted a 12-week feeding trial to evaluate the effects of partially replacing SBM with increasing amounts (0, 5, 10, 15, and 20%) of CFP in Atlantic salmon (initial body weight = 304 g; 5 fish/tank) diets on growth performance, dietary protein utilization, and greenhouse gas (GHG) emissions. Specific details regarding diet composition and formulation were not provided beyond the percentage of SBM replaced in the diets, which was 0, 12.9, 25.8, 37.9, and 50.8% for 0, 5, 10, 15, and 20% inclusion rates of CFP (NexPro), respectively. Fish fed the 10% CFP diet had greater final body weight and feed intake compared with fish fed the 20% CFP diet (**Table 13**). However, there were no differences in feed conversion and protein deposition among dietary CFP inclusion rates.

Table 13. Effects of feeding diets containing 0, 5, 10, 15, and 20% corn fermented protein (NexPro) as a partial replacement for soybean meal to Atlantic salmon (initial weight = 304 g) on growth performance during a 12-week feeding period (adapted from Burton et al., 2021)

	Dietary Corn Fermented Protein Inclusion Rate, %

Measure	0%	5%	10%	15%	20%
Initial body weight, g	295.0	301.9	305.7	304.7	305.0
Final body weight, g	720.0[ab]	701.1[ab]	752.1[a]	690.8[ab]	663.7[b]
Weight gain, g	425.0	399.2	446.4	386.1	358.7
Feed intake/fish, g	411.9[a]	370.5[ab]	414.4[a]	377.8[ab]	348.3[b]
Feed conversion ratio	0.98	0.93	0.93	0.97	0.97
Protein deposition, %	19.8	23.1	23.0	22.1	26.0

[a,b] Means without common superscripts within rows are different ($P < 0.05$).

Feeding increasing dietary levels of CFP had no effect on whole-body dry matter, protein, amino acids (data not shown), lipid, and ash content, nor was there an effect on protein and deposition rate and retention efficiency (**Table 13**). Dietary levels of CFP had no effect on fillet darkness, yellowness, and redness of color in the anterior fillets, and redness and yellowness of color in the posterior fillets, with significant but minor differences in darkness of color (**Table 14**). There were no differences in most blood biochemistry measures except for increases in plasma P and Mg, which may reflect high digestibility in CFP. Total cell count and packed cell volume also increased as CFP inclusion rates increased (data not shown). Creatine kinase is an indicator of tissue inflammation and concentrations were similar across dietary treatments. Histological evaluation showed no evidence of intestinal enteritis and other intestinal disorders, with the majority of distal intestinal samples showing not inflammation of the lamina propria and submucosa (data not shown). These results suggest that CFP is a good protein and energy source in diets for post-smolt Atlantic salmon (*Salmo salar*), and provides similar whole-body composition, protein and lipid utilization, fillet pigmentation, and intestinal histology. However, growth performance may be reduced when adding more than 15% CFP to salmon diets.

Table 14. Effects of feeding diets containing 0, 5, 10, 15, and 20% corn fermented protein (NexPro) as a partial replacement for soybean meal to Atlantic salmon (*Salmo salar*; initial weight = 304 g) on whole body composition, nutrient deposition, and retention rates after a 12-week feeding period (adapted from unpublished data from The Center for Aquaculture Technologies, 2019, provided with permission from POET)

Measure	Dietary Corn Fermented Protein Inclusion Rate, %				
	0%	5%	10%	15%	20%
Dry matter, %	37.1	37.2	38.0	37.8	37.0
Protein, %	18.8	18.4	18.5	18.7	19.0
Protein deposition rate, mg/°C-d	45.4	41.4	47.6	41.1	41.1
Protein retention efficiency, %	19.8	23.1	23.0	22.1	26.0
Lipid, %	17.1	17.5	18.4	18.0	16.8
Lipid deposition rate, mg/°C-d	50.7	50.7	62.6	51.9	43.3
Lipid retention efficiency, %	59.0	50.4	58.7	54.5	50.5
Ash	1.7	1.7	1.8	1.8	1.8
Colorimetric indices					
Anterior filler					
L*	60.0	56.5	56.9	56.3	56.0
a*	7.9	8.0	7.7	7.9	7.9
b*	17.2	17.5	17.2	17.2	17.0
Posterior fillet					
L*	54.9[ab]	54.7[b]	55.5[ab]	55.7[a]	54.6[b]
a*	9.1	9.6	9.1	9.2	9.5

b*	18.8	19.1	18.8	18.6	18.5

[a,b]Means without common superscripts within rows are different (P < 0.05).

Another study was conducted at the University of Idaho Aquaculture Research Institute's Hagerman Fish Culture Experiment Station to determine the nutritional value of CFP (ProCap Gold) on juvenile Atlantic salmon growth performance. Diets were formulated to contain 43% CP and 20% crude lipid. The SBM concentration in the control diet was 22% and was progressively replaced by increasing amounts of CFP resulting in five treatment diets consisting of Diet 1 (22% SBM and 0% CFP); Diet 2 (16.5% SBM and 5.5% CFP); Diet 3 (11.0% SBM and 10.9% CFP); Diet 4 (5.5% SBM and 16.4% CFP); and Diet 5 (0% SBM and 21.9% CFP). Atlantic salmon with an initial body weight of 21 g were fed their respective dietary treatments to satiety for 12 weeks. At study conclusion, survival was 100% across all treatment groups and no statistically significant differences were observed for growth performance measures with increasing dietary CFP inclusion rates (**Table 15**).

Table 15. Effects of feeding increasing dietary levels of corn fermented protein (ProCap Gold) to Atlantic salmon (*Salmo salar*) on growth performance (adapted from unpublished research from the University of Idaho, 2022)

	Dietary Corn Fermented Protein Inclusion Rate, %				
Measure	**0%**	**5.5%**	**10.9%**	**16.4%**	**21.9%**
Initial body weight, g/fish	21.4	21.5	21.5	21.6	21.4
Final body weight, g/fish	169.4	165.3	161.6	168.6	165.2
Weight gain, %	691.1	668.9	653.6	682.3	673.0
Specific growth rate, %/day	2.47	2.42	2.40	2.45	2.43
Feed intake, g/fish	147.1	143.3	142.6	150.8	146.3
Feed conversion ratio	1.00	0.99	1.02	1.03	1.02
Survival, %	100	100	100	100	100

Increasing levels of CFP in the salmon diets resulted in significantly improved dietary lipid digestibility but had no effect on dietary dry matter, CP, or energy digestibility (**Table 16**). These results are supported by high lipid digestibility (97.2%) of CFP (ProCap Gold) fed to Atlantic salmon. Dry matter, CP, and energy digestibility of CFP were 67.5%, 88.7%, and 76.8%, respectively. These results show that CFP is a highly digestible ingredient that can be fed to Atlantic salmon juveniles at levels up to 22% of the diet with no impact on growth performance and survival.

Table 15. Differences in apparent digestibility coefficients (%) for dry matter, protein, lipid, and energy of the experimental diets with increasing dietary levels of corn fermented protein (ProCap Gold) fed to Atlantic salmon (*Salmo salar*) (adapted from unpublished research from the University of Idaho, 2022)

	Dietary Corn Fermented Protein Inclusion Rate, %				
Measure	**0%**	**5.5%**	**10.9%**	**16.4%**	**21.9%**
Dry Matter	69.9	68.3	69.1	69.7	69.8
Protein	88.3	87.5	87.3	87.6	87.4
Lipid	95.7[a]	95.9[ab]	96.7[bc]	97.5[c]	97.3[c]
Energy	78.6	78.2	78.1	78.4	78.5

[a,b,c]Means (n = 3) without common superscripts within rows are statistically different (P<0.05).

Conclusions

Feeding diets containing up to 50% CFP to partially replace SBM in diets for European seabass (*Dicentrarchus labrax*) juveniles improves growth performance and may positively affect fish health status. Diets containing up to 37.5% CFP can provide optimum growth performance and fillet composition for Nile tilapia (*Oreochromis niloticus*). Corn fermented protein is a good plant-based protein source that can be added up to 30% of juvenile Pacific white shrimp (*Litopeneaus vannamei*) diets to replace SBM, or up to 18% to replace a combination of SBM and FM without negatively affecting growth performance. However, energy and amino acid digestibility of CFP sources can be variable and sometimes less than in SBM. Although growth responses from two growth performance suggest different maximum dietary inclusion rates of CFP for Atlantic salmon, results from one study indicates that diets containing up to 22% CFP can be fed without compromising growth rate and feed intake.

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Chapter 3
Feeding Applications of Corn Fermented Protein Co-Products in Poultry Diets

Introduction

The use of corn fermented protein (CFP) co-products in poultry diets is much less studied than applications in swine and aquaculture diets. However, the high metabolizable energy (ME) and digestible amino acid content of CFP co-products are best suited in broiler and turkey diets due to the need to provide high energy and nutrient dense diets to support rapid growth. The following sections summarize ME content and amino acid composition and digestibility of various sources of CFP and include a growth performance and environmental impact studies with broilers and turkeys using CFP. Unfortunately, no studies have been conducted to evaluate the use of CFP in layer diets.

Nutrient Profile of Corn Fermented Protein Co-Products for Poultry

Nutritional composition

The protein, lipid, fiber, and ash content of three different brands of CFP produced using three different technologies is shown in **Table 1**. Note that although these CFP co-products contain similar crude protein, the Lys:Crude protein ratio varies from 3.82 to 4.19, but is much greater than found in conventional DDGS sources. Furthermore, lipid, fiber, and ash content are highly variable among CFP sources. Like DDGS, the calcium content of CFP co-products is low, and the P content varies from 0.68 to 1.1%. These results indicate that due to the variable non-protein nutritional components of CFP, it is essential for end-users to know the specific source being used in poultry feed formulations for optimizing nutritional efficiency and poultry performance.

Table 1. Comparison of protein, lipid, fiber, and ash composition of corn fermented protein sources and technologies

Analyte	ANDVantage 50Y[1]	NexPro[2]
Dry matter, %	90.0	100.00
Crude protein, %	51.1	53.0
Lys:crude protein	3.82	4.19
Ether extract, %	9.6	5.1
Acid hydrolyzed ether extract, %	9.90	-
Crude fiber, %	8.5	-
Neutral detergent fiber, %	27.5	24.1
Acid detergent fiber, %	20.0	4.83
Soluble dietary fiber, %	2.8	-
Insoluble dietary fiber, %	29.2	-
Total dietary fiber, %	32.0	-
Ash, %	2.17	5.49
Ca, %	0.01	0.05
P, %	0.68	1.1

S, %	0.64	-
Mg, %	0.07	-
K, %	0.29	-
Na, %	0.04	0.05

[1]Data from product specifications (as-fed basis) provided with permission by The Andersons, Inc.
[2]Published data (dry matter basis) obtained from Correy et al. (2019).

Metabolizable energy

Fewer estimates for metabolizable energy (ME) content of CFP sources have been determined in poultry compared with swine, but all three of the primary CFP production technologies have been evaluated (**Table 2**). Nitrogen-corrected true ME (TME_n) values have been determined for ANDVantage 50Y and NexPro co-products, while nitrogen-corrected apparent ME (AME_n) content for ProCap Gold have been determined (3,546 kcal/kg; unpublished data from Dr. Bill Dozier, Auburn University provided with permission from Marquis Energy). As a result, it is difficult to compare the relative ME content between these three sources, but it is clear that they all contain about 130 to 150% of the ME concentrations in conventional DDGS sources which makes CFP an excellent ingredient in broiler and turkey diets.

Table 2. Comparison of gross energy (GE), metabolizable energy (ME), and ME:GE of corn fermented protein sources for poultry (dry matter basis)

Analyte	**ANDVantage 50Y[1]**	**NexPro[2]**
Dry matter, %	93.76	93.52
GE, kcal/kg	5,636	5,366
ME, kcal/kg	3,378	3,713
ME:GE	0.60	0.69

[1]TME_n = nitrogen-corrected true metabolizable energy; Unpublished data provided with permission from The Andersons, Inc.
[2]TME_n value (average of 6 samples); Unpublished data provided with permission from POET.

Digestible amino acids

A comparison of indispensable and dispensable amino acid content and digestibility of ANDVantage 50Y and NexPro is shown in **Table 3**. Amino acid concentration and digestibility varies by source, but in general, CFP is a highly digestible amino acid ingredient for use in poultry diets. However, it is essential for end-users to know the specific source being used in feed formulations for optimizing nutritional efficiency and poultry performance.

Table 3. Comparison of crude protein and amino acid content and ileal digestibility of corn fermented protein sources for poultry

Analyte[1]	**ANDVantage 50Y[2]**	**NexPro[3]**
Dry matter, %	90.0	93.0
Crude protein, %	51.1	50.2
Lys:Crude protein	3.82	4.19
Arg	2.62 (91)	2.37 (96)
His	1.81 (89)	1.46 (91)
Ile	2.16 (87)	2.22 (93)
Leu	6.53 (93)	6.65 (94)
Lys	1.95 (83)	2.11 (85)

Met	1.08 (91)	1.26 (94)
Phe	2.75 (90)	2.82 (95)
Thr	1.98 (85)	2.17 (87)
Trp	0.42 (89)	0.51 (89)
Val	2.58 (87)	2.95 (90)
Ala	3.82	3.51 (91)
Asp	3.49	3.62 (87)
Cys	1.12 (92)	0.90 (87)
Glu	8.87	7.61 (93)
Gly	1.96	2.00
Pro	4.17	3.46 (93)
Ser	2.39	2.25 (89)
Tyr	2.32	2.08 (87)

[1]Values in parentheses are ileal digestibility coefficients (%) for amino acids in each co-product sources for poultry.
[2]Unpublished digestibility coefficients of amino acid data were obtained with permission from The Andersons, Inc.
[3]Total amino acid concentrations (dry matter basis) and digestibility coefficients were obtained with permission from POET.

Digestible phosphorus

No studies have been conducted to determine the phosphorus digestibility or relative availability in CFP sources for poultry. Mutucumarana et al. (2014) reported that the use of non-phytate P to estimate digestible phosphorus concentration in feed ingredients is not accurate because the digestible P content often determined in feed ingredients is often greater than the non-phytate concentrations, which suggests that birds can utilize a portion of nonphytate P. However, it is reasonable to use estimates of P digestibility and availability for poultry obtained from studies evaluating DDGS sources. Mutucumarana et al. (2014) reported that the true digestible phosphorus content of corn DDGS was 0.59%, which represented about 73% of the total P. Wamsley et al. (2013) determined that the availability of phosphorus in the DDGS source they evaluated was between 66 to 68%, which is in agreement with the values reported by Martinez-Amezcua et al. (2006). Therefore, until studies are conducted to determine the phosphorus digestibility and availability in CFP for poultry are conducted, it is reasonable to assume that about 60% of the total phosphorus in CFP is available to birds. However, it is important to note that several ethanol plants add phytase during the fermentation process which further increases the conversion of indigestible phytate to digestible phosphate (Reis et al., 2018). Nutritionists should request information about whether or not phytase is being used during the production process for the source of corn co-products they are using because it affects phosphorus digestibility values.

Summary of Corn Fermented Protein Feeding Trials with Broilers

Burton et al. (2021) conducted a growth performance trial to evaluate the effects of replacing soybean meal with CFP (NexPro) for broilers. Male Ross broilers were obtained from a commercial hatchery on the day of hatch, weighed, assigned to floor pens (9 birds/pen), and fed diets containing 0, 5, or 10% CFP. Diets were fed using a 2-phase feeding program with starter diets fed from day 0 to 21, and grower diets fed from days 21 to 42. Dietary inclusion rate of CFP had no effect on final body weight and weight gain, but birds fed the 10% CFP diets had greater feed intake and poorer feed conversion compared with birds fed the control diet without CFP (**Table 4**). Nitrogen retention was similar for broilers fed the 10% CFP diets compared to those fed the control diet and was improved by feeding the 5% CFP diets (**Table 4**). Presumably, this improvement in dietary nitrogen utilization was a result of adding crystalline lysine, methionine, arginine, threonine, and valine to correct amino acid imbalances resulting from partially replacing soybean meal with CFP in these diets.

Table 4. Effects of feeding increasing dietary levels of corn fermented protein (NexPro) to broilers on growth performance, nitrogen retention, and carcass component yield during a 42-day feeding period (adapted from Burton et al., 2021)

	Dietary Corn Fermented Protein Inclusion Rate, %		
Measure	**0%**	**5%**	**10%**
Initial body weight, g	45	45	44
Final body weight, g	3,360	3,439	3,339
Weight gain, g	3,315	3,394	3,295
Feed intake, g/bird	4,878[b]	5,042[ab]	5,151[a]
Feed conversion ratio[2]	1.47[a]	1.49[a]	1.57[b]
Nitrogen retention, %	29.4[b]	30.4[a]	28.7[b]
Carcass breast, thigh, drum yield, kg	1.41	1.49	1.45

[a,b] Means without common superscripts within rows are different ($P < 0.05$).

Summary of Corn Fermented Protein Feeding Trials with Turkeys

Similar to the broiler study, Burton et al. (2021) conducted a growth performance trial to evaluate the effects of replacing soybean meal with CFP (NexPro) in turkey diets. Male BUT6 turkey poults were obtained from a commercial hatchery on the day of hatch, weighed, assigned to floor pens (5 birds/pen), and fed diets containing 0, 4, or 8% CFP. Diets were fed using a 2-phase feeding program with starter diets fed from day 0 to 21, and grower diets fed from days 21 to 42. Dietary inclusion rate of CFP had no effect on final body weight, weight gain, feed intake, and feed conversion compared with birds fed the control diet without CFP (**Table 5**). Nitrogen retention was greater for turkeys fed the 8% CFP diets compared to those fed the control diet (**Table 5**). Presumably, this improvement in dietary nitrogen utilization was a result of adding crystalline lysine, methionine, and threonine to correct amino acid imbalances resulting from partially replacing soybean meal with CFP in these diets.

Table 5. Effects of feeding increasing dietary levels of corn fermented protein (NexPro) to turkey poults on growth performance during a 42-day feeding period (adapted from Burton et al., 2021)

	Dietary Corn Fermented Protein Inclusion Rate, %		
Measure	**0%**	**4%**	**8%**
Initial body weight, g	66	66	66
Final body weight, g	2,328	2,423	2,518

Weight gain, g	2,262	2,357	2,452
Feed intake, g/bird	3,741	3,850	3,743
Feed conversion ratio[2]	1.66	1.64	1.61
Nitrogen retention, %	18.3[b]	21.0[ab]	21.8[a]

[a,b] Means without common superscripts within rows are different ($P < 0.05$).

Conclusions

The limited data available on the feeding value and growth performance responses of feeding corn fermented protein (CFP) co-products to broilers and turkeys indicate that CFP is a higher energy and more digestible amino acid ingredient compared with conventional DDGS sources and appears to support acceptable growth performance and nitrogen retention at inclusion rates up to 10% in broiler diets and 8% in turkey diets.

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Chapter 4
Feeding Applications of Corn Fermented Protein Co-Products in Swine Diets

Introduction

Corn fermented protein (CFP) co-products are attractive feed ingredients for use in weaned pig diets because of their high metabolizable energy (ME) and digestible amino acid and phosphorus content. This high energy and nutritional density allows use of less quantity to supply significant amounts of energy and nutrients in diets with limited "formulation space". Furthermore, weaned pig diets must be formulated to be highly concentrated in energy and amino acids, which can only be achieved by using ingredients that are high in ME and digestible amino acid content because they are more likely to support acceptable growth during a stressful time in the pig's life when feed intake is often low and variable. Because of the spent yeast in CFP, feeding diets containing these co-products to weaned pigs may also provide health benefits when added to diets at relatively high inclusion rates resulting from the mannooligosaccharides, β-glucans, and nucleotides found in yeast cell walls (Shurson, 2018). Therefore, this chapter summarizes the results from several recent studies that have determined the digestible energy (DE), ME, standardized ileal digestibility (SID) of amino acids, and standardized total tract digestibility (STTD) of phosphorus (P) of the three different types of technologies used to produce CFP, and a summary of growth performance results in nursery pig feeding trials.

Nutritional Profile of Corn Fermented Protein Co-Products for Swine

There are three different types of proprietary processing technologies used to produce corn fermented co-products which include ICM's Advanced Processing Package™ (APP™); FluidQuip's Maximized Stillage Co-Products Technology™ (MSC™); and Marquis ProCap Technology™. Although each of these types of technologies concentrate the protein and yeast in the final co-products, their nutritional profiles are different. Therefore, to optimize energy and nutritional efficiency when including these co-products in swine diets, it is essential to use appropriate ME, SID of amino acids, and STTD phosphorus values during feed formulation. Fortunately, digestibility studies have been conducted to determine the DE and ME content, as well as SID of amino acids for swine for each of these types of CFP co-products.

Nutritional composition

The protein, lipid, fiber, and ash content of different brands of CFP is shown in **Table 1**. Note that although these CFP co-products contain similar crude protein (CP) concentrations. In contrast, ether extract (crude fat) and acid hydrolyzed ether extract, neutral detergent fiber (NDF), total dietary fiber (TDF), and ash content are highly variable among sources. Like DDGS, the calcium content of CFP co-products is low, and the P content varies from 0.68 to 1.04%. These results indicate that due to the variable nutritional profiles among CFP sources, it is essential for end-users to know the specific source being used in swine feed formulations for optimizing nutritional efficiency and animal performance.

Table 1. Comparison of protein, lipid, fiber, and ash composition of corn fermented protein sources (as-fed basis)

Analyte	ANDVantage 50Y[1]	A+Pro[2]	NexPro[3]	ProCap Gold[4]
Dry matter, %	93.76	91.73	93.00	88.00
Crude protein, %	51.79	50.20	50.1	49.09
Lys:crude protein	3.46	3.96	3.95	3.93
Ether extract, %	9.60*	4.62		-
AEE[5], %	9.90	-	5.6	9.49
Neutral detergent fiber, %	27.50*	24.33	-	-
Acid detergent fiber, %	20.00*	4.83	-	-
Soluble dietary fiber, %	2.8	-	3.4	1.02
Insoluble dietary fiber, %	29.2	-	24.4	21.77
Total dietary fiber, %	32.0	-	27.8	22.79
Ash, %	1.44	5.49	7.9	7.38
Ca, %	0.01*	0.04	-	0.04
P, %	0.68*	0.82	-	0.77

[1]Unpublished data from Lee and Stein (2021) with permission from The Andersons, Inc.
[2]Published data from Yang et al. (2021).
[3]Published data from Acosta et al. (2021).
[4]Published data from Cristobal et al. (2020).
[5]AEE = acid hydrolyzed ether extract
*Values obtained from supplier nutrient specification sheets provided with permission from The Andersons, Inc.

Metabolizable energy

Because of the wide ranges in lipid, fiber, and ash content among CFP sources, the DE and ME content also varies from 3,837 and 3,643 kcal/kg, respectively, for A+ Pro to 4,560 and 4,306 kcal/kg, respectively, for ProCap Gold (**Table 2**). However, the ME content of these CFP sources is 117 to 150% of the ME content of conventional DDGS sources. The ME to gross energy (GE) ratio is similar among co-product sources except for ProCap Gold, which has a ratio of 0.84 and indicates a much greater proportion of gross energy is utilized by pigs presumably because of the relatively higher oil and lower fiber content compared with other corn-products.

Table 2. Comparison of gross energy (GE), digestible energy (DE), metabolizable energy (ME), and energy ratios of corn fermented protein sources for swine (as-fed basis)

Analyte	ANDVantage 50Y[1]	A+Pro[2]	NexPro[3]	ProCap Gold[4]
Dry matter, %	93.76	91.73	93.00	88.00
GE, kcal/kg	5,284	4,908	4,937	5,100
DE, kcal/kg	4,421	3,837	4,070	4,560
ME, kcal/kg	4,085	3,643	3,705	4,306
ME:DE	0.92	0.95	0.91	0.94
DE:GE	0.84	0.78	0.82	0.89
ME:GE	0.77	0.74	0.75	0.84

[1]Unpublished data from Lee and Stein (2021) with permission from The Andersons, Inc.
[2]Published data from Yang et al. (2021).
[3]Published data from Acosta et al. (2021).
[4]Published data from Cristobal et al. (2020).

Digestible amino acids

The amino acids profiles of CFP co-products vary, but as expected the greater CP content results in increased concentrations of amino acids (**Table 3**). Amino acid ratios relative to Lys content are improved compared to the amino acid profile of conventional DDGS sources (data not shown), which is a result of the greater spent yeast content and associated amino acid profile (Shurson, 2018). Note that the standardized ileal digestibilities are generally greater than found in conventional DDGS sources but vary among CFP sources. For example, SID of Lys ranges from 61% (A+ Pro and NexPro) to 85% in ProCap Gold. Again, because of these differences, it is essential for end-users to know the specific source being used in swine feed formulations to optimize nutritional efficiency and pig performance.

Table 3. Comparison of crude protein and amino acid content, and standardized ileal digestibility of corn fermented protein sources for swine (as-fed basis)

Analyte[1]	**ANDVantage 50Y[2]**	**A+Pro[3]**	**NexPro[4]**	**ProCap Gold[5]**
Dry matter, %	93.76	91.73	93.00	88.00
Crude protein, %	51.79 (80)	50.20 (70)	50.1 (75)	48.09 (84)
Lys:Crude protein	3.46	3.96	3.95	3.93
Arg	2.37 (90)	2.36 (81)	2.31 (81)	2.47 (92)
His	1.41 (84)	1.44 (77)	1.33 (80)	1.40 (88)
Ile	2.01 (81)	2.26 (74)	2.19 (75)	2.03 (87)
Leu	6.44 (89)	6.30 (84)	5.68 (85)	5.57 (90)
Lys	1.79 (72)	1.99 (61)	1.98 (61)	1.89 (85)
Met	1.28 (89)	1.07 (81)	1.01 (84)	1.09 (89)
Phe	2.75 (86)	2.66 (81)	2.49 (81)	2.51 (89)
Thr	2.00 (80)	2.01 (67)	2.00 (70)	1.89 (83)
Trp	0.58 (83)	0.37 (75)	0.42 (81)	0.49 (90)
Val	2.54 (82)	2.94 (74)	2.83 (74)	2.84 (85)
Ala	3.82 (86)	3.75 (78)	3.47 (79)	3.41 (86)
Asp	3.49 (78)	3.57 (67)	3.55 (69)	3.38 (82)
Cys	1.12 (81)	0.98 (70)	0.87 (73)	1.00 (84)
Glu	8.87 (87)	8.15 (82)	7.39 (83)	7.52 (89)
Gly	1.96 (81)	2.00 (56)	2.01 (65)	2.06 (76)
Pro	4.17 (100)	-	3.50	3.52 (73)
Ser	2.39 (86)	2.27 (77)	2.17 (77)	2.20 (86)
Tyr	2.32 (90)	2.04 (83)	1.98 (82)	1.90 (90)

[1]Values in parentheses are standardized ileal digestibility coefficients (%) for amino acids in each co-product sources for swine.
[2]Unpublished data from Lee and Stein (2021) provided with permission from The Andersons, Inc.
[3]Published data from Yang et al. (2021)
[4]Published data from Acosta et al. (2021).
[5]Published data from Cristobal et al. (2020).

Digestible phosphorus

Corn fermented protein contributes a significant amount of digestible P to swine diets and can be captured by formulating swine diets on a STTD of P basis. The relatively high total P content of corn co-products and high digestibility allows reducing the amounts of inorganic supplements (i.e. monocalcium phosphate) needed to meet the pig's P requirements while reducing P excretion in manure and diet cost. However, only one study has been conducted to determine the STTD of P in CFP co-products. Cristobal et al. (2020) determined and compared the STTD of P and apparent total tract digestibility (ATTD) of calcium (Ca) in reduced-oil DDGS and CFP (ProCap Gold). The STTD of phosphorus in CFP was less than for conventional DDGS but significantly greater than in corn grain (**Table 4**). This result indicates that some phytate remained after fermentation and processing, and that the addition of phytase would be useful to release more P for utilization by pigs. Similarly, the ATTD of Ca in CFP was less than in conventional DDGS, but this is of minimal importance because of the very low total Ca contributed to diets from reduced-oil DDGS and CFP. No studies have been conducted to determine the P digestibility in other CFP sources, but it is presumed that STTD of P is comparable to results obtained with ProCap Gold. However, it is important to note that several ethanol plants add phytase during the fermentation process which further increases the conversion of indigestible phytate to digestible phosphate (Reis et al., 2018). Therefore, it is important for nutritionists to know the source of corn co-products they are using and to determine if phytase is being using during the production process because it affects phosphorus digestibility values.

Table 4. Comparison of apparent total tract digestibility of calcium and standardized total tract digestibility of phosphorus between conventional reduced oil DDGS and corn fermented protein (ProCap Gold) for swine (as-fed basis; adapted from Cristobal et al., 2020)

Measure	Reduced-oil DDGS	Corn fermented protein
Ca, %	0.04	0.04
P,%	1.01	0.77
ATTD of Ca, %	83	66
STTD of P, %	81	56

Summary of Corn Fermented Protein Feeding Trials with Weaned Pigs

The most appropriate use of CFP co-products is in phase 1 and 2 diets for weaned pigs because of its high ME and digestible amino acid content compared with corn. Highly digestible animal-derived proteins, such as spray-dried animal plasma (SDAP), and plant proteins such as enzyme treated soybean meal, are common additions to nursery pig diets but are expensive. Furthermore, nutritionists want to minimize the amount of soybean meal in phase 1 diets due to the antigenic effects of soy protein upon initial consumption. Therefore, there is considerable interest in using less expensive, highly digestible energy and protein sources as alternatives to soybean meal, enzyme treated soybean meal, and SDAP in newly weaned pig diets.

An initial study was conducted by Martindale et al. (2018) to determine the effects of increasing dietary levels (0, 8, 16, and 24%) of CFP (NexPro) in phase 1 (0 to 14 days post-weaning) and phase 2 (14 to 28 days post-weaning), with a common corn-soybean meal diet fed during phase 3 (days 28 to 35 post-weaning) on growth performance of pigs weaned at 21 days of age. No differences in average daily gain (ADG), average daily feed intake (ADFI), and Gain:Feed (G:F) were observed among dietary treatments during phase 1, but pigs fed the 24% CFP diet during phase 2 had reduced ADG and ADFI compared with pigs fed the control (0% CFP) diet. There were no effects on growth performance during phase 3 and the overall 35-day trial. However, the statistical power to detect differences among dietary treatments in this study is questionable because only 4 replicates (pens) per treatment were used, and each pen contained only 5 pigs which does not represent commercial production conditions. The researchers concluded that adding up to 16% CFP to phase 1 and phase 2 nursery diets does not negatively affect growth performance.

Acosta et al. (2021) evaluated the pig growth performance responses and fecal scores when feeding diets containing various amounts of CFP to partially replace SDAP and enzyme treated soybean meal (ES) during phase 1 and 2 post-weaning (**Table 5**). Feeding the control phase 1 diet containing 5% ES and 2.5% SDAP for the first 7 days after weaning resulted in greater ADG and G:F than feeding diets containing 4.5% ES + 5% CFP and 10% CFP, but there was no significant difference in ADFI among dietary treatments. However, the amount of CFP (0 to 10%) in phase 2 diets, fed from day 8 to 21 post-weaning, had no effect on ADG, ADFI, and G:F. All pigs were fed common corn-soybean meal diets during phase 3 (day 22 to 35 post-weaning) and no differences in subsequent growth performance were observed. These results indicate that adding 5% CFP to phase 1 diets for weaned pigs can provide acceptable growth performance if 2.5% SDAP is also included in the diet but not when 4.5% ES is included in the diet. Adding 10% CFP to phase 1 nursery diets appears to be excessive to support optimal growth performance without addition of SDAP or ES. However, adding 10% CFP to phase 2 diets supports acceptable growth performance comparable to feeding the control diet containing 7.5% ES.

Results from these studies indicate that CFP (NexPro) can be successfully added to phase 1 and phase 2 diets at levels up to 16% depending on the other ingredients used. However, CFP co-products contain high concentrations of leucine (Leu), which negatively affects the utilization and metabolism of valine (Val) and isoleucine (Ile), has been recognized as a nutritional challenge by many researchers (Harris et al., 2004; Cemin et al., 2019; Kwon et al., 2019; Yang et al., 2019). In addition, excess Leu competes with tryptophan (Trp) transport through the blood into the brain which reduces serotonin synthesis and consequently reduces ADFI (Kwon et al., 2019; Yang et al., 2019). Furthermore, the high dietary fiber content in CFP likely increases mucin production and threonine (Thr) losses in the small intestine which may increase the Thr requirement of pigs (Mathai et al., 2016). Therefore, additions of crystalline Thr, Trp, Val, and Ile appear to be required to optimize growth performance of weaned pigs fed diets containing CFP.

Table 5. Growth performance of weaned pigs fed diets containing variable amounts of animal plasma protein (PP), enzyme treated soybean meal (ES), and corn fermented protein (CFP; NexPro) during phase 1 and 2 post-weaning (adapted from Acosta et al., 2021)

Measure	**Control – No CFP**	**Low CFP**	**Moderate CFP + ES**	**High CFP**
Initial body weight, kg	5.86	6.03	6.02	6.02
Final body weight, kg	18.53	18.58	18.51	18.20
Phase 1 (day 1 to 7)	**5% ES + 2.5% PP**	**2.5% PP + 5% CFP**	**4.5% ES + 5% CFP**	**10% CFP**
ADG, kg	0.134[a]	0.106[ab]	0.088[bc]	0.074[c]
ADFI, kg	0.162	0.146	0.147	0.136
Gain:Feed	0.836[a]	0.731[ab]	0.604[bc]	0.538[c]
Phase 2 (day 8 to 21)	**7.5% ES**	**5% ES + 2.5% CFP**	**1% ES + 7.5% CFP**	**10% CFP**
ADG, kg	0.285	0.292	0.277	0.267
ADFI, kg	0.433	0.430	0.418	0.404
Gain:Feed	0.662	0.681	0.663	0.661

Phase 3 (day 22 to 35) – common corn-soybean meal diets				
ADG, kg	0.554	0.552	0.572	0.566
ADFI, kg	0.837	0.848	0.851	0.859
Gain:Feed	0.663	0.653	0.672	0.662
Overall (day 1 to 35)				
ADG, kg	0.362	0.359	0.357	0.348
ADFI, kg	0.541	0.540	0.537	0.533
Gain:Feed	0.673	0.666	0.666	0.656

[a,b,c]Values within rows with uncommon superscripts are different ($P < 0.05$).

Summary of Corn Fermented Protein Feeding Trials with Growing-Finishing Pigs

An unpublished study (data provided with permission from POET) conducted by Clizer et al. at South Dakota State University evaluated the Ile to Lys and Val to Lys ratios in growing-finishing pig diets (59.5 kg to market) containing low dietary concentrations (10 to 15%) of CFP (NexPro). Results from this study showed that an adjustment in the SID Val and Ile levels using soybean meal or crystalline amino acids were required during the early grower phase to overcome the negative effects of excess Leu concentrations contributed from CFP. Although pigs fed the 10 to 15% CFP diets had similar growth performance to those fed corn-soybean meal control diets, providing soybean in the CFP diets to provide greater amounts of Val and Ile resulted in similar overall growth performance compared with pigs fed the corn-soybean meal control diets. Therefore, although the addition of 10% or 15% CFP to growing-finishing pig diets had minimal negative effects on growth performance and carcass composition, soybean meal should be used instead of crystalline amino acids to increase the SID Val and Ile concentrations to mitigate the negative effects of excess Leu.

Conclusions

Corn fermented protein co-products are a high energy, digestible amino acid and phosphorus ingredients that are best suited for phase 1 and 2 diets for newly weaned pigs. Due to the variability in nutritional profiles among sources, it is essential for end-users to know the specific source being used in swine feed formulations to optimize nutritional efficiency and animal performance. When adding CFP to nursery diets, the Thr, Trp, Val, and Ile concentrations relative to Lys content should be calculated and adjusted using crystalline amino acids to achieve optimal pig growth performance.

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Chapter 5
Feeding Applications of Corn Fermented Protein Co-Products in Dairy and Beef Cattle Diets

Introduction

The use of corn fermented protein (CFP) co-products in beef and dairy cattle diets has not been extensively evaluated but energy and protein digestibility values have been determined, and positive results have been reported when feeding CFP to growing beef calves and lactating dairy cows. The following sections summarize dry matter (DM), crude protein (CP), and neutral detergent fiber (NDF) degradability, along with metabolizable energy (ME), net energy (NE), amino acid and fatty acid profiles of some CFP sources.

Nutrient Profile of Corn Fermented Protein Co-Products for Beef and Dairy Cattle

Nutritional composition

An *in vitro* digestibility study was conducted to compare the degradability of DM, NDF, and CP of one source of CFP (A+ Pro), a source of hydrolyzed yeast (Ultramax), a HP-DDG source, and two common sources of conventional DDGS (Palowski et al., 2021). The hydrolyzed yeast had comparable DM degradability to the two DDGS sources, which were greater than for the CFP and HP-DDG sources evaluated (**Table 1**). Degradability of NDF of the hydrolyzed yeast and CFP sources was less than in HP-DDG and DDGS sources, and it was actually negative for the hydrolyzed yeast due to fine particle size and loss through filter bags during incubation. Ruminal degradable and undegradable protein was similar among corn co-products. Estimated intestinal degradable protein and total digestible dietary protein was similar among all co-products except for hydrolyzed yeast which was the lowest. Additional nutritional analyses and sample variation has been conducted for CFP (NexPro) to include other carbohydrates, minerals, fatty acids, and amino acids (**Table 2**).

Table 1. Ruminant NDF degradability, in vitro total dry matter degradability, ruminal protein degradation, and intestinal protein degradation of corn co-products (adapted from Palowski et al., 2021)

Measure, %	CFP A+ Pro	Hydrolyzed Yeast Ultramax*	HP-DDG	DDGS Dakota Gold	DDGS Absolute Energy
NDF degradability[1]	24	-8	53	62	79
Degradable NDF	4	-1	24	16	30
Undegradable NDF	14	7	21	10	8
In vitro total DM degradability[2]	86	93	79	90	92
Ruminal undegradable protein	57	52	59	55	56
Estimated intestinal degradable protein	74	52	80	68	77
Ruminal degradable protein[3]	43	48	41	45	44
Intestinally absorbable dietary protein[4]	43	27	47	38	43

Total digestible dietary protein[5]	85	75	88	82	87

[1]Neutral detergent fiber degradability determined after a 48-hour incubation.
[2]In vitro dry matter degradability determined after a 48-hour incubation.
[3]Ruminal degradable protein = 100 – ruminal undegradable protein.
[4]Intestinally absorbable dietary protein = ruminal undegradable protein × estimated intestinal degradable protein.
[5]Total digestible dietary protein = ruminal degradable protein + intestinally absorbable dietary protein.
*Negative degradability values were likely due to small particle size of this co-product which resulted in loss of product through the filter bags during incubation.

Table 2. Nutrient composition and variability of a source of corn fermented protein (NexPro) from 10 samples obtained from the same production facility (Fairmont, NE; adapted from unpublished data from the University of Nebraska provided with permission from POET)

Measure, % of dry matter	**Mean ± Standard Deviation**
Dry matter	92.1 ± 2.57
Crude protein	53.6 ± 1.13
Soluble protein	4.52 ± 0.82
Neutral detergent-insoluble crude protein	5.00 ± 2.22
Acid detergent-insoluble crude protein	3.73 ± 1.46
aNDF (determined using α-amylase and sodium sulfite)	31.2 ± 3.53
Acid detergent fiber	19.2 ± 2.43
Lignin	1.96 ± 0.76
Sugar	1.25 ± 0.39
Starch	1.47 ± 0.28
Ether extract	5.81 ± 0.46
Minerals	
Ash, %	3.47 ± 0.37
Ca, %	0.03 ± 0.01
P, %	0.72 ± 0.16
Mg, %	0.22 ± 0.08
K, %	0.52 ± 0.26
S, %	0.71 ± 0.10
Na, %	0.12 ± 0.03
Cl, %	0.08 ± 0.01
Fe, mg/kg	120 ± 12.9
Mn, mg/kg	16.7 ± 7.51
Zn, mg/kg	116 ± 67.8
Cu, mg/kg	3.80 ± 0.98
Fatty acids, % of dry matter	
Total fatty acids	7.17 ± 0.50
C14:0	0.01 ± 0.005
C16:0	1.24 ± 0.09
C16:1	0.01 ± 0.003
C17:0	0.01 ± 0.003
C18:0	0.17 ± 0.01
C18:1ω9	1.63 ± 0.16

C18:2ω6	3.87 ± 0.30
C18:3ω3	0.15 ± 0.01
C20:0	0.02 ± 0.005
C20:1ω9	0.02 ± 0.005
C22:0	0.01 ± <0.001
C24:0	0.02 ± 0.005
C24:1	0.01 ± 0.007
Amino acids, % dry matter	
Arg	2.29 ± 0.13
His	1.39 ± 0.08
Ile	1.83 ± 0.17
Leu	6.53 ± 0.34
Lys	1.99 ± 0.13
Met	1.34 ± 0.09
Phe	2.81 ± 0.13
Thr	2.26 ± 0.10
Trp	0.62 ± 0.03
Val	3.51 ± 0.24
Total indispensable amino acids	12.7 ± 0.56
Ala	3.86 ± 0.16
Asp	3.96 ± 0.15
Cys	1.23 ± 0.07
Glu	9.37 ± 0.43
Gly	2.11 ± 0.09
Pro	4.89 ± 0.29
Ser	3.00 ± 0.13
Tyr	2.33 ± 0.10
Total dispensable amino acids	30.8 ± 1.26
Total amino acids	55.3 ± 0.10

Summary of Corn Fermented Protein Feeding Trials with Lactating Dairy Cows

Lactating Jersey cows were fed diets containing corn silage (40%), alfalfa hay (18.1%), ground corn (14.3%), soybean meal (2.66%), soybean hulls (8.61%), fat (3%), urea (0.64%), vitamins and minerals, with increasing inclusion rates (0, 2.64, 5.36, and 8.0%) of CFP (NexPro) to replace non-enzymatically browned soybean meal. This resulted in a slight decrease in CP content (16.14 to 16.06%) and an increase in total fatty acid concentration of the diets because CFP had a higher lipid content than nonenzymatically browned soybean meal. There were no differences in oxygen consumption, or carbon dioxide and methane production with increasing dietary levels of CFP (**Table 3**). However, there was a quadratic effect on respiratory quotient, which is the volume of carbon dioxide released over the volume of oxygen absorbed during respiration, as dietary CFP levels increased. There was also a quadratic trend for DM intake, and a linear trend for increased milk yield as diet inclusion rates of CFP increased (**Table 4**). In addition, there were significant linear increases in energy corrected milk (ECM) production, ECM per dry matter intake, milk fat concentration and yield, and milk lactose concentration and yield as diet inclusion levels of CFP increased (**Table 4**). However, although no differences were observed for milk protein concentration, and milk urea nitrogen, there was a linear trend for increased milk protein yield as cows consumed greater amounts of CFP. These results indicate that feeding up to 8.0% CFP of diet dry matter to lactating dairy cows results in improvements in milk production, composition, and energy utilization efficiency.

Table 3. Oxygen consumption, carbon dioxide and methane production, respiratory quotient, and energy utilization of lactating Jersey cows fed increasing amounts of CFP (NexPro; adapted from unpublished data from the University of Nebraska provided with permission from POET)

Measure	0% CFP	2.64% CFP	5.36% CFP	8% CFP
Gases, L/d				
O_2 consumption	4,892	4,674	4,779	4,770
CO_2 production	4,995	4,861	4,984	4,869
CH_4 production	436	403	413	402
Respiratory quotient[b]	1.02	1.04	1.04	1.02
Energy, Mcal/kg DM				
GE[a]	4.25	4.26	4.28	4.31
DE	2.81	2.84	2.83	2.83
ME	2.48	2.54	2.54	2.53
NE_L	1.60	1.72	1.76	1.72
Energy efficiencies				
ME:DE	0.88	0.90	0.90	0.89
NE_L:ME[a]	0.65	0.68	0.69	0.68

[a] Linear effect ($P < 0.05$) of dietary CFP inclusion rate.

[b] Quadratic effect ($P < 0.05$) of dietary CFP inclusion rate.

Table 4. Dry matter intake, milk production and composition, water intake, and body condition scores pf lactating Jersey cows fed increasing amounts of CFP (NexPro; adapted from unpublished data from the University of Nebraska provided with permission from POET)

Measure	0% CFP	2.64% CFP	5.36% CFP	8% CFP
Dry matter intake[d], kg/d	19.2	19.9	20.7	19.9
Milk yield[b], kg/d	27.8	28.6	29.8	29.0
Energy corrected milk[1,a], kg/d	34.3	35.7	37.3	37.4
Energy corrected milk/dry matter intake[a]	1.80	1.81	1.81	1.89
Milk protein, %	3.35	3.43	3.40	3.40
Milk protein[b], kg/d	0.93	0.98	1.01	0.99
Milk fat[a], %	5.05	5.18	5.15	5.47
Milk fat[a], kg/d	1.40	1.46	1.53	1.58
Lactose[a], %	4.86	4.89	4.90	4.93
Lactose[a], kg/d	1.35	1.40	1.46	1.43
Milk urea nitrogen, mg/dL	12.9	13.0	12.8	13.5

Free water intake[b,d], L/d	79.0	90.6	84.7	80.9
Body weight, kg	436	440	440	439
Body condition score	3.05	3.04	3.16	3.04

[1]Energy corrected milk = 0.327 × milk yield (kg) + 12.95 × fat (kg) + 7.20 × true protein (kg).
[a] Linear effect ($P < 0.05$) of dietary CFP inclusion rate.
[b] Linear trend ($P < 0.1$) of dietary CFP inclusion rate.
[c] Quadratic effect ($P < 0.05$) of dietary CFP inclusion rate.
[d] Quadratic trend ($P < 0.1$) of dietary CFP inclusion rate.

Summary of Corn Fermented Protein Feeding Trials with Growing Beef Cattle

Wiseman et al. (2020) conducted a growth performance study using 250 kg crossbred steers to compare the effects of supplementing CFP (NexPro), SoyPass (non-enzymatically browned soybean meal), and soybean meal at increasing dietary levels (0, 4.5, 9, 13.5, and 18%) as protein supplements in corn silage-based diets. Compared with feeding the control diet, steers fed 18% SoyPass, CFP, and soybean meal had 56, 42, and 32% improvement in ADG, respectively, and 33, 26, and 23% improvement in feed:gain, respectively. These results indicate that growth performance was improved by supplementing CFP, SoyPass, and soybean meal in corn silage-based diets for growth feedlot steers, and the greater improvements were observed when feeding CFP and SoyPass compared with soybean meal which suggests that CFP and SoyPass have similar but greater ruminal undegradable protein content than soybean meal.

Conclusions

Corn fermented protein is an excellent rumen undegradable protein and energy source for lactating dairy cows, where feeding up to 8.0% CFP of diet dry matter can improve milk production, milk composition, and energy utilization efficiency. In growing beef cattle diets, growth performance can be improved by supplementing CFP, SoyPass, and soybean meal in corn silage-based diets for growth feedlot steers, with greater improvements achieved by feeding CFP and SoyPass compared with soybean meal, which suggests that these ingredients have similar but greater ruminal undegradable protein content than soybean meal.

References

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Chapter 6
Nutritional Characteristics and Feeding Value of High-Protein DDG(S) Sources in Animal Feeds

Introduction

Except for conventional distillers dried grains with solubles (DDGS), more research studies have been conducted to evaluate the nutritional value and animal responses from feeding high-protein distillers grains without solubles (HP-DDG) sources than any other corn co-product produced by the U.S. ethanol industry. Unfortunately, HP-DDG is also the most confusing category of all corn co-products in the market today because it has been and continues to be produced using a wide variety of technologies that result in substantially different nutrient profiles among sources. The term “high-protein” DDG was first introduced around 2006-2007 as a way of differentiating new corn co-products that contained 36 to 48% crude protein (CP) from conventional DDGS sources containing 27 to 30% CP. These new corn co-products were produced using various fractionation processes which concentrated the protein by removing a portion of corn fiber and oil. Although HP-DDG is a distinctly different category of corn co-products than DDGS, it is often confused with corn fermented protein (CFP) co-products which also contain high concentrations of CP (>50%). However, while some CFP co-product sources contain similar CP content compared with some HP-DDG sources, the processes used to produce CFP result in greater estimated spent yeast content (20 to 27%) compared with HP-DDG sources, that likely contain about 0 to 18% spent yeast. Unfortunately, corn co-product producers, marketers, and researchers have not carefully described and used appropriate terminology when communicating information about these co-products in research publications, websites, presentations, technical brochures, and product specifications sheets. Therefore, nutritionists are cautioned to be aware of the significantly different nutrient profiles among various HP-DDG sources that have been produced and evaluated in animal feeding trials during the previous 15 years when using data from various published references. Be sure to contact your supplier to ensure that you have received the most accurate information.

Fractionation process technology used to produce HP-DDG has evolved dramatically since 2005. A summary of published animal feeding studies evaluating HP-DDG sources that were produced using older front-end fractionation processes, the majority of which are no longer used today, is shown in **Table 1**. All HP-DDG sources currently being produced use ICM, Inc. FST™ technology. While results from these studies may be useful for providing a general indication of the relative feeding value of HP-DDG for various animal species, they do not accurately represent the nutritional composition, digestibility, and feeding applications of the HP-DDG sources currently being produced by a few U.S. ethanol plants. To emphasize this point, **Table 2** provides a summary of the nutrient profiles and digestibility coefficients of HP-DDG sources for swine evaluated in recent publications compared with the nutrient profile in NRC (2012), which is based on older front-end fractionation technology and publications listed in **Table 1**. Note that NRC (2012) value for CP content is greater, while values for ether extract and phosphorus are less than all other HP-DDG sources produced using new fractionation processes (**Table 2**).

For example, the nutritional profile of HP-DDG from the swine NRC (2012) shown in **Table 2**, is representative of the HP-DDG sources evaluated in many of the studies listed in **Table 1**. Note that in comparison with the nutritional profile of HP-DDG sources that have been evaluated in recent studies using new production technologies, the CP content was relatively high (45%) while the crude fat content was relatively low (3.5%). However, because of the high variability in nutrient content, energy value, and amino acid and phosphorus digestibility, it is essential to know your source and use nutritional profiles specific to that source for accurate diet formulation.

Table 1. Summary of published studies evaluating HP-DDG sources produced using older process technologies that are no longer used today

Species	Reference
Swine	Widmer et al. (2007, 2008)
	Gutierrez et al. (2009a,b)
	Kim et al. (2009)
	Jacela et al. (2010)
	Seabolt et al. (2010)
	Anderson et al. (2012)
	Adeola and Ragland (2012)
	Adeola and Ragland (2016)
	Peterson et al. (2014)
	Rojo et al. (2016)
Poultry	Batal (2007)
	Kim et al. (2008, 2010)
	Applegate et al. (2009)
	Jung and Batal (2009, 2010)
	Rochell et al. (2011)
	Tangenjaja and Wina (2011)
Aquaculture	Barnes et al. (2012a,b)
	Øverland et al. (2013)
	Prachom et al. (2013)
	Herath et al. (2016a,b)
Dairy cows	Mjoun et al. (2009)
	Christen et al. (2010)
	Maxin et al. (2013a,b)
	Swanepoel et al. (2014)

Nutritional Composition and Digestibility of Current HP-DDG Sources

Swine

Most of the published studies that have determined the energy and amino acid digestibility of HP-DDG sources have been conducted in swine (**Table 2**). Because of the various types of production technologies used to produced HP-DDG, the composition among sources can be highly variable with CP levels ranging from 34-43%, lysine (Lys) from 1.0-1.4%, and standardized ileal digestibility (SID) of Lys from 47-76%. Furthermore, gross energy (GE) can range from 4,813-5,296 kcal/kg and digestible energy (DE) content ranging from 3,352-4,424 kcal/kg. Surprisingly, the phosphorus content (0.40-0.50%) is less variable than DE and amino acid concentrations among HP-DDG sources, but the limited estimates of standardized total tract digestibility (STTD) of phosphorus are more variable ranging from 48-68% (**Table 2**). The SID of amino acids is also highly variable among HP-DDG source and generally range from 60-89%, with the exception of Lys where SID ranges for most sources between 47-66%. These results indicate that HP-DDG producers need to determine specific energy, digestible amino acids, and digestible phosphorus values for their products for various animal species and provide this information to their customers to optimize economic and nutritional value of this ingredient in practical feed formulations.

Table 2. Comparison of chemical composition (as-fed basis), energy, amino acid, and phosphorus digestibility of branded and unbranded high-protein distillers dried grains (HP-DDG) sources for swine from recently published studies

Analyte	NRC (2012)[1]	Rho et al. (2017)[2]	Rho et al. (2017)[2]	Paula et al. (2021)[3]	Paula et al. (2021)[4]	Espinosa and Stein (2018)[5]	Lee and Stein (2021)[6]
Dry matter, %	91.20	91.9	91.3	89.62	92.30	86.50	87.45
Crude protein, %	45.35	38.9 (61)[7]	39.4 (73)	34.83 (62)	42.93 (67)	37.11 (77)	39.05 (76)
Ether extract, %	3.54	9.27	8.63	7.80	10.30	*	8.50**
Acid hydrolyzed ether extract, %	*	*	*	*	*	7.59	8.46
Neutral detergent fiber, %	33.63	29.4	28.4	47.48	37.40	31.87	*
Acid detergent fiber, %	20.63	14.6	14.8	19.81	17.53	14.68	*
Total dietary fiber, %	*	*	*	*	*	34.20	37.6
Soluble dietary fiber, %	*	*	*	*	*	2.40	2.2
Insoluble dietary fiber, %	*	*	*	*	*	31.80	35.4
Gross energy, kcal/kg	5,173	4,986	4,935	4,915	5,296	4,825	4,813
Digestible energy, kcal/kg	4,040	4,130	4,157	3,352	4,060	4,424	3,688
Metabolizable energy, kcal/kg	3,732	*	*	3,116	3,757	4,275	3,496
Ash, %	2.39	2.40	2.34	3.39	2.81	2.41	1.80
Ca, %	0.02	0.05	0.06	0.02	0.02	*	< 0.10**
P, %	0.36	0.50	0.47	0.46	0.48	*	0.40**
STTD of P, %	73	*	*	68	48	*	*
Mg, %	0.09	*	*	0.18	0.01	*	*
Na, %	0.06	*	*	0.47	0.09	*	*
K, %	0.37	*	*	0.63	0.41	*	*
Cu, mg/kg	2.03	*	*	7.9	7.10	*	*
Fe, mg/kg	65.30	*	*	52.1	112.5	*	*
Mn, mg/kg	7.00	*	*	9.00	9.97	*	*
Zn, mg/kg	27.30	*	*	56.40	75.55	*	*
Indispensable amino acids, %							
Arg	1.62 (85)	1.64 (72)	1.66 (79)	1.50 (76)	2.06 (83)	1.63 (87)	1.59 (84)
His	1.07 (79)	1.01 (66)	1.04 (72)	0.89 (66)	1.26 (76)	0.97 (82)	1.00 (75)
Ile	1.83 (80)	1.48 (68)	1.50 (75)	1.46 (68)	1.79 (76)	1.59 (82)	1.53 (75)
Leu	6.18 (86)	4.78 (81)	5.01 (84)	4.38 (72)	5.30 (81)	4.39 (89)	4.92 (86)
Lys	1.22 (69)	1.19 (47)	1.20 (56)	1.00 (53)	1.37 (66)	1.43 (76)	1.34 (62)
Met	0.93 (86)	0.79 (79)	0.82 (83)	0.54 (75)	0.95 (82)	0.70 (87)	0.84 (83)
Phe	2.42 (84)	2.01 (77)	2.07 (80)	1.86 (72)	2.16 (78)	2.03 (86)	2.00 (80)

Thr	1.59 (75)	1.45 (60)	1.46 (67)	1.32 (67)	1.66 (76)	1.39 (75)	1.52 (72)
Trp	0.24 (82)	-	-	0.22 (71)	0.23 (73)	0.30 (80)	0.42 (81)
Val	2.12 (78)	1.92 (69)	1.95 (75)	1.82 (69)	2.37 (76)	2.07 (81)	1.89 (73)
Dispensable amino acids, %							
Ala	3.32 (82)	2.78	2.87	2.65 (72)	3.28 (82)	2.58 (85)	2.83 (80)
Asp	2.75 (74)	2.62	2.60	2.72 (64)	3.29 (73)	2.44 (73)	2.64 (73)
Cys	0.82 (78)	0.73	0.78	0.80 (72)	1.09 (82)	0.69 (75)	0.80 (70)
Glu	7.52 (83)	6.69	6.92	6.21 (70)	7.98 (81)	5.61 (88)	6.83 (82)
Gly	1.39 (70)	1.44	1.43	1.40 (73)	1.77 (93)	1.45 (71)	1.38 (65)
Pro	3.65 (79)	3.29	3.40	3.08 (43)	3.99 (55)	-	3.26 (92)
Ser	1.96 (82)	1.89	1.93	1.74 (64)	2.18 (79)	1.46 (82)	1.94 (82)
Tyr	1.92 (85)	-	-	1.45 (70)	1.91 (79)	1.46 (87)	1.59 (86)
Total amino acids	-	-	-	34.76 (65)	44.39 (68)	35.11 (83)	38.45 (80)
Lys:CP	2.69	3.06	3.05	2.87	3.19	3.85	3.43

[1]Data from National Research Council (2012) for swine.
[2]Data from Rho et al. (2017) for two high-protein distillers dried grains samples produced using Fiber Separation Technology™ developed by ICM, Inc., Colwich, KS.
[3]Data from Paula et al. (2021) for high-protein distillers dried grains produced by Corn Plus Co-op (Winnebago, MN, USA) using Fiber Separation Technology™ developed by ICM, Inc., Colwich KS
[4]Data from Paula et al. (2021) for high-protein distillers dried grains produced by FS Bioenergia, Inc. (Lucas do Rio Verde, MT, Brazil) using Fiber Separation Technology™ developed by ICM, Inc., Colwich, KS.
[5]Data from Espinosa and Stein (2018) for high-protein distillers dried grains produced by Lincolnway Energy (Nevada, IA) using mechanical separation of fiber based on solublility before fermentation, oil extraction after fermentation, and low heat compression drying.
[6]Unpublished data from Lee and Stein (2021) provided with permission from The Andersons, Maumee, OH. High-protein distillers dried grains (ANDVantage™ 40Y) produced by using Fiber Separation Technology™ developed by ICM, Inc., Colwich, KS.
[7]Values in parentheses are standardized ileal digestibility coefficients for the corresponding amino acid.
*No data were provided.
**Values obtained from supplier nutrient specification sheets.

As shown in **Table 3**, HP-DDG contains relatively low amounts of starch (2.3%) and high concentrations of neutral detergent fiber (NDF; 41.3%) and total dietary fiber (39.7%), which is similar to conventional DDGS. Because of the relatively high concentrations of fiber in DDGS and HP-DDG, swine and poultry nutritionists have evaluated the addition of various commercially available carbohydrases and proteases in DDGS diets (Jang et al., 2021), which may provide similar responses in HP-DDG diets based on similar physiochemical attributes such as swelling and water-binding capacity (**Table 3**). Boucher et al. (2021) evaluated the effects of adding a multi-carbohydrase enzyme blend (xylanase, glucanase, cellulase, amylase, invertase, and protease) to diets containing DDGS and HP-DDG for swine to determine if they were effective in improving DE and metabolizable energy (ME) content of the diets. The HP-DDG source was produced using mechanical separation technology (ICM, Inc., Colwich, KS, USA) to remove large non-fermentable fiber particles prior to fermentation to increase throughput and ethanol production. However, the nutrient profile reported for this HP-DDG source reported in this study does not reflect the typical composition of HP-DDG produced using ICM, Inc. FST technology because of lower crude protein and greater fiber content. This may be an example of researchers using incorrect terminology or misunderstanding the process used to produce the corn co-product being evaluated. Regardless, the results showed that compared with DDGS, this HP-DDG source had about 50% less starch, 20% more protein, 14% greater water-binding capacity, and greater DE (3,896 and 4,405 kcal/kg DM, respectively) and ME (3,494 and 3,872 kcal/kg DM, respectively) content for swine, but the multi-carbohydrase enzyme was ineffective in improving DE and ME values in both DDGS and HP-DDG diets.

Table 3. Chemical and physiochemical characteristics of corn and co-products (adapted from Boucher et al., 2021)

Characteristic	Corn	DDGS	HP-DDG	Dried Corn Bran + Solubles
Chemical composition				
Dry matter, %	86.1	89.3	88.9	94.9
Gross energy, kcal/kg	3,769	4,600	4,950	4,629
Crude protein, %	6.5	27.1	32.5	19.4
Ether extract, %	2.7	7.6	9.6	6.8
Starch, %	67.1	4.5	2.3	7.4
Total dietary fiber, %	11.2	36.7	39.7	37.0
NDF, %	12.3	30.5	41.3	33.5
ADF, %	3.2	7.1	15.1	7.6
Physiochemical attributes				
Bulk density, g/L	522	507	478	386
Swelling, L/kg	2.4	3.5	3.6	4.4
Water-binding capacity, g/g	2.1	2.9	3.3	2.9

Poultry

Fries-Craft and Bobeck (2019) determined the nitrogen-corrected apparent metabolizable energy (AME_n) and SID of amino acids of a HP-DDG source for broilers (**Table 4**). Compared with a conventional DDGS source, HP-DDG had greater CP (34.1%), AME_n (2,725 kcal/kg), and amino acid content, with relatively high SID of amino acid coefficients ranging from 81% for Lys, threonine (Thr), and cysteine (Cys) to 90% for arginine (Arg) and leucine (Leu). Unpublished data for ANDVantage™ 40Y (provided with permission from The Andersons) showed greater CP and amino acid content than reported in the Fries-Craft study, but comparable amino acid digestibility coefficients (**Table 4**). The TME_n content of ANDVantage™ 40Y was also substantially greater than found in a conventional DDGS source.

Table 4. Nutrient content, nitrogen-corrected apparent metabolizable energy (AME_n) and true metabolizable energy (TME_n), and standardized ileal digestibility of amino acids (as-fed basis) of high-protein distillers dried grains (HP-DDG) sources for broilers (adapted from Fries-Craft and Bobeck, 2019)

Analyte	DDGS[1]	HP-DDG[1]	ANDVantage™40Y[2]
Dry matter, %	89.80	83.10	90.0

Crude protein, %	27.10	34.10	40.4
Ether extract, %	9.63	7.91	8.50
Crude fiber, %	7.85	8.35	8.80
AME_n, kcal/kg	2,629	2,725	NR[4]
TME_n, kcal/kg	2,509	NR	3,286
Arg	1.10	1.49 (90)[3]	1.69 (93)[3]
His	0.62	0.88 (86)	1.15 (88)
Ile	1.15	1.26 (84)	1.65 (87)
Leu	2.40	4.32 (90)	4.93 (94)
Lys	0.70	1.16 (81)	1.35 (81)
Met	0.50	0.74 (89)	0.80 (91)
Phe	1.35	1.57 (88)	2.11 (91)
Thr	0.93	1.31 (81)	1.56 (85)
Trp	0.20	0.30 (82)	0.30 (88)
Val	1.40	1.60 (86)	1.97 (87)
Ala	NR	NR (86)	NR
Asp	NR	NR (82)	NR
Cys	0.45	0.58 (81)	NR
Glu	NR	NR (90)	NR
Gly	0.60	1.25 (NR)	NR
Pro	NR	NR (82)	NR
Ser	1.30	1.60 (87)	NR
Tyr	0.80	1.34 (84)	NR
Lys:CP	2.58	3.40	3.34

[1]Published data from Fries-Craft and Bobeck (2019)
[2]Unpublished data provided with permission from The Andersons, Maumee, OH.
[3]Values in parentheses are standardized ileal digestibility coefficients of amino acids.
[4]NR = not reported

Aquaculture

A recent study compared the nutritional differences between HP-DDG (ANDVantage™ 40Y), SBM (SBM), and poultry meal, and the effects of replacing increasing amounts of SBM or poultry meal with HP-DDG in channel catfish diets (Nazeer et al., 2022). A comparison of the nutritional profiles of these three ingredients is shown in **Table 5**. Poultry meal contains greater CP and indispensable amino acid content than HP-DDG except for Leu. Similarly, SBM contains greater concentrations of amino acids than HP-DDG except for Leu and methionine (Met). Therefore, supplementation of synthetic Lys, Met, Thr, and tryptophan (Trp) is likely necessary when partially substituting poultry meal and SBM with HP-DDG in aquaculture diets to support optimal growth performance and fillet composition.

Table 5. Comparison of the nutrient content (as-fed basis) of poultry meal, SBM, and high-protein distillers dried grains (HP-DDG; adapted from Nazeer et al, 2002)

Analyte, %	Poultry meal	SBM	ANDVantage™40Y[2]
Dry matter	91.05	88.52	90.86
Crude protein	64.59	46.66	42.25
Ether extract	12.29	0.48	8.48
Crude fiber	-	3.59	7.05

Ash	9.88	6.47	2.13
Indispensable amino acids			
Arg	4.32	3.49	1.84
His	1.41	1.24	1.18
Ile	2.64	2.27	1.88
Leu	4.55	3.64	5.48
Lys	4.11	3.02	1.30
Met	1.22	0.61	0.86
Phe	2.57	2.38	2.34
Thr	2.55	1.83	1.58
Trp	0.60	0.64	0.34
Val	3.21	2.31	2.30
Indispensable amino acids			
Ala	4.05	2.04	3.19
Asp	5.29	5.31	2.86
Cys	0.77	0.69	0.83
Glu	8.58	9.00	7.17
Gly	5.54	2.00	1.56
Hydroxylysine	0.23	0.02	0.00
Hydroxyproline	1.55	0.11	0.07
Pro	3.59	2.21	3.44
Ser	2.53	2.26	1.82
Taurine	0.47	0.12	0.10
Tyr	2.15	1.73	1.79

Summary of Swine HP-DDG Feeding Trials

Yang et al. (2019) evaluated the use of experimentally determined ME and SID values of amino acids for HP-DDG (37.6%) produced by Lincolnway Energy (Nevada, IA) in nursery pig diets. Weaned pigs were fed a common phase 1 diet for the first week after weaning, followed by 1 of 4 diets containing 0, 10, 20, or 30% HP-DDG during phase 2 (days 7-21 post-weaning) and phase 3 (days 21-42 post-weaning). Diets were formulated to contain equivalent concentrations of ME, digestible Lys, Met, Thr, and Trp, and digestible phosphorus. As dietary HP-DDG levels increased, calculated SID Leu to Lys ratios increased from 119 to 173% in phase 2 diets, and from 120 to 160% in phase 3 diets. Similarly, SID isoleucine (Ile) to Lys ratios ranged from 60 to 69% in phase 2 diets and 54 to 59% in phase 3 diets, while SID valine (Val) to Lys ratios ranged from 63 to 79% in phase 2 and from 64 to 68% in phase 3 diets. A linear reduction in average daily gain (ADG), average daily feed intake (ADFI), and gain:feed (G:F) was observed during phase 2 and 3 as diet inclusion rates of HP-DDG increased. Although pigs in this study were challenged with *Streptococcus suis* and *Escherichia coli*, there was no difference in morbidity among treatments, but including HP-DDG in the diets tended to reduce mortality compared with feeding the control diets with no HP-DDG. These results indicate that the linear reduction in growth performance observed from adding increasing dietary levels of this HP-DDG source were likely due to an overestimation of the SID amino acid content, antagonistic effects of excess digestible dietary Leu content relative to digestible Val and Ile content and increasing dietary fiber content which may have increased Thr requirements.

Similarly, Cemin et al. (2019b) conducted a study to determine the effects of feeding increasing amounts (0, 10, 20, 30, or 40%) of HP-DDG produced using ICM, Inc. Fiber Separation Technology in nursery pig diets and to estimate the productive energy content of HP-DDG. Net energy (NE) content of HP-DDG was estimated using three different DE prediction equation approaches. Caloric efficiency was calculated by multiplying ADFI by the kcal of estimated net energy per kg of diet and dividing by ADG. For the overall 21-day feeding period, feeding diets containing increasing levels of HP-DDG resulted in linear decreases in ADG, ADFI, and final body weight. There was a quadratic effect for feed:gain (F:G) with the best response observed when 40% HP-DDG diets were fed. As a result, the caloric efficiency of HP-DDG was linearly reduced as dietary levels increased, and the approach used to apply DE prediction equations underestimated the NE content of HP-DDG. Based on the caloric efficiency calculations, the NE of this HP-DDG source was estimated to be about 97% of the NRC (2012) value of NE content in corn.

Two experiments were conducted to determine the effects of feeding 30% HP-DDG diets in 4-phase feeding programs to growing-finishing pigs on growth performance, carcass characteristics, and pork fat quality (Yang et al., 2020). The first experiment used a HP-DDG source from IGPC Ethanol, Inc. (Alymer, Ontario, Canada) which contained relatively low concentrations of deoxynivalenol (DON; 1.7 mg/kg), total fumonisins (FUM; 0.60 mg/kg), and zearalenone (ZEA; 0.2 mg/kg). The second experiment evaluated a source of HP-DDG obtained from ICM, Inc. (St. Joseph, MO) that also contained relatively low concentrations of DON (1.0 mg/kg), FUM (3.80 mg/kg), and ZEA (0.06 mg/kg). Guidelines for “safe” maximum concentrations of DON (< 1 mg/kg), FUM (5 mg/kg), and ZEA (< 1 mg/kg) suggested that no negative effects on growth performance would be expected when HP-DDG was added at levels of 30% of the total diet. Results from experiment 1 showed that feeding the 30% HP-DDG diets with low concentrations of DON, FUM, and ZEA resulted in reduced ADG and ADFI during the first 8 weeks of the 16-week feeding trial compared with feeding corn-SBM control diets. To determine if this reduction in growth rate and feed intake was due to excess Leu in HP-DDG diets or the low concentrations of mycotoxins, a commercial mycotoxin mitigation product was added to both the control and 30% HP-DDG diets for half of the pigs in the trial, while the other half of these pigs continued to be fed diets without the mycotoxin mitigant for the remaining 8 weeks of the overall 16-week feeding period. The addition of the mycotoxin mitigant to diets was effective in restoring growth performance of pigs fed the HP-DDG diets to be comparable to pigs fed the control diets. These results indicate that the reduction in growth performance during the first 8 weeks of the feeding period was a result of the additive negative effects of low concentrations of DON, FUM, and ZEA and not excess Leu in the diets.

For the second experiment, a mycotoxin mitigation product was added to the diets at the beginning of the feeding period. Results showed that pigs fed the 30% HP-DDG diets had reduced ADG, final body weight, ADFI, and G:F during the 16-week feeding period (**Table 6**). Furthermore, feeding the 30% HP-DDG diets resulted in reduced hot carcass weight, carcass yield, loin muscle area, and percentage of fat-free carcass lean but did not affect backfat thickness compared with pigs fed the control diets (**Table 6**). Pigs fed the HP-DDG diets also had greater polyunsaturated fatty acid content and iodine value of pork fat than pigs fed the corn-SBM control diets indicating that carcass pork fat was less firm when feeding the HP-DDG diets. These results indicate that 1) low concentrations of mycotoxins in diets containing contaminated HP-DDG can reduce growth performance, but effective mitigation additives can alleviate these negative effects, 2) excess Leu in 30% HP-DDG diets interferes with the utilization of Ile and Val resulting in suboptimal feed intake, growth, gain efficiency, and carcass lean, and 3) the high unsaturated fatty acid content of corn oil present in HP-DDG when used at a 30% diet inclusion reduces carcass pork fat firmness.

Table 6. Growth performance and carcass characteristics of growing-finishing pigs fed 30% high-protein distillers dried grains (HP-DDG) diets with a mycotoxin mitigation agent (adapted from Yang et al., 2020)

Measure	**Control**		**30% HP-DDG + MA**	
Initial BW, kg	22.75		22.74	
Final BW, kg	133.37[a]		126.58[b]	
ADG, kg	1.01[a]		0.95[b]	
ADFI, kg	2.63[a]		2.57[b]	
G:F	0.41[a]		0.39[b]	
Carcass characteristics	**Gilt**	**Barrow**	**Gilt**	**Barrow**
Hot carcass weight[1], kg	98.34	98.16	96.07	95.86
Carcass yield[1], %	75.55	75.33	74.04	73.78
Backfat depth[2], mm	19.75	23.45	20.72	23.22
Loin muscle area[1,2,3], cm	49.26	44.91	42.58	43.71
Fat-free lean[1,2,3], %	52.40	49.38	50.10	49.04

[a,b] Means within rows with uncommon superscripts are different ($P < 0.05$).
[1]Diet effect ($P < 0.01$).
[2] Sex effect ($P < 0.05$).
[3] Diet × sex interaction ($P < 0.01$).

The most recent study evaluating diets containing increasing levels of HP-DDG was conducted by Rao et al. (2021). Growth performance and carcass composition responses were compared between growing-finishing pigs fed increasing dietary levels (0, 15, and 30%) of conventional DDGS or HP-DDG (ICM, Inc.). All diets were formulated to contain equal digestible Lys content but different levels of NE. Dietary branched-chain amino acid ratios were adjusted based on the equation from Cemin et al. (2019) to account for excess Leu in DDGS and HP-DDG diets. Caloric efficiency was calculated by dividing estimated NE intake by weight gain (Cemin et al., 2020). Results showed that increasing diet inclusion rate of conventional DDGS significantly decreased final body weight linearly, while increasing dietary HP-DDG inclusion rates tended to decrease final body weight (**Table 7**). These decreases in final body weight were a result of linear decreases in ADG during the grower phase when feeding increasing dietary amounts of either DDGS or HP-DDG. Pigs fed the HP-DDG diets had greater ADFI and G:F than pigs fed the DDGS diets. Hot carcass weight and carcass yield were linearly reduced as dietary inclusion rates of DDGS or HP-DDG increased. Iodine value was calculated as an estimate of the unsaturated to saturated fatty acid ratio in carcass fat and linearly increased when increasing amounts of DDGS and HP-DDG were fed. These results indicate that pigs fed comparable dietary levels of HP-DDG to DDGS have similar ADG but pigs fed HP-DDG diets had greater gain efficiency. The greater carcass fat iodine value from pigs fed the HP-DDG diets was likely a result of the greater corn oil content in HP-DDG (10.27% ether extract) compared with conventional DDGS (8.03%).

Table 7. Comparison of growth performance, caloric efficiency, and carcass characteristics of growing-finishing pigs fed increasing dietary levels of conventional DDGS and HP-DDG (adapted from Rao et al., 2021)

Measure	Control (0%)	DDGS		HP-DDG	
		15%	30%	15%	30%
Initial body weight, kg	27.1	27.1	27.1	27.1	27.1
Final body weight, kg	130.0	127.3	127.8	129.0	128.0
Grower phase					
ADG, g	893	879	862	875	852
ADFI, g	1,870	1,840	1,828	1,825	1,721
G:F, g/kg	479	479	472	480	497
Caloric efficiency, kcal/kg	5,395	5,317	5,322	5,420	5,300
Finisher phase					
ADG, g	855	833	864	860	870
ADFI, g	2,609	2,604	2,644	2,555	2,510
G:F, g/kg	328	321	327	336	347
Caloric efficiency, kcal/kg	8,040	8,136	7,890	7,937	7,743
Overall					
ADG, g	876	857	865	870	863
ADFI, g	2,262	2,243	2,259	2,212	2,139
G:F, g/kg	388	382	384	394	404
Caloric efficiency, kcal/kg	6,747	6,758	6,655	6,699	6,586
Carcass characteristics					
Hot carcass weight, kg	94.9	92.5	92.1	94.0	92.0
Carcass yield, %	73.1	72.6	72.1	72.9	71.9
Backfat depth, mm	15.9	15.5	15.9	15.8	15.6
Loin depth, mm	67.0	67.0	66.9	67.3	66.7
Lean, %	57.2	57.5	57.2	57.3	57.4
Iodine value, g/100 g	64.8	69.0	73.7	72.9	80.0

Summary of HP-DDG Feeding Trials with Broilers

Fries-Craft and Bobeck (2019) determined the AME_n content, SID amino acid digestibility, and growth performance (42-d) of broilers fed diets containing of an unspecified source of HP-DDGS (34% CP). The AME_n content was determined to be 2,725 kcal/kg and SID of indispensable amino acids ranged from 81% (Lys) to 90% for arginine (Arg) and Leu. Feeding diets containing 15 and 20% HP-DDGS resulted in reduced body weight gain and feed conversion but had no effect on feed intake compared with feeding the 10% HP-DDGS diets (**Table 8**). Results from this study indicate that this source of HP-DDGS can be included up to 10% in broiler diets with no negative effects on growth performance and without requiring supplemental Lys and Arg in diets.

Table 8. Comparison of growth performance of Cobb 500 broilers fed diets containing 5% conventional DDGS and increasing concentrations of HP-DDGS for 42 days (adapted from Fries-Craft and Bobeck, 2019)

Measure	5% DDGS	10% HP-DDGS	15% HP-DDGS	20% HP-DDGS

Initial body weight, g	37.93	37.74	37.40	37.48
Starter (d 0 to 14)				
Day 14 body weight, kg	0.39^{a}	0.39^{a}	0.35^{b}	0.37^{a}
Body weight gain, kg	0.34^{a}	0.35^{a}	0.31^{b}	0.34^{a}
Feed intake, kg	0.51^{ab}	0.53^{a}	0.51^{b}	0.53^{a}
Feed:Gain	1.49^{c}	1.51^{c}	1.63^{a}	1.58^{b}
Grower (d 14 to 35)				
Day 35 body weight, kg	1.99^{ab}	2.02^{a}	1.91^{c}	1.93^{bc}
Body weight gain, kg	1.61^{ab}	1.64^{a}	1.56^{b}	1.55^{b}
Feed intake, kg	2.66^{ab}	2.74^{a}	2.63^{b}	2.70^{ab}
Feed:Gain	1.66^{c}	1.67^{bc}	1.69^{b}	1.76^{a}
Finisher (d 35 to 42)				
Day 42 body weight, kg	2.70^{a}	2.72^{a}	2.56^{b}	2.58^{b}
Body weight gain, kg	0.70^{a}	0.70^{ab}	0.65^{b}	0.65^{b}
Feed intake, kg	1.30^{a}	1.29^{ab}	1.24^{b}	1.26^{ab}
Feed:Gain	1.86	1.86	1.91	1.94
Overall (d 0 to 42)				
Body weight gain, kg	2.65^{a}	2.68^{a}	2.52^{b}	2.54^{b}
Feed intake, kg	4.47^{ab}	4.55^{a}	4.38^{b}	4.49^{ab}
Feed:Gain	1.69^{c}	1.70^{c}	1.74^{b}	1.77^{a}

^{a,b,c} Means within rows with uncommon superscripts are difference ($P < 0.05$).

Hussain et al. (2019) evaluated diets containing 6.4% HP-DDGS (43% CP from an unspecified U.S. source) and the addition of protease, combination of mannanase and xylanase, and a combination of all three enzyme on growth performance, nutrient digestibility, and intestinal morphology of broilers. There were no effects of enzyme supplementation on body weight gain, feed intake, feed conversion, carcass characteristics, organ weight, intestinal morphology, nor energy and amino acid digestibility. These results indicate that the carbohydrases and protease evaluated in this study were not effective in improving growth performance, nutrient digestibility, and intestinal morphology of broilers.

Summary of HP-DDG Feeding Trials with Layers

Foley et al. (2022) evaluated the effects of feeding diets containing two new HP-DDG sources produced using ICM, Inc. fiber separation technology that contained 40.3% CP (FST1) and 39.1% CP (FST2) on feed intake, egg production, and AME content in White Leghorn laying hens from 21 to 45 weeks of age. Dietary treatments consisted of a corn-SBM control with no HP-DDG, and diets containing 5, 10, or 15% FST1 or FST2. Time × dietary treatment interactions were found for egg production, yolk color score, and eggshell breaking strength. Egg production improved during the later weeks of the trial in hens fed the 15% HP-DDG diets from either source. Yolk color score increased as HP-DDG level increased in the diet but decreased over time regardless of dietary treatment. Eggshell breaking strength was highest in hens fed the control and 15% FST2 diets, but HP-DDG source or level did not affect feed intake, egg weight, or hen body weight. The AME content of the 5% FST1 and 10% FST2 treatment groups and for all hens fed the HP-DDG diets compared to those fed the control diet. In summary, laying hens can be fed diets containing up to 15% HP-DDG produced using the ICM, Inc. fiber separation technology with no detrimental effects on feed intake or egg production with some improvements to yolk color and egg production in later stages of the laying cycle.

Summary of HP-DDG Feeding Trials with Aquaculture

Nile tilapia (*Oreochromis niloticus*)

Herath et al. (2016a) determined the effects of totally replacing fishmeal (21.8%) with CPC (19.4%), HP-DDG (33.2%), corn gluten meal (CGM; 23.5%), or DDGS (52.4%) in isonitrogenous diets on growth performance and body composition of juvenile (4.5 g initial average weight) Nile tilapia (*Oreochromis niloticus*) in a 12-week feeding trial. Fish fed the control diet containing 21.8% fishmeal and the 52.4% DDGS diet had the highest specific growth rate, feed intake, protein retention, and survival among all dietary treatments (**Table 9**). In contrast, fish fed the CGM and CPC diets had the lowest specific growth rate, thermal growth rate, feed intake, protein retention, and survival. Fish fed the HP-DDG diet had lower specific growth rate and thermal growth rate, but comparable feed intake and protein retention compared with those fed the control and DDGS diets. In addition, feeding the HP-DDG diet resulted in greater whole body and fillet protein content than fish the control and DDGS diets, along with greater lipid content compared to fish fed the control diet (**Table 9**). However, no differences were observed for any of the body indices measured. Results from this study indicate that completely replacing fishmeal with various corn co-products in juvenile Nile tilapia diets results in different effects on growth performance and whole body and fillet composition. Among the corn co-products evaluated, diets containing DDGS provided the best growth performance and composition responses but feeding the HP-DDG diet resulted in greater growth performance and whole body and fillet protein composition than feeding diets containing CGM and CPC without fishmeal.

Table 9. Comparison of growth performance, body indices, and fillet color of Nile tilapia (*Oreochromis niloticus*) fed corn co-product diets for 12 weeks (Adapted from Herath et al., 2016a)

Measure	Control	HP-DDG[1]	DDGS[2]	CGM[3]	CPC[4]
Growth performance					
Specific growth rate, %	3.56[a]	3.30[b]	3.53[a]	2.75[c]	2.63[d]
Thermal growth coefficient	1.21[a]	1.06[c]	1.16[b]	0.81[d]	0.76[e]
Feed intake, g dry weight	84.05[a]	71.05[a]	81.20[a]	40.2[b]	38.80[b]
Feed conversion ratio	1.00	1.05	1.05	1.00	1.10
Protein efficiency ratio	3.20	2.99	3.06	3.10	2.84
Protein retention, %	49.62[a]	46.17[ab]	46.70[ab]	42.02[bc]	38.42[c]
Survival, %	100.0[a]	80.6[bc]	97.2[ab]	66.6[c]	75.0[c]
Whole body composition, % wet basis					
Moisture	69.4	68.9	69.7	70.9	71.6
Protein	15.5[b]	16.7[a]	15.4[b]	14.6[c]	13.9[d]
Lipid	8.5[b]	9.9[a]	10.0[a]	9.8[a]	9.6[a]
Ash	6.9[a]	5.4[c]	5.7[b]	4.0[e]	5.0[d]
Fillet composition, % wet basis					
Moisture	78.2	76.2	77.2	77.9	78.5

Protein	18.8[b]	19.8[a]	18.3[b]	19.2[b]	18.7[b]
Lipid	1.6[c]	2.4[b]	3.1[a]	2.2[b]	1.9[bc]
Ash	1.4	1.2	1.3	1.3	1.4
Body indices					
Viscerosomatic index[5]	10.8	11.6	12.9	12.1	12.8
Hepatosomatic index[6]	3.0	2.1	2.7	2.2	2.0
Fillet yield[7], %	30.4	30.8	32.4	31.9	28.3
Coefficient of condition[8]	2.0	2.0	2.0	1.8	1.9

[a,b,c,d,e]Means with uncommon superscripts in each row are different (P < 0.05).
[1]HP-DDG = high protein distillers dried grains.
[2]DDGS = distillers dried grains with solubles.
[3]CGM = corn gluten meal.
[4]CPC = corn protein concentrate.
[5]Viscerosomatic index = 100 × visceral weight (g)/body weight (g).
[6]Hepatosomatic index = 100 × liver weight (g)/body weight (g).
[7]Fillet yield = 100 × fillet weight (g)/body weight (g).
[8]Coefficient of condition = 100 × body weight (g)/total length (cm^3).

In a subsequent longer term comparative study, Herath et al. (2016b) evaluated the effects of feeding corn co-product-based diets on growth performance, fillet color and composition of Nile tilapia (*Oreochromis niloticus*) during a 24-week feeding period. In this study, diets consisted of a control diet containing 10% FM (FM), and four other diets without fishmeal but containing HP-DDG (33.2%), DDGS (52.4%), CGM (23.5%), or CPC (19.4%) to replace 50% of the dietary protein. Fish (initial body weight = 21 g) fed the control, HP-DDG, and DDGS diets had greater mean weight gain, specific growth rate, mean feed intake, protein, efficiency ratio and improved feed conversion and survival than those fed CGM and CPC diets (**Table 10**). However, there was no effect of corn co-product on lightness, redness, yellowness, crude protein, and total amino acid content of fillets. Fish fed the CGM diet had the greatest lipid and ash content in fillets, while fillet fatty acid composition varied among dietary treatments. Results from this study indicate that adding HP-DDG or DDGS to non-fishmeal diets at levels up to 50% of dietary protein had no negative effects on growth performance or fillet color, but feeding diets containing CGM and CPC were detrimental to growth performance at these inclusion rates.

Table 10. Comparison of growth performance, body indices, fillet composition and color of Nile tilapia (*Oreochromis niloticus*) fed diets containing high-protein distillers dried grains (HP-DDG), distillers dried grains with solubles (DDGS), corn gluten meal (CGM), and corn protein concentrate (CPC) during a 24-week feeding period (adapted from Herath et al., 2016b)

Measure	Control	HP-DDG	DDGS	CGM	CPC
Growth performance					
Mean weight gain, g	162[a]	161[a]	161[a]	88[b]	75[b]
Specific growth rate, %	1.27[a]	1.26[a]	1.27[a]	0.96[b]	0.90[b]
Mean feed intake, g/fish	216[a]	222[a]	226[a]	149[b]	124[b]
Feed conversion ratio	1.33[b]	1.38[b]	1.40[b]	1.72[a]	1.66[a]
Protein efficiency ratio	2.31[a]	2.12[a]	2.30[a]	1.69[b]	1.68[b]
Survival, %	97.2[a]	97.2[a]	97.2[a]	91.7[a]	52.7[b]
Body indices					
Intraperitoneal fat ratio	1.88	2.22	1.50	2.02	1.34
Hepatosomatic index	2.70[b]	2.70[b]	1.93[c]	3.45[a]	2.30[bc]

Viscerosomatic index	9.33	10.92	9.44	11.62	11.50
Fillet yield	28.16	27.52	27.34	27.14	26.37
Condition factor	2.01^{a}	1.83^{c}	1.89^{bc}	1.94^{b}	1.87^{bc}
Fillet composition					
Moisture, %	77.85	77.60	77.35	77.30	77.70
Crude protein, %	19.60	19.60	19.65	19.40	19.35
Crude lipid, %	1.80^{b}	2.05^{ab}	2.20^{ab}	2.35^{a}	2.05^{ab}
Ash, %	1.30^{b}	1.30^{b}	1.26^{b}	1.60^{a}	1.50^{ab}
Tristimulus color of fillets					
L*	47.8	48.0	47.8	41.5	41.8
a*	1.3	0.7	1.2	1.8	2.3
b*	3.2	2.3	2.3	1.3	2.2
Chroma[1]	3.5	2.4	2.7	1.9	3.3
Hue angle[2], degrees	67.5	74.0	54.5	53.6	43.3
ΔE[3]	0	1.11	0.97	6.61	6.22

[a.b.c] Means within rows with uncommon superscripts are different ($P < 0.05$)
[1]Chroma = intensity of color.
[2]Hue angle = 0° for redness and 90° for yellowness.
[3]ΔE = total color difference compared with control.

Striped catfish (*Pangasianodon hypophthalmus*)

A HP-DDG co-product containing 40% CP, 3.1% ether extract, 28.1% crude fiber, and 2.4% ash was added to isonitrogenous, isolipidic, and isocaloric diets for striped catfish (*Pangasianodon hypophthalmus*) at increasing levels (0, 5.8, 11.6, and 17.4%) to partially replace FM to evaluate growth performance and economic benefits (Allam et al., 2020). Replacing 25% of FM with HP-DDG (5.8% of total diet) resulted in acceptable growth rate and feed conversion but replacing greater amounts of FM linearly decreased growth and feed conversion. Furthermore, whole-body protein content was reduced, and lipid content was increased at the highest dietary HP-DDG inclusion rate. The negative effects of HP-DDG added at 11.6 and 17.4% on growth performance and body composition was likely due to inadequate Lys, Met, and other essential amino acids which can be corrected with the addition of adequate amounts of supplemental crystalline amino acids.

Channel catfish (*Ictalurus punctatus*)

Tidwell et al. (2017) evaluated a HP-DDG co-product to determine effects of increasing dietary levels (0, 20, 40, and 40% + crystalline lysine) on pellet characteristics and growth performance of juvenile channel catfish (*Ictalurus punctatus*). Average harvest weight of fish fed the 20% HP-DDG diet was greater (86.8 g) than those fed the 40% HP-DDG (57.0 g) and 40% HP-DDG + supplemental lysine (73.7 g), but there were no differences in feed conversion or survival among dietary treatments. Whole-body protein concentration was greater in fish fed the control diet compared with those fed the 40% HP-DDG with and without supplemental lysine, but moisture, lipid, and ash content were not affected. Increasing dietary HP-DDG levels resulted in decreased pellet expansion ratio, tended to increase unit density and pellet durability index. These results indicate that supplemental Lys, and perhaps other essential amino acids in HP-DDG diets is necessary at diet inclusion rates greater than 20% to support optimal growth performance and fillet composition. However, producing pellets with high pellet durability index can be achieved at high dietary inclusion rates of HP-DDG.

A recent study compared the effect of adding increasing dietary levels of HP-DDG (ANDVantage™ 40Y) to partially replace poultry meal or SBM in diets for juvenile channel catfish (Nazeer et al., 2022). Isonitrogenous (32% CP) and isolipidic (6.5% lipid) diets were formulated to contain 0, 3.1, 6.2, and 9.3% HP-DDG to replace 6, 4, 2, and 0% poultry meal, respectively, and 5, 10, 15, 20, 30, and 40% HP-DDG to replace 51, 46.5, 41.9, 37.4, 28.2, and 19.2% SBM, respectively. All diets were pelleted and fed to juvenile channel catfish (*Ictalurus punctatus*; average initial weight of 1.8 g) in the first trial. A second trial was conducted to confirm the low feed intake responses of fish fed the 9.3% HP-DDG diet replacing poultry meal at two feeding rates. There was a significant interaction between dietary inclusion level of HP-DDG and protein source replaced (poultry meal or SBM). When increasing levels of HP-DDG replaced increasing amounts of poultry meal in the diets, growth, feed intake, feed conversion, and net protein retention were reduced, especially when feeding the 9.3% HP-DDG diet (**Table 11**). However, there were no differences among dietary HP-DDG levels on survival, and whole-body moisture, crude protein, crude lipid, and ash content (**Table 11**). However, when increasing HP-DDG levels were added to replace portions of SBM in diets, there were no differences in growth performance among dietary treatments except for the 30 and 40% HP-DDG diets (**Table 12**). Again, fish survival and whole-body moisture, crude protein, crude lipid, and ash content was not affected by dietary HP-DDG inclusion rate (**Table 12**). Results from this study indicate that HP-DDG is a good protein source for channel catfish diets but should be limited to no more than 20% of the diet when partially replacing SBM to avoid reductions in growth performance. However, when HP-DDG (9.3%) was used to completely replace poultry meal, poor growth performance resulted which was likely due to a nutritional deficiency.

Table 11. Comparison of growth performance and whole-body composition of channel catfish fed diets containing increasing amounts of high-protein distillers dried grains (HP-DDG; (ANDVantage™ 40Y) to partially replace poultry meal during a 10-week feeding period (adapted from Nazeer et al., 2022)

Measure	Control	3.1% HP-DDG	6.2% HP-DDG	9.3% HP-DDG
Growth performance				
Final biomass, g	479[a]	445[ab]	411[b]	351[c]
Final weight, g/fish	24.26[a]	22.25[ab]	21.40[b]	18.02[c]
Weight gain, g/fish	22.41[a]	20.50[ab]	19.62[b]	16.18[c]
Weight gain, %	1,215[a]	1,169[a]	1,103[a]	882[b]
Total dry feed, g/fish	24.35[a]	23.27[a]	23.52[a]	20.50[b]
Feed conversion ratio	1.09[c]	1.14[bc]	1.20[ab]	1.27[a]
Survival, %	98.75	100.0	96.25	97.50
Net protein retention, %	42.85[a]	40.43[ab]	38.47[ab]	33.90[b]
Whole body composition, %				
Moisture	72.15	72.15	73.12	75.13
Crude protein	14.65	14.40	14.40	13.80
Crude lipid	8.98	9.16	8.42	7.78
Ash	2.64	3.17	2.89	2.49

[a.b.c] Means within rows with uncommon superscripts are different ($P < 0.05$)

Table 12. Comparison of growth performance and whole-body composition of channel catfish fed diets containing increasing amounts of high-protein distillers dried grains (HP-DDG; (ANDVantage™ 40Y) to partially replace SBM during a 10-week feeding period (adapted from Nazeer et al., 2022)

	Dietary HP-DDG inclusion rate, %						
Measure	**0**	**5**	**10**	**15**	**20**	**30**	**40**
Growth performance							
Final biomass, g	479^{a}	493^{a}	504^{a}	512^{a}	507^{a}	403^{b}	253^{c}
Final weight, g/fish	24.26^{a}	24.64^{a}	25.18^{a}	25.92^{a}	26.00^{a}	20.15^{b}	12.65^{c}
Weight gain, g/fish	22.41^{a}	22.85^{a}	23.33^{a}	24.13^{a}	24.19^{a}	18.35^{b}	10.88^{c}
Weight gain, %	$1{,}215^{a}$	$1{,}277^{a}$	$1{,}263^{a}$	$1{,}349^{a}$	$1{,}340^{a}$	$1{,}020^{b}$	613^{c}
Total dry feed, g/fish	24.35^{a}	24.24^{bc}	24.83^{ab}	25.30^{ab}	25.65^{a}	23.32^{c}	18.30^{d}
Feed conversion ratio	1.09^{c}	1.06^{c}	1.07^{c}	1.05^{c}	1.06^{c}	1.27^{b}	1.68^{a}
Survival, %	98.75	100.0	100.0	98.75	100.0	100.0	100.0
Net protein retention, %	42.85^{a}	42.11^{ab}	44.82^{a}	43.78^{a}	43.65^{a}	35.26^{b}	24.39^{c}
Whole body composition, %							
Moisture	72.15	72.47	70.72	71.65	71.55	73.37	73.40
Crude protein	14.65	13.57	15.02	14.05	13.92	13.90	13.15
Crude lipid	8.98	9.31	9.50	9.52	9.86	8.78	8.23
Ash	2.64	3.15	3.19	3.31	2.82	2.96	3.21

[a.b.c,d] Means within rows with uncommon superscripts are different ($P < 0.05$)

Yellow perch (*Perca flavescens*)

Von Eschen et al. (2021) evaluated a source of HP-DDG containing 40% CP as a partial or complete replacement for herring fishmeal (72% CP) in juvenile yellow perch (*Perca flavescens*) diets in a 105-day feeding trial. Experimental diets contained increasing replacement levels of 25, 50, 75, and 100% of FM with HP-DDG. Weight gain, feed conversion, apparent protein digestibility, and condition factor were negatively correlated with increasing dietary levels of HP-DDG. As the fishmeal inclusion rate decreased in diets, growth performance also decreased, but survival was 100% across all treatments. Results from this study indicate that the addition of HP-DDG to yellow perch diets should not exceed a 50% replacement rate, and supplemental synthetic lysine may improve growth performance.

Summary of HP-DDG Feeding Trials with Lactating Dairy Cows

An unpublished study conducted by Zynda et al. (2021) evaluated feeding diets containing HP-DDG (ICM, Inc.) at 20% of dry matter intake, with and without yeast or manipulation of dietary cation and anion difference (DCAD) on milk production, nutrient digestibility, and gas emissions from manure in lactating dairy cows. Compared with feeding the control SBM-based diet, feeding HP-DDG reduced milk yield as a result of decreased organic matter and NDF digestibility, and reduced milk fat yield as a result of high polyunsaturated fatty acid content and low DCAD. However, elevating DCAD in HP-DDG diets by supplementing cations was effective in alleviating milk fat depression, but there were no beneficial effects of HP-DDG with yeast for any measures evaluated. Furthermore, because of the relatively high concentration of phosphorus and sulfur in

HP-DDG, phosphorus and sulfur excretion were increased in manure of cows fed HP-DDG which also increased hydrogen sulfide emissions. These results emphasize the importance of balancing DCAD when feeding high amounts of HP-DDG to lactating dairy cows to avoid milk fat depression but feeding HP-DDG with greater yeast content did not provide improvements in milk production, milk composition, nutrient digestibility, or reduce gas emissions from manure.

Conclusions

The sources of HP-DDG available in the market have a substantially different nutritional profile than HP-DDG sources produced and evaluated 10 to 15 years ago, and also varies significantly among current sources. Therefore, it is essential to communicate with your HP-DDG supplier to obtain the actual energy, digestible amino acids, and digestible phosphorus data specific to HP-DDG source being fed to ensure accurate diet formulation and achieve optimal animal performance. Theoretically, the addition of appropriate carbohydrases and proteases to swine, poultry, and aquaculture diets may improve the utilization of dietary fiber and ME content in HP-DDG diets, but limited studies thus far for swine and poultry indicate that this is not an effective strategy. Although HP-DDG has greater CP and digestible amino acid content than conventional DDGS, it contains excess Leu relative to Ile and Val which reduces feed intake and growth rate in swine nursery and growing-finishing diets containing increasing levels of HP-DDG. Therefore, dietary supplementation of several crystalline amino acids (e.g., Lys, Thr, Trp, Ile, Val) may be needed to overcome reduced feed intake and growth depending on the diet inclusion rate of HP-DDG used. Limited studies in broilers and layers indicate that HP-DDG can support satisfactory performance when HP-DDG is limited to 10% of the diet for broilers and 15% for layers. In general, it appears that HP-DDG can be used to replace up to 50% of dietary protein in non-fishmeal diets for Nile tilapia and yellow perch, but supplemental lysine may be necessary to support optimal growth performance. For striped catfish and channel catfish, no more than 20% HP-DDG as a partial replacement for SBM is recommended, and supplementation of Lys and other indispensable amino acids may be necessary to support optimal growth performance. The use of HP-DDG in lactating dairy cow diets can support satisfactory milk production and composition but diet formulation adjustments to balance the dietary cation and anion difference is an important consideration for optimizing its use.

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Chapter 7
Nutritional Characteristics and Feeding Value of Corn Protein Concentrate in Aquaculture and Broiler Diets

Introduction

Historically, fish meal (FM) has been the “gold standard” high crude protein (CP) feed ingredient used in aquaculture diets but its continued used is not sustainable (Naylor et al., 2009). Therefore, finding suitable replacements for FM is essential, and protein concentrates from grains, oilseeds and pulses have generally considered to be attractive alternatives. Unfortunately, using plant-based alternative protein sources, such as corn protein concentrate (CPC) and distillers dried grains with solubles (DDGS), can result in suboptimal growth performance and reduced protein efficiency, especially in carnivorous fish, when fed diets containing low amounts of FM and high amounts of plant-based protein concentrates even though the requirements of all known essential nutrients, including amino acids, appear to be met (Gomes et al., 1995; Davies et al. 1997; Refstie et al., 2000; Martin et al., 2003; Gómez-Requeni et al., 2004). There are several potential reasons for reduced growth performance of fish fed relatively high amounts of plant-based protein sources including reduced feed intake; presence of anti-nutritional factors, anabolic steroids and phytoestrogens; unidentified nutrient deficiencies, and an imbalance of essential amino acids (Gatlin et al. 2007; Glencross et al., 2007; Krogdahl et al., 2010). The most likely cause of suboptimal growth is inadequate amounts of digestible amino acids provided by plant-based protein sources because they are generally lower in lysine (Lys), threonine (Thr), and tryptophan (Trp) than FM, which may cause deficiencies relative to amino acid requirements of fish. To correct these deficiencies, supplemental synthetic amino acids must be added to all diets containing plant-based protein sources including corn co-products such as CPC. In addition, Brezas and Hardy (2020) also suggested that the dynamics of protein digestion for plant-based protein ingredients may vary depending on the synchronization and homogeneity of amino acid digestion and absorption which can ultimately affect growth. Therefore, although there are nutritional challenges for using high protein corn co-products such as CPC in aquaculture diets to achieve optimal growth and fillet composition, some of these challenges may be overcome by supplementing diets with appropriate amounts of synthetic amino acids rather than rely solely on direct substitution of fishmeal without dietary amino acid adjustments.

AAFCO Definition of Corn Protein Concentrate

Corn protein concentrate (CPC) is unique compared with all other corn co-products because it contains the greatest concentration of CP (~ 80%). It is produced using a unique wet milling process compared with the different processes used to produce corn fermented protein (CFP) and high protein distillers dried grains (HP-DDG) in dry grind ethanol facilities. Corn protein concentrate is produced by Cargill Corn Milling facilities in the United States and is marketed under the brand name Empyreal® 75. A modified process has also been used to produce Lysto™, which contains much greater lysine content and improved amino acid profile compared with the process used to produce Empyreal® 75 (Yu et al., 2013). Because of its very high CP content, CPC is of great interest to aquaculture nutritionists due to its potential for partially or completely replacing FM (64% CP) in aquaculture diets while maintaining the high total dietary CP and amino acid concentrations necessary to meet the nutritional requirements of all species of fish. The Association of American Feed Control Officials defines corn protein concentrate as follows:

48.89 Corn Protein Concentrate
"Corn Protein Concentrate is the dried proteinaceous fraction of the corn primarily originating from the endosperm after removal of the majority of the non-protein components by enzymatic solubilization of the protein stream obtained from the wet-milling process. The proteinaceous fraction of the corn must contain not less than 80% protein on a moisture free basis and not more than 1% starch on a moisture free basis. The product must be labeled on "as fed" basis. This fraction shall be free of fermented corn extractives, corn germ meal, and other non-protein components except in such amounts as might occur unavoidably in good manufacturing processes. Vegetable oils or other appropriate ingredients as defined in Section 87 in the Association of American Feed Control Officials Official Publication (AAFCO OP) may be added in concentrations not to exceed 3% to reduce dust during handling. The name of the dust control agent, if used, must be shown as an added ingredient."

Therefore, CPC primarily contains the proteins from the endosperm of corn grain which results in minimal amounts of fiber and ash compared with other corn co-products. Furthermore, unlike CFP, corn protein concentrate contains no residual spent yeast.

Nutrient Profile of Corn Protein Concentrate

There are limited published data on the nutritional profile of CPC, but some commercial nutritional specifications and information on Empyreal® 75 can be obtained online at (https://agripermata.com/brochure/commodity/corn_protein_concentrate/brochure2.pdf). Yu et al. (2013) compared the nutritional composition of two types of CPC with Menhaden FM, dehulled solvent extracted soybean meal (SBM), and corn gluten meal (**Table 1**). Although the CP content of CPC is also much greater than Menhaden FM (64%), corn gluten meal (CGM; 65%), and SBM (50%), it contains relatively low Lys and Trp compared with SBM and FM. Furthermore, CPC and CGM contain extremely high concentrations of leucine (Leu) which interferes with the utilization of isoleucine (Ile), valine (Val), and Trp. A detailed discussion regarding the challenges of managing the amino acid profile imbalances of corn protein from all corn co-products in monogastric animal diets is provided in Chapter 1 of this handbook.

Table 1. Nutrient composition (as-fed basis) of two types of corn protein concentrate and compared with menhaden fish meal (FM), dehulled solvent extracted soybean meal and corn gluten feed (Adapted from Yu et al., 2013)

Measure, %	Menhaden FM	Solvent extracted soybean meal	Corn gluten meal	Corn protein concentrate Empyreal®[1]	Corn protein concentrate Lysto™[1]
Dry matter	90.61	88.36	91.59	90.16	88.39
Crude protein	64.3	49.9	64.8	79.7	79.8
Ether extract	10.7	1.19	0.46	2.36	2.58
ADF	-	2.83	2.82	9.8	7.5
Ash	15.1	5.34	6.63	0.91	0.91
Indispensible amino acids					

Arg	4.99	3.26	2.03	2.11	2.16
His	2.21	1.16	1.30	2.05	1.40
Ile	3.10	1.86	2.51	2.36	2.99
Leu	5.50	3.36	10.04	10.40	11.95
Lys	6.04	2.81	1.03	1.37	5.66
Met	1.47	0.82	1.45	1.77	1.67
Phe	2.97	2.16	3.88	5.00	4.57
Thr	3.46	1.56	2.02	2.42	2.19
Trp	1.10	NR[2]	0.34	0.55	0.37
Val	4.09	1.78	3.03	2.85	3.29
Dispensable amino acids					
Ala	6.45	1.72	5.32	8.26	6.17
Asp	6.84	6.55	3.72	3.89	4.10
Cys	0.43	0.88	1.10	1.28	1.27
Glu	9.70	9.64	12.89	14.20	14.06
Gly	6.05	1.89	1.79	1.84	1.83
Pro	4.48	2.36	5.82	7.42	6.78
Ser	3.37	1.95	2.97	3.53	2.78
Tyr	2.50	1.49	3.08	3.74	3.75

[1]Cargill Corn Milling, Cargill, Inc., Blair, NE.
[2]Not reported.

Summary of Feeding Trials with Nile Tilapia (*Oreochromis niloticus*)

Most of the published studies conducted with CPC in aquaculture feeds involve feeding Nile tilapia (*Oreochromis niloticus*). One of the initial studies was conducted by Herath et al. (2016a) to determine the effects of totally replacing FM (21.8%) with CPC (19.4%), HP-DDG (33.2%), CGM (23.5%), or DDGS (52.4%) in isonitrogenous diets on growth performance and body composition of juvenile (4.5 g initial average weight) Nile tilapia (*Oreochromis niloticus*) in a 12-week feeding trial. Fish fed the control diet containing 21.8% FM and the 52.4% DDGS diet had the highest specific growth rate, feed intake, protein retention, and survival among all dietary treatments (**Table 2**). In contrast, fish fed the CGM and CPC diets had the lowest specific growth rate, thermal growth rate, feed intake, protein retention, and survival. The reduced protein retention in tilapia fed the CGM and CPC diets was reflected in lower whole body protein content, but not in protein content of fillets (**Table 2**). Whole body lipid content was greater and ash content was lower in fish fed corn co-product diets compared with those fed the control diet. However, no differences were observed for any of the body indices measured. Results from this study indicate that completely replacing fishmeal with various corn co-products in juvenile Nile tilapia diets results in different effects on growth performance and whole body and fillet composition. Among the corn co-products evaluated, diets containing DDGS provided the best growth performance and composition responses while the feeding the CPC diet resulted in the poorest growth performance in diets without FM.

Table 2. Comparison of growth performance, body indices, and fillet color of Nile tilapia (*Oreochromis niloticus*) fed corn co-product diets for 12 weeks (Adapted from Herath et al., 2016a)

Measure	Control	HP-DDG[1]	DDGS[2]	CGM[3]	CPC[4]
Growth performance					
Specific growth rate, %	3.56^{a}	3.30^{b}	3.53^{a}	2.75^{c}	2.63^{d}
Thermal growth coefficient	1.21^{a}	1.06^{c}	1.16^{b}	0.81^{d}	0.76^{e}
Feed intake, g dry weight	84.05^{a}	71.05^{a}	81.20^{a}	40.2^{b}	38.80^{b}
Feed conversion ratio	1.00	1.05	1.05	1.00	1.10
Protein efficiency ratio	3.20	2.99	3.06	3.10	2.84
Protein retention, %	49.62^{a}	46.17^{ab}	46.70^{ab}	42.02^{bc}	38.42^{c}
Survival, %	100.0^{a}	80.6^{bc}	97.2^{ab}	66.6^{c}	75.0^{c}
Whole body composition, % wet basis					
Moisture	69.4	68.9	69.7	70.9	71.6
Protein	15.5^{b}	16.7^{a}	15.4^{b}	14.6^{c}	13.9^{d}
Lipid	8.5^{b}	9.9^{a}	10.0^{a}	9.8^{a}	9.6^{a}
Ash	6.9^{a}	5.4^{c}	5.7^{b}	4.0^{e}	5.0^{d}
Fillet composition, % wet basis					
Moisture	78.2	76.2	77.2	77.9	78.5
Protein	18.8^{b}	19.8^{a}	18.3^{b}	19.2^{b}	18.7^{b}
Lipid	1.6^{c}	2.4^{b}	3.1^{a}	2.2^{b}	1.9^{bc}
Ash	1.4	1.2	1.3	1.3	1.4
Body indices					
Viscerosomatic index[5]	10.8	11.6	12.9	12.1	12.8
Hepatosomatic index[6]	3.0	2.1	2.7	2.2	2.0
Fillet yield[7], %	30.4	30.8	32.4	31.9	28.3
Coefficient of condition[8]	2.0	2.0	2.0	1.8	1.9

[a,b,c,d,e]Means with uncommon superscripts in each row are different ($P < 0.05$).
[1]HP-DDG = high protein distillers dried grains.
[2]DDGS = distillers dried grains with solubles.
[3]CGM = corn gluten meal.
[4]CPC = corn protein concentrate.
[5]Viscerosomatic index = 100 × visceral weight (g)/body weight (g).
[6]Hepatosomatic index = 100 × liver weight (g)/body weight (g).
[7]Fillet yield = 100 × fillet weight (g)/body weight (g).
[8]Coefficient of condition = 100 × body weight (g)/total length (cm^3).

In a subsequent longer term comparative study, Herath et al. (2016b) evaluated the effects of feeding corn co-product-based diets on growth performance, fillet color and composition of Nile tilapia (*Oreochromis niloticus*) during a 24-week feeding period. In this study, diets consisted of a control diet containing 10% FM, and four other diets without fishmeal but containing HP-DDG (33.2%), DDGS (52.4%), CGM (23.5%), or CPC (19.4%) to replace 50% of the dietary CP. Fish (initial body weight = 21 g) fed the control, HP-DDG, and DDGS diets had greater mean weight gain, specific growth rate, mean feed intake, protein, efficiency ratio and improved feed conversion and survival than those fed CGM and CPC diets (**Table 3**). However, there was no effect of corn co-product on lightness, redness, yellowness, crude protein, and total amino acid content of fillets. Fish fed the CGM diet had the greatest lipid and ash content in fillets, while fillet fatty acid composition varied among dietary treatments. Results from this study indicate that adding HP-DDG or DDGS to non-fishmeal diets at levels up to provide up to 50% of dietary CP has no negative effects on growth performance or fillet color but feeding diets containing CGM and CPC were detrimental to growth performance at these inclusion rates.

Table 3. Comparison of growth performance, body indices, and fillet color of Nile tilapia (*Oreochromis niloticus*) fed corn co-product diets for 24 weeks (Adapted from Herath et al., 2016b)

Measure	Control	HP-DDG	DDGS	CGM	CPC
Growth performance					
Mean weight gain, g	162.2[a]	160.7[a]	161.4[a]	88.3[b]	74.9[b]
Specific growth rate, g	1.27[a]	1.26[a]	1.27[a]	0.96[b]	0.90[b]
Mean feed intake, g	216.2[a]	222.2[a]	225.5[a]	148.8[b]	124.1[b]
Feed conversion ratio	1.33[b]	1.38[b]	1.40[b]	1.72[a]	1.66[a]
Protein efficiency ratio	2.31[a]	2.12[a]	2.30[a]	1.69[b]	1.68[b]
Survival, %	97.2[a]	97.2[a]	97.2[a]	91.7[a]	52.7[b]
Body composition					
Intraperitoneal fat ratio	1.99	2.22	1.50	2.02	1.34
Hepatosomatic index	2.70[b]	2.70[b]	1.93[c]	3.45[a]	2.30[bc]
Viscerosomatic index	9.33	10.92	9.44	11.62	11.50
Fillet yield	28.16	27.52	27.34	27.14	26.37
Condition color	2.01[a]	1.83[c]	1.89[bc]	1.94[b]	1.87[bc]
Fillet color measures					
L*	47.8	48.0	47.8	41.5	41.8
a*	1.3	0.7	1.2	1.8	2.3
b*	3.2	2.3	2.3	1.3	2.2
Chroma[1]	3.5	2.4	2.7	1.9	3.3
Hue angle[2], degrees	67.5	74.0	54.5	53.6	43.3
ΔE[3]	0	1.11	0.97	6.61	6.22

[a,b,c]Means with uncommon superscripts in each row are different ($P < 0.05$).
[1]Chroma = intensity of color.
[2]Hue angle = 0° for redness and 90° for yellowness.
[3]ΔE = total color difference compared with control.

In contrast to the studies conducted by Herath et al. (2016a,b) where diets containing 19.4% CPC were fed, Khalfia et al. (2017) fed four isocaloric-isonitrogenous diets containing lower inclusion rates (0, 5, 10 and 19%) of CPC as a replacement for FM to Nile tilapia (*Oreochromis niloticus*) fingerlings for 8 weeks. There were no differences in growth performance of fish fed the 5 and 10% CPC diets compared with fish fed the 0% CPC diet, and all of these diets provided better growth performance compared with feeding the 19% CPC diet. Furthermore, there were no differences in fillet yield and body composition among dietary treatments. Interestingly, the stomach size of fish fed the control diet was slightly smaller and the stomach wall was thinner than observed in fish fed the CPC diets when using an electron microscope. Furthermore, feeding the 10 and 19% CPC diets reduced total aerobic bacteria and coliform counts compared with fish fed diets with 0 and 5% CPC diets. Results from this study indicate that up to 10% CPC can be added in tilapia fingerling diets to replace up to 53% FM without any negative effects on growth performance and body composition.

Most recently, Ng et al. (2019) evaluated the effects of replacing fishmeal with CPC on growth performance, nutrient utilization, gut morphology, and skin coloration of red hybrid tilapia (*Oreochromis* sp.). Five isonitrogenous (35% CP) and isolipidic (1% ether extract) diets were formulated to contain CPC that replaced 0, 25, 50, 75, or 100% of FM and were fed to triplicate groups of tilapia (average initial weight = 10.33 g) for 63 days. The results showed that replacing up to 50% FM in red hybrid tilapia diets with CPC had no negative effects on growth rate, feed utilization, haematocrit counts, condition factor, and gut morphology of tilapia, but when CPC replaced 75 or 100% of fishmeal, negative effects were observed. In addition, the carotenoids present in CPC increased skin yellowness in fish fed the diet where CPC replaced 100% of FM. Using regression analysis, the optimal replacement rate of FM by CPC was 25% for percentage weight gain, 33% for FCR and 29% for protein efficiency ratio. Results from this study suggest that CPC can be used as a single plant protein source to substitute up to 50% FM in red hybrid tilapia diets.

Summary of Feeding Trials with Pacific White Shrimp (*Litopenaeus vannamei*)

Three tank feeding trials and a pond production trial were conducted to evaluate the addition of increasing amounts of CPC on growth performance of Pacific white shrimp (*Litopenaeus vannamei*) during various feeding periods (Yu et al., 2013). In the first tank trial, juvenile shrimp (0.52 g average initial weight) were fed diets containing 8% CGM and 6.5 or 13.0% CPC for 6 weeks. The second tank trial involved feeding juvenile shrimp (0.36 g average initial weight) diets containing 0, 4, 8, and 16% CPC and supplemental synthetic L-Lys to replace SBM on an isonitrogenous basis, along with a diet containing 9.7% CPC with an enhanced amino acid profile and greater Lys content as a replacement for CPC and synthetic L-Lys for a 10-week feeding period. The third tank trial involved feeding diets containing 0, 4, 8, and 16% CPC to juvenile shrimp (0.128 g average initial body weight) for a 44-day growth performance trial. Results of the first two trials showed no significant differences in final average weight, weight gain, feed conversion ratio, or survival. At the end of trial two, there were no differences in dry matter and CP of shrimp or differences in protein retention efficiency among dietary levels of CPC. However, results from trial 3 showed reductions in final biomass, final weight, and feed conversion for shrimp fed the 8 and 12% CPC diets compared with those fed the 0 and 4% CPC diets.

In the pond production trial (Yu et al., 2013), juvenile shrimp (0.023 g average initial weight) were placed in 16 production ponds and fed one of four diets containing 0, 4, 8, or 12% CPC for a 16-week feeding period before harvest. As shown in **Table 3**, there were no differences in final weight, yield, feed conversion ratio, survival, and production value of shrimp among dietary treatments. However, feed cost was significant reduced with increasing CPC levels in the diet, resulting in lower feed cost/kg of shrimp for those fed 8 and 12% CPC diets compared with those fed 0 and 4% CPC diets. Results from this study indicate that CPC can be added up to 12% of juvenile Pacific white shrimp diets without affecting growth performance while significantly reducing diet cost/kg of shrimp produced.

Table 3. Growth performance, feed cost, and production value of Pacific white shrimp (*Litopenaeus vannamei*) fed diets containing increasing levels of corn protein concentrate (CPC) for 16 weeks (adapted from Yu et al., 2013)

Measure	0% CPC	4% CPC	8% CPC	12% CPC
Final weight, g	20.51	17.48	17.17	18.71
Yield, kg/ha	5,008	5,190	5,421	5,440
Feed conversion ratio	1.38	1.34	1.27	1.29
Survival, %	64.9	77.6	83.6	75.9
Feed cost, $	791[a]	716[b]	651[c]	598[d]
Feed cost/kg shrimp	1.60[a]	1.39[ab]	1.20[b]	1.11[b]
Production value, $	2,107	1,808	1,844	2,018

[a,b]Means with uncommon superscripts in each row are different ($P < 0.05$).

Summary of Feeding Trails with Laying Hens

One study has been conducted to evaluate the nutritional value of adding CPC to laying hen diets on egg production and egg quality (Herrera et al., 2019). Laying hens (64 weeks of age, 2.05 kg body weight) were fed isocaloric (2,850 kcal/kg) and isonitrogenous (15% CP) diets containing 0, 0.5, 1.0, 1.5, 2.0, or 2.5% CPC for 10 weeks. Quadratic responses were observed for hen body weight gain, feed intake, feed conversion, egg production, egg mass, and egg weight as dietary CPC levels increased. Increasing levels of CPC in layer diets also linearly increased feed intake, feed conversion, shell thickness and breaking strength, and yolk color. However, albumen height and Haugh units were not affected by dietary CPC level. Results from this study indicate that adding up to 2.5% of CPC to laying hen diets improves egg production

Conclusions

Corn protein concentrate is an attractive alternative high protein feed ingredient for use in aquaculture and poultry diets. Limited studies have been conducted to evaluate the addition of CPC to Nile tilapia (*Oreochromis niloticus*) and Pacific white shrimp (*Litopenaeus vannamei*) and indicate that feeding diets containing up to 10% CPC or replacing up to 50% of FM in tilapia diets, and up to 12% in shrimp diets, provides satisfactory growth performance and body and fillet composition. Feeding diets containing up to 2.5% CPC to laying hens has been shown to improve egg production and quality.

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Chapter 8
Nutritional Characteristics and Feeding Value of Dried Corn Bran and Solubles, De-oiled (Solvent Extracted DDGS), and Corn Distillers Oil in Animal Diets

Introduction

In addition to corn fermented protein (CFP; Chapters 1, 2, 3, 4, and 5), high-protein distillers dried grains without solubles (HP-DDG) described in Chapter 6, and corn protein concentrate (CPC) described in Chapter 7, several other new corn co-products are being produced by a few ethanol plants using new industrial processes that result in different nutritional profiles and feeding applications. These include wet and dried corn fiber/bran and solubles (CBS), de-oiled DDGS, and corn distillers oil (CDO). Therefore, the purpose of this chapter is to provide current nutritional profiles of each co-product category, describe the benefits and limitations for their use in diets for different animal species, and provide summaries of feeding trials that have been conducted.

Dried Corn Bran and Solubles

Nutritional composition of corn bran and solubles for ruminants

A few ethanol plants that use ICM's Fiber Separation Technology™ are producing high moisture (40% dry matter) CBS. Because of the high moisture content affecting transportation costs, this co-product is not exported but has been evaluated in beef feedlot cattle diets. See the section in this chapter that contains a brief summary of results from feeding trials that have evaluated high moisture corn bran and distillers solubles in beef feedlot cattle diets.

Nutritional composition of dried corn bran and solubles for swine

New corn ethanol facilities in Brazil are using ICM's Fiber Separation Technology™ to produce dried CBS for use in swine, poultry, and cattle diets. Paula et al. (2021) determined the digestible energy (DE), metabolizable energy (ME), standardized ileal digestibility (SID) of amino acids, and standardized total tract digestibility (STTD) of phosphorus (P) in dried CBS compared with conventional sources of DDGS and HP-DDG produced in the U.S., and a HP-DDG source produced using ICM's Fiber Separation Technology™ in Brazil. As expected, the crude protein (CP) content of CBS is relatively low (13.87%), and the ether extract (9.00%) and neutral detergent fiber (NDF; 39.07%) content is relatively high compared with the other corn co-products evaluated (**Table 1**). The ME content of CBS was about 91% of the ME content in U.S. DDGS, and 80% and 71% of the ME content in U.S. HP-DDG and Brazilian HP-DDG, respectively. Although the P content of CBS (0.71%) was greater than found in the other corn co-products, the STTD of P was the lowest (46.4%) of the co-products compared (**Table 1**). The SID of lysine (Lys), methionine (Met), threonine (Thr), and tryptophan (Trp) in CBS were lower than for the other corn co-products. These results indicate that dried CBS has substantially less ME and digestible amino acid content than conventional sources of DDGS and HP-DDG produced in the U.S., and HP-DDG produced in Brazil. However, this nutritional profile would be suitable for use in sow gestation diets where limiting energy intake is necessary to control body condition, and the requirements for digestible amino acids are relatively low.

Table 1. Chemical composition (as-fed basis) of U.S. corn dried distillers grains with solubles (DDGS) and high-protein distillers dried grains (HP-DDG) compared with Brazilian HP-DDG and dried corn bran with solubles (CBS; adapted from Paula et al., 2021)

Analyte	U.S. DDGS	U.S. HP-DDG	Brazil HP-DDG	Brazil CBS
Dry matter, %	86.08	89.62	92.30	87.59
Crude protein, %	26.37 (72)	34.83 (62)	42.93 (67)	13.87 (59)
Ether extract, %	6.40	7.80	10.30	9.00
NDF, %	36.59	47.48	37.40	39.07
ADF, %	14.31	19.81	17.53	13.31
Gross energy, kcal/kg	4,532	4,915	5,296	4,513
DE (swine), kcal/kg	3,134	3,352	4,060	2,843
ME (swine), kcal/kg	2,941	3,116	3,757	2,680
Ash, %	4.89	3.39	2.81	4.80
Ca, %	0.04	0.02	0.02	0.02
P, %	0.68	0.46	0.48	0.71
STTD P, %	62.7	67.6	48.3	46.4
Mg, %	0.28	0.18	0.01	0.33
Na, %	0.44	0.47	0.09	0.24
K, %	1.09	0.63	0.41	1.50
Cu, mg/kg	14.26	7.9	7.10	7.14
Fe, mg/kg	59.56	52.1	112.5	87.32
Mn, mg/kg	12.72	9.00	9.97	16.81
Zn, mg/kg	63.39	56.40	75.55	61.26
Indispensable amino acids, %				
Arg	1.10 (84)	1.50 (76)	2.06 (83)	0.69 (74)
His	0.64 (72)	0.89 (66)	1.26 (76)	0.36 (69)
Ile	0.98 (67)	1.46 (68)	1.79 (76)	0.46 (65)
Leu	2.90 (74)	4.38 (72)	5.30 (81)	1.20 (72)
Lys	0.73 (55)	1.00 (53)	1.37 (66)	0.40 (46)
Met	0.43 (75)	0.54 (75)	0.95 (82)	0.25 (73)
Phe	1.21 (72)	1.86 (72)	2.16 (78)	0.54 (64)
Thr	0.95 (68)	1.32 (67)	1.66 (76)	0.51 (54)
Trp	0.15 (74)	0.22 (71)	0.23 (73)	0.11 (66)
Val	1.30 (66)	1.82 (69)	2.37 (76)	0.64 (65)
Dispensable amino acids, %				
Ala	1.86 (78)	2.65 (72)	3.28 (82)	0.90 (79)
Asp	2.02 (65)	2.72 (64)	3.29 (73)	1.02 (53)
Cys	0.59 (70)	0.80 (72)	1.09 (82)	0.34 (59)
Glu	4.34 (75)	6.21 (70)	7.98 (81)	2.03 (69)
Gly	1.08 (94)	1.40 (73)	1.77 (93)	0.66 (80)
Pro	2.14 (59)	3.08 (43)	3.99 (55)	1.08 (52)

Ser	1.20 (66)	1.74 (64)	2.18 (79)	0.61 (63)
Tyr	1.09 (69)	1.45 (70)	1.91 (79)	0.49 (62)
Total amino acids	24.44 (62)	34.76 (65)	44.39 (68)	12.16 (65)
Lys:CP	2.77	2.87	3.19	2.88

Previous studies by Anderson et al. (2012) and Rochell (2011) determined the nutrient profile, DE and ME content for swine, and the AME_n content of a similar dried CBS source for poultry (**Table 2**). Although there are no recent studies that have estimated AME_n in CBS for poultry, the DE (3,282 kcal/kg DM) and ME (3,031 kcal/kg DM) content of CBS for swine determined by Anderson et al. (2012) were almost identical to the DE (3,246 kcal/kg DM) and ME (3,060 kcal/kg DM) content for CBS determined by Paula et al. (2021). Although the amino acid content of CBS differed between the Anderson et al. (2012) and Paula et al. (2021) studies, the P content was similar.

Table 2. Published values (dry matter basis) of nutritional composition of corn bran and solubles for swine and poultry (adapted from Anderson et al., 2012, and Rochell et al., 2011)

Analyte, % DM basis	**Corn bran + solubles**
Dry matter	90.82
Gross energy, kcal/kg	4,982
DE (swine), kcal/kg	3,282
ME (swine), kcal/kg	3,031
AME_n (poultry), kcal/kg	3,030
Crude protein	34.74
Ether extract	9.68
TDF	26.65
NDF	25.21
ADF	5.35
Ash	5.31
Ca	0.03
P	0.76
Indispensable amino acids	
Arg	0.77
His	0.44
Ile	0.50
Leu	1.30
Lys	0.62
Met	0.23
Phe	0.55
Thr	0.61
Trp	0.09
Val	0.76
Dispensable amino acids	
Ala	1.04
Asp	1.02
Cys	0.30
Glu	1.95
Gly	0.77
Pro	1.08

Ser	0.65
Tyr	0.41

Summary of corn bran and solubles feeding trials for ruminants

Garland et al. (2019a) conducted a study to compare energy and nutrient digestibility of diets containing corn (control), 20 and 40% HP-DDG, 40% corn bran plus solubles (CBS), and 40% conventional wet distillers grains with solubles (WDGS) and dried distillers grains with solubles (DDGS) of dry matter (DM) intake. Feeding CBS resulted in lower digestibility of DM and organic matter (OM), equivalent neutral detergent fiber (NDF) digestibility, but greater acid detergent fiber (ADF) digestibility and digestible energy than cattle fed corn. Dry matter and OM digestibility and digestible energy in CBS was similar to that of the conventional WDGS and DDGS co-products. In addition, DM, OM, NDF, ADF digestibility, as well as digestible energy at the 40% diet inclusion rate of CBS were similar to feeding HP-DDG. These results indicate that although feeding HP-DDG and CBS resulted in reduced DM and OM digestibility, energy intake was increased when these co-products were included in the diet. Furthermore, CBS has comparable feeding value with WDGS and DDGS.

In a subsequent study, Garland et al. (2019b) compared feeding diets containing 20% or 40% of DM intake using wet CBS with feeding diets containing 20% or 40% of DM intake using wet distillers grains (WDG) to finishing steers on growth performance and carcass characteristics. Feed intake and feed conversion increased with increasing diet inclusion rate of either corn co-product, and ADG was greater when feeding the CBS or WDG diets compared with feeding the control diet which consisted of high moisture and dry rolled corn. Results from this study showed that feeding wet CBS at the same diet inclusion rates as WDG resulted in similar growth performance and carcass characteristics.

Garland et al. (2019c) also compared feeding diets containing 40% of DM intake from HP-DDG, conventional DDGS, WDGS, and wet CBS on growth performance and carcass characteristics of crossbred steers. There were no differences in feed intake among dietary treatments, but cattle fed HP-DDG and wet CBS had greater ADG and carcass weight than steers fed the WDGS and DDGS diets. Based on feed conversion observed in finishing steers in this trial, the feeding values of HP-DDG and wet CBS were estimated to be 121% and 125% the feeding value of corn, respectively.

De-oiled (solvent extracted) DDGS

De-oiled DDGS is a co-product (NovaMeal) produced using solvent extraction to remove corn oil from DDGS, but limited quantities are currently being produced in the U.S. However, this may change in the future as a result of increasing demand for fats and oils to produce renewable diesel in the U.S. Almost all of the current de-oiled DDGS being produced is used in diets for lactating dairy cows. Therefore, most of the research on nutritional composition and feeding value has focused on it feeding value for lactating dairy cows.

AAFCO Definition

The Association of American Feed Control Officials defines deoiled corn distillers dried grains with solubles as follows:

27.9 Deoiled Corn Distillers Dried Grains with Solubles, Solvent Extracted, is the product resulting from the solvent extraction of oil from corn distillers dried grains with solubles (DDGS) to result in a crude fat content of less than 3% on an as fed basis. It is intended as a source of protein. The label shall include a guarantee for minimum crude protein and maximum sulfur. The words "solvent extracted" are not required when listing as an ingredient in a manufactured feed."

Nutritional composition of de-oiled DDGS for ruminants

Mjoun et al. (2010c) evaluated and compared the nutrient composition, rumen degradable and undegradable protein and intestinal digestibility of amino acids in conventional solvent extracted soybean meal (SBM), high-oil DDGS, de-oiled DDGS, and HP-DDG for lactating Holstein dairy cows (**Table 3**). The rate of degradation of slowly degradable protein was greatest for SBM (11.8%/hr) to 2.7%/hr for de-oiled DDGS. Rumen undegradable protein ranged from 32% for SBM to 60% for de-oiled DDGS. Although total digestible protein was greater for SBM than distillers co-products, they all exceeded 95%. Similarly, the intestinal digestibility of most amino acids in distiller's co-products exceeded 92%, which was slightly less than for SBM (>94%), except for Lys digestibility which was 84 to 87% in distillers co-products compared with 96% digestibility in SBM. Intestinal absorbable dietary protein was greater in de-oiled DDGS (55%) compared with DDGS (48%) and HP-DDG (51%), which was also greater than in SBM (31%). These results indicate that protein and amino acid digestibility of de-oiled DDGS and other corn co-products are comparable to those in soybean meal when fed to lactating dairy cows.

Table 3. Comparison of chemical composition, rumen degradable and undegradable protein and intestinal digestibility of amino acids in lactating dairy cows (adapted from Mjoun et al., 2010c)

Analyte, % DM basis	Soybean meal	DDGS	De-oiled DDGS	HP-DDG
Dry matter	90.2	88.5	87.7	93.2
Crude protein (CP)	49.6	30.8	34.0	41.5
Soluble protein, % of CP	15.0	14.0	10.9	6.4
Rumen degradable protein, % of CP	68	48	40	46
Rumen undegradable protein, % of CP	32	52	60	54
Estimated intestinal protein digestibility, % of RUP	97	92	91	94
Intestinally absorbable dietary protein, % of CP	31	48	55	51
Total digestible dietary protein, % of CP	99	96	95	97
NDICP, % of CP	3.4	9.1	19.7	10.1
ADICP, % of CP	3.2	8.8	13.2	9.9
NDF	12.0	31.5	42.5	30.4
ADF	6.2	9.4	12.4	10.5
Ether extract	1.1	10.6	3.5	3.2
Starch	2.0	8.9	5.1	8.3

NFC	29.9	22.7	14.7	22.5
Ash	7.4	4.4	5.3	2.4
Ca	0.70	0.06	0.07	0.06
P	0.73	0.75	0.77	0.51
Mg	0.33	0.32	0.34	0.16
K	2.34	0.92	0.93	0.53
S	0.42	0.62	0.74	0.79
Indispensible amino acids, g/kg CP[1]				
Arg	71.0 [85] (99)	47.4 [66] (93)	46.9 [59] (93)	37.1 [57] (93)
His	27.9 [87] (96)	30.0 [71] (93)	30.5 [65] (93)	27.7 [68] (93)
Ile	48.0 [84] (98)	40.4 [65] (93)	43.1 [59] (93)	41.8 [56] (93)
Leu	79.7 [84] (98)	117.4 [59] (96)	125.3 [50] (96)	135.3 [51] (96)
Lys	64.7 [86] (96)	34.8 [77] (84)	32.2 [69] (86)	29.5 [70] (87)
Met	14.3 [82] (94)	20.4 [55] (95)	19.9 [37] (95)	20.4 [48] (94)
Phe	50.2 [84] (98)	45.2 [53] (95)	47.3 [45] (95)	50.9 [49] (95)
Thr	38.2 [83] (98)	37.8 [63] (88)	38.0 [51] (90)	36.5 [56] (91)
Val	50.0 [83] (97)	53.0 [67] (92)	53.4 60] (92)	51.4 [59] (92)
Dispensable amino acids, g/kg CP				
Ala	43.3	69.3	71.2	73.1
Asp	114.3	63.7	68.5	65.0
Cys	14.7	19.3	18.1	18.3
Glu	149.9	130.4	143.8	160.8
Gly	42.9	41.1	41.1	32.6
Pro	47.8	86.3	74.3	88.0
Ser	43.3	40.7	43.1	43.6
Total amino acids	918.1 [84]	877.0	896.9	912.0

[1]Values in [ ] are ruminal degradation (%) of indispensable amino acids and values in ( ) are intestinal digestibility (%) of indispensable amino acids from RUP

Nutritional composition of de-oiled DDGS for swine

Two studies have been conducted to determine the DE and ME content (Jacela et al., 2011; Anderson et al. 2012), and one study has estimated the standardized ileal digestibility (SID) of amino acids (Jacela et al., 2011) in de-oiled DDGS for swine (**Table 4**). Although the gross energy of de-oiled DDGS sources evaluated in these studies was comparable, the DE and ME content directly determined by Anderson et al. (2012) was much greater than the *in vivo* determined DE content and calculated ME content by Jacela et al. (2011). Jacela et al. (2011) used the Noblet and Perez (1993) and Noblet et al. (1994) equations to estimate ME and NE content, respectively, of de-oiled DDGS, but the accuracy of this approach is questionable because these equations were derived and are intended to be used for complete feeds, not individual ingredients. Regardless, the DE and ME values for de-oiled DDGS are comparable to those obtained for reduced oil DDGS in recent studies (Paula et al., 2021; Yang et al., 2021). The SID coefficients of amino acids determined by Jacela et al. (2011) are also comparable to those observed for reduced oil DDGS sources from recent studies (Paula et al., 2021; Yang et al., 2021), but no estimates are available for the STTD of P in de-oiled DDGS for swine.

Table 4. Published values of nutritional composition of de-oiled DDGS for swine		
Analyte, % DM basis	**De-oiled DDGS (Jacela et al., 2011)**	**De-oiled DDGS (Anderson et al., 2012)**

Dry matter	87.69	87.36
Gross energy, kcal/kg	5,098	5,076
Digestible energy, kcal/kg	3,100	3,868
Metabolizable energy, kcal/kg	2,858[1]	3,650
Net energy, kcal/kg	2,045[2]	-
Crude protein	35.58	34.74
Ether extract	4.56	3.15
TDF	-	37.20
NDF	39.46	50.96
ADF	18.36	15.82
Ash	5.29	5.16
Ca	0.06	0.08
P	0.87	0.84
Indispensable amino acids		
Arg	1.50 (83)[3]	1.44
His	0.93 (75)	0.89
Ile	1.38 (75)	1.25
Leu	4.15 (84)	4.12
Lys	0.99 (50)	1.00
Met	0.67 (80)	0.64
Phe	1.92 (81)	1.51
Thr	1.26 (69)	1.26
Trp	0.22 (78)	0.18
Val	1.75 (74)	1.76
Dispensable amino acids		
Ala	2.43 (79)	2.48
Asp	2.10 (65)	2.19
Cys	0.62 (67)	0.61
Glu	4.85 (79)	5.43
Gly	1.35 (65)	1.39
Pro	2.41 (88)	2.54
Ser	1.48 (77)	1.58
Tyr	1.29 (82)	1.22

[1]Calculated as ME = 1 × DE – 0.68 × CP (Noblet and Perez, 1993).
[2]Calculated as NE = (0.87 × ME) – 442 (Noblet et al., 1994).
[3]Values in parentheses are standardized ileal digestibility coefficients determined for each amino acid.

Nutritional composition of deoiled DDGS for poultry

The same source of de-oiled DDGS evaluated by Anderson et al. (2012) for swine, was also used to determine the AME_n content for broilers by Rochell et al. (2011). Therefore, the nutrient profile for de-oiled DDGS shown in **Table 4**, represents the same de-oiled DDGS source which contained 2,146 kcal/kg AME_n for poultry (Rochell et al., 2011).

Summary of feeding trials evaluating de-oiled DDGS in lactating dairy cow diets

Mjoun et al. (2010a) conducted a study to determine the optimal concentration of de-oiled DDGS in mid-lactation Holstein cow diets during an 8-week feeding trial. Diets contained 0, 10, 20, and 30% de-oiled DDGS to replace soybean-based ingredients on a DM basis. Results of this study showed no differences in diet inclusion rate of de-oiled DDGS on DM intake and milk production (**Table 5**). Milk fat percentage and yield increased linearly with increasing dietary levels of de-oiled DDGS, while milk protein concentration was affected quadratically with no effect on milk protein yield from feeding increasing dietary levels of de-oiled DDGS. The efficiency of milk production tended to increase linearly, but the efficiency of N utilization for milk production was not affected by increasing dietary levels of de-oiled DDGS. These results indicate that feeding up to 30% de-oiled DDGS diets to lactating dairy cows provides similar performance to cows fed control diets contain soy-based co-products as protein and energy sources.

Table 5. Dry matter intake, milk yield, and milk composition of mid-lactation dairy cows fed 0, 10, 20, and 30% de-oiled DDGS to replace soybean feed ingredients in diets (Mjoun et al., 2010a)

	Dietary inclusion rate of de-oiled DDGS (% of DMI)			
Measure	**0%**	**10%**	**20%**	**30%**
Body weight, kg	705	713	721	710
Body weight change, g/d	-167	15	230	-36
Body condition score[1]	3.56	3.37	3.36	3.53
Net energy intake[2], Mcal/d	34.7	37.0	38.3	35.2
Net energy for maintenance[3], mcal/d	10.9	11.2	11.0	11.0
Net energy required for milk[4], Mcal/d	22.6	24.0	24.7	25.0
Energy balance[5], Mcal/d	3.18	1.60	2.80	-0.81
Energy efficiency[6]	64.6	66.8	64.2	71.2
Dry matter intake, kg/d	22.7	23.0	23.7	22.2
Crude protein intake, kg/d	4.0	4.1	4.2	4.0
Milk production, kg/d	34.5	34.8	35.5	35.2
Energy corrected milk production[7], kg/d	32.6	34.6	35.6	36.0
Fat corrected milk production[8], kg/d	30.0	31.7	32.1	33.1
Feed efficiency[9]	1.47	1.53	1.49	1.61
N efficiency[10]	25.5	27.0	25.8	26.0
Milk composition				
Fat, %	3.18	3.40	3.46	3.72
Fat yield, kg/d	1.08	1.19	1.23	1.32
Protein, %Ash	2.99	3.06	3.13	2.99
Protein yield, kg/d	1.03	1.07	1.10	1.06
Lactose, %	4.95	4.96	4.94	5.06
Lactose yield, kg/d	1.71	1.74	1.75	1.76
Total solids, %	12.10	12.39	12.40	12.67
Total solids, kg/d	4.15	4.35	4.43	4.45

[1]Body condition score: 1 = emaciated to 5 = obese.

[2]Net energy required for lactation (Mcal/kg) × dry matter intake (kg/d).

[3]Net energy for maintenance = body weight$^{0.75}$ × 0.08
[4]Net energy required for milk = milk yield (kg) × [(0.0929 × fat %) + (0.0563 × protein %) + (0.0395 × lactose %)]
[5]Energy balance = net energy intake – (net energy for maintenance + net energy for lactation).
[6]Energy efficiency = net energy for lactation/net energy intake.
[7]Energy corrected milk = [0.327 × milk yield (kg)] + [12.95 × fat yield (kg)] + [7.2 × protein yield (kg)].
[8]Fat corrected milk = [0.4 × milk yield (kg)] + [15 × fat yield (kg)].
[9]Feed efficiency = energy corrected milk/dry matter intake.
[10]Nitrogen efficiency = milk N (kg/d)/N intake (kg/d).

Mjoun et al. (2010b) also compared the lactation responses of early lactation dairy cows fed diets containing no distillers co-products (control with soybean meal, expeller soybean meal, and soybean hulls), 22% conventional DDGS, or 20% de-oiled DDGS for a 14-week trial. Diets were formulated to contain similar CP, ether extract, NDF and net energy for lactation concentrations. There were no differences in body weight, body weight change, body condition score, DM intake, milk yield, milk fat, and milk lactose content among dietary treatments (**Table 6**). However, milk protein concentration and yield were similar between cows fed the DDGS and de-oiled DDGS diets but greater than in cows fed the control diet. Feed efficiency tended to be greater, and nitrogen efficiency was greater in cows fed the DDGS and de-oiled DDGS diets compared with those fed the control diet. These results indicate that feeding diets containing 20% de-oiled DDGS to dairy cows in early lactation results in equal or improved lactation performance and milk composition compared with feeding soy-based diets.

Table 6. Milk production, composition, and nutritional efficiency of feeding early-lactation dairy cows diets containing soy products (control), 22% DDGS, and 20% de-oiled DDGS (Mjoun et al., 2010b)

Measure	Control	22% DDGS	20% De-oiled DDGS
Initial body weight, kg	693	682	660
Final body weight, kg	734	722	704
Body weight change, kg/d	0.47	0.47	0.53
Body condition score[1]	3.43	3.32	3.34
Net energy intake[2], Mcal/d	41.3	40.1	40.3
Net energy for maintenance[3], mcal/d	11.0	11.0	11.0
Net energy required for milk[4], Mcal/d	26.4	26.5	27.4
Energy balance[5], Mcal/d	4.39	1.98	1.98
Energy efficiency[6]	63.1	66.9	68.1
Dry matter intake, kg/d	24.8	24.7	24.6
Crude protein intake, kg/d	4.3	4.3	4.3
Milk production, kg/d	39.2	38.9	39.8
Energy corrected milk production[7], kg/d	38.0	37.8	39.5
Fat corrected milk production[8], kg/d	35.7	35.3	37.1
Feed efficiency[9]	1.50	1.57	1.61
N efficiency[10]	24.5[b]	26.9[a]	26.5[a]
Milk composition			
Fat, %	3.63	3.24	3.57

Fat yield, kg/d	1.33	1.34	1.40
Protein, %	2.82[b]	2.88[a]	2.89[a]
Protein yield, kg/d	1.07[b]	1.15[a]	1.14[a]
Lactose, %	4.90	4.99	4.96
Lactose yield, kg/d	1.94	1.94	1.96
Total solids, %	12.3	12.0	12.4
Total solids, kg/d	4.73	4.70	4.90

[1]Body condition score: 1 = emaciated to 5 = obese.
[2]Net energy required for lactation (Mcal/kg) × dry matter intake (kg/d).
[3]Net energy for maintenance = body weight$^{0.75}$ × 0.08
[4]Net energy required for milk = milk yield (kg) × [(0.0929 × fat %) + (0.0563 × protein %) + (0.0395 × lactose %)]
[5]Energy balance = net energy intake – (net energy for maintenance + net energy for lactation).
[6]Energy efficiency = net energy for lactation/net energy intake.
[7]Energy corrected milk = [0.327 × milk yield (kg)] + [12.95 × fat yield (kg)] + [7.2 × protein yield (kg)].
[8]Fat corrected milk = [0.4 × milk yield (kg)] + [15 × fat yield (kg)].
[9]Feed efficiency = energy corrected milk/dry matter intake.
[10]Nitrogen efficiency = milk N (kg/d)/N intake (kg/d).
[a,b] Means within rows with uncommon superscripts are difference ($P < 0.05$).

Summary of feeding trials evaluating diets containing deoiled DDGS for nursery and growing-finishing pigs

Jacela et al. (2011) conducted two feeding trials to evaluate the effects of increasing dietary levels (0, 5, 10, 20, and 30%) of de-oiled DDGS in diets for nursery pigs (initial BW = 9.9 kg) for a 28-day feeding period on growth performance (**Table 7**), and to growing-finishing pigs (initial BW = 30 kg) for a 99-day feeding period on growth performance and carcass characteristics (**Table 8**). Diets were formulated to contain equal ME content by adding increasing amounts of soybean oil as de-oiled DDGS levels increased, and equal SID lysine content based on determined values obtained from previous experiments. During the grower-finisher trial, a 4-phase feeding program was used. As shown in **Table 7**, the were no differences in growth performance of nursery pigs between dietary treatments, indicating that feeding diets containing up to 30% de-oiled DDGS to nursery pigs provided acceptable growth performance when supplemental energy from soybean oil was provided to maintain dietary ME density. However, increasing de-oiled DDGS levels in diets fed to growing-finishing pigs resulted in a linear decrease in average daily gain (ADG), average daily feed intake (ADFI), carcass weight, and carcass yield (**Table 8**). However, gain efficiency tended to be improved with no effects on carcass backfat, percentage lean, and fat-free lean index as dietary inclusion rate of de-oiled DDGS increased (**Table 8**). It is unclear why reductions in ADG and ADFI occurred during the growing-finishing trial and not during the nursery trial when it is more likely for these negative responses to be observed.

Table 7. Effects of increasing dietary inclusion rates of de-oiled DDGS in diets for nursery pigs on growth performance during a 28-day feeding period (adapted from Jacela et al., 2011)

	Dietary deoiled DDGS inclusion rate, %				
Measure	**0**	**5**	**10**	**20**	**30**

Initial BW, kg	10.0	10.0	9.6	9.9	9.9
Final BW, kg	22.7	22.8	22.2	22.4	22.3
ADG, kg	0.455	0.459	0.452	0.445	0.442
ADFI, kg	0.749	0.771	0.760	0.751	0.761
G:F	0.609	0.595	0.594	0.593	0.582

Table 8. Effects of increasing dietary inclusion rates of de-oiled DDGS in growing-finishing pig diets on growth performance during a 99-day feeding period and carcass characteristics (adapted from Jacela et al., 2011)

Measure	Dietary deoiled DDGS inclusion rate, %				
	0	**5**	**10**	**20**	**30**
Initial BW, kg	29.6	29.6	29.6	29.6	29.6
Final BW[1], kg	121.4	119.3	118.8	118.2	116.2
ADG[1], kg	0.909	0.893	0.887	0.887	0.873
ADFI[1], kg	2.16	2.17	2.11	2.11	2.04
G:F[2]	0.420	0.413	0.422	0.421	0.431
Carcass weight[1], kg	91.1	89.0	89.1	87.7	86.3
Carcass yield[1], %	75.5	75.0	75.0	74.7	74.3
Backfat, mm	16.46	16.53	16.53	16.38	16.96
Loin depth[3], mm	63.5	62.2	62.5	63.0	60.7
Carcass lean, %	56.48	55.91	56.30	56.43	55.78
Carcass fat-free lean index	50.4	50.4	50.4	50.5	50.2

[1]Linear reduction ($P < 0.01$) with increasing dietary levels of deoiled DDGS.
[2]Trend ($P < 0.10$) of a linear improvement with increasing dietary levels of deoiled DDGS.
[3]Trend ($P < 0.10$) of a linear reduction with increasing dietary levels of deoiled DDGS.

Corn Distillers Oil

AAFCO Definition

The Association of American Feed Control Officials defines corn distillers oil as follows:

> "33.10 ____ Distillers Oil, Feed Grade, is obtained after the removal of ethyl alcohol by distillation from the yeast fermentation of a grain or a grain mixture and mechanical or solvent extraction of oil by methods employed in the ethanol production industry. It consists predominantly of glyceride esters of fatty acids and contains no additions of free fatty acids or other materials from fats. It must contain, and be guaranteed for, not less than 85% total fatty acids, not more than 2.5% unsaponifiable matter, and not more than 1% insoluble impurities. Maximum free fatty acids and moisture must be guaranteed. If an antioxidant(s) is used, the common or usual name must be indicated, followed by the words "used as a preservative." If the product bears a name descriptive of its kind of origin, i.e., "corn, sorghum, barley, rye," it must correspond thereto with the predominating grain declared as the first word in the name." Proposed 2015, Adopted 2016 rev. 1)

Corn distillers oil (CDO) is produced in large quantities by the U.S. ethanol industry and is used in renewable diesel production and as a supplemental energy source in swine and poultry diets.

The ME content of CDO is comparable to that in crude degummed soybean oil, which is due to its high concentrations of polyunsaturated fatty acids (PUFA), especially linoleic acid. As a result of the high PUFA content in CDO, it is highly susceptible to oxidation when exposed to thermal processes, oxygen, and transition metals (Cu and Fe). Therefore, the addition of antioxidants may be necessary to prevent oxidation during transport and storage because oxidized lipids can have adverse effects on health and growth performance of pigs and broilers when included in diets (Hung et al., 2017). In addition, adding CDO to corn-soybean meal grower-finisher diets increases the PUFA content of pork carcass fat which reduces firmness and shelf-life stability.

Chemical composition of corn distillers oil

One of the distinguishing features of CDO compared with refined corn oil is that CDO sources have greater free fatty acid (FFA) content (**Table 9**), which can range from less than 2% FFA to as much as 18% FFA. Previous studies evaluating various feed lipids have shown that increasing FFA content reduces ME content for pigs and poultry, which led to the development of DE (swine) and AME_n (poultry) prediction equations (Wiseman et al., 1998). Corn oil is distinguishable from other lipid sources because of its relatively high polyunsaturated acid (PUFA) content, especially oleic (9c-18:1; 28 to 30% of total lipid) and linoleic (18:2n-6; 53 to 55% of total lipid) acid content. Vegetable oils have greater PUFA content than animal fats, which results in vegetable oils having greater ME content (Kerr et al., 2015). As a result, CDO contains one of highest ME concentrations of all feed fats and oils, but it is also more susceptible to peroxidation (Kerr et al., 2015; Shurson et al., 2015; Hanson et al., 2015). Feeding peroxidized lipids to pigs and broilers has been shown to reduce growth rate, feed intake, and gain efficiency (Hung et al., 2017), and highly peroxidized corn oil reduces efficiency of energy utilization and antioxidant status in nursery pigs (Hanson et al., 2016). However, the addition of commercially available antioxidants to distillers corn oil are effective in minimizing peroxidation of CDO when stored at high temperature and humidity conditions (Hanson et al., 2015). Although the extent of peroxidation (peroxide value, anisidine value, and hexanal) in CDO is somewhat greater than in refined corn oil, it is much less than in the peroxidized corn oil fed in the nursery pig study by Hanson et al. (2016), where reductions in growth performance were observed.

Table 9. Chemical composition and peroxidation measures of refined corn oil and corn distillers oil (CDO) sources (adapted from Kerr et al., 2016)

Measurement	Refined corn oil	CDO (4.9% FFA[1])	CDO (12.8% FFA)	CDO (13.9% FFA)
Moisture, %	0.02	1.40	2.19	1.19
Insolubles, %	0.78	0.40	1.08	0.97
Unsaponifiables, %	0.73	0.11	0.67	0.09
Ether extract, %	99.68	99.62	98.96	99.63
Free fatty acids, %	0.04	4.9	12.8	13.9
Fatty acids, % of total lipids				
Palmitic (16:0)	11.39	13.20	11.87	13.20
Palmitoleic (9c-16:1)	0.10	0.11	0.11	0.11
Margaric (17:0)	0.07	0.07	0.07	0.07
Stearic (18:0)	1.83	1.97	1.95	1.97

Oleic (9c-18:1)	29.90	28.26	28.92	28.26
Linoleic (18:2n-6)	54.57	53.11	54.91	53.11
Linolenic (18:3n-3)	0.97	1.32	1.23	1.32
Nonadecanoic (19:0)	ND[2]	0.65	0.65	0.65
Arachidic (20:0)	0.40	0.39	0.39	0.39
Gonodic (20:1n-9)	0.25	0.24	0.24	0.24
Behenoic (22:0)	0.13	0.13	0.12	0.13
Lignoceric (24:0)	0.17	0.19	0.18	0.19
Other fatty acids	0.21	0.41	ND	0.41
Peroxidation measures				
Peroxide value, MEq/kg	1.9	2.9	3.3	2.0
Anisidine value[3]	17.6	80.9	70.3	73.3
Hexanal, µg/g	2.3	4.4	3.9	4.9

[1]FFA = free fatty acids.
[2]ND = not detected.
[3]There are no units for anisidine value.

Metabolizable energy content of corn distillers oil for swine and poultry

Kerr et al. (2016) determined the DE and ME content of refined corn oil (0.04% FFA) and 3 sources of commercially produced CDO with FFA content ranging from 4.9 to 13.9% for use in swine diets, and AME_n content of the same sources in broiler diets. As shown in **Table 10**, the ME content (swine) of CDO samples ranged from 8,036 to 8,828 kcal/kg, with the 4.9% FFA CDO sample containing similar ME content compared with refined corn oil. The ME values for refined corn oil (8,741 kcal/kg), 4.9% FFA CDO (8,691 kcal/kg), and 13.9% FFA CDO (8,397 kcal/kg) were similar to the value of 8,570 kcal/kg for corn oil reported in NRC (2012). Except for the 12.8% FFA CDO source having the lowest ME content of all sources, there was no significant detrimental effect of FFA content on DE or ME content of CDO for swine. For broilers, the AME_n content was not different among the CDO sources, which ranged from 7,694 to 8,036 kcal/kg (**Table 10**), and were not different than the AME_n content of refined corn oil (8,072 kcal/kg). However, these values were substantially less than the AME_n values for refined corn oil (9,639 to 10,811 kcal/kg) reported in NRC (1994). Ether extract digestibility was not different for nursery pigs or broilers fed the different sources of CDO with variable FFA content. Kerr et al. (2106) also reported that the use of the Wiseman et al. (1998) equations over-estimated the DE content (swine) in refined corn oil and the 12.8% and 13.9% FFA CDO sources but provided a similar estimate of DE content for the 4.9% FFA CDO source. However, these equations over-estimated AME_n content of all corn oil sources by 379 to 659 kcal/kg for broilers. These results suggest that new DE and AME_n prediction equations need to be developed that are more accurate and specific for CDO for both swine and broilers but indicate that CDO containing up to 14% FFA can serve as an excellent supplemental energy source in swine and broiler diets.

Table 10. In vivo determined DE and ME content of refined corn oil and distillers corn oil (CDO) sources with variable free fatty acid (FFA) content for nursery pigs and broilers (adapted from Kerr et al., 2016)

Measurement	Refined corn oil	CDO (4.9% FFA[1])	CDO (12.8% FFA)	CDO (13.9% FFA)
GE, kcal/kg	9,423	9,395	9,263	9,374
DE (swine), kcal/kg	8,814[a]	8,828[a]	8,036[b]	8,465[ab]
ME (swine), kcal/kg	8,741[a]	8,691[a]	7,976[b]	8,397[ab]
EE[2] digestibility (swine), %	93.2	94.0	91.7	95.0
AME_n[3] (poultry), kcal/kg	8,072	7,936	8,036	7,694
EE digestibility (poultry), %	91.6	89.8	89.0	88.4
UFA:SFA[4]	6.13	5.00	5.61	5.00

[a,b]Means with uncommon superscripts within rows are different ($P < 0.05$).
[1]FFA = free fatty acids.
[2]EE = ether extract.
[3]AME_n = nitrogen-corrected apparent metabolizable energy.
[4]UFA = unsaturated fatty acids; SFA = saturated fatty acids.

Conclusions

Corn bran and solubles is currently produced in a wet form by a limited number of ethanol plants and has historically been used exclusively in beef cattle feedlots diets as an energy source to replace of corn co-products, high moisture corn, and dry-rolled corn. Availability of dried CBS with lower transportation costs could provide the opportunity for greater use in a larger variety of ruminant diets, including dairy cattle. The relatively low ME, digestible amino acid content of dried CBS would have limited feeding value in swine and poultry diets if it were to be produced and available in significant quantities. Dried de-oiled (solvent extracted) DDGS is produced in limited quantities and marketed under the brand name of NovaMeal. De-oiled DDGS is best suited for use in lactating dairy cow diets where is can be fed up to 20% of DM intake to provide improved milk production and composition compared with feeding soy-based diets. Although studies have shown that de-oiled DDGS can be added to nursery diets to support acceptable growth performance, its use in growing-finishing swine diets requires dietary energy and digestible amino acid supplementation to achieve optimal growth performance. Corn distillers oil (CDO) is an excellent supplemental energy source in swine and poultry diets. The FFA content of CDO can be as high as 14% and does not appear to affect the ME content for swine, but this FFA concentrations appears to reduce ME content of CDO for broilers. However, with the tremendous demand for feed fats and oils for renewable diesel production in the U.S., the future availability of CDO may be limited in the export market.

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