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PERSPECTIVE

Upcycling Renewable Ethanol Grain Fermentation Co-Products in a Circular Bioeconomy: Technological Pathways to High-Value, Low-Impact Protein Production

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Abstract

In 2024 European renewable ethanol producers produced 6.9 million tons of food and feed co-products and 6.8 billion litres of renewable ethanol biofuel. Liquid renewable fuels such as bioethanol make an average greenhouse gas saving of 79% compared to fossil fuels. Recent advances in mechanical up-cycling of these traditional feed coproducts produces a new high-quality protein, Corn Fermented Protein (CFP) (Crude Protein content>50%) that can replace imported GM plant proteins currently used in feed formulations for aquaculture, pet food and livestock feeds. The fuel ethanol fermentation technology is undervalued because in fermentation protein is created. Fermentation to produce ethanol relies on the activity of yeast that is grown using approximately 8-10% of the feedstock grain starch, plus either gaseous ammonia or urea as a nitrogen source. Yeast cells are approximately 40% protein and form part of the feed co-products produced in the bioethanol process. Novel fractionation technologies up-cycle the traditional protein co-product (distillers dried grains and solubles; DDGS; a median protein approx. 30% crude protein) to produce a new Super Protein product (CFP) (>50-60% crude protein concentration) in so doing recovering a major proportion of the spent yeast that contains important immuno stimulants. CFP has been extensively tested, as a replacement of soybean meal in feed for poultry, swine, ruminants, aquaculture and companion animals. The new protein is devoid of any anti nutritional factors and highly suited for formulation in feed for aquaculture and companion animals. In addition, the spent yeast cell wall beta-glucans, act as immuno stimulants proven to reduce mortality when used in aquaculture feed. When used in feed for dogs CFP increases palatability. CFP has a significantly lower carbon index compared with many traditional feed proteins. Using CFP in feed formulation lowers the carbon index of feed products. Upcycling distillers dried grains and solubles into CFP helps lower Europe's protein deficit, reduces feed carbon footprint, and creates additional valuable markets for ethanol co-products.

Keywords Biofuels · Renewables · Protein · Protein-gap · Distillers Dried Grains and Solubles · Corn Fermented Protein · Biofuels-food Competition

1. European protein requirements and alternative agronomies

The circular economy is increasingly recognised as essential in agriculture. It improves resource efficiency and reduces waste by transforming by-products into valuable inputs within closed-loop systems (Gazal et al., 2025). The dry grind ethanol process is an industry that generates significant quantities of co-products (Distillers Dried Grains and Solubles: DDGS) that are extensively used in feed for livestock. Circular approaches can enhance food production while lowering environmental impacts and supporting long-term

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sustainability in agri-food systems. The use of European grains in the dry grind ethanol process to produce renewable ethanol liquid fuel is a technology that is challenged on the basis that crops that can be used for food should not be used to produce fuel. This manuscript is a perspective which challenges this supposition on the basis that a significant commercial technological development up cycles the dry grind bioethanol commodity co-product (DDGS) into a valuable Super Protein. The process produces a feed protein which can be used to replace imported soybean meal in European feed formulation. Indeed, the renewable fuel ethanol biorefinery is a potential major producer of food, feed and fuel from non-GM European grain. There are references in the text to the extensive efficacy trials program that has been completed on the protein product, but it is not the objective of this document to review this data. The objective here is to demonstrate that this process can deliver a short-term response to the European protein gap without the need for alternative agronomy.

The transition toward a circular economy (CE) demands that agri-food systems reduce their dependence on virgin materials while maximising the value of existing resources. Within livestock and aquaculture production, this challenge is especially acute: animal agriculture consumes substantial quantities of primary food-grade crops, and conventional feed supply chains remain heavily reliant on imported protein sources such as soybean meal. Europe's reliance on soy imports much of it linked to land-use change, deforestation risk, and genetically modified (GM) production, highlights both environmental and geopolitical vulnerabilities. Yet alternatives that avoid the use of primary crops have struggled to gain regulatory approval or commercial scalability (Burton et al., 2021)

Europe is only 29% self-sufficient in high quality protein (the European Protein Gap) and is therefore short of protein suitable for animal feed. It relies heavily on imported soybean meal. Although soy can be purchased under certification schemes that verify it is not directly associated with land-use change, the continued reliance on imported soybean for animal feed reinforces a production system that remains a major driver of deforestation in South America.

Establishing a new plant protein crop to produce protein for animal feed in Europe faces a mix of agronomic, economic, regulatory, and social challenges. It could take a decade to create the elite, geographically adapted varieties, adopt new agronomic practices, and establish appropriate supply chains. The European Union (EU Feed Protein Balance Sheet (forecast) 2022/23) highlights microbial protein, algae and insects as alternative sources of concentrated protein. Currently these sources are far from economically and commercially viable sources of protein (Blue H, 2024). Microbial protein from bacteria, yeast, algae and fungi, is derived via fermentation processes and generally has significant energy requirements, with high carbon costs and in addition strict toxicological testing. Such challenges prevent rapid expansion of these industries. The current high cost of production and lack of availability of commercially viable quantities required by the animal feed compound industry for feed production, are major challenges for many of these new technologies (Blue H, 2024).

Given these challenges, innovative solutions such as upcycling ethanol fermentation co-products into high-value protein sources are valuable. Currently approximately 9 million tons of European non-GM grains (maize, wheat, barley and rye) are converted annually by fermentation into bioethanol, a renewable fuel. The residue of the grain is currently turned into a medium quality protein animal feed (distillers dried grains and solubles - DDGS). Technology is now available and proven to fractionate the residue into bespoke streams with characteristics optimized to market sector requirements. This allows upcycling of moderate quality DDGS protein into a range of feed proteins that can successfully compete with the imported protein products - with the added advantage of non-GM status due to the European origin of the cereal grains used. This approach not only supports the circular bioeconomy but also aligns with regulatory and commercial demands for scalable, low-carbon feed ingredients.

2. Production of ethanol as a renewable transport fuel in Europe

The production of ethanol as an alternative to carbon-based fossil fuels is a major international industry. The average GHG intensity (excl. Indirect Land Use Change (ILUC)) for bioethanol was 20.3 gCO2e/MJ overall (down from 20.8 gCO2e/MJ in 2022). This equals to a 78.4% average GHG emission reduction compared to fossil fuels (Epure 2024). The feedstock breakdown of bioethanol used in the EU in 2023 was: 51.6% corn, 17.0% wheat, 11.0% sugar cane, 27.7% other, 0.73% N/A. The average fuel GHG intensity (excl. ILUC) for EU27 in 2023 was 88.2 gCO2e/MJ, broken down per feedstock type: 20.3 gCO2e/MJ for cereals and other starch-rich crops, 23.3 for sugars, 93.3 for oil crops and 17.5 for other.

The principles of production of ethanol as a renewable fuel are straightforward. The starch component of grain is fermented into ethanol. The residual components are a mixture of grain protein, plant fibre and oil that are combined and processed into either a moist or dried product that is used as feed for livestock (Distillers Dried Grains and Solubles: DDGS). Carbon dioxide liberated during fermentation is captured, liquefied and used in soft drinks. In the context of this discussion there is one component that has been seriously ignored, and which adds significant value to the residual co-products. The ethanol fermentation process is a net generator of protein from the yeast which is generated to ferment the starch to ethanol. Either urea or liquid ammonia is added to the ferment and together with approximately 8-10% of the total grain starch is used to grow the yeast which is required for fermentation. There are approximately 10 life cycles of yeast growth to provide the total quantity required for the successful fermentation in a commercial fermenter. Dried yeast contains 40-44% crude protein. The spent yeast generated in fermentation is a valuable additional component of the residue that is processed into DDGS co-products. Precise calculation of the spent yeast cell content of ethanol co-products has proven difficult and the industry has relied on proxy estimations based on estimated number of life cycles in yeast generation and via the measurement of mannose, a component of yeast cell wall which is not present in any other component of the fermentation mix. Based on these proxy analyses the spent yeast content of the dry matter of DDGS, is estimated to be approximately 6% of total dry matter (Shurson 2018).

3. Distillers Dried Grains and Solubles (DDGS) co-products

Distillers Dried Grains and Solubles is the traditional coproduct produced during the production of ethanol and potable alcohol. It is a medium quality protein (15-30% crude protein) product (U.S. Grains 2023: Shurson 2023). The earliest reference relates to the production in Scotland in 1790 as a co-product from potable alcohol production. The product remains essentially unchanged and is extensively used as animal feed. Co-products *per se* are a unique category of feed materials in that they do not compete with food. When used in animal feed they contribute to a circular economy (Mottet et al., 2017). However, DDGS was never designed for any specific purpose and has only limited application across a wide range of livestock species. DDGS is unsuitable for use in premium aquaculture feed, companion animal diets, or specialised neonatal feeds. Nutritionally, DDGS is not an ideal feed option with only median protein concentration which is associated with a significant amount of indigestible fibre. Until recently, little effort has been made to further process these by-products to enhance their nutritional value. The recent growth of the bioethanol industry with the requirement for renewable liquid fuels has given impetus to focusing on the value of the co-product.

4. Corn Fermented Protein, production methods and applications

Corn fermented protein is an illustration of the application of technology to upcycle a median value commodity co-product into a high-quality feed protein. Current production is of the order of one million tons per year from 17 ethanol plants principally in North America. Production in Europe is at a nascent stage with one plant in full production and additional capacity pending. The fact that grain can be mechanically processed to produce a high protein product is already demonstrated in the wet milling process which was originally designed to produce pure corn starch. In the wet grind process the germ fraction of the grain is mechanically separated at the start of processing to produce a high-pro (>50% crude protein) gluten protein product from either wheat and/or corn (Applegate and Richert 2024).

The point at which novel fractionation technologies can be introduced into the process, after fermentation of the starch and recovery of the ethanol, is shown in Figure 1 (Applegate and Richert 2024).

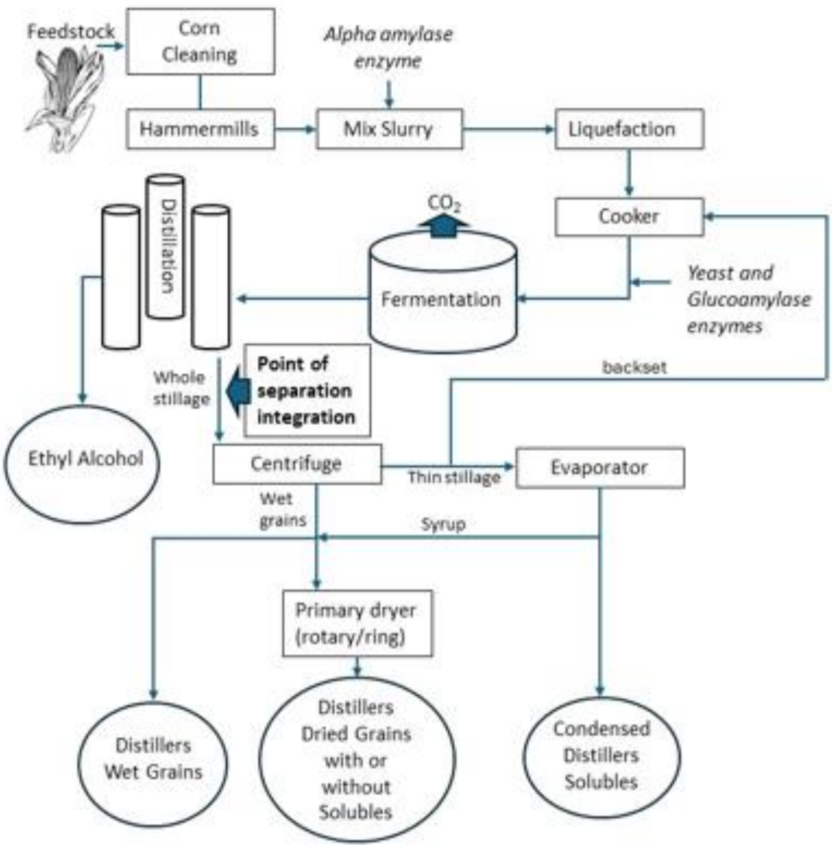

Figure 1. The dry grind ethanol process

Corn Fermented Protein is produced by separation of the whole stillage stream after ethanol distillation. The term corn fermented protein (CFP) refers to the fact that the products are derived from an initial fermentation lasting up to 70 hours. Fermentation of feed ingredients *per se* is recognized as providing nutritional benefits to animal feed products, fermentation of proteins is reported to increase peptide concentration (Bocheng et al 2020). CFP ranges in protein concentration from 50% crude protein (CP) as received to over 60% CP when either higher protein crops such as wheat are used as ethanol feedstock or enzymes are employed during fermentation to aid in protein recovery. Currently there are four different processes used to recover a Super Protein co-product from the dry grind ethanol process. Two of the processes involve post distillation, centrifugal separation of the liquid whole stillage fraction, achieving differential separation of suspended solids by centrifugal forces (MSC™: ICM Inc), a third involves flocculant separation of protein from the stillage fraction (Marquis) and a fourth electrostatic separation of dry particles (ST Equipment & Technology). A high proportion of the yeast generated during fermentation is recovered in the centrifugation step. Based on the proxy yeast analyses the spent yeast content of the dry matter of CFP 50% protein and CFP 60% protein is estimated to be approximately 24% and 16% respectively. For precise details of these industrial processes the reader is referred to respective company literature.

An operational bioethanol plant benefits from established high volume feedstock logistics, existing product supply chains, combined heat and power, and the capability of delivering essential feed quantities in commercial volumes (1000's tons annually). Close to one million tons of CFP protein from 17 ethanol plants is produced annually in America. In Europe, located in Hungary, the largest ethanol production facility has progressed with the production of a barley-based food protein and evolved into an advanced grain biorefinery. From production of sustainable renewable fuels to producing renewable natural gas, protein-rich animal feed and high-value food ingredients the dry grind ethanol process has evolved into a fully diversified, functional biorefinery.

5. Climate impact comparisons of commercial protein sources.

The sustainability characteristics of individual feed ingredients is a new decision factor in the choice of livestock feed ingredients. Sustainability (meeting energy and carbon emission reduction targets) was one of the key goals identified by the International Feed Industry Federation as a key global issue facing the industry. Indexes of sustainability such as Green House Gas (GHG) and Land Use Change (LUC) metrics are likely to be two new parameters that will become components of feed specification sheets in addition to the nutritional data that has been the norm.

A Cradle-to-Gate, Carbon Index (CI) life cycle assessment following the framework and principles of ISO 14040, 14044 and 14067 was made for CFP (Table1). Energetic production values from operational CFP production in a US bioethanol facility were used to create a CI evaluation in kilograms of CO_2 per metric ton of CFP. The assessment included a CI from the Climate Change impact category of Environmental Footprint (EF) 3.0 methodology in kilograms of CO2 per metric ton of product. It used an economic allocation to compare results with other common feed ingredients included in the Global Feed Lifecycle Assessment database (Green Plains Sustainability Report 2023; Ingredients that Matter). It is important that such comparisons are based on a geographically equivalent basis. The Carbon Index (CI), of corn fermented protein compares very favourably with many common, currently marketed, feed ingredients (Table 1). The values indicate that use of CFP has the potential to reduce the carbon index of feeds when in the formulation, it replaces other common proteins of similar crude protein concentration.

Table 1. Feed Proteins Climate Impact Comparison

Feed Proteins: Climate Impact Comparisons **GFLI 2.0 Database (Cradle-to-gate, Economic Allocation in USD)**	
Product	**Climate change impact (Kg CO_2/Ton product)**
Corn Fermented Protein (60% CP) at US dry grind bioethanol plant	600
Corn distillers dried grains with solubles at U.S. ethanol plant	655
Corn gluten meal at U.S. wet mill plant	799
Fishmeal at Norwegian fishmeal and oil production plant	1041
Pea Protein concentrate at German plant	2560
Soybean meal at Brazilian crushing plant	4258
Soybean protein concentrate at Brazilian crushing plant	7271

6. Alternative Proteins in Feed Formulation

Over the past decade, an emphasis on increased yield has led to a decline in protein content of two major feed crops, soybean and corn. Each crop has experienced a reduction of approximately two percentage units in protein content, attributable to the inverse pleiotropic relationship between yield and protein concentration. Furthermore, crop breeding which impacts the expression of developmental genes can affect plant morphology and source capacity, which can also negatively impact seed protein content and productivity. This reduction in protein concentration is totally contrary to the needs of livestock production. Over time livestock, have been bred for increased liveweight gain which has required increased nutrient concentration of the diet. Capacity for dietary intake has not kept pace with nutrient demand. Therefore, the livestock and aquaculture feed industries have increased demand for high concentration proteins. In addition, the impact of livestock production on environmental pollution and in particular nitrogen excretion increases the drive for reduced nitrogen excretion. Reduction in nitrogen excretion is achievable in the first instance by ensuring that the feed protein is highly digestible. Corn fermented protein is suitable for all compound feed production. It is incorporated into feed for livestock (poultry and pigs), aquaculture and companion animals. The trials data has been extensively reviewed for poultry (Burton *et al.* 2021; Williams 2024a), swine (Williams 2024b) and aquaculture (Wilson, 2026). The product is appropriate for inclusion in specialized diets requiring high digestibility, such as those for aquaculture, companion animals, and feed for neonates. CFP protein digestibility is greater than 87% in swine and poultry and measured in salmon and trout is approximately 88%. The consistency of CFP is demonstrated by a coefficient of lysine availability <2% across several different production facilities and over fifteen years of production. Compared to other supplementary proteins such as soybean meal, CFP does not contain many commonly identified anti-nutritional factors plus in addition to the positive impact of the upstream fermentation process. Furthermore, the fiber component has been exposed to fermentation which trials have demonstrated has a positive influence on hind gut fermentation.

A commercially viable alternative complementary protein for aquaculture is an important development to reduce the reliance on the use of fishmeal in diets for carnivorous fish e.g. salmon and trout. The alternative protein must complement and not undermine the animal proteins such as fishmeal, essential in diets for carnivorous fish. Growth trials have been completed with salmon, trout, tilapia, catfish, barramundi and shrimp. When included in feeds for aquaculture, CFP makes an ideal complimentary protein when used in combination with animal-based proteins such as fishmeal (Wilson, 2026). Specific examples are provided for salmon an example of a carnivorous fish and Channel Catfish a bottom feeder.

6.1. Atlantic salmon

An 84-day feeding trial with post-smolt (grower stage) Atlantic salmon of the St. John River strain (initial body weight 304.0±10.7g) was undertaken to assess the effect of graded inclusion levels of CFP on growth, feed efficiency, nutrient utilization, fillet pigmentation, blood biochemistry and gut histology. There was no significant negative impact on growth, feed intake, feed conversion ratio (FCR) and whole-body composition of salmon, with up to 15% inclusion level of CFP. Feed conversion ratios varied between 0.93 and 0.98 and were not significantly impacted by dietary treatment. The impact of feed supplements on fillet colour is an essential component of commercial salmon production. Due to the high carotenoid content of corn the use of corn proteins in diets for Atlantic salmon tends to be severely limited. There was no significant treatment effect on fillet pigmentation (redness and yellowness) CFP50 had no significant effect on fillet colour. Histological examination of the distal intestine confirmed that there was no irritation nor inflammation in the intestine of salmon offered the test diets. The histological examination conducted in this study indicated that the risks of developing enteritis and other intestinal disorder in salmon fed CFP50 at ≤15% dietary inclusion were low or absent. In conclusion CFP 50 was an ideal alternative protein for use in diets of post-smolt Atlantic salmon.

6.2. Channel Catfish

A trial was completed to assess the value of CFP for channel catfish (*Ictalurus punctatus*). The trial evaluated production performance, apparent digestibility coefficients, physiological responses, intestinal microbiota, and disease resistance of juvenile catfish offered diets containing graded levels of dietary CFP, replacing SBM on a protein basis (Yamamoto et al 2024). The apparent protein digestibility coefficient of CFP was high (89%) and similar to SBM (91%). However, phosphorus and lipid were twice as available from CFP than SBM. The 60-day feeding trial evaluated the gradual replacement of SBM by CFP on an equal nitrogen basis at 0, 25, 50, 75, and 100% replacement. CFP replaced up to 58% of the SBM in the diet while providing similar fish performance and body composition as fish fed the control diet. No differences were observed for hepatosomatic index, survival, or serum superoxide dismutase and lysozyme activities. Also, no treatment effects were observed for whole-body protein, ash, and protein conversion efficiency. The graded incorporation of corn fermented protein had no detrimental effects on the overall intestinal health and did not disrupt the posterior intestinal microbiome in juvenile channel catfish. A bacterial challenge test was used to investigate the potential impact of CFP containing spent yeast components on the immune response of the fish. On day 8, catfish were exposed to a virulent strain of *Edwardsiella ictaluri* through immersion. Survival after the bacterial challenge gradually increased as the inclusion levels of CFP increased in the diets, with the 100% replacement treatment survival being significantly higher than the control. The inclusion of CFP appeared to confer protection when catfish were challenged with *Edwardsiella ictaluri*. In conclusion, CFP was a promising alternative plant protein ingredient with high protein and phosphorus digestibility, that can replace up to 58% of the SBM in feed formulations for juvenile channel catfish based and potentially increase disease resistance. The results of the two trials provide evidence that incorporating CFP into aquaculture feed formulations offers additional health benefits that may be attributed to the mannans and β-glucans, present in spent yeast cell walls.

7. Use of Corn Fermented Protein in diets for Companion Animals

Corn fermented protein was evaluated as an alternative protein in food formulations for dogs (Kilburn-Kappeler et al., 2023; Vogel et al., 2025) and cats (Kilburn-Kappeler et al 2023). The objectives were to determine the palatability and apparent total tract digestibility (ATTD) of diets containing CFP. In addition, in the trials with female adult beagles, the influence of CFP-containing diets was tested on serum metabolites (haematology), and faecal characteristics, (metabolites, and microbiota). In formulations for dogs 15% CFP replaced soybean meal, corn gluten meal and brewer's yeast. All diets were highly digestible, and inclusion of CFP improved faecal score. In diets for cats 17.5% CFP provided a novel protein source based on acceptable stool quality, digestibility, and palatability but when fed to cats the maximum inclusion level of CFP appeared to be lower (10%) due to its increased fibre content.

In the European context the carbon footprint of diets manufactured using CFP was reduced by 14% compared with imported soybean meal. CFP provides an option to reduce or replace many traditional sources of imported vegetable protein with a highly digestible functional protein that derived from an industrial process, is not in competition with human food.

8. The drive for protein for feed

The use of vegetable crops such as corn, wheat and soybean that have traditionally been used for food as sources of feedstock for bioenergy has generated considerable controversy. The origins of this debate have failed to acknowledge that these bioprocesses produce feed and/or food products simultaneously. The soybean crop produces oil that is used in the production of biodiesel. Soybean meal is also a primary source of global feed protein meal. Grains such as corn and wheat that supply starch that is fermented to produce bioethanol also produce co-products for animal feed which now includes high quality protein products. These processes produce both food and fuel.

A factor often overlooked in creating novel animal feed products is that the animal feed industry relies on critical high volumes, of consistent products, to produce animal feed. Key aspects of supply chain performance are Resilience, Redundancy and Reliability. Changing a feed formulation to accommodate changes in raw material nutrient composition is an expensive and time-consuming exercise. Resilience with more than one supplier to supply consistently, the same product is key. Feed producers will not work with a single source of supply, in case of a plant stoppage. There needs to be redundancy in volume production to account for increased demand. The dry-grind ethanol industry with operational plants located world-wide meets these requirements.

Establishing new European protein crops is a significant challenge that will not be met in the short term. But there is an immediate need. The answer to provide an immediate solution, could lie in embracing traditional crops together with appropriate bioprocessing technology. The dry grind ethanol industry is an international industry converting traditional crops into renewable fuel and feed co-products. The current co-product Distillers Dried Grains and Solubles is a valuable feed product but has limited application across a wide range of livestock species. The biorefinery approach to recover protein has now been installed and established in corn ethanol plants. Corn fermented protein (CFP), produced by up-cycling DDGS is classed as a Super Protein (>50%crude protein). It is suitable for livestock, aquaculture and companion animals and capable of contributing to Europe's need for home-grown, high-quality feed protein. Within the next three years the renewable fuels industry could make a significant contribution to the requirement for highly versatile, non-GM, high quality, vegetable protein for animal feed, without any competition in the use of the crops for food.

The development of corn fermented protein (CFP) has emerged as a key advancement, offering a highly digestible protein alternative that can be tailored to the nutritional requirements of various animal species. By integrating CFP into feed formulations, producers can better balance protein levels while minimising anti-nutritional factors, enhancing overall feed efficiency and reducing the CI of the feed. This approach not only supports optimal animal growth and health but also contributes to reducing nitrogen excretion, thereby addressing environmental concerns associated with intensive animal production.

Moreover, the adoption of CFP aligns well with the European Union's ambitions to increase the sustainability and self-sufficiency of animal feed production. By utilising domestically available resources and reducing reliance on imports, particularly those associated with deforestation and land-use change, the integration of CFP supports both environmental and economic objectives. As regulatory frameworks continue to evolve, the flexibility offered by CFP enables feed manufacturers to adapt rapidly to new requirements while maintaining high standards of animal nutrition and welfare.

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