Review of the Usage of Corn DDGS & CFP in Aquafeeds

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Executive Summary

The trend in aquaculture to increase its sustainability profile by making feeds more environmentally-friendly is here to stay. The reduction of the use of marine ingredients like fish meal and increasing crop-based ingredients in aquaculture feeds (aquafeeds), particularly soy and corn-based ingredients, not only improves sustainability, it also reduces the cost of feed, and in turn improves farm profitability. There are two main differences between feeds for livestock and poultry and aquafeeds; 1) Crude protein levels are much higher, in the range of 25-50%, and high fiber ingredients are generally avoided, and; 2) Aquafeed formulators are looking for concentrated, high quality, highly-digestible plant proteins that are available in large quantities with attractive prices relative to animal protein ingredients. While soybean meal has been the go-to ingredient, new developments in corn ethanol co-products make corn distiller's dried solubles (DDGS) and corn fermented protein (CFP) very attractive alternatives.

This report comprehensively reviews the latest information on the use of corn distiller's dried solubles (DDGS) and corn fermented protein (CFP) in aquafeeds. Key findings:

- Ethanol DDGS (27-30% protein) is an excellent ingredient in feeds for herbivorous and omnivorous fish like carps, tilapia, and catfish, with highly available amino acids, lipids, xanthophylls, and phosphorus. However, its fiber content is relatively high and this limits its use in feeds for shrimp and carnivorous marine fish. For suitable species, DDGS inclusion levels of 30% - 40% in feeds are well-tolerated, particularly if L-lysine is supplemented, or feed enzymes like xylanase, mannanase and glucanase are added to manage the fiber components.
- CFP (≥48% protein) is a refined product with a protein level equivalent to soybean meal but with higher methionine, low crude fiber and fat, and a much higher available phosphorus percentage. It is an excellent ingredient in feeds with >45% protein. CFP typically contains 25% spent yeast (contains >25% protein), which contributes about 20% of the protein content in CFP, provides prebiotic yeast cell wall fractions, and is a ready source of nucleotides, all noted as beneficial to animal gut health and immunity, particularly for marine shrimp. Research reports on the use of CFP in feeds for carnivorous fish like salmon and European seabass is somewhat limited, but levels up to 20% - 25% have been used successfully to replace fish meal and soybean meal. For the Pacific white shrimp, evidence shows CFP can be used at 20% - 30% in the formulation, completely replacing fish meal and costlier corn proteins like corn gluten meal and corn protein concentrate. With CFP having 30% of the xanthophylls of DDGS, and 20% that of corn gluten meal, it is an excellent option for sustainable feeds for Pangasius, where white flesh is a requirement.

Addressing aquafeed processing technologies, using DDGS at levels above 10% in feeds made with single-screw extrusion has long been known to cause problems with production capacity, pellet quality and bulk density. However, with most new fish feed mills now choosing to install feed-specific twin-screw extruders instead, this removes one of the main impediments to greater use of DDGS in aquafeeds. Of course, CFP, with its lower fiber and lipid content can be incorporated at much higher levels in aquafeeds, even in press-pelleted shrimp feeds.

To conclude, DDGS and CFP are plentiful, cost-effective alternatives to fish meal and traditional plant ingredients like soybean and rapeseed/canola meals in aquafeeds. With high protein digestibility, low phytic acid, and high phosphorus availability, DDGS and CFP reduce the potential environmental impact of nitrogen and phosphorus pollution, fully supporting and reinforcing aquaculture's compliance with sustainable development goals.

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Introduction

Feeds used in aquaculture for both fish and shrimp have one notable difference from livestock and poultry feeds: Aquafeeds have considerably higher protein levels, typically in the range of 45-55% crude protein (CP) for small animals and 25-45% CP for large animals. Protein then becomes the single largest nutritional component and cost factor of the feed. The ingredients in a typical fish or shrimp feed are many, and in order to incorporate a large quantity of protein into a feed formulation, concentrated protein ingredients are preferred. In the past, aquafeeds relied heavily on fish meal as it is a highly concentrated, highly digestible protein source. After fish meal, rendered animal protein by-products from meat processing and soybean meal have been the main alternative sources.

For several decades, the aquaculture feed industry worldwide has been working to reduce its reliance on marine proteins like fish meal for two reasons; 1.) Sustainability, and 2.) Cost Reduction. The incorporation of plant crop ingredients other than soybean meal has been hampered somewhat by limited development of products with concentrated protein, and the high protein corn and wheat ingredients that have been available, such as wheat gluten and corn protein concentrate, have been too expensive for common, widespread use in aquafeeds.

What are DDGS and CFP?

First, while the biofuels industry around the world uses a number of starch-rich grains, including corn, wheat, sorghum, barley, oats and rice for alcohol production, all of which result in a form of DDG/DDGS, this report focuses only on corn DDGS, such as that produced primarily in the United States. Other countries producing large volumes of corn DDGS include India and China, but the nutritional composition and quality of the DDGS is reportedly more variable than that produced in the United States (https://www.chinimandi.com/tnvgf-urges-bis-to-frame-specific-quality-benchmarks-for-corn-based-ddgs-used-in-feed-formulations/).

Second, it is important to note that here we are referring to DDGS produced by modern ethanol biorefineries, not traditional DDGS (a.k.a. brewers's dried gains), which initially caused some confusion when the same name was used. Shurson et al. (2003) mentioned research conducted by the University of Minnesota that showed that DDGS produced in "new generation" modern ethanol plants had higher digestible amino acids and higher available phosphorus compared with DDGS (BDG) produced in older traditional ethanol beverage plants. The two types of DDGS are easy to distinguish, because ethanol DDGS is yellow to light brown color, whereas old BDG-DDGS is usually dark brown. Widespread production of 'new" corn DDGS started in 2005, and the first research reports of "new" DDGS being used in aquafeeds began to appear about 2006-2007. Hruby (2012) provides an excellent overview of the use of enzymes in improving the fermentative ethanol extraction process and the output of improved corn co-products.

Grain corn (maize), with its high starch content, is often used as an ingredient in floating extruded feeds for herbivorous and omnivorous freshwater fish because an extruder's temperature and wet high-pressure processing gelatinizes the starch, and causes extruded pellets to expand upon leaving the extruder die. Corn, however, with its typical low protein content (7-8%), adds only a minor quantity of protein to the feed formulation, and is more often used as a filler and for its functional binding properties rather than as a source of nutrients.

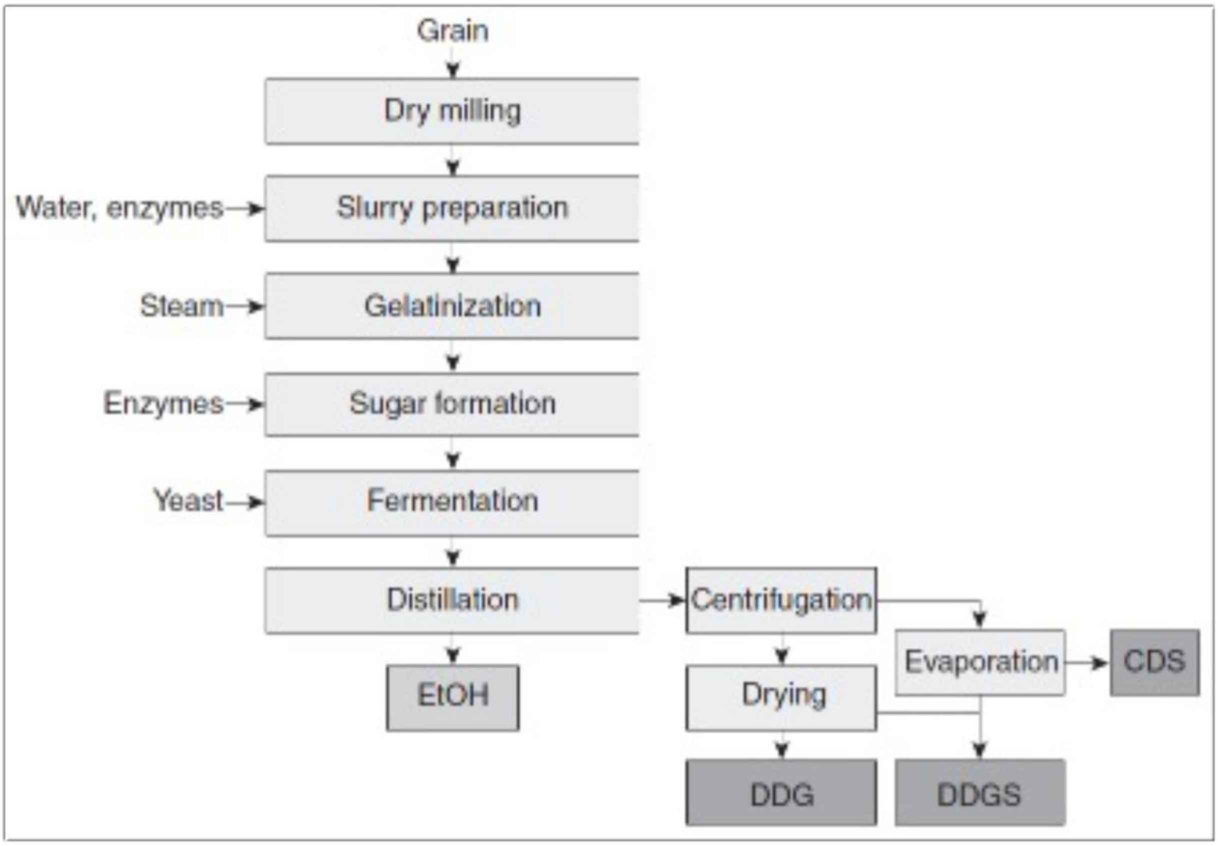
If a feed formulator seeks to use corn products with higher protein, then two corn co-products from ethanol production are suitable; Corn distiller's dried gains with solubles

(DDGS) in feeds with a lower protein requirement, and corn fermented protein (CFP) in very high protein aquafeeds (>40%) for juvenile and carnivorous fish species, and shrimp feeds with a low crude fiber limit. What are DDGS and CFP, and how do they differ from one another?

A graphic description of the process (Granby et al. 2012) is shown in Figure 1. A comprehensive review of the production processes involved in the production of corn DDGS and CFP has been written by Shad et al. (2021).

Briefly, there are two main processes used to produce the corn by-products the feed industry is familiar with. A 'wet milling' process, not detailed here, is used to produce high fructose corn syrup, with the main feed ingredient co-products being corn gluten feed, corn gluten meal, and corn protein concentrate. On the other hand, DDGS and CFP are produced with a 'dry grinding" process, in which pulverized corn is turned into a wet slurry with water, added enzymes and yeast, resulting in the fermentation of the starches in the corn, converting them first into sugars and then ethanol. A distillation process removes the alcohol, leaving behind a wet non-fermentable residue. At this point the residue is centrifuged, separating it into liquid corn distiller's solubles (CDS) and distiller's dried grains (DDG). If some portion of the CDS is blended back into the DDG, DDGS is the final product. Not shown in Figure 1, oil content of the final DDGS product may be reduced if corn oil is extracted during the centrifugation step.

Figure 1: Bioethanol production by the "dry grind" process (Granby et al. 2012).



DDGS

As a consequence of the removal of the starch during processing, DDGS typically has a protein and fiber content approximately 3-4 times that of grain corn. There are two main factors that contribute to the observed range of analytical values often seen with DDGS (see Table 1);

a.) Corn genetics, farming region, climate, (temperature, rainfall/irrigation, solar radiation exposure), soil quality, fertilizer use, storage conditions. The impact of soil quality on nutrients in DDGS is clear from the relatively high Coefficient of Variation (CV>10%) values for almost all of the assessed mineral elements.

b) Management of production of ethanol from corn according to each factory's manufacturing process.

DDGS is a widely available processed corn product with a protein level of 27-30%, a moderate amount of fat (about 10%, although the exact amount depends on whether the corn ethanol plant extracts any of the corn oil in the process), and a manageable fiber level. In most aquafeeds for fish and shrimp, there is a maximum set level for crude fiber, and the fiber content of DDGS is often the limiting factor controlling how much of it can be used in the aquafeed formulation.

If, in addition to the ethanol production process to produce standard reduced fat DDGS, additional fermentation steps with carbohydrase enzymes such as xylanases, mannanases and glucanases are included, the fiber content can be significantly degraded (to sugars and simple starches) resulting in a quite high protein (36-48%), low fat, low fiber ingredient, corn co-product known as high protein distiller's dried gains with solubles (HP-DDG). Notably, the HP-DDG process does not eliminate all of the fiber, so cannot produce the highest protein corn co-products. AFFCO keeps HP-DDG in the same category as conventional DDGS (code 27.6).

CFP

In contrast, the manufacturing process used to produce CFP has been engineered to produce an ingredient with concentrated protein greater than 48%. HP-DDG and CFP began to appear commercially in the feed ingredients market during 2012-2014

The American Association of Feed Control Officials (AAFCO) defines CFP as "Corn fermented protein, mechanically separated" in code 27.5 (AAFCO 2020). All CFP production steps up to alcohol extraction are the same as in the DDGS process. However, after the alcohol has been extracted from the liquid corn stillage, no enzymatic or chemical steps are used in the CFP process. Instead, a series of mechanical multi-stage separations and water washing steps isolates and concentrates the protein particles and yeast cells from the liquid stillage into a liquid slurry, which then is flash-dried to produce CFP. Unless indicated, corn distiller's solubles are not blended back into the final CFP product. Shurson (2018), compared the mean concentration of purified mannan from cell wall of ethanol yeast (10.3g/100g) with the mannan content of DDGS (1g/100g) and the mannan content of CFP (3g/100g) and estimated that the yeast content of CFP was three times higher than for DDGS, typically about 25%, but possibly as high as 29%.

Development of proprietary "bolt-on" mechanical systems to produce what is now called CFP started in the early 2010's. Current CFP production systems include Maximized Stillage Co-products (MSC™, Fluid Quip Technology), Marquis Inc.'s ProCap Technology™ (Procap™), and Advanced Processing Package™ (APP™), ICM Inc's patented four-part system which includes Selective Milling Technology (SMT), Fiber Separation Technology Next Gen (FST Next Gen), and patent-pending Thin Stillage Solids Separation System (TS4). More systems are being developed and commercialized (USGC, 2023). Chapter 1 in the USGC

High-Pro DDGS-Handbook notes that while CFP produced by each of these systems meets the AAFCO definition of CFP, their nutritional profiles are different. All available types of FCP can be used independent of the production process as long as the nutritionist-formulator makes allowances for the differences in nutrient profiles.

Comparing the nutrient profile of the CFP shown in Table 2 to the DDGS analysis shown in Table 1, protein content of the CFP was 1.8 times greater, fat content was 1/5th that of DDGS, ash content was nearly the same (DDGS 4.54%, CFP 4.76%) and fibre content of the CFP was 1/3rd (4.13%) of DDGS (6.21%). With such high protein and low fibre, CFP has a very attractive nutrient profile for a corn protein ingredient to use in aquafeeds for all species. In following sections, a more detailed overview of the nutrient specifications of these ingredients as well as reviews of published scientific articles regarding their use with numerous aquatic species will be presented.

Materials and Methods in this study

This study started with two excellent United States Grains Council reports on DDGS and high protein corn co-products, the *DDGS User Handbook 4th Edition – Precision DDGS Nutrition* (2019), and the more recent *High-Pro DDGS-Handbook* (2023). Another important report was *Corn Processing Co-products Manual - A review of current research on distillers grains and corn gluten* prepared by the Nebraska Corn Board and the University of Nebraska-Lincoln (2005). The Renewable Fuels Association (RFA) *2025 ETHANOL INDUSTRY OUTLOOK- Back to our Roots* provided useful information on current bioethanol refining and US production volumes of DDGS and other corn co-products.

Several reference texts were perused, including: *Distillers Grains - Production, Properties, and Utilization* (Liu and Rosentrater, 2012), *Corn: Chemistry and Technology, 3rd Edition* (Serna-Saldivar, Ed. 2019), and *Cereal Grains Composition, Nutritional Attributes and Potential Applications* (Nayik et al. Eds. 2023).

Another very valuable reference was a recent report, *Animal Feed Consumption (February 2025)*, prepared for iFeeder and the American Feed Industry Association (AFIA), which provides not only 2019 and 2023 aquaculture feed production volumes for every US state, but also lists of ingredients used in aquafeed production. For example, the report says that 24.87% of all ingredients used in American aquafeed production in 2023 were corn-related ingredients.

A search for scientific papers available online was conducted primarily with Google Scholar (https://scholar.google.com), but also Researchgate.net and Academia.edu. Although the search for peer-reviewed publications was the main focus, several interesting PhD. dissertations published by graduate students at US universities on corn ethanol production, corn DDGS, high protein corn co-products, and emerging processing technologies were found to be very helpful.

Several websites providing feed ingredient reference data to support feed formulation were consulted to see what baseline values for corn products from ethanol biorefining were reported in Europe and elsewhere. These included *Feedipedia.org* and *Feedtables.com* sponsored by a couple corporate sponsors in partnership with the FAO and several EU/French governmental organizations, and the USDA-sponsored National Animal Nutrition Program's website *Animalnutrition.org*.

Finally, computer and phone apps for two artificial intelligence agents, Perplexity (perplexity.ai) and DeepSeek (deep-seek.ai) were used when surveying for statistics on US corn products and production, FCP manufacturing technologies, American manufacturers of DDGS and CFP, and FCP products being marketed for use in aquaculture.

Nutrient Specifications of DDGS & CFP

DDGS Nutrient Specifications

Herrick and Breitling (2016) of POET Research Inc. published a short note on the results of independent third-party laboratory analysis of DDGS produced at 27 POET corn ethanol biorefineries which had been collected over the past two production seasons. Averages and standard deviations for their analysis (dry matter basis) were:

Dry Matter – 89.2 ± SD 1.13%
Crude protein - 30.7 ± 1.57% DM
Ether extract - 5.36 ± 0.96% DM

Acid detergent fiber - 10.6 ± 1.76% DM
Neutral detergent fiber - 27.8 ± 3.27% DM
Crude fiber - 8.31 ± 0.82% DM
Sulphur - (0.92 ± 0.13% DM

Interestingly, Herrick and Breitling also conducted a statistical variance components analysis to see which factors (time, location, other) had the biggest impact on DDGS variability. Time (season/month) accounted for 25.6% of the variability while location (region/factory) accounted for only 7.1% of the variability. Other factors (presumably farm conditions, storage, etc.) accounted for a majority of the variability. For those interested, the authors also indicated the impact of time and location on each of the nutritional parameters listed above.

Waldroup et al. (2007) compiled nutrient analytical data from five separate reports to create a nutrient matrix for US DDGS, shown in Table 1.

Table 1. A nutrient matrix for US DDGS (% as-is basis). Adapted from Waldroup et al. (2007)

Nutrient	% (Weighted average As-is basis)
Dry matter	89.36
Crude protein	26.45
Fat	10.08
Fiber	6.99
Ash	4.67
Arginine	1.09
Histidine	0.68
Isoleucine	0.96
Leucine	3.00
Lysine	0.73
Methionine	0.50
Cystine	0.54
Phenylalanine	1.31
Threonine	0.96
Tryptophan	0.21
Valine	1.30
Serine	1.07

Spiehs et al. (2002) published an excellent report entitled "*Nutrient database for distiller's dried grains with solubles produced from new ethanol plants in Minnesota and South Dakota*", detailing the proximate chemical composition, essential amino acid levels, and mineral composition of 118 DDGS samples collected from 10 recently installed corn ethanol plants. The report is worth reviewing, keeping in mind that production technologies have changed over the past 20 years, and improvements have occurred with the quality of DDGS.

With the corn bioethanol industry continually improving its manufacturing processes, the quality of DDGS has improved over time. The as-is analytical composition of six DDGS samples (Kerr et al. 2015) as shown in Table 2, reflects this, with crude protein levels 3-6% higher than that shown in the earlier Waldroup et al. values (Table 1). The information in Table 2 is very comprehensive, including proximate composition, macro-minerals, fatty acid profiles and even analysis for mycotoxins.

Table 2. Analyzed composition of corn DDGS (% as-is basis). Adapted from Kerr et al. (2015)

C-DDGS source						
A	B	C	D	E	F	Item
0.492	0.508	0.477	0.516	0.508	0.492	Bulk density,[1] g/cm^3
544	514	491	310	338	368	Particle size,[1] μm
88.66	88.88	89.34	89.80	90.52	91.28	DM,[2] %
5,227	5,094	5,052	4,981	4,918	5,155	GE,[1] kcal/kg
29.65	32.00	31.59	30.58	32.21	29.83	CP,[2] %
1.07	1.14	1.13	1.18	1.15	1.10	Lysine,[2] %
2.50	2.33	3.82	4.93	4.40	4.68	Total starch,[2] %
31.47	31.62	31.12	32.41	32.81	32.10	TDF,[3] %
38.27	38.49	39.58	30.95	31.05	27.84	NDF,[2] %
11.48	12.14	11.60	8.90	8.55	8.55	ADF,[2] %
26.79	26.35	27.98	22.05	22.50	19.29	Hemicellulose,[4] %
4.79	4.71	5.38	5.63	5.51	5.53	Ash,[2] %
0.16	0.16	0.17	0.21	0.21	0.19	Chloride,[2] %
0.83	0.87	0.92	0.90	0.94	0.85	Phosphorus,[2] %
1.16	1.14	1.18	1.29	1.27	1.30	Potassium,[2] %
0.19	0.14	0.18	0.26	0.18	0.19	Sodium,[2] %
0.56	0.54	0.73	1.10	1.05	0.11	Sulfur,[2] %
13.34	10.41	9.11	8.01	6.99	11.38	Ether extract,[2] %
0.00	0.00	0.08	0.09	0.00	0.06	Myristic, 14:0[2,5]
15.02	14.08	14.20	15.05	14.08	14.30	Palmitic, 16:0
0.14	0.15	0.13	0.19	0.14	0.15	Palmitoleic, 16:1
2.02	2.10	1.90	2.81	2.13	2.21	Stearic, 18:0
25.02	25.41	24.40	27.15	25.73	25.81	Oleic, 18:1
54.54	55.17	56.29	51.39	54.78	54.29	Linoleic, 18:2
1.73	1.61	1.65	1.52	1.62	1.54	Linolenic, 18:3
0.00	0.00	0.00	0.00	0.00	0.00	Arachidonic, 20:4
0.00	0.00	0.00	0.00	0.00	0.00	Eicosapentaenoic, 20:5
0.00	0.00	0.00	0.00	0.00	0.00	Docosapentaenoic, 22:5
0.14	0.18	0.16	0.23	0.28	0.20	Docosahexaenoic, 22:6
1.88	1.10	1.25	0.99	0.72	1.21	FFA,[2] %
11.73	8.19	14.04	8.15	10.85	5.90	Thiobarbituric acid, absorbance[2]
10.21	13.27	3.46	6.73	4.23	2.77	Peroxide value,[2] mEq/kg
						Mycotoxins[6]
ND	1.35	ND	5.12	ND	ND	Aflatoxin B1, μg/kg
ND	ND	ND	ND	ND	ND	Aflatoxin B2, μg/kg
ND	ND	ND	ND	ND	ND	Aflatoxin G1, μg/kg
ND	ND	ND	ND	ND	ND	Aflatoxin G2, μg/kg
0.23	0.56	1.57	0.22	0.88	0.77	Deoxynivalenol, mg/kg
0.34	3.26	4.93	3.67	1.66	1.64	Fumonisin B1, mg/kg
ND	0.56	0.78	0.67	0.22	0.22	Fumonisin B2, mg/kg
ND	0.23	0.34	0.22	ND	ND	Fumonisin B3, mg/kg
ND	ND	ND	ND	ND	ND	Ochratoxin A, μg/kg
ND	ND	ND	ND	ND	ND	T-2 Toxin, μg/kg
ND	ND	77.12	ND	ND	ND	Zearalenone, μg/kg

In a study on the quality of U.S. DDGS exports, Salim et al. (2010) reported on the chemical composition of corn DDGS imports to South Korea during 2006-2009, shown in Table 3. The data shows mean values, the range of values observed (min-max), the coefficient of variation (CV), as well as the number of tests performed (n) for each assay. The mean protein content from 395 DDGS samples was 27.15% (CV 8.92%), mean fat 10.67% (CV 6.94%), mean ash 4.54% (CV 10.79%) while mean fibre from 393 samples was 6.21% (CV
7.25%).

Table 3 provides Min-Max data as well as coefficients of variation showing that the core proximate values of moisture, protein, fat, fiber or ash have CV (%) values of 8.92, 2,72, 6,94, 7.25, and 10.79 respectively. For an agricultural co-product of this nature, CV's under 15% are quite acceptable.

Table 3. The mean proximate composition of DDGS samples exported from the US to South Korea (% as-is basis) from 2006 – 2009. Adapted from Salim et al. (2010).

Nutrient	Mean	Min-Max	CV	n
Moisture, %	11.10	8.47-14.16	8.92	395
Crude Protein, %	27.15	23.87-30.41	3.72	395
Fat, %	10.67	7.80-12.17	6.94	395
Fiber, %	6.21	5.07-10.61	7.25	393
Ash, %	4.54	2.60-6.58	10.79	395
Starch, %	8.12	3.93-12.33	16.26	352
Acid Value, %	19.01	12.45-57.53	38.72	33
Neutral detergent fiber, %	26.75	19.78-34.13	11.81	18
Acid detergent fiber, %	8.48	6.27-13.40	23.47	18
Calcium (Ca), %	0.04	0.01-0.38	150.0	38
Phosphorus (P), %	0.76	0.48-0.91	10.53	39
Sodium (Na), %	0.17	0.04-0.33	41.18	23
Potassium (K), %	0.91	0.76-1.20	12.09	23
Chloride (Cl), %	0.15	0.13-0.19	6.67	47
Copper (Cu), ppm	3.86	2.16-6.16	27.98	21
Zinc (Zn), ppm	57.26	44.62-71.20	12.84	21
Iron (Fe), ppm	81.54	61.58-116.70	37.45	3
Manganese (Mn), ppm	19.37	6.24-18.95	37.61	8
Carotene, ppm	8.58	4.64-16.97	36.48	16
Xanthophylls, ppm	36.72	23.26-54.40	25.05	16

In a recent report prepared by POET Bioprocessing, the mean nutritional values of more than 200 DDGS samples produced by 30 different corn ethanol plants for the period 1 January and 1 August 2025 was provided. This data is shown in Table 4.

Table 4. The mean nutrient values of corn DDGS produced from more than 30 production facilities from 1 January to 1 August 2025 (provided by POET).

PROTEIN, FAT, FIBER	222 Samples	
ITEM	VALUE	Standard Deviation
Moisture, %	11.08	1.26
Dry Matter, %	88.92	1.26
Crude Protein, %	28.82	1.41
Crude Fat, %	4.82	1.09
Acid Hydrolysis Fat, %	8.52	0.91
Crude Fiber, %	8.16	0.76
ADF, %	11.05	1.70
NDF, %	27.72	2.28
Ash, %	5.27	0.49

MINERALS	203 Samples	
ITEM	VALUE	Standard Deviation
Calcium, %	0.04	0.02
Phosphorus, %	0.91	0.09
Sodium, %	0.22	0.1
Potassium, %	1.28	0.13
Magnesium, %	0.36	0.04
Sulfur, %	0.82	0.12
Copper, ppm	5.15	0.56
Iron, ppm	66.38	19.77
Manganese, ppm	14.52	2.89
Zinc, ppm	56.97	6.09

MYCOTOXINS	278 Samples	
ITEM	VALUE	Standard Deviation
Deoxynivalenol, ppm	2.1	1.53
Total Aflatoxin, ppb	0.5	0.98
Total Fumonisin, ppm	1.54	2.35
Zearalenone, ppb	72.37	58.68

AMINO ACIDS, %	202 Samples	
ITEM	VALUE	Standard Deviation
Alanine	2.11	0.12
Arginine	1.26	0.08
Aspartic Acid	1.92	0.11
Cystine	0.46	0.02
Glutamic Acid	5.18	0.32
Glycine	1.16	0.06
Histidine	0.8	0.06
Isoleucine	1.04	0.06
Leucine	3.27	0.22
Lysine	0.96	0.07
Methionine	0.57	0.04
Phenylalanine	1.34	0.09
Proline	2.49	0.13
Serine	1.44	0.08
Threonine	1.12	0.05
Tryptophan	0.24	0.03
Tyrosine	1.06	0.07
Valine	1.36	0.07

NOT A GUARANTEED ANALYSIS.
***These Third Party Lab results are not a guarantee of nutritional value, as laboratory results are influenced by factors beyond the control of POET Nutrition.**

1: All Values: As Is Basis

2: Values only include samples that had detectable values

3: A zero indicates that samples had no detectable values.

Samples taken during: 1/1/2025 - 8/1/2025

DDGS Protein and Amino Acids

When investigating the nutritional value of any new ingredient, the protein and amino acid content is probably the primary concern of the nutritionist. While the crude protein level can be easily analyzed by common feed mill labs, analysis of the amino acid profile is not common.

Olukosi and Adebeyi (2013) compiled and summarized the nutrient composition of maize DDGS from 42 published data sets, and were able to compile an excellent table of values for Indispensible and dispensible amino acids, shown in Table 5 below. The CV% value is important in understanding the variability of the indispensable amino acids.

Welker et al. (2014) provided the data regarding the essential amino acid profiles of menhaden fish meal (MFM), soybean meal (SBM), and DDGS from corn, wheat and sorghum shown below in Table 6. The values are expressed as grams EAA/kg of dry matter, while values in parentheses are grams EAA/kg of crude protein, assuming menhaden fish meal with 65% CP, soybean meal is 45% CP, maize DDGS is 28% CP, wheat DDGS is 51% CP, and sorghum DDGS is 34% CP.

Table 5. The Amino acid composition (g/kg) of DDGS made from corn (maize) Olukosi and Adebeyi (2013)

	Maize-DDGS[a,b] (g/kg)					
	n[d]	Max	Min	Mean	SD	CV (%)
Indispensable amino acids						
Arg	26	14.6	10.6	12.2	0.978	7.99
His	24	9.10	6.50	7.37	0.695	9.43
Ile	27	12.5	9.60	10.7	0.723	6.73
Leu	24	36.2	28.9	32.1	2.10	6.57
Lys	28	11.1	6.20	9.01	1.18	13.1
Met	28	7.20	4.40	5.24	0.628	12.0
Phe	24	15.1	10.9	12.9	1.23	9.59
Thr	28	11.6	9.30	10.3	0.668	6.46
Trp	27	2.60	1.60	2.16	0.222	10.3
Val	26	16.1	13.0	14.2	0.949	6.70
Dispensable amino acids						
Ala	21	21.0	15.6	18.3	1.39	7.61
Asp	21	19.7	14.9	17.3	1.32	7.62
Cys	26	7.00	4.10	5.14	0.571	11.1
Glu	21	54.8	29.3	36.1	6.17	17.1
Gly	21	12.4	9.50	10.8	0.732	6.81
Pro	21	22.1	16.6	19.3	1.67	8.68
Ser	22	14.5	10.1	11.7	1.07	9.13
Tyr	22	12.0	9.10	10.1	0.731	7.22

Table 6. The essential amino acid composition of menhaden fish meal, soybean meal, and DDGS from corn, wheat and sorghum, expressed as k/kg dry matter. Values in parentheses are g/kg crude protein. Welker et al. (2014).

Essential amino acid	MFM[a] (g/kg)	SBM[a] (g/kg)	DDGS (g/kg[a])		
			Maize[b]	Wheat[c]	Sorghum[d]
Arginine	38 (59)	41 (91)	12 (41)	18(3.5)	11 (32)
Histidine	15 (22)	15 (33)	7 (23)	10(2.0)	7 (21)
Isoleucine	27 (41)	30 (67)	11 (37)	16(3.1)	14 (41)
Leucine	45 (69)	43 (96)	30 (104)	30(5.9)	42 (124)
Lysine	47 (73)	34 (76)	9 (30)	7 (14)	7 (21)
Methionine	18 (27)	8 (18)	5 (19)	7 (14)	5 (15)
Phenylalanine	24 (37)	31 (69)	13 (44)	22 (43)	17 (50)
Threonine	25 (38)	23 (51)	10 (34)	13 (25)	11(3.2)
Tryptophan	7 (10)	8 (18)	2 (7)	4 (8)	4 (12)
Valine	32 (50)	31 (69)	13 (44)	19(3.7)	17 (50)

[a] Values are expressed as g/kg of dry matter. Values in parentheses are expressed as g/kg crude protein (based on 650 MFM: 450 SBM: 280 maize DDGS: 510 wheat DDGS: 340 sorghum DDGS).
[b] Feedstuffs (2011).
[c] Nyachoti et al. (2005), Widyaratne and Zijlstra (2007) and Ortin and Yu (2009).
[d] Sotak et al. (2010) and Stein (2008).

DDGS Lipids and Fatty Acids

The fatty acids and other fat-soluble nutrients in DDGS basically retain many of the chemical characteristics of the whole corn it was made from. The oil is concentrated from 3-5% as it is in whole corn to 8-12% in corn DDGS (Rausch and Belyea 2006). The DDGS lipid profile includes the fats and fat-soluble nutrients of the corn germ, which is usually the part of the corn kernel used to produce refined corn oil. The fatty acid profile of DDGS is shown in Table 7 (Abuddabos et al. 2017).

DDGS oil is high in palmitic acid (C16:0), linoleic acid (C18:2n-6), and oleic acid (C18:1n-9). Fish can use the palmitic and oleic acids to produce energy, while the linoleic acid can be elongated and desaturated by fish to produce longer poly-unsaturated fatty acids as needed.

Many freshwater fish species such as tilapia, catfish, and carps have essential fatty acid requirements for linoleic (C18:2n-6) and α-linolenic (C18:3n-3) fatty acids, but not for the longer highly unsaturated fatty acids (EPA, DHA). The lipids in DDGS can help to provide these essential fatty acids.

DDGS is rich in phytosterols and ferulic phytosterol esters (FPE) (Winkler-Moser and Vaughn 2009). When compared to corn oil, DDGS is particularly high in sitostanol (12-17% of total sterols) and campestanol (7-9%), The oil also has a high vitamin E content with γ-tocopherol (210-460 mg/kg, α-tocopherol (70-170 mg/kg) and δ-tocopherol (6-8m mg/kg) and
is rich in tocotrienols, a class of powerful antioxidants. Details are shown in Table 8 (Winkler-Moser 2011).

Table 7. The fatty acid composition of DDGS samples). Abudabos et al. (2017)

Fatty acid	Mean	Median	Std. deviation	SEM	Maximum	Minimum	Range
Myristic acid $C_{14}H_{28}O_2$	0.07	0.07	0.004	0.001	0.07	0.06	0.01
Palmitic acid $C_{16}H_{32}O_2$	21.05	22.59	5.198	1.342	23.24	2.40	20.84
Palmitoleic acid $C_{16}H_{30}O_2$	0.37	0.33	0.239	0.062	1.19	0.15	1.04
Heptadecanoic (margaric) acid $C_{17}H_{34}O_2$	0.05	0.05	0.007	0.002	0.06	0.04	0.02
Stearic acid $C_{18}H_{36}O_2$	2.66	2.66	0.097	0.025	2.87	2.51	0.36
Elaidic acid $C_{18}H_{34}O_2$	0.02	0.02	0.004	0.001	0.02	0.01	0.01
Oleic acid $C_{18}H_{34}O_2$	22.12	22.10	0.436	0.113	22.80	21.20	1.60
Methyl (8E,11E)-8,11-octadecadienoate $C_{18}H_{32}O_2$	0.18	0.15	0.175	0.045	0.80	0.02	0.78
Linolelaidic acid $C_{18}H_{32}O_2$	0.09	0.06	0.135	0.035	0.58	0.04	0.54
Linoleic acid $C_{18}H_{32}O_2$	49.92	49.99	0.787	0.203	51.56	48.33	3.23
3,6-octadecadienoic acid, methyl ester $C_{19}H_{34}O_2$	0.85	0.84	0.333	0.086	1.97	0.49	1.48
Linolenic	1.38	1.38	0.032	0.008	1.43	1.33	0.10
11-eicosenoic acid $C_{20}H_{38}O_2$	0.20	0.20	0.027	0.007	0.27	0.16	0.11
Docosanoic (bhenic) acid $C_{22}H_{44}O_2$	0.13	0.14	0.023	0.006	0.18	0.09	0.09
Tetracosanoic (lignoceric) acid $C_{24}H_{48}O_2$	0.26	0.26	0.019	0.005	0.31	0.24	0.07

Table 8. The content of tocopherols, tocotrienols and carotenoids in corn germ (CG) and DDGS. Winkler-Moser 2011)

	CG	DDGS
Total tocopherols (µg/g)	1433.6	1104.2
Alpha-tocopherol	213.8	295.6
Gamma-tocopherol	1185.4	760.8
Delta-tocopherol	34.3	47.8
Total tocotrienols (µg/g)	235.6	1762.3
Alpha-tocotrienol	21.9	471.9
Gamma-tocotrienol	165.6	1210.0
Delta-tocotrienol	48.1	80.3
Total carotenoids (µg/g)	1.33	75.02
Lutein	0.37	46.69
Zeaxanthin	0.4	24.16
Beta-cryptoxanthin	0.56	3.31
Beta-carotene	ND[b]	0.86
OSI (h)	3.91 ± 0.04	6.62 ± 0.06

DDGS Yeast Content

Fermentation of starch by yeast into ethanol plays a significant part in the bioethanol production process. Consequently, DDGS typically contains 7-10% spent yeast, and corn fermentation protein (CFP) is typically 20-25% spent yeast. Earlier it was noted that Shurson (2018) had estimated that the yeast content of CFP is about three times higher than for DDGS, possibly as high as 29%.

Spent yeast has >25% protein (DM basis). Han and Liu (2010) calculated that about 20% of the protein content in DDGS came from the yeast component, with a part of that actually being nucleotides. In addition to protein, yeast cells have a cell wall composed of both mannans and B-glucans, which are recognized as prebiotics beneficial to animal health and immunity.

Hadiuzzaman et al. (2022) wrote an extensive review on the mode of action of β-glucans in fish, and how it stimulated the immune systems of both fish and shrimp. Suphantarika et al. (2003) investigating the application of extracted β-glucans from brewer's spent grains and the immunostimulant effect on the black tiger shrimp (*Penaeus monodon*), found a significant increase in hemocyte phenoloxidase activity after feeding the shrimp 0.2%
β-glucans for 3 days.

Böttger and Südekum (2018) suggest that yeast could contribute about 100g mannan/kg DDGS. Lim et al. (2009) reported that they had analyzed the β-glucan content of DDGS and it was 0.57%. Shurson (2018), citing unpublished data, said that an industry researcher had found the β-glucan content in a new 50% crude protein, maize distillers dried yeast co-product was
8.2–8.4% on an "as-fed" basis.

Ray et al. (2022) reviewed the use of DDGS in aquaculture feeds, and noted that although there were few published reports on the impact of DDGS on fish and shrimp health, studies with channel catfish showed an increase in serum antibodies and immunoglobulin, improving disease resistance against bacterial pathogens like *Streptococcus iniae* and *Edwardsiella ictaluri*.

DDGS Phosphorus Availability to Fish

Li et al. (2015) conducted a study to determine the apparent phosphorus availability coefficients for a group of plant feedstuffs commonly used in U.S. catfish feeds: Soybean meal, cottonseed meal, wheat middlings, corn gluten feed and corn DDGS. These authors concluded that the milling and fermentation processes used to produce ethanol, Corn gluten feed and DDGS degrades phytic acid in the corn, making a greater percentage of P available than soybeasn meal or cottonseed meal.

Table 9. Total Phosphorus, phosphorus apparent availability coefficients (AAP) and available phosphorus in several common feedstuffs including DDGS.

Ingredient	Soybean Meal	Cottonseed Meal	Wheat Middlings	Corn Gluten Feed	Corn DDGS
Total P (% of DM)	0.8	1.32	1.17	0.90	0.86
AAC*	36.2	22.2	20.3	74.5	77.4
Available P (% of DM)	0.29	0.29	0.24	0.67	0.67
*Apparent Availability Coefficient					

DDGS Sugar, Starch, and Polysaccharides

DDGS in all its forms typically has a sweet smell due to the presence of sugars. Srichuwong and Jane (2011) reported that a commercial sample of corn DDGS contained (DM basis) 8.76 ± 0.08 g/100g free glucose, 10.25 ± 0.09 g/100g total soluble sugars (TSS) and 5.54 g/100g of residual starch. The quantities are not large, but these mostly digestible carbohydrates can contribute dietary energy.

The soluble and insoluble fiber content of DDGS is one of the key limiting factors on its use in aquafeeds. Most aquatic carnivorous and many omnivorous animals do not possess endogenous intestinal carbohydrase enzymes, although some may benefit from fermentative bacteria in their intestines to some extent. Thus, researchers have shown that both insoluble and insoluble polysaccharides pose problems to aquatic animals by interfering in digestion and assimilation of nutrients.

Indigestible insoluble polysaccharides like cellulose and lignin fill the digestive tract and create a sensation of fullness, reducing feed intake for many aquatic species. (Sinha et al. 2011, Haidar et al. 2016, Deng et al. 2021). On the other hand, soluble fibers swell and create a gel-state which inhibits both enzymatic activity and nutrient absorption. Sinha et al. (2011) listed the following anti-nutritional effects of non-starch polysaccharides in fish:

1. Changes in digesta viscosity (reducing mixing of digestive enzymes and substrates).
2. Alteration in the gastric emptying and rate of gut passage (reduced rate of emptying).
3. Alteration of gut physiology (hinder endogenous excretion of water, enzymes, electrolytes).
4. Alteration of gut morphology
5. Alteration in gut microflora (stimulates microbial fermentation)
6. Alteration in the gut mucus layer.

Thus, aquafeed nutritionists concerns about the content of non-starch polysaccharides in feed ingredients such as DDGS gives them pause about using too much in feeds, although the magnitude of the anti-nutritional consequences do vary from species to species.

Many herbivorous species do produce endogenous carbohydrases, and with the longest intestines relative to their body length when compared to omnivores and carnivores, there is a substantial gut microflora that can ferment these indigestible fiber components into usable nutrients.

In a study to investigate the non-starch polysaccharide content of DDGS, Pedersen et al. (2014) reported on the composition of 72 corn DDGS samples collected from 21 ethanol plants in Nevada, Iowa, Indiana, Minnesota, and Kentucky (Table 10).

Table 10. The Non-starch polysaccharide (NSP) and Non-cellulosic polysaccharide (NCP) composition of 72 DDGS samples collected from 21 US ethanol plants (g/kg DM). Pedersen et al. 2014

	Corn DDGS		
	Mean[a]	Range[b]	S.D. (CV)
Total NSP			
Total	283[g]	(250–337)	20 (0.09)
Soluble	31[g]	(16–65)	8 (0.47)
Cellulose	67[g]	(52–91)	8 (0.16)
NCP			
Xylose			
Total	77[g]	(67–100)	7 (0.10)
Soluble	6[g]	(1–16)	3 (0.62)
Arabinose			
Total	62[g]	(56–72)	4 (0.07)
Soluble	7[g]	(2–15)	3 (0.45)
Glucose			
Total	28[g]	(21–44)	4 (0.13)
Soluble	3[g]	(0–16)	4 (1.90)
Mannose			
Total	17[g]	(12–20)	2 (0.12)
Soluble	6[g]	(4–9)	1 (0.19)
Galactose			
Total	15[g]	(13–21)	2 (0.11)
Soluble	3[g]	(2–5)	1 (0.29)
Uronic acids			
Total	16[g]	(14–20)	1 (0.08)
Soluble	5[g]	(3–6)	1 (0.11)
Klason lignin	25[g]	(15–47)	7 (0.26)
A/X ratio	0.80[g]	(0.71–0.85)	0.0 (0.05)
UA/X ratio	0.20[g]	(0.16–0.23)	0.0 (0.08)

Using Enzymes to Reduce the Impact of Fiber in Feeds containing DDGS

One approach has been to do additional treatment of corn DDG wet stillage using solid-state fermentation with (bacteria and fungi) after ethanol extraction to hydrolyze fiber and produce a low-fiber product known as high protein DDG (HP-DDG), as was mentioned earlier.

An example of this approach was published by Iram et al. (2019), who used DDGS as a feedstock to screen different strains of bacteria like *Bacillus subtilis*, and fungi like *Aspergillus niger* to break down the DDGS fiber components.

West (2014) obtained corn DDGS from the Dakota Ethanol LLP company in South Dakota, USA with a phytic acid content of 0.220% - 0.225%. He then conducted solid-state fermentation with it using 2 and 4 FTU of a purified *Aspergillus ficuum* phytase/g DDGS. After fermenting the DDGS with phytase for 2 hours at different temperatures (28C, 30C, 37C, 40C and 45C), he concluded that

The second approach is use supplemental enzymes in fish feeds containing DDGS to improve digestibility. The effectiveness of this approach depends on whether the feed formulation contains sufficiently high quantities of the enzyme's preferred substrate, otherwise little benefit may be seen. An excellent review on phytate from plant-derived ingredients in aquafeed and its mitigation with phytase enzyme was prepared by Kumar et al. (2011).

Nascimento et al. (2023) fed Nile tilapia (7.5g) four diets with (18.5%) and without (0%) DDGS, and with and without added xylanase (1130 TXU) and β-glucanase (510 TGU). The additional enzymes had a modest impact on the performance of the DDGS-free diet, but resulted in the greatest body weight gain among fish fed the four diets

In another experiment with Nile tilapia, Amorocho et al. (2024) prepared four diets with 30% DDGS for tilapia, the first with no enzymes, added protease enzyme to a second, a carbohydrase (xylanase- beta mannanase mix) to the third, and protease and carbohydrase to the fourth batch. The protease improved net energy retention.

Goda et al. (2019) fed European seabass (*Dicentrarchus labrax*) diets containing 11.2%, 15% and 18.7% HP-DDG with and without 0.5g/kg phytase. The test diets also contained soybean meal (18.7 - 37.5%), corn gluten meal (9%), rice bran (5.0 - 6.5%), and wheat middlings (7.0 - 8.6%), all of which contain substnatial amounts of phytic acid. The researchers found the best growth and lowest FCR with the diet containing the highest HP-DDG (18.7%) with supplemented phytase.

In another report, Goda et al. (2020), fed European seabass diets containing 11.2%, 15% and 18.7% HP-DDG which were supplemented with and without 1g/kg protease.

All diets supplemented with protease gave better feed performance than the control. More details of this research by Goda et al. can be found in Table 20.

DDGS Xanthophyll Content

Salim et al. (2010) determined the mean xanthophyll content of 16 DDGS samples to be 36.72 ppm (range 23.26-54.40) as shown in Table 3,

Winkler-Moser (2011) compared the carotenoid content of corn germ to DDGS and found the DDGS sample contained 75.02 mg/kg total carotenoids, 46.69 mg/kg lutein, 24.16 mg/kg zeaxanthin, and 0.86 mg/kg beta-carotene (Table 7).

Cortes-Cuevas et al. (2015) reported the total xanthophyll content of two low-oil DDGS samples (ether extract 6.54 and 5.39%), as 24.2 and 25.6 mg/kg, respectively, with lutein content at 5.9 and 6.0 mg/kg, and zeaxanthin at 8.1 and 10.3 mg/kg respectively. They commented that the xanthophyll content of DDGS is reduced during the oil reduction process, which is reasonable considering that carotenoids are fat-soluble nutrients.

Researchers Li and Engelberth (2018) investigated whether DDGS could serve as a source of purified xanthophylls, and stated that they recovered 36.09 ± 16.87 ppm of lutein and
15.48 ± 6.13 ppm of zeaxanthin from DDGS, a three to fivefold increase in xanthophylls as compared to corn itself.

DDGS in the Export Market

According to the 2024 Renewable Fuels Association report *U.S. Distillers Grains Trade Statistical Summary, the United States* (RFA 2024) exported 12.2 million metric tons of DDGS to more than 50 countries in 2024. Due to the wide nutrient variability of DDGS produced in the United States, it is difficult to establish a standard specification for exported DDGS, and the U.S. government has let producers handle the issue rather than establishing federal guidelines. Consequently there is no specific set of quality standards that apply to exported DDGS. Purchase specifications for DDGS quality need to be agreed by buyer and seller. In addition to covering basic nutrients, specifications may include min-max levels on fiber components, Hunter color range, mycotoxins, etc.

Looking at some DDGS specifications offered by commodities traders (Table 8), Amatheus, (https://ametheus.com/ddgs/), a commodities trader with presences in the USA, India, Hong Kong, and Dubai shows their technical specifications for both USA and Indian Corn DDGS. India is also a significant producer and exporter of corn DDGS, but the quality and consistency has been reported to be an issue with many users (Makkar, 2012). The core specifications (moisture, ProFat, fibre, ash) of the USA product is slightly better than the Indian product. In the Amatheus examples in Table 11 below, ProFat is 36% min for the USA product while fat is declared as >9%, giving a minimum crude protein content of 2%, and a ProFat value of 35% for the Indian product, with fat declared as >8%, minimum crude protein would also be 27%.

It is very important to note that the declared minimum vomitoxin (deoxynivalenol) level is 5ppm for the USA DDGS and double that at 10ppm for the Indian DDGS. Likewise, the specification for combined aflatoxins (B1, B2, G1, G2) is 20 ppb max (USA) versus 50 ppb max (India), suggesting that from a feed and food safety perspective, purchasing the American DDGS is a much safer option for both farmed animals and consumers of farmed fish.

Table 11 (a,b). DDGS specifications offered by Amatheus, a commodities trader with presences in the USA, India, Hong Kong and Dubai, shows technical specifications for corn DDGS from both USA and India .

11a. Full USA Corn DDGS Specifications (As Provided):		
Type:	**Corn DDGS**	
Moisture:	**12% Max**	
ProFat:	**36% Min**	**(Crude Fat 9% Min)**
Crude Fiber:	**12% Max**	
Crude Ash:	**8% Max**	
Sand/Silica:	**1.5% Max**	
Color:	**Golden Yellow**	**(Hunter Scale 50 min)**
Vomitoxin	**5 ppm Max**	
Aflatoxin (B1, B2, G1, G2)	**20 ppb Max**	

11b. Full Indian Corn DDGS Specifications (Representative Sample):		
Type:	**Corn DDGS**	
Moisture:	**13% Max**	
ProFat:	**35% Min**	**(Crude Fat 8% Min)**
Crude Fiber:	**14% Max**	
Crude Ash:	**9% Max**	
Sand/Silica:	**2% Max**	
Color:	**Golden Yellow/Light Brown**	**(Hunter Scale 50 min)**
Vomitoxin	**10 ppm Max**	
Aflatoxin (B1, B2, G1, G2)	**50 ppb Max**	

ProFat is a term commonly used in the animal feed and grain industry to represent the combined percentage of crude protein and crude fat in a feed ingredient, and is commonly used with DDGS specifications. It is calculated by simply adding the values (in percentage) of crude protein and crude fat found in a sample. If a DDGS sample contains: Crude Protein: 28% and Crude Fat: 8% then ProFat = 28% + 8% = 36%.

CFP Nutrient Specifications

The products known as HP-DDG and Corn fermented protein (CFP) are quite similar, and this has created some confusion about what distinguishes them from one another. Previously it was mentioned that HP-DDG is produced by direct enzymatic treatment of, or solid-state fermentation by bacteria and yeasts of the fiber component of, distiller's grains solids after ethanol extraction, whereas CFP involves mechanical separation and washing out and collection of the protein and yeast components of the distiller's grains whole stillage, leaving the thin stillage with fiber components behind for further processing.

Since some plant fiber is left behind, HP-DDG has a crude protein content of 36% < 48%, higher than standard DDGS, but less than 48%CP. The concentration of extracted corn protein and yeast protein without plant fiber gives CFP a higher crude protein content of ≥48%. The fiber content in CFP comes mainly from the mannan and β-glucan oligosaccharide components of yeast cell wall rather than from corn fiber.

Verbeek et al. (2024) compared the nutrient profiles of HPDDG and CFP in a study with turkey poults, shown in Table 12.

Table 12. The nutrient profile of HP-DDG and CFP, sourced from The Andersons Inc, and analyzed by Verbeek et al. (2024).

Item	HP-DDG[1]	CFP[1]
Dry matter, %	90.32	91.99
Particle size, μm	570	377
Gross energy, kcal/kg	5,575	5,597
Ether extract, %	8.89	7.57
Total starch, %	6.37	6.28
Acid detergent fiber, %	21.55	21.94
Neutral detergent fiber, %	38.06	30.98
Phosphorus, %	0.39	0.50
Crude protein, %	47.3	55.5
Amino acid, %		
Ala	3.52	3.97
Arg	2.02	2.51
Asp	3.01	3.59
Cys	0.86	1.08
Glu	7.94	9.14
Gly	1.73	2.02
His	1.38	1.63
Ile	1.98	2.29
Leu	6.11	6.83
Lys	1.37	1.92
Met	1.03	1.33
Phe	2.51	2.86
Pro	3.94	4.41
Ser	2.00	2.32
Thr	1.69	2.01
Trp	0.24	0.37
Tyr	1.92	2.23
Val	2.41	2.86

[1]HP-DDG: High protein-distillers grain; CFP, corn fermented protein; The Andersons, Inc., Maumee, OH.

The nutrient profile of POET NexPro™ CFP produced by the MSC™ process (Maximized Stillage Co-products Technology) is shown in Table 13. This product is now known as POET CFP.

Table 13. The nutrient profile of POET NexPro CFP produced by the Fluid-Quip Process Technologies company MSC™ process (Fluid-Quip Process Technologies LLC) with analysis reported by madbarn.com (https://madbarn.com/feeds/nexpro-protein-supplement-poet/).

		% as-fed
SUMMARY ANALYSIS	Moisture, %	7
	Dry Matter, %	93
	Crude Protein, %	50.1
	Ether Extract, %	3.11
	Total Fatty Acids %	2.47
	Glycerol %	0.27
	Palmitic acid %	0.35
	Stearic Acid %	0.06
	Oleic Acid %	0.61
	Linoleic Acid %	1.38
	Alpha-linolenic Acid %	.0.4
	Crude Fiber, %	5.5
	ADF, %	13
	NDF, %	33
	Soluble Fiber %	0.91
	Sugar %	2.32
	Starch %	1.78
	Lignin %	0.75
	Non-fiber carbohydrate %	5
	Non-structural carbohydrate %	4.09
AMINO ACIDS	Crude Protein, %	50.1
	Soluble Protein %	3.47
	Arginine %	2.3
	Histidine %	1.33
	Isoleucine %	2.19
	Leucine %	5.57
	Lysine %	2.01
	Methionine %	1.01
	Phenylalanine %	2.57
	Threonine %	2
	Tryptophan %	0.43
	Valine %	2.87
MINERALS	Ash, %	3.33
	Calcium, %	0.02
	Phosphorus, %	0.52
	Sodium, %	0.01
	Potassium, %	0.47
	Magnesium, %	0.14
	Sulfur, %	0.62
	Copper, ppm	0.52
	Iron, ppm	10.6
	Manganese, ppm	0.74
	Zinc, ppm	5.36
	Selenium %	0.06
	Cobalt %	0.02

In a recent report prepared by POET Bioprocessing, the mean nutritional values with standard deviations of 52 CFP samples produced at the Shell Rock (Iowa) facility, shown in Table 14. A smaller number of samples were analyzed for minerals, amino aids, and mycotoxins.

Table 14. The mean nutrient values of POET CFP produced at the Shell rock (Iowa) POET Bioprocessing facility from 1 January - 9 August 2024 (provided by POET).

PROTEIN, FAT, FIBER		52 Samples
ITEM	VALUE	Standard Deviation
Moisture, %	7.03	0.67
Dry Matter, %	92.97	0.67
Crude Protein, %	51.97	0.70
Crude Fat, %	4.64	0.59
Crude Fiber, %	4.97	0.52
ADF, %	19.72	3.08
NDF, %	30.26	4.05
Ash, %	3.33	0.46

MINERALS		8 Samples
ITEM	VALUE	Standard Deviation
Calcium, %	0.02	0
Phosphorus, %	0.69	0.03
Sodium	0.14	0.01
Potassium, %	0.54	0.04
Magnesium, %	0.17	0.01
Sulfur, %	0.79	0.06
Copper, ppm	5.33	1.07
Iron, ppm	0.01	0
Manganese, ppm	9.2	0.49
Zinc, ppm	48.75	3.2

MYCOTOXINS		23 Samples
ITEM	VALUE	Standard Deviation
Deoxynivalenol, ppm	0.42	0.28
Total Aflatoxin, ppb	0.37	0.53
Total Fumonisin, ppm	1.33	0.72
Zearalenone, ppb	65.88	47.81

AMINO ACIDS, %		7 Samples
ITEM	VALUE	Standard Deviation
Alanine	3.98	0.1
Arginine	2.29	0.1
Aspartic Acid	3.87	0.13
Cystine	0.85	0.03
Glutamic Acid	9.13	0.23
Glycine	2.11	0.05
Histidine	1.44	0.03
Isoleucine	2.19	0.05
Leucine	6.64	0.19
Lysine	2.2	0.17
Methionine	1.15	0.03
Phenylalanine	2.83	0.09
Proline	4.12	0.06
Serine	2.7	0.09
Threonine	2.12	0.07
Tryptophan	0.52	0.02
Tyrosine	1.81	0.04
Valine	2.86	0.13

NOT A GUARANTEED ANALYSIS

***These Third Party Lab results are not a guarantee of nutritional value, as laboratory results are influenced by factors beyond the control of POET Nutrition.**

1: All Values: As Is Basis

2: Values only include samples that had detectable values

3: A zero indicates that samples had no detectable values.

Samples taken during: 1/1/2024 - 9/4/2024

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feedingredients@poet.com

Sealey et al. (2025) published the nutrient profiles and apparent digestibility for rainbow trout of two CFP products, ANDVantage40Y and AndVantage 50Y, manufactured by The Andersons Inc (Maumee, Ohio). Table 15 shows the nutritional profiles of the two CFP products, and Table 16 reports the apparent digestibility coefficients for dry matter, protein, fat and energy as well as amino acids.

Table 15. The nutrient profiles of ANDVantage40Y and AndVantage 50Y regarding dry matter, protein, fat and energy , essential and non-essential amino acids as well as some important minerals (Sealey et al. 2025).

	Ingredients	
	ANDVantage 40Y	ANDVantage 50Y
Crude protein	44.2	54.8
Crude lipid	10.0	10.1
Dry matter	93.2	93.6
Energy (cal g^{-1})	5406	5608
Ala	3.32	4.22
Arg	1.86	2.40
Asp	2.97	3.76
Cys	0.88	1.16
Glu	7.93	10.23
Gly	1.61	2.05
His	1.18	1.54
Ile	1.89	2.42
Leu	5.80	7.21
Lys	1.38	1.84
Met	0.99	1.43
Phe	2.53	3.02
Pro	3.75	4.65
Ser	2.03	2.57
Tau	0.12	0.12
Thr	1.67	2.11
Trp	0.40	0.54
Tyr	1.88	2.39
Val	2.29	2.90
P (%)	0.56	0.60
Cu (ppm)	6.62	7.69
Fe (ppm)	76	35
Mn (ppm)	6.81	14.84
Zn (ppm)	45	182

Table 16. The apparent digestibility coefficients for dry matter, protein, fat and energy as well as amino acids for the Anderson ANDVantage40Y and AndVantage 50Y CFP products.

	ANDVantage 40Y	ANDVantage 50Y	SEp[1]	Pr>F
Dry matter	59.8	59.9	1.9	0.9734
Protein	81.7	83.0	1.3	0.4153
Fat	98.1	98.3	0.6	0.7654
Energy	70.7	72.5	1.8	0.3910
Ala	87.5	86.8	0.98	0.5058
Arg	87.4	89.7	0.89	0.0562
Asp	76.8	77.5	1.69	0.6784
Cys	72.8	74.9	2.23	0.4004
Glu	89.3	88.1	1.18	0.3741
Gly	72.3	76.0	1.99	0.1425
His	83.0	85.4	1.01	0.0828
Ile	81.4	82.9	1.35	0.3369
Leu	90.3	88.5	0.95	0.1255
Lys	69.3[b]	76.4[a]	1.20	0.0041
Met	90.0	89.7	1.18	0.7724
Phe	87.5	87.0	0.98	0.6640
Pro	87.5	86.6	1.33	0.5514
Ser	83.9	82.9	1.32	0.5124
Thr	74.3[b]	77.2[a]	1.84	0.0192
Trp	79.2	86.5	3.02	0.0736
Tyr	92.3	91.3	1.03	0.3785
Val	82.4	84.3	1.36	0.2479
Sum AA	84.5	84.7	1.37	0.8932
P	86.3[a]	40.3[b]	8.25	0.0051

[1] Pooled standard error.

Xanthophyll Content of CFP

Since the total carotenoid, lutein, and xanthophyll content of CFP is of concern to aquaculture feed producers seeking to avoid pigmenting effects when CFP is included in fish and shrimp feeds, several producers have prepared analyses of their products.

Craig and Rens (2023) of Green Plains Inc. reported on the xanthophyll content of two CFP products, one with 50% crude protein and one with 60% CP (Green Plains Sequence™), and compared them to corn gluten meal (CGM) as shown in Table 17. While the total carotenoids in CGM was over 300 ppm, the two CFP products contained about one-fifth the amount, 61-69 ppm.

Table 17. The xanthophyll content of two CFP products, one with 50% crude protein and one with 60% CP (Green Plains Sequence™), compared with corn gluten meal (CGM) and corn protein concentrate (CPC, Empyreal75™)

CAROTENOID	PRODUCT (ppm)			
	CFP 50	**CFP 60**	**CGM**	**CPC**
Lutein	22.0	22.7	102	181.0
Zeaxanthin	28.9	34.2	169.0	208.0
β-Carotene	1.13	1.94	6.49	11.3
Cis β-carotene	0.50	0.95	3.52	5.75
Trans β-carotene	0.64	0.99	2.97	5.51
α-Cryptoxanthin	4.62	4.46	12.2	27.2
β-Cryptoxanthin	4.79	5.25	19.3	28.7
Total Carotenoids	61.5	68.6	309.0	457.0

Feeding DDGS and CFP to Fish and Shrimp

This overview of feeding DDGS is limited to studies published from the year 2000 onwards. Prior to that time, DDGS was usually a byproduct from the production of beverage alcohol from corn, and it is sometimes difficult to determine the provenance of the DDGS that was used in early studies.

Carotenoid Utilization in Fish and Crustaceans

The utilization of dietary carotenoids by aquatic animals varies considerably from species to species. Carotenoids are stored in animal tissues and organs in several different forms; 1.) Free carotenoids, usually found in eggs and muscle tissue; 2.) Carotenoid mono- and di-esters in skin and chromatophores; and 3.) Carotenoproteins (mainly in crustacean exoskeletons). All animals can readily convert carotenoids from esters to the free forms and *vice versa*.

Carps, goldfish and other cyprinids can convert zeaxanthin to astaxanthin to obtain their red skin coloration, but their flesh does not pigment (Hata and Hata 1973, 1975a). Using corn gluten meal to feed Nile tilapia or red tilapia (xanthophylls >25 ppm) makes the black stripes on Nile tilapia more prominent, and makes the orange red-coloration on red tilapia brighter.

Rainbow trout and other salmonids cannot convert β-carotene, lutein or zeaxanthin into astaxanthin, and must be fed dietary astaxanthin to obtain their characteristic pigmentation (Hata and Hata 1975b). Peterson et al. (1966) fed brook trout (*Salvelinus fontinalis*), brown (trout (*Salmo trutta*), and rainbow trout (*O. myki*ss) diets containing crayfish extracts, paprika, marigold petals, and pure B-carotene. Each species deposited dietary pigments differently in their skin, fins and flesh. The authors noted that most of the pigments in well-colored brown trout were found in the skin when against a dark background, but shifted their pigments from their skin into flesh when placed against a light background for two days or less.

Chanel catfish (*Ictalurus punctatus*) deposit dietary xanthophylls (lutein and zeaxanthin) as pigments in the skin and flesh (Li et al. 2007), while β-carotene is not deposited as pigmentation, and is converted into vitamin A instead (Lee, 1987). Dr. Tom Lovell of Auburn University) is credited with saying that keeping total xanthophyll content in feed below 11 ppm (lutein plus zeaxanthin) would not lead to coloration of catfish flesh from feed (Lovell 1989). However, Li et al. (2009) later proposed that channel catfish feed should contain no more than 7 ppm xanthophylls to avoid catfish flesh coloration. Hu (2012) analyzed the carotenoid content of 60 catfish fillets removed from a fillet processing plant

Marine shrimp and prawns can convert dietary xanthophylls and β-carotene from terrestrial crops like corn, or microalgae like *Dunaliella salina* into astaxanthin (Boonyaratpalin et al. 2001, Aguirre-Hinijosa 2012), although the process is time-consuming and energy-intensive.

Latscha (1989) reported the carotenoid content of several species of wild shrimp, and yellow xanthophylls composed 30%, 0.4%, 19.0% and 23% of total carotenoids in *P. vannamei,*
P. monodon, P. japonicus and M. monoceros, respectively. In comparision, astaxanthin content of total carotenoids was 65%, 98%, 79% and 72%, for the same four species respectively.

Herbivorous Species

Carp (See Table 18)

Common Carp (*Cyprinus carpio*), Mrigal catfish (*Cirrhinus mrigala*), Grass carp (*Ctenopharyngodon idellus*)

Five studies were found with common carp (*Cyprinus carpio*), while two studies involved grass carp (*Ctenopharyngodon idellus)* and only one study used mrigal carp (*Cirrhinus mrigala*), one of the Indian major carps. Recommended levels of DDGS in carp feeds ranged from 20% up to 40% of diet. One group (Naz et. al. 2023) found 750 FTU/kg of added phytase improved nitrogen and phosphorus retention. Révész et al. (2019b) and Naz et al. (2023) also determined some digestibility coefficients (DM, protein, lipid, energy) on their carp diets.

Nile Tilapia (*Oreochromis niloticus*) and Hybrids (See Tables 19 and 20)

There is more DDGS research with tilapia and hybrid tilapia than for any other species group that has been investigated. Twenty-six studies from 2004 to 2023 were found. Fifteen reported on DDGS fed to Nile tilapia, ten were for hybrid tilapia, and only one was with Mozambique tilapia. While most of the published reports were using a standard DDGS, several reported using HP-DDGS and one paper reported using FCP. In most of these studies, DDGS was used to replace fish meal, corn, and soybean meal. A large percentage of the research was conducted in Egypt, where tilapia aquaculture is very important.

The optimal level of DDGS to use in feeds was in the range of 20% - 30%, but in a few studies (Lim et al 2007, Shelby et al 2008, Chatvijitkul et al. 2016) where L-lysine was supplemented (0.4 – 0.9%) inclusion of 40% - 60% was possible without any significant impact of growth and feed conversion.

Welker et al. (2023) tested four American DDGS products in diets with and without supplemental phytase and xylanase to determine the enzymes impact on nutrient digestibility. As with other digestibility studies, 70% of a reference diet (mainly menhaden fish meal (15%), 48%CP soybean meal (43%) and wheat flour (38%) was mixed together with an additional 30% of each of the DDGS products. All diets were produced with a twin-screw cooking extruder and the two enzymes were top-coated on the finished dried pellets. The phytase target was 2500 FTU/kg diet and the target for the birchwood xylanase used was 8,000 BXU/kg diet. Fish were fed the basal diet with and without enzymes (treatments Ref and Ref+), and the basal + DDGS diets (treatments DDGS and DDGS+). Faecal collection from the tilapia lasted 7 weeks. Looking at their results, for diets without enzymes, apparent crude protein digestibility of the different DDGS diets were similar to the reference diet, but the digestible energy of the DDGS diets was significantly lower than the two Reference diets and the DDGS+ diets with sprayed-on enzymes.

The authors concluded that corn DDGS is a highly digestible protein source in tilapia feeds, and while enzyme treatment does improve DDGS nutrient digestibility overall, the degree of improvement in digestibility for each nutrient varies. The improvement in apparent dry matter and apparent energy digestibility of the DDGS+ diets hinted that better growth performance could be obtained when these diets were fed to fish long term.

DDGS with Feed Enzymes

Several studies used feed enzymes in the DDGS diets to improve feed digestibility and performance. A couple of researchers (Abo-State et al. 2009, Tahoun et al. 2009) added phytase enzyme up to 300 ppm, and saw improved growth.

Soltan et al. (2015) tested a multi-enzyme mixture (amylase, xylanase, beta-glucanase, protease, lipase, cellulase) on their tilapia diets, and reported that without the added enzymes 20% DDGS in their diets was optimal, but with the multi-enzymes added, the DDGS level could be raised to 30%.

Finally, Amorocho et al. (2024) formulated a series of six low-fiber (LF) diets based on soybean meal, and four high fiber (HF) diets with DDGS (Flint Hills Resources, LLC, Pelham, GA, USA.) replacing the soybean meal and providing the additional fiber. The diets varied with the addition of enzymes along or in combination.

The LF diets basic ingredients were menhaden fish meal (2%), meat and bone meal (6%), soybean meal (48%), corn (30.5%), corn starch (5.58%) and fish oil (3,3%). The HF diets basic ingredients were somewhat different, with menhaden fish meal (2%), meat and bone meal (6%), lower soybean meal (36.8%), lower corn (15.7%), corn starch (2.85%) and lower fish oil (1.55%).

Diets were supplemented with free protease (diets LF-FP and HF-FP), a protected protease (diets LF-PP and HF-PP), a carbohydrase (diets LF-FC and HF-FC), or a combination of both enzymes (diets LF-MFPFC and HF-MFPFC). Juvenile sex-reversed Nile tilapia (mean wt. 9.29 g) were stocked in glass aquaria and fed the various treatment diets for 70 days. In another area, they added 1% chromic oxide to their lab-made feeds to assess nutrient digestibility of the feeds and the DDGS ingredients.

Looking at growth performance results, there were no significant differences in weight gain, FCR or survival between the LF control diet and the any of the enzyme-treated diets. However, addition of the two proteases to the diets (LF-FP and LF-PP) did result in significantly higher apparent net energy retention (ANER), while ANER of the carbohydrase (LF-FC) or mixed enzyme (LF-MFPFC) treatments were not different than the LF control.
For the high fiber (HF) diets containing DDGS, none of the added single enzyme treatments (HF-FP, HF-FC) or the combination (HF-MFPFC) treatment were significantly different for weight gain, FCR, survival, ANPR or ANER compared with the control HF diet. The lack of differences led the authors to conclude that the high nutrient levels in the LF and HF diets met the needs of the tilapia and adding enzymes offered no additional benefit to most of the measured growth and digestibility parameters.

HP-DDG and CFP

Nazeer et al. (2023) tested two HP-DDG ingredients (HP-40Y and HP50-Y from The Andersons, Maumee, OH, USA) as well as a corn protein concentrate (CPC Empyreal75, Cargill Corn Milling, Blair NE). Lysine and methionine were also added. All the diets contained menhaden fish meal (4%) and soybean meal (37.8%). The basal diet (DDGS 0%) contained 12% CPC. In the two HP-DDG diets, levels were set at 0%, 5%, 10%, 15% and 20%, and as
their levels increased CPC levels decreased from 12% to 9%, to 6% 2.5%, and 0% respectively. Juvenile fish (5.23 g) were stocked in aquariums and fed for 70 days. Final tank biomass, weight gain, FCR, and survival were assessed. Final weights were 55 – 60 g. Percent weight gain of the fish fed HP40Y were not significantly different between the basal diet (CPC with no DDG) or the HH-DDG treatment levels (p = 0.15), nor for fish fed HP50Y compared to the basal diet (p=0.99). The study concluded that the two HP-DDG products could effectively replace the CPC without apparent reduction in diet performance.

Milkfish

(*Chanos chanos*)

Only two studies have been published on the use of corn DDGS in feeds for milkfish. Mamauag et al. (2016) conducted a 90-day feeding trial using 3g milkfish juveniles with six prepared treatments. The main ingredients in their diets were: Peruvian fishmeal (22%), Soybean Meal (0 – 35%), Copra meal (12%), Bread flour (23%), Fish and soybean oils (2+2%). A U.S.-sourced DDGS (30.6% CP) was included at 0% (D-1), 150 g/kg (Diet 2), 25 g/kg (Diet 3), 300 g/kg (Diet 4), 350 g/kg (Diet 5) and 450 g/kg (Diet 6). Fish were grown to a weight of approximately 20 g. Based on Weight gain, Feed intake and Feed conversion efficiency, the authors concluded that DDGS could be used at up to 450g/kg (45%) in milkfish diets. The authors also estimated the apparent digestibility of dry matter, protein, fat and carbohydrate.

Bharathi et al. (2020) raised 1.25g juveniles on a series of 9 experimental diets at three protein levels (35%, 40%, and 45% CP) to a final size of 4.8-5.6 g). Three of the experimental diets contained DDGS: FD35 (35% CP - FM + DDGS), FD40 (40% CP - FM + DDGS), FD45
(45% CP- FM + DDGS). These 3 diets contained corn gluten meal (27 - 44%), fish meal (13%), no Soybean meal (0%), corn flour (13-20%), rice bran (5-16%), and corn DDGS (15%). Other diets these were compared with contained higher levels of fishmeal (27-43%) and soybean meal (15%). The DDGS diets were the worst performing treatments in the growth trials, and the researchers concluded that it was better to use SBM than DDGS to replace fish meal.

Table 18. Summary of published studies reporting on the outcome of feeding DDGS to several species of carp. A blue reference indicates apparent digestibility trials were performed

Type[##]	Body Weight Initial, Final (g)	Feeding Trial (days)	DDGS Inclusion (%)	DDGS was used to replace	Fish Meal (%)	Added LYS (%)	Added MET (%)	Test Parameters*	Optimum DDGS (%)	References
CC	63.1-215	84	0-20-40	Sunflower meal, Wheat	0	0-0.2	0.1	WG, FCR, PER, PPV	40	Révész et al. 2019a
CC	40±7-86	42	0-30	Sunflower meal, Fish meal Wheat	29-41.4	0	0	WG, FCR, PER, PPV	40	Révész et al. 2019b
GC	5-20.8	60	0-10.3-20.6	Cottonseed Meal	3	0	0	WG, SGR, FR, FE	20.6	Kong et al. 2021
GC	5-24.9	60	DDGS USA & China 0-20-30	Rapeseed Meal	3	0	0	WG, FCR, FR, FE	30 US DDGS was superior to Chinese	Azm et al. 2022
CC	Juveniles 45±1- 498 Adults 362±10 - 1533	155	40		4	0	0	WG, FCR, SGR, aPER, aPPV	40	Sandor et al. 2022
CC	86-1467	49	0-25-35	Corn, sunflower meal	20	0	0	WG, FCR, RGR, SGR, PER	35	Barbacariu et al. 2022
MC	12.14-	90	54	Phytase at 0, 250, 500, 750, 1000, 1250 FTU/kg	14	0	0	WG, SGR, FI, FCR, PER	750 FTU Optimum Phytase Level for N retention	Naz et al. 2023

[##] Type: CC -Common carp, GC – Grass carp, MC – Mrigal carp

*WG – Weight gain, FCR – Feed conversion ratio, FE – Feed efficiency, FI – Feed intake, FR- Feeding rate, SGR– specific growth rate, RGR – Relative growth rate, PER– Protein efficiency ratio, PRE- Protein retention efficiency, PPV – Protein productive value, NPR = Net protein retention

Table 19. Summary of published studies reporting on the outcome of feeding DDGS, HP-DDG and CFP to Nile Tilapia (*Oreochromis niloticus*) and Hybrid Tilapia (*Oreochromis niloticus* x *Oreochromis aureus*). A blue reference indicates apparent digestibility trials were performed.

Type##	Body Weight Initial, Final (g)	Feeding Trial (days)	DDGS Inclusion (%)	DDGS was used to replace	Fish Meal (%)	Added LYS (%)	Added MET (%)	Test Parameters*	Optimum DDGS (%)	References
HB	2.7-68.5	70	0-30	Fish meal SBM	8-12	0	0	WG, FCR, SGR, PER	30 DDGS + MBM	Coyle et al. 2004
HB	190-907	120	0-5-10-15	Corn, Rice Bran	0	1.75-1.79	0.42-0.47	WG, FCR,	15	USGC. 2006.
HB	9.4-60.5	70	0-10-20-30-40	Corn, SBM	8	0-0.4	0	WG, FI, FER, PER	40 with LYS 20 w/o LYS	Lim et al. 2007
HB	6.7-68.6	84	0-30-60	Corn, SBM	8	0.5-0.9	0	WG, FI, FER	40 w/o LYS, up to 60 w/LYS	Shelby et al. 2008
HB	6.7-11.6	42	0-20-30-40	Corn, SBM	5	0	0	WG, FCR, PER	20	Schaeffer et al. 2009
NT	34.9-126	55	0-17.5-20-22.5-25-27.5	Corn, SBM	5	0	0	WG, FCR, PER	17.5-20	Schaeffer et al. 2010
NT	0.64-116.9	112	0-11.5-23-35-46-58	Corn, SBM	17.4	0	0	WG, FCR, SGR, PER, PPV	23	Labib et al. 2010
NT	5.21-	84	0-11-18-23-29-36	Corn, SBM	10	0.1	0.05	WG, FCR, FE, SGR, PER, PPV	23-29	Goda et al. 2011
NT	18.6-35.7	84	0-30	Corn, SBM	20	0-0.6	0	WG, FI, FCR, PER	30	Ibrahim et al. 2012
NT	6-30.8	72	0-5-10-15-20	Corn, SBM	20	0	0	WG, SGR, ADG, PER, PPV	10	Abou-Zied and Hassouna 2012
NT	6-30.8	72	0-5-10-15-20	Corn, SBM	20	0	0	WG, SGR, ADG, PER, PPV	10	Khalil et al. 2013
NT	6-32	72	0-4-8-12-16-20	Corn, fish meal	11-20	0	0	WG, FI, FCR, FE, SGR, PER, PPV	16	Gabr et al. 2013
HB	3.72-66.8	70	28.5-31.6-31.8	Corn, corn starch	8	0	0	WG, FI, FER, PER	30	Welker et al. 2014
NT	27.1-286	123	0-3.75-7.5-11.25-15	Fish meal	0-15	0	0	WG, FI, FCR, SGR, PER, PPV	15 gives best efficiency 11.25 best growth	Abdelhamid et al. 2015
HB	31.6-278	120	0-20-30-40	SBM, rice bran	0	0	0	WG, SGR, FE, PRE	40	Suprayudi et al. 2015
NT	4.5-82	84	DDGS 52.4	Fish meal, poultry by-product meal	0-21.8	0	0	WG, SGR, FCR, PER, PPV	DDGS 52.4	Herath et al. 2016

Table 19. Continued. Summary of published studies reporting on the outcome of feeding DDGS to Nile Tilapia (*Oreochromis niloticus*) and Hybrid Tilapia (*Oreochromis niloticus* x *Oreochromis aureus*). A blue reference indicates apparent digestibility trials were performed.

HB	Exp1 6.0-81.4 Exp 2 2.1-63.2	Exp1 56 Exp 2 84	0-20-30-40-50	SBM, Wheat	5	Exp1 0-0.25 Exp 2 0-0.14-.027	0	WG, FCR, NPR	Exp1 Up to 30 Exp 2 Up to 50 with LYS and lipids	Chatvijitkul et al. 2016
MT	45-61		15	Fish meal, Wheat, SBM	5-20	0	0	WG, digestibility	20	Valdez-González et al. 2016
NT	10-	126	0-8.4-16.8	Corn, poultry by-product meal	0	0	0	WG, FI, SGR, FCR, PER, PPV	16.8	Fouda et al. 2018
NT	12.86-37.1	112	0-5-10-20-30	Corn, SBM	8.5			WG, SGR, FCR, PER, PPV	30	Khadr et al. 2018

Type: NT – Nile tilapia, HB- Hybrid red tilapia (*O. niloticus* x *O. aureus*), MT – Mozambique tilapia
*WG – Weight gain, FCR – Feed conversion ratio, FE – Feed efficiency, FI – Feed intake, SGR– specific growth rate, PER– Protein efficiency ratio, PRE- Protein retention efficiency, PPV – Protein productive value, NPR = Net protein retention NER = Net energy98 retention
++ Described by Cristobal et al (2020). See references.

Table 20. Summary of published studies reporting on the outcome of feeding HP-DDG and CFP to Nile Tilapia (*Oreochromis niloticus*) and Hybrid Tilapia (*Oreochromis niloticus* x *Oreochromis aureus*). A blue reference indicates apparent digestibility trials were performed.

Type##	Body Weight Initial, Final (g)	Feeding Trial (days)	DDGS Inclusion (%)	DDGS was used to replace	Fish Meal (%)	Added LYS (%)	Added MET (%)	Test Parameters*	Optimum DDGS (%)	References
NT	4.5-82	84	DDGS 52.4 HPDDG 33.2	Fish meal, poultry by-product meal	0-21.8	0	0	WG, SGR, FCR, PER, PPV	DDGS 52.4	Herath et al. 2016
NT	6.4-32	56	DDGS 17 CPC 0.71-20 HL CPC 3.9-19.5		0	0-1.0	0.06	WG, FCR, NPR	DDGS + HL CPC As good as DDGS + L-Lys	Nguyen and Davis 2016
NT	10.4-50.4	56	CFP (ProCap Gold)++ 0-4.9-9.8-14.7-19.6-24.5	Fish meal, SBM	14.5-29	0	5	WG, FE, PCE,	24.5 (375g CP/kg diet)	Suehs and Gatlin III 2022
NT	5.23-	70	HP-DDGS HP50Y^ 0-5-10-15-20 HP40Y^ 0-5-10-15-20	CPC Empyreal 75	4	0-0.2	0-0.03	WG, SGR, FCR, NPR	In both Exp. HP-DDGS could completely replace CPC	Nazeer et al. 2023

Type: NT – Nile tilapia, HB- Hybrid red tilapia (*O. niloticus* x *O. aureus*), MT – Mozambique tilapia
*WG – Weight gain, FCR – Feed conversion ratio, FE – Feed efficiency, FI – Feed intake, SGR– specific growth rate, PER– Protein efficiency ratio, PRE- Protein retention efficiency, PPV – Protein productive value, NPR = Net protein retention NER = Net energy98 retention
++ Described by Cristobal et al (2020). See references.
^ ANDVantage HP50Y & HP40Y provided by the The Andersons, Inc.

Omnivorous Species

Catfish

(See Tables 21and 22)

Channel Catfish (*Ictalurus punctatus*)
Channel catfish x Blue catfish hybrids (*Ictalurus punctatus x Ictalurus furcatus)*

Investigation into the use of DDGS and other corn ethanol co-products has been undertaken with channel catfish by researchers in the American south where most of the catfish farming occurs (Mississippi, Alabama, Arkansas and Texas). With the catfish farming industry losing profitability over the past few years, in part due to high feed costs, catfish nutritionists are looking for economical alternatives to fish meal and soybean meal, and "new" DDGS is an excellent candidate. The Thad Cochran National Warmwater Aquaculture Center in Mississippi has been the center of most research followed by Auburn University in Alabama, and Kentucky State University in Kentucky.

Table 14 reports on studies published from 2008 up to 2025, with 6 groups using pure strain channel catfish, 5 groups using hybrid catfish, 2 groups tested DDGS with Pangasius, and just 1 paper reporting research with the European catfish *Silurus glanis*. The three papers discussing Pangasius and the European catfish will be detailed, but only a small selection of the channel catfish papers will be mentioned.

Li et al. (2010) conducted an aquarium study with juvenile catfish (starting weight 12.6 g) that were fed one of six different diets. Final weight of the fish after 63 days of feeding was ~ 157
g. The "control" diet main ingredients were 41% soybean meal, 41.3% cooked corn meal and catfish offal oil (1.5%). Another diet "control + fat" had some corn meal removed and replaced w/w with 2.3% corn oil. There were two diets of interest, one contained DDGS (30%) and the other diet HP-DDG (20%) with soybean meal and corn meal reduced accordingly. Making up 15.2% of each of the formulas was an ingredient blend described as "other ingredients", which contained cottonseed meal, wheat middlings, pork meat and bone meal, vitamins and minerals. The diet containing 30% DDGS performed better than either of the two control diets, with significantly higher weight gain ($P \leq 0.05$). The 20% HP-DDG diet performed about the same as the control + fat diet and better than the control diet without extra energy. Other researchers have similarly reported that 30% DDGS inclusion in Catfish diets seems to be about right.

One concern of the Li et al. (2010) was the definite yellow color of the skin and the slight yellow color of the flesh which came from the two DDG diets (carotenoid analysis showed these diets contained 14-17 ppm yellow xanthophylls). To avoid any yellow pigmentation, the researchers suggested the amount of DDGS or HP-DDG would need to be reduced to keep total xanthophylls at or below 11 ppm. Other researchers have similarly reported that 30% DDGS inclusion in channel catfish diets seems to be about right.

Tidwell et al (2017) tested several diets containing either 20% HP-DDG, 40% HP-DDG or 40% HP-DDG + 1% L-lysine against a control diet. The HP-DDG was sourced from Poet Nutrition, Sioux Falls, South Dakota. Starting weight of the fish was 7.1 g, and after 63 days, the final weight was 87 g. The control diet contained 2% fish meal, 57% soybean meal, 4% poultry by-product meal and 31.5% corn. The 20% HP-DDG diet also contained 2% fish meal with reductions in both poultry meal and soybean meal, while both of the 40% HP-DDG diets had no fish meal (0%) and no poultry meal (0%). As noted, one of the 40% HP-DDG diets had 1% added Lysine. The best performing diet was the 20% HP-DDG diet, although it was not significantly better than the control diet or the 40% HP-DDG + Lys diet. The worst performing diet was the 40% HP-DDG diet, and the authors concluded that the poor performance was related to an inadequate lysine level that needed supplementation to restore performance.

Nazeer et al. (2021) tested one HP-DDG product (ANDvantage 40Y) in a 70-day trial with juvenile catfish (starting weight 1.8 g) by feeding a series of diets with 0%, 10%, 20% and 30% HP-DDG to replace poultry meal and soybean meal. In addition to the HP-DDG. poultry meal and soybean meal, the test diets contained menhaden fish oil, corn starch and corn. After 70 days the catfish had reached their final weight of 24.3 g. The researchers concluded that the protein in HP-DDG at 30% of the diet could effectively replace the equivalent quantity of soybean meal protein.

Yamamoto et al. (2024) have published the first study feeding corn fermented protein (CFP, Green Plains, Omaha, NE) to channel catfish. Several trials were highlighted. In one trial, a control diet (main ingredients: Dehulled soybean meal (37.95%), animal protein concentrate (7.95%), cottonseed meal (10%), corn germ (7%), wheat middlings 16.5%) and corn meal (16.4%), was compared to four diets with CFP at 8.8%, 17.6%, 26.4% and 35.25%, representing replacement of 25%, 50%, 75% and 100% of soybean meal protein, with soybean meal reduced to accommodate the CFP. L-lysine was added at 0.05% in the 26.4% CFP diet, and at 0.15% in the diet containing 35.25% CFP. Starting weights of the catfish were 11.6 g and after 60 days, the final weight of fish fed the 8.8% CFP (25% SBM protein replacement) was the highest of all treatments. While not significant, growth was lower than control for the diets with CFP at 8.8%, 17.6%, 26.4% and 35.25%. The authors stated that CFP could safely replace 50% of the protein coming from soybean meal.

Paladines-Parales et al (2025) very recently published a catfish study where they tested a standard solvent-extracted soybean meal against an enzyme-treated soybean meal, a low oligosaccharide soybean meal, and a fourth diet containing a reduced level of soybean meal and 10% CFP (Green Plains, St Louis MO). Other ingredients shared across the four experimental diets included poultry meal (8%), wheat middlings (10%), and corn adjusted to accommodate the other ingredient changes (20.3% – 34.7%). Both an indoor aquarium study lasting 84 days was completed and also a trial conducted in an outdoor IPRS in-pond system. In this outdoor trial, young catfish (mean weight 32.56 g) were reared for 70 days, reaching a final weight of 128.6 g. Although results were not statistically significant, the weight gain of the CFP catfish was better than the growth of both the standard soybean meal and the low-oligosaccharide soybean meal. was the best overall weight gain was obtained with the enzyme treated soybean meal. The researchers concluded with CFP typically costing less than soybean meal on a unit-protein basis, the success of the 10% CFP diet against soybean meal warranted further testing

Pangasius
(*Pangasianodon hypopthalmus*)
and
(*Pangasius bocourti*)

Research into using DDGS and other corn proteins with Pangasius is rare, because the catfish flesh is being marketed as a very white fish meat, and the industry tries to avoid anything that contains carotenoids or xanthophylls that would create yellow pigmentation in the fish skin or flesh.

In a report published by the USGC (2015) on feeding DDGS to Pangasius, 15% dietary inclusion was recommended. Allam et al (2020) fed four diets containing 0%, 5.8%, 11.61% and 17.41% HP-DDG to replace 25%, 50%, and 75% of the protein provided by fish meal (2.5% - 10%).

Other ingredients remained constant in their diets: Soybean meal (48%), corn gluten meal (3.5%) rice bran (14%), wheat bran (9%) and wheat flour (13% - 1.59%). Catfish with a starting weight of 108 g were fed for 98 days. The researchers concluded that the diet with 5.8% HP-DDG (25% fish protein replacement) gave the best growth and feed conversion. On the other hand, 11.61% HP-DDG was the most profitable option when considering feed cost per unit gain and net income.

European Catfish

(Silurus glanis)

Sandor et al. (2021) conducted an experiment investigating the growth, nutrient utilization and metabolism of European catfish (starting weight 272 g) when fed one of four diets: A control diet with 0% DDGS, and another three diets with 10%, 20%, and 30% DDGS. Other main ingredients included poultry meal (25% - 12%), soybean flour (21.0 – 23.5), wheat (25% - 6.7%) and 60%CP fish meal (20% across all diets). After 56 days of rearing, final weights were approximately 630 g). The authors concluded that up to 30% DDGS could be used in diets for this species.

Table 21. Summary of Published Studies reporting on the outcome of feeding DDGS to several species of catfish. A blue reference indicates apparent digestibility trials were performed.

Type[##]	Body Weight Initial, Final (g)	Feeding Trial (days)	DDGS Inclusion (%)	DDGS was used to replace	Fish Meal (%)	Added LYS (%)	Added MET (%)	Test Parameters*	Optimum DDGS (%)	References
CC	48-1,277	330	0-40	SBM, Wheat midds	1	0.28-0.8	0	WG, FI, FCR	30 to 40 with supp. LYS	Robinson and Li 2008
CC	13.3-67.1	84	0-10-20-30-40	Corn, SBM	8	0.4	0	WG, FI, FER, PER, APU	40	Lim et al. 2009
CC	86-491	150	0-30	Corn, SBM	0	0.10-0.20	0	WG, FCR	30 or more	Zhou et al. 2010a
HB	1.16-8.7	56	0-20-30	Corn, SBM, Wheat midds	0	0.2	0	WG, FCR, FER	-	Zhou et al. 2010b
CC	12.6-156.7	63	0-30	Corn, SBM	0	0.3-0.39	0	WG, FI, FER	30	Li et al. 2010
CC	9.1-80.4	56	0-30	Corn, SBM, Wheat midds	5	0.3-0.4	0	WG, FCR, FER	30	Li et al. 2011
CC	47-703	186	0-20	Corn, SBM	0	0.2	0	WG, FI, FCR	30	Renukdas et al. 2014
PG	40-500	118	0-15	SBM, Rice bran	0	0.15-0.25			15	USGC 2015
EC	272-630	56	0-10-20-30	Poultry meal, Wheat	20	0.06-0.28	0.04-0.10	WG, SGR, FCR, PER, PPV	Up to 30	Sandor et al. 2021
[##] Type: CC – Channel catfish, HB2021- Hybrid catfish (*I. punctatus x I. furcatus*), PG – Pangasius, EC – European catfish										
*WG – Weight gain, FCR – Feed conversion ratio, FE – Feed efficiency, FI – Feed intake, SGR– specific growth rate, PER– Protein efficiency ratio, PRE- Protein retention efficiency, PPV – Protein productive value, NPR = Net protein retention, APU – Apparent protein utilization										
[++] Described by Cristobal et al (2020). See references.										

Table 22. Summary of Published Studies reporting on the outcome of feeding HP-DDG and CFP to several species of catfish. A blue reference indicates apparent digestibility trials were performed.

Type[##]	Body Weight Initial, Final (g)	Feeding Trial (days)	DDGS Inclusion (%)	DDGS was used to replace	Fish Meal (%)	Added LYS (%)	Added MET (%)	Test Parameters*	Optimum DDGS (%)	References
HB	7.1-87	63	HPDDG 0-20-40	Fish meal, SBM, Corn	0-2	0-0.10	0	WG, FCR	20 w/o LYS, 40% w LYS	Tidwell et al. 2017
PG	108-221	98	HPDDG 0-5.8-11.61-17.41	Fish meal, Wheat flour	2.5-5.0-7.5-10	0	0	WG, SGR, FI, FCR, PER, PPV	11.61 50% Fishmeal replacement for greatest economic benefit	Allam et al. 2019
HB	1.8-24.3	70	HP-DDGS HP40Y^ 0-5-10-15-20	Poultry meal, SBM	0	0	0	WG, SGR, FCR, NPR	Up to 20 to replace SBM	Nazeer et al. 2021
EC	272-630	56	0-10-20-30	Poultry meal, Wheat	20	0.06-0.28	0.04-0.10	WG, SGR, FCR, PER, PPV	Up to 30	Sandor et al. 2021
HB	11.6-54.4	60	CFP 0-8.8-17.6-26.4-35.25	SBM	0	0-0.05-0.15	0	WG, FI, FCR, PER, PPV	17.6 CFP protein can replace 50% SBM protein	Yamamoto et al. 2024
HB	Indoor 2.14-60.6 IPRS Ponds 32.56-128.6	Indoor 84 IPRS Ponds 70	CFP 10	SBM	0	0	0	WG, FI, FCR, NPR,	10 to replace SBM	Paladines-Parales et al. 2025

[##] Type: CC – Channel catfish, HB2021- Hybrid catfish (*I. punctatus x I. furcatus*), PG – Pangasius, EC – European catfish

*WG – Weight gain, FCR – Feed conversion ratio, FE – Feed efficiency, FI – Feed intake, SGR– specific growth rate, PER– Protein efficiency ratio, PRE- Protein retention efficiency, PPV – Protein productive value, NPR = Net protein retention, APU – Apparent protein utilization

[++] Described by Cristobal et al (2020). See references.

^^ ANDVantage HP40Y provided by the The Andersons, Inc.

Carnivorous Species

Rainbow Trout

(*Oncorhynchus mykiss*)
(See Tables 23 and 24)

DDGS

Trout is the most important freshwater carnivorous species group farmed worldwide,
with the FAO estimating worldwide 2019 production at 940,000 metric tons (MT), of which 911,000 MT was rainbow trout (FAO 2022). Additionally in the American northwest, there is an anadromous form of rainbow trout called Steelhead trout that migrates to the sea like Pacific salmon, and can be farmed in both freshwater and seawater. As carnivores, farmed rainbow trout have been fed high-protein feeds, which until recent times dictated that feeds contain high percentages of fish meal. Researchers have been seeking alternatives to fish meal for decades, and high-protein ingredients from soy, corn, rapeseed/canola and other similar ingredients have been investigated as a way to reduce feed's dependence on fish meal.

Considerable research has been conducted on using DDGS in trout feeds, but uptake by nutritionists has been hindered by DDGS's poor amino acid balance relative to fish meal, its high content of non-starch polysaccharides and perceived threat of mycotoxin contamination. Today, these problems can largely be managed by formulators with supplemental amino acids, feed enzymes such as xylanase and mannanase, and mycotoxin binders.

The first studies with DDGS from fuel ethanol production were conducted at the Hagerman Fish Culture Experiment Station in the state of Idaho, which has the largest trout production volumes in the USA. Publications by researchers in Idaho included Cheng et al. (2003), Cheng and Hardy (2004a), Cheng and Hardy (2004b) and Stone et al. (2005).

Main ingredients in the DDGS test diets used by Cheng et al. (2003) included herring meal (17.5%), soybean meal (17.5%), DDGS (18.5%), fish oil (19.8%), white corn gluten (~15%) and whole wheat (~8%). They started with 49 g fish and reared them to 114 g in their 49-day feeding trial.

Cheng and Hardy (2004a) grew rainbow trout for 42 days, increasing in weight from 50 g to 104 g. Ingredients in the diets used by included herring meal (7.5% - 22.5%), DDGS (22.5% - 7.5%), fish oil (17.6 to 18.1%), whole wheat 1.9% - 18.1%), soybean meal (15%) and white corn gluten (16.9% - 30.6%).

Finally, Cheng and Hardy (2004b) conducted two trials to assess the impact of adding dietary phytase at 0, 300, 600, 900, and 1,200 FTU/kg diet. In trial 1, they used a purified casein-gelatin-dextrin test diet 70%, and added DDGS 30% in a standardized nutrient digestibility assessment. Their results showed that nutrient digestibility of DDGS was high, and phytase was able to increase availability of phosphorus and some other minerals.

Trial 2 used a more conventional diet to grew trout from ~20 g to ~70-80 g in 70 days.
Their diets in this trial contained as main ingredients herring meal (15%), soybean meal (15%), DDGS (15%) wheat flour (7.9% - 8.1%), fish oil (17.8%) and white corn gluten (25.8%). Trace mineral premix levels were reduced from 0.1% down to 0.08%, 0.06%, 0.04%, 0.02% and finally 0%. They showed phytase addition could allow the mineral premix to be reduced without affecting fish WG, FCR, body composition, and apparent nutrient retention.

Cumulatively, these reports supported the inclusion of DDGS in rainbow trout feeds at levels of 15-20%, possibly higher if feeds were supplemented with lysine and methionine.

In 2012, Barnes et al. located in the northern state of South Dakota, published two papers (2012a, 1012b), the first of which used DDGS (Poet BPX) with amino acid supplementation of lysine, methionine, isoleucine, and histidine. Main ingredients in their three diets were: menhaden fish meal (40%), DDGS (0, 10% 20%), whole wheat 20%, 13%, 11%), yellow corn
gluten (25%, 22%, 22%).

Based on the previous work of Cheng and Hardy (2004b), a granular heat stable phytase enzyme was also added to the diet mixture. The amount of added phytase was not declared. However, unlike Cheng and Hardy who used cold pelleting to make their diets, Barnes used extrusion, and the likelihood is that the phytase would have been completely destroyed by heating during the extrusion process, and would have had no impact. In conclusion, the researchers found that the inclusion of 10% DDGS or greater in trout diets significantly decreased (P< 0.05) both final weight gain and feed conversion. The diets were similar to the those being used in Idaho, and it was difficult to explain why the DDGS performed poorly. In all likelihood, the extrusion parameters (which were not defined) may have had an impact on the experimental diets nutritional value.

Next, several papers have been published by Turkish researchers: Aydin et al. (2017), Aydin & Gümüs (2020), and Yildrim et al. (2024). The second and third papers will be outlined here.

- Aydin & Gümüs (2020), fed diets containing 0%, 10%, 20%, and 30% DDGS to 19 g rainbow trout. Other ingredients in their four diets were fish meal (54% - 65%) corn starch. Over an 84-day rearing period fish grew from 19.88 g to 104 g. The authors concluded that 30% DDGS could be effectively used in trout feed.

- Yildrim et al. (2024) The main ingredients in their diets were anchovy meal (34%), wheat flour (13% - 0%), Soybean meal (24% - 9.5%). They also looked at histology of fish liver and intestines, specific digestive enzyme activity and performed gene expression (PCR analysis) on liver and head kidney to investigate changes in some immune factors. Their conclusion was that 20% DDGS in their diet had the best overall result on all factors they examined with trout.

HP-DDG and CFP

In the second paper published that year, Barnes et al. (2012b) tested a new HP-DDG (Poet Dakota Gold HP, 41.7% CP) at 10% and 20% formula inclusion, and once again supplemented lysine, methionine, isoleucine and histidine. Diets were once again extruded which may explain why phytase enzyme, added at 0.37% to one of the 10% HP-DDG and one of the 20% HP-DDG diets, did not seem to have any impact on their test diet outcomes. They found no significant differences (P<0.05) among their 5 diets on fish weight gain, feed conversion or mortality. The concluded that HP-DDG could be included at 20% or higher as long as amino acids were supplemented.

Øverland et al. (2013) tested both normal DDGS at 0% 25% and 50% in 35% CP diets, and HP-DDG at 0%, 22.5% and 45% in 43% CP cold-pressed diets. The trout rearing period in both trials was 77 days. Their intention was to use DDGS and HP-DDG to replace sunflower meal, rapeseed meal, and field peas. Their DDGS diets contained 18.9% fish meal and their HP-DDG diets contained approximately 21% fish meal and varying amounts of soy protein concentrate. These researchers were able to advise that DDGS could be used at 50%, and HP-DDG at 45% in trout diets without any impact on feed performance.

Recently Grayson et al. (2025) published a study of the partial and total replacement of soybean meal with CFP (ProCap Gold) in feeds for rainbow trout. The researchers prepared four diet treatments with 40% crude protein and 20% lipids. The main ingredients in the Control diet were dextrin (20.47%), menhaden fish meal (17.2%), soybean meal (17.55%), soy protein isolate (11.28%), fish oil (7.8%), krill meal (5%) and fish protein hydrolysate (5%). The 20%CFP treatment diet (20% replacement of soybean protein) contained 3.67% CFP, the 50%CFP diet contained 9.18% CFP and the 100%CFP diet contained 18.17% CFP. In these CFP diets, fish meal was constant (17.2%), as was soy isolate (11.28%), krill meal (5%) and fish protein hydrolysate (5%). Soybean meal was reduced accordingly as CFP was introduced, and dextrin was adjusted to maintain dietary energy.

Young rainbow trout (approx. weight 49 g) were stocked in fiberglass tanks and the feeding trial lasted 70 days. Fish were fed at a slightly restricted feeding rate to keep them hungry and avoid any palatability bias on feed intake. After the feeding trial ended, fish from the best-performing 50%CFP treatment were retained and fed for an additional two weeks during which fish faeces were collected to assess apparent nutrient digestibility of feed and ingredients. Furthermore, histological cross-sections of the intestine were prepared to assess intestinal health.

At the end of the feeding trial, final fish weight across treatments ranged from 135.5 g to 143 g), with weight gain there were no significant differences between the control and 50%FCP treatments for % weight gain, SGR, FCR or survival. The digestibility assessment found no difference in apparent lipid digestibility, but protein digestibility was about 3% higher, which was a statistically significant increase. Histologically, the control and low CFP – high SBM treatments showed signs of enteritis, which was not found with the 50%CFP treatment. It is known that SBM at 25% dietary inclusion causes enteritis when fed to several fish species. The high yeast content of the CFP may have supported better gut health. The authors concluded that using CFP instead of soybean meal made no difference in terms of growth, the improved gut health of the high CFP diet, along with the increase in apparent protein digestibility made it a suitable replacement for soybean meal.

Atlantic Salmon (*Salmo salar*)

Williams (2020), in a conference proceeding referred to a high-density distiller's protein (HDDP) with 52.4% crude protein that had been prepared by a mechanical process (Fluid Quip Technologies) downstream of dry grind corn ethanol fermentation. The name HDDP has now been replaced with CFP, so from this point it will be called CFP. He described a trial where 525 post-smolt Atlantic salmon (mean initial weight 304 g) were raised in a salt-water recirculating aquaculture system (RAS) for 84 days. There were five dietary treatments, with a control (no CFP), and four diets with increasing levels of CFP at 5%, 10%, 15% and 20%. He stated that growth of fish on all of the CFP diets exceeded commercial growth rates. The best performing diet appeared to the 10%CFP diet. Finally, he noted that the fish fed the CFP diets had higher intestinal villi length and width compared to the no-CFP control.

Burton et.al (2021) used a series of graded CFP diets for feeding trials with turkeys, broiler chickens and Atlantic salmon. The intention was to replace soybean meal. With regards to the salmon diets, CFP was included at 0%, 5%, 10%, 15% and 20%, and as the CFP increased, SBM quantities in the formulations were decreased 12.9, 25.8%, 37.9% ad 50.8%, respectively. Other ingredients included poultry by-product meal, herring fish meal, soy protein concentrate, wheat flour, corn protein concentrate and wheat gluten. Lysine was supplemented in all diets, including control. Crude protein and crude lipid levels in all feeds were 44%, and 28% respectively. Diets were produced by twin-screw extrusion and oil was applied by vacuum coating. Atlantic salmon (stat weight 304g) were reared in saltwater tanks for 84 days. The results of their trial indicated that 10% CFP inclusion gave the highest final growth and body weight, the highest feed intake and lowest FCR. Increasing CFP to 15% and 20% reduced feed intake, feed performance and growth.

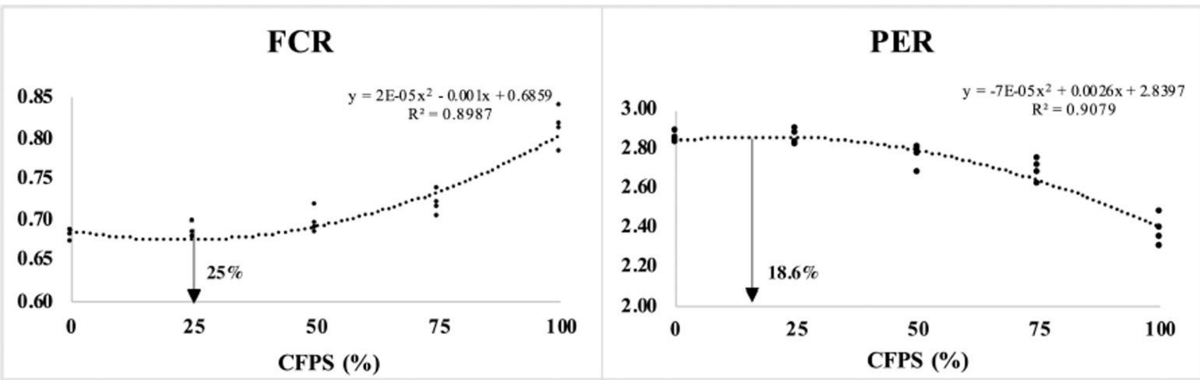
Hossain et al. (2023) conducted an 84-day feeding trial on Atlantic salmon with diets using corn fermented protein with solubles (CFPS, ProCap Gold, Marquis Energy, Hennepin, IL, USA) to replace soybean meal. Trial diets included a diet with no CFPS (control), and four diets containing 5.46% CFPS ($CFPS_{25}$), 10.93% CFPS ($CFPS_{50}$), 16.39% CFPS ($CFPS_{75}$),
and 21.86% CFPS ($CFPS_{100}$). The control diet contained fish meal (15%), poultry by-product meal (10%), soybean meal (22%), fish oil (16.4%), wheat flour (16.2%), corn protein concentrate (5%), ME-Pro, a fermented soy protein (5%), wheat gluten (4%), and soy protein concentrate (3%) as its main ingredients. The four CFPS diets shared common ingredients, including fish meal (15%), poultry by-product meal (10%), wheat flour (16.2%), corn protein concentrate (5%), ME-Pro, a fermented soy protein (5%), wheat gluten (4%), and soy protein concentrate (3%) as its main ingredients. The four CFPS diets shared common ingredients, including fish meal (15%), poultry by-product meal (10%), wheat flour (16.2%), corn protein concentrate (5%), ME-Pro (5%), and wheat gluten (4%). The remaining ingredients (SBM, wheat flour, fish oil) were adjusted to maintain protein, lipid and energy levels.

Regarding the feeding trials, fish (initial weight 21.5 g) were stocked into tanks and fed for 84 days. At the end of the trial, fish weighed approximately 165 g. Weight gain, SGR, FI, FCR, PER and PR did not differ across the five treatments (See notes under Table 15 for explanation of these acronyms). The researchers also conducted a digestibility trial and obtained apparent digestibility coefficients for dry matter, protein, lipid, energy, phosphorus and amino acids for feeding CFPS top Atlantic salmon.

Hong et al. (2025) raised juvenile Atlantic salmon (initial weight 11.6 g) with a series of diets containing graded levels of CFP (ProCap Gold, Marquis Energy, Hennepin, IL, USA) to replace fish meal. The treatments to substitute CFP for fish meal were called CFP_0, CFP_{25},
CFP_{50}, CFP_{75}, and CFP_{100}, with subscripts representing the percentage of fish meal replaced in successive 10% reductions. For example, the Control diet (CFP_0) consisted of 40% meal, while fish meal was reduced to 30% (CFP_{25}) 20% (CFP_{50}), 10% (CFP_{75}) and finally 0% (CFP_{100}). Aside from fish meal and CFP, the tested diets also contained soybean meal, poultry-
by-product meal, wheat gluten, corn protein concentrate, blood meal, wheat flour, and fish oil.

At the end of the feeding trial, the fish weighed between 88 and 96 g. There were no significant differences in weight gain or feed intake across treatments. However, as CFP levels in diets increased from 0 to 40%, FCR increased and PER decreased significantly ($p>0.05$).
Figure 2 shows the impact of CFP level on FCR and PER of the salmon.

Figure 2. Polynomial analysis of the feed conversion ratio (FCR) and protein efficiency ratio (PER) obtained when feeding the Atlantic salmon increasing levels of CFP (Hong et al. 2025).



European Seabass

(*Dicentrarchus labrax*)
(Tables 25 and 26)

Five studies published from 2015 to 2023 reported on feeding trials with DDGS and HP-DDG to European Seabass *dicentrarchus labrax.*

The first research group (Magalhães et al. 2015) did not do a growth trial, but instead assessed apparent nutrient digestibility and digestive enzyme activities obtained with two different samples of DDGS. The first DDGS sample was from Spain, and had 30.4% crude protein, 11.8% lipids, 4.7% ash, 7.2% crude fiber, 0.5% phosphorus, 0.5% starch, and 45.9% nitrogen free extract. The second DDGS sample came from Hungary, and had 29.4% crude protein, 12.8% lipids, 4.9% ash, 7.8% crude fiber, 0.8% phosphorus, 2.9% starch, and 45.1% nitrogen free extract. The main difference between the DDGS samples seems to be the starch content of one was 0.5%, while the other was 2.9%. Differences in essential amino acids were minor. The standard procedure in digestibility trials is to formulate a high-quality semi-purified reference diet, and in this case, the reference diet contained 63.2% fish meal, 22.1% pre-gelatinized corn starch, and 10.2% cod liver oil. The two DDGS diets were formulated to contain 44.2% fish meal, 15.4% gelatinized starch, 7.2% cod liver oil and 30% DDGS. To conduct the digestibility trials a mixture of 70% of the reference diet was mixed with 30% of the DDGS diet. Fish faeces were collected for 24 days. Apparent digestibility coefficients (ADC) of the two DDGS samples were determined for dry matter, protein, lipids, and energy, as well as essential and non-essential amino acids. In addition to the DDGS digestibility trials, they also measured protease, lipase and amylase activity in the anterior, mid and distal intestinal sections of the seabass fed the reference diet and the two DDGS diets. The authors noted that the apparent digestibilities of many of the nutrients tested (eg. Dry matter, protein, energy, methionine), were better for the Spanish DDGS than for the Hungarian DDGS, which would probably be due to differences in their manufacturing processes.

Felipe et al. (2022) also conducted a digestibility study in which they compared a conventional reduced-oil corn DDGS produced in Portugal, with the same DDGS that had passed solid state fermentation with three species of *Aspergillus* fungi noted for their carbohydrase enzymes. These researchers used the same protocol as (Magalhães et al. 2015) above. The reference diet was exactly the same, the two DDGS diets were formulated the same as above as well, except one of the DDGS samples had undergone the solid-state fermentation. Apparent digestibility coefficients of dry matter, organic matter, and phosphorus were not significantly different between the two DDGSs, but the APCs for protein, lipids, starch, and energy were significantly much higher ($p < 0.5$) for the SSF-treated DDGS compared to the conventional DDGS. Also measuring protease, lipase and amylase activity in the anterior, mid, and distal intestinal sections of the seabass fed the reference diet and the two DDGS diets, differences between the DDGSs were not significant ($p < 0.5$), with the exception of lipase activity, Lipase activity in the anterior intestine was 497.0 mU/mg protein for the standard DDGS, and 541.2 mU for the SSF-DDGS. In the distal intestine, the results were reversed, with 864.6 mU for the normal DDGS and 694.6 mU for the SSF-DDGS. It appears the SSF treatment broke down cell walls substantially, so that fat was easily available to enzymes in the anterior intestine, whereas for the normal DDGS, cell walls had to be digested first, the lipids were liberated more slowly, and they only became available to lipase in the distal intestine.

Three growth trial studies by Goda et al. (2019a, 2019b, 2020) were conducted with seabass in Egypt, testing an American HP-DDG (Mirasco Inc, Atlanta GA USA). The purpose was to find the right level of HP-DDG to replace soybean meal and rice bran. The first study diet used no supplemental feed enzymes, the second study diet was supplemented with phytase (Axtra PHY®)., and the third study diet supplemented with protease (PROXYM ULTRA®). The main ingredients in the control diet consisted of 30% fish meal, 37.5% soybean meal, 9% corn gluten meal, 7% wheat middlings and 6.5% rice bran. In the HP-DDG diets, fish meal remained constant at 30%, corn gluten meal constant at 9%, but HP-DDG levels were set at 11.2%, 15%, and 18.75% to respectively replace 30%, 40% and 50% of the soybean protein. In addition to the growth trials, several blood parameters were measured, and intestinal histology of fish raised on the four diets was photographed and measured. Interestingly, as the HP-DDG increased and SBM decreased, intestinal villi depth and number of mucin-secreting goblet cells in the fish increased, possibly due to decreasing levels of anti-nutritional non-starch polysaccharides and also to increasing levels of yeast, since the HP-DDG product reportedly contained 25% yeast. This would have provided greater quantities of prebiotic yeast cell wall and nucleotides, all known to improve intestinal health.

To conclude, the author said that the three HP-DDG diets performed better than the high soy diets, and the most economical recommendation was to use 18.7% DDG in the diet to replace 18.7 % SBM (50% of the soy protein) compared to 37.5% SBM in the control.

Table 23. Summary of published studies reporting on the outcome of feeding DDGS to rainbow trout (*Oncorhynchus mykiss*). A blue reference indicates apparent digestibility trials were performed.

Body Weight Initial, Final (g)	Feeding Trial (days)	DDGS Inclusion (%)%	DDGS was used to replace	Fish Meal (%)	Added LYS (%)	Added MET (%)	Test Parameters*	Optimum DDGS (%)	References
49.5 – 114.6	49	18.5	Herring meal, Wheat, White corn gluten	17.5	0-0.48	-/+ MHA 0-0.28	*WG, FCR, body composition PER, Phosphorus	17.5 or 50% FM replacement	Cheng et al. 2003
49.8-104.1	42	7.5, 15, 22.5	Fish meal Wheat flour	7.5-22.5	0-1.23	0-0.40	*WG, FCR	15, or 50% FM (22.5, or 100% FM replacement with added LYS MET)	Cheng & Hardy 2004a
19.9-178.3	84	0-10-20-30	Fish meal Wheat flour	10-40	0-.11	.02-.11	*WG, FCR SGR, PRE, ERE,	18	Stone et al. 2005
143-359	77	EXP 1- 0-25-50	Sunflower meal Rapeseed meal Field peas	18.9	0	0	*WG, FCR, Feed intake PER, Phosphorus digestibility	50 45	Overland et al. 2013
19.88-104.1	84	0-10-20-30	Fish meal Corn starch	5.4-6.5	0	0	body composition fatty acids, pigmentation	30	Aydin et al. 2017
19.88-109.7	84	0-10-20-30	Fish meal Corn starch	5.4-6.5	0	0	*WG, SGR, FCR, Liver & gut histology	30	Aydin & Gümüs 2020
18.5-60.2	60	0-10-20-30	Soybean meal Wheat flour	33.9	0	0	*WG, FCR, body composition, Gut histology, pigmentation	20	Yildrim et al. 2024

*WG – Weight gain, FCR – Feed conversion ratio, FI – Feed intake, SGR– specific growth rate, PER– Protein efficiency ratio, PRE- Protein retention efficiency

Table 24. Summary of published studies reporting on the outcome of feeding HP-DDG and CFP to rainbow trout (*Oncorhynchus mykiss*). A blue reference indicates apparent digestibility trials were performed.

Body Weight Initial, Final (g)	Feeding Trial (days)	DDGS Inclusion (%)%	DDGS was used to replace	Fish Meal (%)	Added LYS (%)	Added MET (%)	Test Parameters*	Optimum DDGS (%)	References
33.6-57	36	BPX HPDDG 0-10-20	Fish Meal Wheat 0-500 FTU/kg added Phytase	30-40	0.5	0.5	*WG, FCR, body composition PER, Phosphorus	20	Barnes et al. 2012a
33.6-57	36	BPX HPDDG 0-10-20	Fish Meal Wheat	30-40	0.5	0.5	*WG, FCR, body composition PER, Phosphorus	none	Barnes et al. 2012b
143-359	77	EXP 1- 0-25-50 EXP 2- HPDDG 0-22.5-45	Sunflower meal Rapeseed meal Field peas	18.9	0	0	*WG, FCR, Feed intake PER, Phosphorus digestibility	50 45	Overland et al. 2013
7.5-52.7	98	HPDDG 5-10-15-30	Corn gluten meal, wheat flour	20	22g/kg	MHA 9g/kg	*WG, SGR, FCR, Feed intake PRE, P retention	15	Prachom et al. 2013

*WG – Weight gain, FCR – Feed conversion ratio, FI – Feed intake, SGR– specific growth rate, PER– Protein efficiency ratio, PRE- Protein retention efficiency

Table 25. Summary of published studies reporting on the outcome of feeding DDGS to European seabass (*Dicentrarchus labrax*). A blue reference indicates apparent digestibility trials were performed.

Body Weight Initial, Final (g)	Feeding Trial (days)	DDGS Inclusion (%)	DDGS was used to replace	Fish Meal (%)	Added LYS (%)	Added MET (%)	Test Parameters *	Optimum DDGS (%)	References
		Two sources: 30	Fish meal, Corn starch						Magalhães et al. 2015
171		DDGS 30 SSF-DDGS *Aspergillus* 30	Fish meal, corn starch	44-63	0	0			Felipe et al. 2023

*WG – Weight gain, FCR – Feed conversion ratio, FE – Feed efficiency, FI – Feed intake, FR- Feeding rate, SGR– specific growth rate, RGR – Relative growth rate, PER– Protein efficiency ratio, PRE- Protein retention efficiency, PPV – Protein productive value, NPR = Net protein retention, PE – protein retention, DGI = Daily growth index, NR = Nitrogen retention

Table 26. Summary of published studies reporting on the outcome of feeding HP-DDG and CFP to European seabass (*Dicentrarchus labrax*). A blue reference indicates apparent digestibility trials were performed.

Body Weight Initial, Final (g)	Feeding Trial (days)	DDGS Inclusion (%)	DDGS was used to replace	Fish Meal (%)	Added LYS (%)	Added MET (%)	Test Parameters *	Optimum DDGS (%)	References
7.5-18.03	56	HPDDG (47%CP) 0-11.2-15-18.7	SBM, Rice Bran	30	0	0	WG, SGR, FCR, PER	HPDDG at 18.7 (50% SBM replaced)	Goda et al. 2019a
7.5-18.9	56	HPDDG (47%CP) 0-11.2-15-18.7	SBM, Rice Bran Phytase 0.5g/kg	30	0	0	WG, SGR, FCR, PER	HPDDG at 18.7 (50% SBM replaced)	Goda et al. 2019b
7.4-1.319	70	HPDDG (47%CP) 0-11.2-15-18.7	SBM, Rice Bran Protease 1g/kg	30	0	0	WG, FI, FCR, PER, PPV	HPDDG at 18.7 (50% SBM replaced)	Goda et al. 2020
26-93	85	POET CFP 0, 5.3, 10.4, 15.6, 20.8	CGM, SBM	20	0	0	WG, DGI, FI, FE, PER, PE, NR	CFP can completely replace CGM and CGM+SBM	Martins et al. 2025

*WG – Weight gain, FCR – Feed conversion ratio, FE – Feed efficiency, FI – Feed intake, FR- Feeding rate, SGR– specific growth rate, RGR – Relative growth rate, PER– Protein efficiency ratio, PRE- Protein retention efficiency, PPV – Protein productive value, NPR = Net protein retention, PE – protein retention, DGI = Daily growth index, NR = Nitrogen retention

Marine Shrimp

Pacific White Shrimp
(*Penaeus vannamei*)

(Tables 27 and 28)

DDGS

Almost all of the research conducted with Pacific white shrimp has been undertaken at Auburn University in Alabama, under the direction of Dr. D. Allan Davis. Roy et al. (2009) at that university prepared two trials with whiteleg shrimp using the same diets, one conducted in indoor tanks, another conducted in circular outdoor tanks with pumped water continuously recirculating through an adjacent shrimp pond. The common composition of the diets included soybean meal, sorghum (milo) and fish oil. The control diet (Diet 1) contained 10% poultry by-product meal, which was subsequently reduced in the remaining diets, being replaced with 10% menhaden fish meal in Diet 2, 10% DDGS in Diet 3, and 10% ground field peas in Diet 4. After 43 days of rearing in the laboratory, shrimp had grown to approximately 9 g (8.89-9.74 g). Although there were no significant results, the best weight gain (%) was obtained with the DDGS diet (Diet 3).

In the outdoor tank trial, which lasted 63 days, the best weight gain result was obtained with Diet 2 (10% fish meal), but once again, there were no significant differences. The researchers suggested that 10% DDGS or 10% field pea meal could replace the poultry by-product meal and indeed the fish meal as well.

Sookying and Davis (2011) stocked Pacific white shrimp post-larvae (0.038 g) in 0.1-hectare ponds and at the same time stocked larger (2.1 g) juveniles into outdoor tanks, and fed both trials for 126 days. Their experimental diets were the same as used by Roy et al. (2009) above. In both the outdoor tanks and the small ponds growth and weight gain was not significantly different between treatments, and FCRs were basically the same as well. Once again, the conclusion was that 10% DDGS or pea meal in combination with poultry by-product meal could replace fish meal.

Cummins (2013) fed juvenile Pacific white shrimp (mean weight 0.99 g) prepared five experimental diets, Diet 1 with 20% menhaden fish meal and 24.5% soybean meal among the ingredients served as the Control, while the remainder of the diets were all fish meal free. Diet 2, had no fish meal, with 52.5% soybean meal included to replacie the fish meal protein completely. The final three diets contained increasing levels of DDGS of 10% (D-3), 20% (D-4), and 30% (D-5). Diets 2 to 5 all included supplemental lysine and methionine.

Shrimp were reared in an indoor recirculating saltwater tank system at the University of Kentucky. Diet 1with 20% fish meal significantly outperformed all the other diets with a final shrimp weight of 10 g, a 1,051% increase. The other DDGS diets (D3, 4, 5) and the high soybean meal diet (D2) attained percent weight gains of only 450 – 670%, and these plant protein diet treatments were not significantly different from one another. The poor overall performance of the DDGS diets led them to conclude that more work needed to be undertaken to improve shrimp feed formulations before they could recommend replacing SBM 100% with DDGS.

Rhodes et al. (2015) conducted one growth trial and two digestibility trials with Pacific white shrimp. There were six experimental diets, with 0%, 10%, 20%, 30% (with 0.06% Lys), 40% DDGS (0.13% Lys), and a final diet with 40% DDGS diet without Lys. As DDGS levels rose, soybean meal was reduced accordingly. The best weight gain and FCR was obtained with the 20% DDGS diet, and with higher DDGS, growth dropped and FCR increased, although the researchers stated that using up to 40% DDGS without Lys gave acceptable results.

Gyan et al, (2022) conducted a 56-day trial to determine the effects on the growth of shrimp if they were fed diets replacing fish meal with increasing levels of DDGS, although in comparison with other similar research the DDGS levels were conservatively low, ranging from 2% to 16%. Diet ingredients other than DDGS included brown fish meal, soybean meal, peanut meal, beer yeast, and shrimp shell meal. In all diets, LYS was supplemented at 1% and 0.5% MET was added as well. An interesting component of this research was the investigation of gut microbiota populations using PCR analysis of 16S ribosomal DNA. They supported adding 8% DDGS while reducing fish meal levels by 40%, but based on the observed changes in gut microbial communities which they did not perceive as positive, they were hesitant to recommend using above that level.

Novriadi et al. (2023) conducted a study with DDGS and *P. vannamei* in net pens inside a shrimp pond. Diets were formulated with decreasing levels of soybean meal and increasing levels of DDGS to replace it. Shrimp post-larvae (1.06 g) were cultured for 90 days, with 10 replicates for each of the 4 experimental diets containing 0% DDGS, 5% DDGS, 10% DDGS and 15% DDGS. The levels of other ingredients, including fish meal, poultry by-product meal, tuna hydrolysate, and squid liver powder, were constant across all diets, while soybean meal and wheat flour levels were adjusted from diet to diet. Diets were supplemented with lysine and methionine to keep these essential amino acid levels constant. After 90 days the final mean weights of the shrimp ranged from 19.84 – 20.25 g. The best growth and average daily gain was obtained with shrimp fed the 10% DDGS diet, yet the final recommendation was to use up to 15% DDGS to replace soybean meal with supplemental lysine.

Worth noting, Yohana Mpwaga (2024, 2025) conducted a couple of trials with *P. vannamei* and DDGS. In the 2024 study, he investigated gut microbiota, antioxidative defense and disease resistance when DDGS replaced soybean meal. In the later 2025 study he fed shrimp diets with a single diet formulation containing 15% fish meal, 8% soybean meal, 17.5% DDGS, 6% brewer's yeast, 15,5% wheat gluten and 23% hi-gluten wheat flour to which he added graded levels of butyric acid (BA, 0%, 0.5%, 1%, 1.5%, 2%, and 2.5%).
Based on all measured parameters, he recommended using BA at 1.6%, but noted that all plant ingredients are not the same and the optimal level of BA might change with diet composition.

HP-DDG, CFP, and FCPC

Guo et al (2019) used HP-DDG sourced from Flint Hills Resources, Wichita, KS USA. A total of seven diets using DDG were prepared, one series of four diets (D1- D4) to replace fish meal with HP-DDG, and another three diets (D5 – D7) using HP-DDG to replace fish meal and corn protein concentrate (Empyreal® 75, Cargill Corn Milling, Cargill, Inc., Blair, NE). Shrimp post-larvae (0.36 g) were grown for 56 days until harvest. The growth performance results showed the HP-DDG to be a good protein source for practical shrimp feeds. They recommended using up to 15 – 20 % HP- DDG.

Nazeer et al. (2023) tested two HP-DDG products, HP40Y (40.83% CP) and HP50Y (49.32% CP) obtained from The Andersons, Maumee, Ohio. In one series of trials HP50Y was increased at graded levels (0%, 5%, 10%, 15% and 20%) in the treatment diets to replace CPC. (Empyreal® 75), and the same protocol was used with HP40Y at the same inclusion levels.
All experimental diets contained 43% soybean meal, 15% whole wheat, and 6% fish meal. As noted, as the two high Protein ingredients were increased, corn protein concentrate was decreased. both shrimp rearing trial started with 0.54 g shrimp and lasted for 40 days. Upon completion, the final weight of shrimp fed the HP50Y reached 2.93 g, while shrimp fed the HP40Y reached 2.88 g). At the conclusion of the feeding trial, growth, feed intake, feed conversion and survival were not significantly different, although there was a trend to higher final weights as the percentages of the two HP-DDG products increased. The authors stated that up to 20% HP-DDG could be used in feeds without compromising shrimp growth.

Galkanda-Arachchige et al. (2021) tested graded levels of fermented corn protein concentrate (FCPC) obtained from Cargill, MN, USA, in a series of diets intended to replace fish meal by FCPC. As FCPC was increased in the diets (0, 4, 8, 11, 13 and 15 %), fishmeal was correspondingly reduced (16, 12, 8, 4, 2, 0 %). Other ingredients in the test diets included soybean meal, whole wheat, and corn protein concentrate (constant at 45.3%, 24.5%, and 1%, respectively). During the 56-day trial, shrimp grew from 0.17 g to a final weight range of 3.83 g to 4.2 g. FCR values across treatments varied from 2.43 to 2.92. The conclusion reached was that the FCPC could be used to replace 100% of fish meal in a feed without reduction of feed performance.

Novriadi et al. (2022) tested the Cargill FCPC as well, using it to replace fish meal and/or poultry meal in Pacific white shrimp diets. The series of five diets each contained 25% soybean meal, 2% tuna hydrolysate, and 7% Korean squid liver powder, while among the diets, the quantities of fish meal and poultry by-product meal were adjusted accordingly.
During a 60-day feeding trial, mean shrimp post-larvae weights increased from 1.01 g initially to about 13.5 g (range 12.13 – 13.88 g) at the end. The researchers concluded that FCPC improved growth and improved resistance against salinity stress

In a paper published by Novriadi et al. (2023), the researchers tested a corn fermented protein product, this time NexPro™ from Poet Bioproducts SD, USA. Four test diets were formulated including a diet with no CFP, then three other diets with CFP at 6%, 12% and 18% while reducing soybean meal, fish meal, and corn gluten meal. The four diets were used in a commercial pond feeding trial lasting 60 days, and in a laboratory-staged controlled feeding trial with a follow-up challenge test with the pathogenic bacteria *Vibrio harveyi.*

In the commercial pond trial lasting 85 days, shrimp fed 12% CFP grew the best, with an initial starting weight of 1.06 g and finishing weights in the range of 13.1 – 13.5 g. The controlled indoor growth trial carried on for 60 days, and shrimp on the CFP diets grew from a mean initial weight of 1.04 g to 11.6 – 11.8 g. CFP at any level performed better than the Control diet, with significantly better weight gain and significantly lower FCRs. The commercial pond trial had been conducted in a private farm, and a couple of the ponds had been heavily infected with pathogenic bacteria in the past. The diets with the CFP improved shrimp disease resistance and the authors suggested it might be due to the high yeast content of the CFP.

Table 27. Summary of Published Studies reporting on the outcome of feeding DDGS to the Pacific white shrimp (P. *vannamei*) and the Freshwater prawn (*M. rosenbergii*). A blue reference indicates apparent digestibility trials were performed.

Type[##]	Body Weight Initial, Final (g)	Feeding Trial (days)	DDGS Inclusion (%)	DDGS was used to replace	Fish Meal (%)	Added LYS (%)	Added MET (%)	Test Parameters *	Optimum DDGS (%)	References
FWP	0.66-60.7	101	0-20-40	Fish meal, SBM	15	0	0	WG, FCR	40	Tidwell et al. 1993
FWP	0.51-43.9	110	0, 40	Fish meal SBM	0-7.5-15	0	0	WG, FCR	40	Tidwell et al. 1993
PWS	Lab 0.61-9.68 Farm 0.45-23.4	Lab 70 Farm 63	0-10	Fish meal, Poultry meal, Milo	0	0	0	WG, FCR	10	Roy et al. 2009
PWS	0.04-16.3	126	0-10	Fish meal, Poultry meal, Milo	0-10	0	0	WG, FCR	10	Sookying and Davis. 2011
PWS	0.99-6.1	56	0-10-20-30	Fishmeal SBM, Wheat flour	0	0-0.4	0-0.18	WG, FCR	In zero fish meal diets, DDGS reduced growth compared to SBM	Cummins et al. 2013
PWS	0.49-7.7	56	0-10-20-30-40	SBM Corn starch	6	0-0.13	0	WG, FCR	40	Rhodes et al. 2015
PWS	0.23-13	56	0-2-4-6-8-12-16	Fish meal	4-20	0.10	0.05	WG, SGR, FCR	8 to replace 40% of fish meal	Gyan et al. 2022
PWS	1.06-20.25	90	0-5-10-15	SBM	8	0-0.14	0.17-0.19	WG, FI, FCR, ADG	10	Novriadi et al. 2023
PWS	0.19-12.65	56	0-2-4-6-8-10-12	SBM	16	0.35-0.58	0.08-0.13	Gut microbiota Disease resistance	10	Yohana Mpwaga et al. 2024
PWS	1.06-15.2	80	0-5-10-15	SBM, Wheat flour	8	0-0.14	0.17-.019	WG, SGR, FE, FCR	13.6-19.5	Herawati et al. 2024
PWS	0.19-14.37	56	17.5	Butyric acid added at 0.5, 1.0, 1.5, 2.0, 2.5%	15	0.07	0.33	WG, SGR, FCR	Optimal BA level was 1.6%	Yohana Mpwaga et al. 2025

[##] Type: PWS – Pacific White Shrimp, GFP – Giant Freshwater Prawn

*WG – Weight gain, FCR – Feed conversion ratio, FE – Feed efficiency, FI – Feed intake, FR- Feeding rate, SGR– specific growth rate, RGR – Relative growth rate, PER– Protein efficiency ratio, PRE- Protein retention efficiency, PPV – Protein productive value, NPR = Net protein retention

Table 28. Summary of Published Studies reporting on the outcome of feeding HP-DDG, CFP and FCPC to the Pacific white shrimp (P. *vannamei*). A blue reference indicates apparent digestibility trials were performed.

Type[#]	Body Weight Initial, Final (g)	Feeding Trial (days)	DDGS Inclusion (%)	DDGS was used to replace	Fish Meal (%)	Added LYS (%)	Added MET (%)	Test Parameters *	Optimum DDGS (%)	References
PWS	T1 0.18-3.5 T2 1.24-9.2 T3 0.25-5.4	42 49 42	CFP (49%CP) 0-10-20-30 6-12-18-24	Fish meal, SBM Fish meal, SBM	6 0-3-6-9-12	0 0	0-0.12 0	WG, FCR WG, FCR	Up to 30 CFP to replace SBM, Up to 16 CFP to replace SBM and fishmeal	Qiu et al. 2017
PWS	0.36-8	56	CFP (49%CP) 0-10-15-20-30	Fish meal, CPC (Empyreal 75)	2.2-17.4	0	0	WG, FCR	Up to 20 CFP	Guo et al. 2019
PWS	0.17-4.67	56	FCPC (69%CP) 0-4-8-11-13-15	Fish meal,	0-16	0	0	WG, FCR	15 to replace 100% fish meal	Galkanda-Arachchige et al. 2021
PWS	1.01-13.88	60	FCPC 7.5	Fish meal, krill meal, Poultry meal	0-2.5-5-9	0.06-0.3	0.3-0.35	WG, FCR	7.5	Novriadi et al. 2022
PWS	0.54-2.9	40	HPDDG HP50Y^ 0-5-10-15-20 HP40Y^ 0-5-10-15-20	Poultry meal, SBM	6	0	0	WG, FI, FCR, NPR	Up to 20 to replace SBM	Nazeer et al. 2023
PWS	1.04-11.88	60	FCPC 12	Fish meal, SBM, Corn gluten meal	7.5-10	0	0	WG, FI, FCR	12	Novriadi et al. 2023
PWS	0.19-14.37	56	17.5	Butyric acid added at 0.5, 1.0, 1.5, 2.0, 2.5%	15	0.07	0.33	WG, SGR, FCR	Optimal BA level was 1.6%	Yohana Mpwaga et al. 2025

*WG – Weight gain, FCR – Feed conversion ratio, FE – Feed efficiency, FI – Feed intake, FR- Feeding rate, SGR– specific growth rate, RGR – Relative growth rate, PER– Protein efficiency ratio, PRE- Protein retention efficiency, PPV – Protein productive value, NPR = Net protein retention

^ ANDVantage HP50Y & HP40Y provided by the The Andersons, Inc.

CPC: Corn Protein Concentrate – Cargill Empyreal75

FCPC: Fermented Corn Protein Concentrate – Cargill Motiv

Commercial Non-Peer Reviewed Studies with CFP

The production of corn fermented protein started relatively recently in the United States in 2012-2014, and with several competing patented and trade-marked production systems installed in corn ethanol plants, each manufacturer is producing corn fermented proteins with unique chemical characteristics and nutritional profiles. CFP products vary mainly by their protein and fat content, yeast strains used during fermentation, and final yeast content. It is not really possible to describe CFPs as generic commodities, as is found with DDGS and to some extent, CGM.

The current trend is for producers to market their CFP as branded products made with specific technologies. Due to a limited number of suitable government/university research facilities with capable researchers in the United States, there is a lack of peer-reviewed studies on the use of corn fermented protein in aquatic animal feeds. For those papers that are published, the brand of CFP that was used is often identified, and as such there are no generic studies.

Consequently, at this moment, it is difficult for nutritionists to read a CFP paper and apply the findings to their formulation work with another product. Of course, as time goes by, familiarity and easy of use will come, as is now the case for SBM, with thousands of studies having been published.

In this section, summaries of some commercial trials will be presented with the intention of providing useful information, keeping in mind they may not have been independently reviewed.

Rainbow Trout

Sealey et al. (2025) presented a paper at the Aquaculture America 2023 annual meeting titled "*EXAMINATION OF CORN FERMENTED PROTEINS TO REPLACE FISH MEAL AND POULTRY MEAL IN JUVENILE RAINBOW TROUT DIETS*".

The study was part of the USDA Trout Grains Program, and they tested two novel CFP products (ANDVantage™ 40Y and ANDVantage™ 50Y, The Andersons, Inc.) with juvenile rainbow trout (346g) in a growth trial, intending to replace dietar fish meal and poultry by-produc meal. Each of these products w included in diets at 0%, 7.5%, 15%, 22.5%, and 30% of the formulation. Extruded test diets were formulated to have 42% digestible protein (52% CP) and

Figure 3. Total carotenoids (ppm) in the different treatments diets.

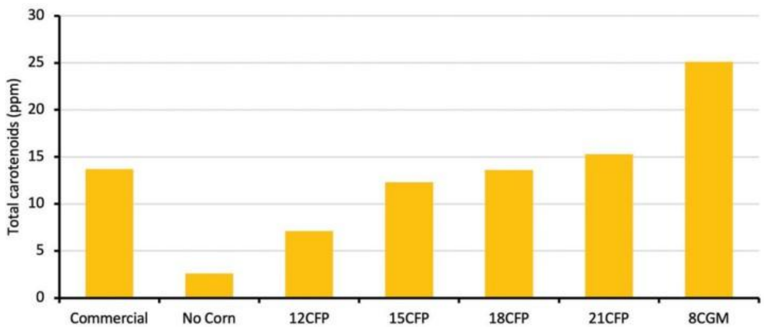
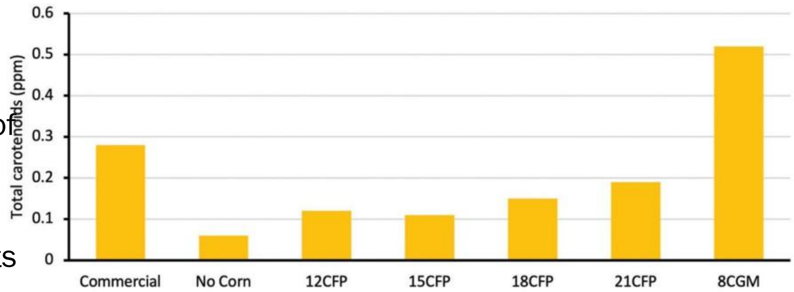


Figure 4. Total carotenoids (ppm) in the fish fillets after feeding rainbow trout the different treatments diets.



18% lipid. Other than the graded levels of CFP, main ingredients in the diets were wheat flour, fish meal, poultry by-product meal, soybean meal, corn protein concentrate (Empyreal75), blood meal, and feather meal. Amino acids lysine, methionine and were supplemented to balance the amino acid profile as corn protein was increased. Ingredient performance was assessed by measuring survival, weight gain, feed intake, FCR, PER and energy retention.

The best growth (g weight gain) was obtained with 7.% CFP inclusion in both trials (CFP 40Y and CFP 50Y), while growth with inclusion up to 15% CFP was nearly as good, and not statistically different compared to the control or 7.5% CFP diets. Increasing levels above 15% (CFP at 22.5% and 30%) in both trials did lead to a significant growth reduction and increase in FCR.

Rainbow Trout

Craig and Rens (2023) prepared a report titled "*Corn fermented protein tested successfully in rainbow trout*" for Aquaculture magazine about a feeding trial with CFP and rainbow trout from Green Plains Inc. Rainbow trout (200g) were separated into seven different treatments. Treatment diets included a commercial trout feed control (45% CP, 13% fat, no ingredient details provided), a "No Corn" control, a diet with 8% CGM as the sole corn product, as well as four diets containing 12%, 15%, 18% and 21% CFP (min. 60% CP). Other main ingredients in their test diets included wheat flour (27-31%), poultry by-product meal 18%), fish meal (12%), fish oil (12%), feather meal (2-7.5%) and blood meal (1.5-5%).

Crude protein in the treatment diets was in the 41 - 43% range with fat ranging from 13-15%. Final weights of fish were similar for all treatments (900g±50g), suggesting that nutrients remailed balanced even with increasing levels of CFP. FCRs were reportedly in the range of 1.05 - 1.2 across treatments, so nutrient digestibility appeared to be high for all diets.

Previously we have shown the carotenoid analysis of the CFP60 and CGM that were used (Table 12). Figure 3 shows the carotenoid analysis of the various test diets. As expected, the "no corn" treatment had the lowest concentration of xanthophylls, with a very small amount probably coming from the SBM. With diets containing the CFP (total xanthophylls 68.6 ppm), xanthophyll levels increased with increasing CFP inclusion. The greatest level of carotenoids was found in the CGM diet. The diet with 21% CFP would have contained approximately 14.4 ppm carotenoids, while the estimated carotenoid content of the CGM diet was 24.7 ppm. Reviewing the data in Figure 4, all tissue carotenoid levels were well below the level needed to prevent meat coloration.

Atlantic Salmon

Green Plains Inc. (Green Plains 2019) sponsored an 84-day feeding trial with their CFP50 product which was undertaken at the Center for Aquaculture Technologies in Prince Edward Island, Canada. The study report was "*Effect of CFP50 on Weight Gain, Nutrient Utilization, Fillet Color, Blood Plasma, Biochemistry and Gut Histology of Post-smolt Atlantic Salmon, Salmo salar*"

The basic nutrient composition of the CFP50 was on a dry metter basis CP, 51.1%, crude lipid 5.4%, gross energy 20.71 Mj/kg , Lysine 2.09% and methionine 1.13%.
The Atlantic salmon used were a native North American strain from the St. John River, New Brunswick, Canada. In addition to a control diet with no CFP50, there were four diets with CFP increasing in 5% increments from 5% to 20%. Their five experimental diets are shown in Table 26. Essentially, CFP was used to replace poultry-byproduct meal, soy protein concentrate, and corn protein concentrate.

Table 29. Feed Ingredient composition of five diets used in the Green Plains trial.

	Dietary Treatments				
Ingredient	Control	CFP50-5	CFP50-10	CFP50-15	CFP50-20
Poultry by product meal (pet food)	20.000	19.118	18.237	17.355	16.473
CFP50	0.000	5.000	10.000	15.000	20.000
Fish oil herring	19.516	19.516	19.516	19.516	19.516
Fish meal herring	15.000	15.000	15.000	15.000	15.000
Soy protein concentrate	13.196	11.522	9.848	8.174	6.500
Wheat flour	12.002	10.803	9.604	8.404	7.205
Corn protein concentrate	8.662	7.470	6.278	5.085	3.893
Wheat gluten meal	5.000	5.000	5.000	5.000	5.000
Canola oil	2.602	2.603	2.604	2.605	2.606
Monocalcium phosphate (21% P)	2.176	2.099	2.022	1.944	1.867
L-Lysine	0.714	0.742	0.770	0.798	0.826
Vitamin and Mineral premix	0.500	0.500	0.500	0.500	0.500
Vitamin C (Stay-C)	0.300	0.300	0.300	0.300	0.300
L-Histidine	0.249	0.242	0.235	0.228	0.221
Carophyll Pink	0.050	0.050	0.050	0.050	0.050
DL Methionine	0.033	0.036	0.038	0.041	0.043

At the end of the 84-day trial, the best growth performance was obtained with the diet containing 10% CFP, although fish performance on the CFP 15% was slightly poorer, it was not significantly different than the Control. However, growth performance did suffer with the CFP20% diet.

All of the diets contained 0.005% astaxanthin (Carophyll Pink) for pigmentation, and the the researchers were interested in finding out whether the inclusion of CFP increased yellow pigments in the fish flesh. Hunter LAB scores taken at both anterior and posterior positions on fish fillets. At the beginning of the trial, L, a, and b scores for the anterior fillet position were respectively 61.0, 2.89 and 10.3, and 59.7, 4.1, and 11.0 for the posterior fillet.

At the end of the trial, Hunter L, a, and b scores for the control feed were in the ranges of 59.7 - 61, 7.9 - 9.1, and 17.2 - 18.8 respectively. L scores for the fillets from fish fed the CFP diets ranged from 56.0 - 56.9 (anterior), and 54.7 - 55.7 (posterior). The differences in a and b scores between the control with no CFP and the four CFP treatments were minor and not significantly different.

The conclusion of this study was that fish could be fed CFP up to 15% of diet without any significant impact on growth performance, but not 20%, which saw significantly lower feed intake and growth. Fish fillet flesh color was not impacted by increasing CFP to to 20% in their diets.

Tilapia

Green Plains Inc. released a white paper report titled "*Validation of CFP50 as a major protein source in diets for tilapia, Oreochromis niloticus*" on feeding CFP50 to Tilapia that was conducted at the Aquaculture Research & Teaching Facility at Texas A&M University, Texas. Their feeding trial had a series of diets with CFP50 inclusion at 0%, 5%, 10%, 15% 20%, 25% and 30%. Juvenile tilapia (starting weight 2.32±0.01g) were reared in 100 liter aquaria for 56 days.

In addition to the graded levels of CFP, main ingredients in the diets were whole wheat (19.75 - 21.6%), Wheat middlings (17.95 - 18.8%), chicken by-product meal (14%), fish meal (5%), soybean meal (25 - 0%), hydrolyzed feather meal (2.0 - 6.0%), and fish oil (4.45 - 5.00%). L-Lysine was supplemented (1.75 - 2.15%) as was methionine (0.40 - 0.45%) and threonine (0.35%). The corn fermented protein was used to completely replace soybean meal, and 0% SBM was added to diets with 3% and 30% CFP.

Performance indicators for the diets were fish eight gain, FCR, Survival, Hepatosomatic index, and protein efficiency ratio (PER). Fish fed CFP at 15%, 25% and 30% grew slightly better than the CFP0% control, while CFP10 and CFP 20 had slightly lower weight gain than control, but results were not significant. FCRs ranged from 1.22 (CFP30) to
1.30 (Control, CFP10, CFP20). Regarding PER, it was 1.67 for control, and CFP treatments ranged from 1.62 (CFP10) to a high of 1.76 for the CFP30 diet.

The study concluded that CFP50 could be included in tilapia diets up to 30% and totally replace SBM without any impact on fish growth performance.

Pacific White Shrimp (*P. vannamei*)

A white paper report by Green Plains Inc. titled "*Corn fermented Protein in Place of Soybean and Fish Meals in Diets for the Pacific White Leg Shrimp Litopenaeus vannamei*" outlined the results of a series of feeding trials conducted with Pacific white shrimp at the
E.W. Shell Fisheries Research Station at Auburn University. The purpose of the trials was to investigate the replacement of soybean meal and fish meal with CFP50. In Trial 1, four experimental diets were prepared with 0%, 10%, 20% and 30% CFP and fed to shrimp post-larvae (0.18g starting weight) for five weeks (35 days). Test diets are shown in Table 30. Fish meal and corn protein isolate remained constant at 6%, and whole wheat at 9% across all diets, while SBM was reduced from 54.25% in the basal diet to 20.3% in the CFP30 diet. Diets were supplemented with Methionine but not lysine.

Table 30. Formulated diets with CFP50 for Pacific White Shrimp used in Trial 1

Ingredient	Basal	CFP10	CFP20	CFP30
Fish Meal	6.00	6.00	6.00	6.00
Soybean Meal	54.25	43.00	31.60	20.30
CFP50	0.00	10.00	20.00	30.00
Corn Protein Isolate	6.00	6.00	6.00	6.00
Fish Oil	5.79	5.75	5.71	5.67
Whole Wheat	9.00	9.00	9.00	9.00
Corn Starch	13.69	15.02	16.50	17.88
Trace Mineral Premix	0.50	0.50	0.50	0.50
Vitamin Premix	1.80	1.80	1.80	1.80
Choline Chloride	0.20	0.20	0.20	0.20
Stay C	0.10	0.10	0.10	0.10
CaP-dibasic	1.50	1.50	1.50	1.50
Lecithin	1.00	1.00	1.00	1.00
Cholesterol	0.05	0.05	0.05	0.05
Methionine	0.12	0.08	0.04	0
TOTAL	100.0	100.0	100.0	100.0

At the end of the feeding trial, feed performance was assessed with mean weight gain,
% weight gain, and FCRs.

Shrimp fed the CFP10 and CFP20 diets had final mean weights,% weight gain, and FCRs not significantly different that the basal (0% CFP) diet. However, shrimp fed the CFP30 diet had significantly poorer growth and a much higher FCR than the other three treatments.

In trial 2, all protocols were the same as in trial 1, except the starting weight of shrimp was a little heavier (0.25g) and there were five diets prepared, as shown in Table 28. In these diets CFP50 was included at 0%, 6%, 12%, 18% and 24%. Unlike trial 1, here fish meal levels were reduced from 12% down to 0%, and corn protein isolate and supplemental methionine were not used, creating a more challenging nutritional environment to test the value of the CFP. Shrimp were grown for 6 weeks (42 days).

The shrimp on the basal diet in trial 2 grew to a final mean weight of 5.07 g with an FCR of 1.81, while shrimp fed the CFP6, CFP12 and CFP18 and CFP24 reached final weights of 5.37%, 5.13%, 4.60%, and 4.29%, and corresponding FCRs were 1.67, 1.74, 1.94, and 2.14, respectively. Although the shrimp growth and FCR of the CFP18 treatment was not significantly different from the basal, CFP6 and CFP12 diets, growth and FCR of the CFP24 was significantly inferior to the other treatments. The authors theorize that without supplemental amino acids (methionine and lysine), there was simply not enough fish meal in the CFP18 and CFP24 diets to sustain growth.

Table 31. Formulated diets with CFP50 for Pacific White Shrimp used in Trial 2.

Ingredient	Basal	CFP6	CFP12	CFP18	CFP24
Fish Meal	12.00	9.00	6.00	3.00	0.00
Soybean Meal	52.40	50.20	48.00	45.80	43.60
CFP50	0.00	6.00	12.00	18.00	24.00
Menhaden Fish Oil	5.27	5.31	5.36	5.41	5.45
Whole Wheat	20.00	20.00	20.00	20.00	20.00
Corn Starch	4.68	3.84	2.99	2.14	1.30
Trace Mineral Premix	0.50	0.50	0.50	0.50	0.50
Vitamin Premix	1.80	1.80	1.80	1.80	1.80
Choline Chloride	0.20	0.20	0.20	0.20	0.20
Stay C	0.10	0.10	0.10	0.10	0.10
CaP-dibasic	2.00	2.00	2.00	2.00	2.00
Lecithin	1.00	1.00	1.00	1.00	1.00
Cholesterol	0.05	0.05	0.05	0.05	0.05
TOTAL	100.0	100.0	100.0	100.0	100.0

Recommended Levels ot CFP to use in Aquafeeds

In an undated Green Plains marketing document prepared by Craig and Rens titled "*Recommended Inclusion Levels in Aquafeed Diets*" the authors recommend the following optimal inclusion levels of Green Plains CFP50 and CFP60 (Sequence™) for various species:

- Rainbow Trout - CFP50 and Sequence™ 14 - 18% of diet
- Channel Catfish - CFP50 10 - 12% of diet
- Tilapia - CFP50 22 - 25% of diet
- Atlantic salmon - CFP50 and Sequence™ 12 - 15% of diet
- Barramundi (*Lates calcarifer*) - CFP50 14 - 18% of diet
- Marine shrimp (*P. vannamei*) - CFP50 and Sequence™ 8 - 14% of diet

Overview of Aquafeed Pelleting Technologies

Die-Press Pelleting

Traditionally, livestock and poultry feeds are pelleted using conventional press pellet mills, so when aquaculture farms began to move away from farm-made feeds with their inconveniences to buying manufactured feeds, press pelleted sinking feeds were the first to be used. Adaptations had to be made to the pellet mill preconditioning stage, and rollers and dies were modified to increase compression ratios needed to produce durable pelleted fish feeds. Further innovations to press pellet mills were needed to produce dense sinking shrimp feed pellets with hours-long water stability. Pre-conditioning times were extended from seconds to minutes, and wet steam was injected into the pre-conditioner to facilitate greater starch gelatinization before the pellet mill. While extruded feeds are almost universally used for fish and shrimp feeds in the US, Europe and South America, in many parts of Asia, press pelleting of fish feeds is still dominant for low-value species. Due to decades of refinement to the manufacturing process, using pellet mills to make durable pelleted shrimp feeds is still the norm in most of Southeast Asia. In India, where shrimp farming is booming, almost all companies investing in new factories to make shrimp feeds are buying extruders.

Single-screw Extrusion

The first generation of single-screw extruders for pelleting animal feeds became available in the mid 1980s, and were quickly adopted by the petfood and aquafeed industries. The advantage of the cooking extruder over pressed pellet mills was that feed ingredients were better cooked and sterilized, greater starch gelatinization occurred so digestible energy increased, expanded floating feeds could be produced, and dry feeds could be stored and transported without refrigeration.

The mechanical design of the single-screw cooking extruder involves the rapid rotation of a large spiral screw inside a barrel, itself lined with spiral segments. The entire screw and barrel elements are designed for forward conveying and pressurizing the feed mixture before passing through the bored openings in the die. In order to increase friction and heating, kneading sections and restrictions as well as cut screw elements are installed in the barrel to increase mechanical shear and residence time inside the barrel. Metered injection of low-pressure wet steam accelerates the cooking process.

Thus, the reliance of the single-screw extruder on friction for conveying and cooking requires that total fat content in the feed mixture be limited. For example, to easily produce an expanded floating feed for tilapia, total fat content from ingredients should not exceed 6%, otherwise high fat will inhibit pellet expansion. In this context, oil-extracted plant-origin ingredients are preferred over their full-fat counterparts.

Fiber content also needs to be controlled, since high fiber interferes with gelatinization and tends to disrupt the carbohydrate matrix needed for binding of the extruded product. Fiber decreases the fluidity and smooth flow of the mixture in the barrel, increases friction and surging, and results in a coarse appearance, often with size and color variability. Due to fibrous particles at the surface of the pellet, excessive fines may be generated during final sieving. Since high fiber scours the inside of the extruder, it causes excessive wear of the internal elements and dies, which shortens the working life of the parts.

More recently, most of the major single-screw extruder manufacturers have been providing a long list of optional in-barrel or bolt-on accessories at the die face to control product density and pellet expansion. Installing these accessories on a modern single-screw extruder together with an automated control system now allows much more flexibility. For instance, sinking feeds can now be made on a single-screw extruder if fat and fiber content are limited.

Twin-screw Extrusion

As the Atlantic salmon farming industry developed, feed research indicated that the best farm performance was obtained with high-fat slow-sinking feeds, Until recently, this type of feed could only be manufactured reliably with expensive fully automated twin-screw extruders originally intended for production of human food products.

Twin-screw extruders use a pair of co-rotating screws with complementary profiles that force the feed mixture to move forward through the spaces between the two screws. Since friction is not a factor in operation, unlike a single-screw extruder, lipid content and fiber content have no impact on function. Hence feed ingredient choices are much less limited, and there is much greater flexibility in handling the physical and chemical quality characteristics of the ingredients, Table 4 provides a comparison of single- and twin-screw extruders, highlighting the main differences in operation and capabilities.

More recently, twin-screw extruders of small and large capacity have been designed specifically for aquaculture feed production, using non-food-grade steels. With Asian manufacturers now producing this kind of extruder, investment costs for twin-screw extruders have come down substantially, making such machines affordable in developing markets producing low value floating feeds for freshwater fish like carps and Pangasius.

Reviewing Table 29, it is apparent that high fat, high fiber, and high moisture formulations that are difficult make with a single-screw extruder are all possible with a twin-screw extruder. Consequently, the ability to select a wider range of ingredients, and operate the extruder more flexibly in terms of formulations.

Extruding feeds with DDGS and CFP

Chevanan et al. (2005, 2007, 2010), have published a number of papers on extrusion of feeds, some with single-screw extruders, and also twin-screw extruders. These authors provide an excellent guiding set of engineering concepts and practical operating parameters for using extruders to pellet feeds containing a difficult high fiber, high fat ingredient like DDGS.

Ayadi et al. published two (Ayadi et al. 2011, 2013) among many papers about using a single-screw extruder to make some very simple feed formulations for Nile tilapia with increasing levels of DDGS (20%, 30% and 40%) and decreasing levels of soybean meal (50%, 40% and 30%) in their experimental feeds. In the 2013 study DDGS levels were increased, die pressure, optimal moisture content and conditioning and cooking temperatures fluctuated, and pellet expansion decreased. Fluctuating moisture and temperature levels caused changes in appearance and color differences in the finished feeds.

Ilić et al. (2023) prepared four 40% CP diets for the European catfish with the inclusion of 10%, 20%, and 30% corn DDGS (Pannonia Gold, Dunaföldvár, Hungary) and used a twin-screw extruder to produce sinking feeds. The different formulated feed mixtures were pre-conditioned to 25% moisture and 95°C prior to extrusion. The formulations used are shown in Table 33.

Table 32. Comparison of the differences in operation and functional capabilities between single-screw and twin-screw extruders (based on information provided by Wenger Manufacturing, Sabetha Kansas, USA)

	Single Screw	Twin screw
Configuration	Mash moves in the space between the screw and the barrel liner causing friction and forward movement. Anything that reduces friction (high moisture/fat) or impedes forward movement (high fiber, very small die opening) reduces capacity and makes production difficult.	The twin screws either counter-rotate or co-rotate, creating a pumping action between them that moves mash forward which is independent of the liner, therefore friction and internal pressure are not factor that affect feed output.
Wider range of ingredients		Yes (high fiber, high fat)
High fat formulations	Difficult	Yes
Moisture > 30%	Difficult	Yes
Moisture > 30% or addition of a high percentage of meat or fish	Difficult	Yes
High fiber formulations	Difficult	Yes
Very small pellets	Difficult	Easy
Sinking or slow-sinking pellets	Difficult	Easy
Water stability (shrimp feed)	Poor without expensive binders	Excellent
Cost of Purchase	$$	$$$$
Cost of Maintenance	$	$$$
Cost of Operation	$	$$$

Table 33. Composition and calculated nutrient content in control and three experimental European catfish diets. Ilić et al. (2023)

Diets	DDGS-0	DDGS-100	DDGS-200	DDGS-300
Ingredients (g/kg)				
Corn DDGS[1]	-	100.0	200.0	300.0
Poultry meal[2]	250.0	205.0	160.0	120.0
Wheat[3]	249.5	188.9	127.5	66.7
Soybean flour[4]	210.2	220.0	230.0	235.0
Fish meal[5]	200.0	200.0	200.0	200.0
Yeast[6]	50.00	50.0	50.0	50.0
Soybean oil[7]	18.0	12.0	6.0	-
Fish oil[5]	15.0	15.0	15.0	15.0
Premix[3]	5.0	5.0	5.0	5.0
Salt[3]	0.8	1.5	3.0	4.0
Lysine[3]	0.6	1.5	2.2	2.8
Methionine[3]	0.4	0.6	0.8	1.0
Yttrium(III)-oxide[8]	0.5	0.5	0.5	0.5

Ilić et al. go into much detail about the extruder screw configuration they set up and also the operating parameters they used including temperatures, screw speed, pressure, and SME, specific mechanical energy are presented in a table. One notable effect of the DDGS inclusion was the drop in SME from 108.9 in the DDGS-free feed down to 86.5-89.9 in the feeds containing DDGS. DDGS inclusions of 20% and 30% reduced pellet expansion. DDGS added at any level increased pellet hardness and durability (PDI). DDGS at the 30% level reduced water stability of the pellets, causing them to soften and leach nutrients. The conclusion of this series of tests was that DDGS, by reducing the amount of SME needed to produce quality sinking fish feeds, might reduce the cost of feed production, and the increased PDI's would improve pellet durability during transportation, storage and pneumatic feeding.

Other Considerations to Improve Pelleting of Feeds containing DDGS

Beyond the choice of pelleting method, there are a few other practices that feed mills have to implement to optimize aquafeed manufacturing and on-farm feed performance:

- Aquafeeds, particularly those for shrimp and juvenile fish, require fine grinding of ingredients to a particle size finer than 60 mesh (typically 95% below 250m). This improves starch binding, water stability and digestion, and reduces the impact of fiber on the extrujsion process.
- Selecting ingredients with high fiber such as rice bran (~ 7-8% CF), DDGS (~ 7-8% CF), wheat bran (~ 10% CF), groundnut meal (~ 13-14% CF), copra meal (>11-15% CF), cottonseed meal (~ 13-19%), and palm kernel meal (17-23%CF) reduces capacity and efficiency of the grinding process.

SWOT Analysis for DDGS

Strengths

- More than 32 million tons of DDGS are produced yearly in the U.S. and volumes are increasing over time.
- Millions of tons of DDGS are exported around the world.
- The quality of DDGS produced today is substantially better than the product that was produced 20 years ago.
- The Xanthophyll content in DDGS is good for improving color pigmentation of red tilapia and shrimp, since most freshwater fish and marine shrimp are capable of taking these plant carotenoids and converting them into canthaxanthin and astaxanthin which give the fish or shrimp more desirable coloration that customers prefer.

Weaknesses

- Corn Protein is quite unlike fish meal with its low LYS and DDGS has the same issue.
- Corn protein has a higher MET content than soybean meal, and can help to balance MET in low fish meal feeds.
- Amino acid supplementation of feeds with high DDGS is often required.
- High Fiber Content impairs digestion and nutrient absorption.
- Xanthophylls in DDGS are considered a risk for pigmenting Pangasius when pure white flesh is desired, so feed formulators often avoid using corn products in pangasius feeds.

Opportunities

- Amino acid supplementation of feeds allows a higher inclusion level of DDGS
- Using DDGS with feed enzymes (carbohydrases, phytase, protease) makes DDGS usable in more feeds for more species than before.
- Selectively promoting bright yellow DDGS rather than dark colored DDGS into the aquafeed market would open new opportunities in developing markets that are unable to afford the high price of synthetic carotenoids.

Threats

- The threat of mycotoxin contamination is perceived to be high, although the presence of mycotoxins is highly variable depending on corn harvest and storage conditions.
- Since mycotoxin surveillance cannot discover every risky lot, using mycotoxin binders is recommended.
- Specific to U.S. DDGS, many countries do not permit the importation or use of GMO crops and processed by-products, and U.S-grown corn is estimated to be about 94% GMO.

SWOT Analysis for CFP

Strengths

- CFP is a high quality corn protein at a cheaper price point than corn gluten meal or corn protein concentrate
- The relatively high digestible MET content for a plant protein makes meeting amino acid requirements easier.
- The relatively high digestible MET is complementary to soy protein with its low MET, and blending corn with soy protein is an effective way to balance these amino acids.

Weaknesses

- CFP is quite new in the export market and is relatively unknown.
- Early in CFP development, multiple names were used (HP-DDG, SSF-DDG, FCFC) and there is lingering confusion about what CFP is.
- AAFCO giving CFP its own definition and code helps, but is the information about this being shared?
- Not much aquaculture feed research with CFP has been done, with peer-reviewed scientific articles only appearing in the last 2-3 years.
- Typically, CFP from the U.S. is a GMO product and may not be accepted in many potential markets.

Opportunities

- The high protein and low fiber content makes CFP a viable source of protein in feeds for carnivorous fish and shrimp, compared to high fiber DDGS which is often avoided in those producing low-fiber feeds for specific animals.
- The production costs of co-products of dry-milled corn for ethanol production compared to protein products from corn wet milling gives DDGS and CFP a cost advantage.
- The lower xanthophyll content of CFP compared to Corn gluten meal and corn protein concentrate

Threats

- The use of CFP in aquaculture feeds is new and threats at this point seem to be unknown
- It is unknown whether the washing steps in the mechanical protein extraction process reduces the content of any specific mycotoxins.

Summary

As the aquaculture feed industry seeks to become more sustainable in every way, reducing the use of marine proteins and finding suitable alternatives has become an enduring trend in feed development for fish and shrimp. The tremendous production volumes and stable supply of high-quality soybean meal available for export from several countries makes it an easy traditional buy for feed manufacturers. After soybean meal, the collectively large production of corn protein ingredients such as DDGS, corn gluten meal, corn protein concentrate, and now corn fermented protein offers the aquatic animal feed industry a wide range of products suitable for more species than ever before. With the less complex production technologies of dry milling process for ethanol production, and the ever-expanding production volumes of valuable co-products like DDGS, prices have become very competitive compared to soy and other products like rapeseed and canola.

In this document we have tried to create a compelling and easy to understand source of information for feed industry professionals who want to understand better the value of incorporating DDGS and CFP into their aquatic animal feeds. We have explained the good and not so good characteristics of DDGS and CFP in great detail.

We have compiled a series of tables with the latest references which show the wide range of species of fish that researchers have used to test DDGS and CFP, how much DDGS can be used in feeds for tolerant species like carp and tilapia. Including research with carnivorous species such as rainbow trout, Atlantic salmon and European seabass in the collated data shows that there are lots of opportunities to use CFP with fiber intolerant species quite effectively.

Recommendations for the inclusion of DDGS in fish and shrimp feeds are as follows (USGC, 2019):

Species	Maximum dietary DDGS inclusion rate %
Channel catfish	30 to 40 with supplemental synthetic amino acids
Common carp	15
Freshwater prawns	40
Milkfish	45
Pacific white shrimp	40 with supplemental synthetic amino acids
Rainbow trout	50
Red claw crayfish	30
Sunshine bass	10
Tilapia	50 with supplemental synthetic amino acids

Green Plains Inc. provides the following recommendations for use of their CFP 50%CP and Sequence™ products in aquafeeds for various species:

SPECIES	Inclusion Level in Diet
Rainbow Trout	14 - 18%
Channel Catfish	10 - 12%
Nile Tilapia	22 - 25%
Atlantic Salmon	12 - 15%
Barramundi (Asian Seabass) *Lates calcarifer*	14 - 18%
Pacific White Shrimp - *P. vannamei*	8-14%

Feed processing technologies have continued to advance, and prior issues with poor performance of DDGS in single-screw extrusion has now largely been overcome with new and advanced accessories that improve the capabilities of single-screw extruders to deal with high fiber and high fat ingredients. The next step up is to move to twin-screw extrusion, and the wide availability of more affordable Asian-made, non-food grade twin-screw extruders has convinced most new feed mill installations in Asia to make the switch. That then addresses one more of the outstanding issues with DDGS and aquafeed manufacturing.

From the nutrition perspective, corn products have the same issues with an imbalanced amino acid profile compared to fish meals and rendered land animal proteins. However, feed formulators have accepted the need to use plant proteins, and many work-arounds to balance amino acids, including multi-ingredient blending and supplementation of crystalline amino acids like LYS and MET which have become standard practices in most feed mills. In the end it comes down to availability and cost, and compared with the alternatives DDGS is very competitive.

The next issue that has sometimes hindered the use of DDGS in aquafeeds is the high fiber content. For those that are comfortable with DDGS, the widespread adoption of effective feed enzymes by the feed industry to deal with phytic acid and non-starch polysaccharides is almost universal in livestock and poultry feeds. This makes it easy to find equipment to incorporate into aquaculture feed mills, and the rate of adoption of feed enzymes for aquaculture feeds in accelerating.

While DDGS has been accepted in low-protein high-fiber feeds for fish like carps and tilapia, the development of high-protein low-fiber CFP has created a large opportunity, both for the producers as well as for feed industry buyers. With CFP, users can now choose a high quality reasonably priced corn protein in feeds for high value species such as carnivorous marine fish.

For feeds used to farm species where yellow skin or flesh pigmentation is unwanted, the availability of a highly-concentrated source of corn protein with reduced xanthophyll levels makes CFP a more acceptable choice than corn gluten meal or corn protein concentrate.

The reasons for fish and shrimp feed formulators to not consider using DDGS in aquafeeds are diminishing. The arrival of CFP has changed the game for high protein plant ingredients, which in the past have come mainly from soy, and the possibilities of using quality corn protein in aquatic animal feeds are greater today than ever before.

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