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Use of an Ethanol Bio-Refinery Product as a Soy Bean Alternative in Diets for Fast-Growing Meat Production Species: A Circular Economy Approach

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Abstract: The recent conceptual pivot from bioethanol production to ethanol biorefining has led to development of protein derived by fractionating the non-ethanol streams post fermentation within the plant. The aim of this study was to identify the effect of replacing dietary soy with corn-fermented protein (CFP) on performance of fast-growing meat species and the impact on the carbon footprint associated with the feed for each species. The study contains trials on 3 species, broiler, turkey and salmon. In trial one, 324 broiler chicks were allocated randomly to 36 pens distributed into 3 dietary treatments; control (0% CFP), 5% CFP and 10% CFP; for 35 days. In trial 2, 150 turkey poults were allocated to 3 treatments: control (0 CFP), 4% CFP and 8% CFP for 35 days. In trial 3, 525 Atlantic Salmon (starting weight 304 g ± 10.7 g) were raised in 15 saltwater tanks for 84 days with 5 treatments, control (0% CFP), 5% CFP, 10% CFP, 15% CFP and 20% CFP. Growth response, nutrient utilisation and carbon footprint were assessed in each trial. Replacement of soy with CFP showed limited differences in growth response and nutrient utilization but replacing soy bean meal with CFP at rate of 5%, 8% and 10% in broiler, turkey and salmon diets, respectively resulted in a 14% decrease in carbon footprint of diet manufacturing. This investigation shows coupling bioethanol production with poultry and salmon production represents a highly effective circular economy contributing to multiple UN Sustainable Development Goals.

Keywords: sustainable development; food security; biorefining; salmon; poultry; net zero

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Citation: Burton, E.; Scholey, D.; Alkhtib, A.; Williams, P. Use of an Ethanol Bio-Refinery Product as a Soy Bean Alternative in Diets for Fast-Growing Meat Production Species: A Circular Economy Approach. *Sustainability* **2021**, *13*, 11019. https://doi.org/10.3390/su131911019

Academic Editor: Michael S. Carolan

Received: 2 September 2021
Accepted: 28 September 2021
Published: 4 October 2021

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1. Introduction

Poultry and fish are both increasing in popularity as protein sources in human diets. Fish consumption has increased by 122% between 1990 and 2018 [1] with an over 500% rise in aquaculture production globally over the same timescale. Salmon production is estimated to reach 2.7 million tonnes (MT) by 2021, compared to 0.8 MT in 2000 [2]. Similarly, poultry meat production is also increasing year on year and is predicted to have reached 137 MT in 2020 [1]. This rapid increase in the scale of meat production inevitably creates a conflicting global role for poultry and fish production: in rapidly increasing their contribution to UN Sustainable Development Goal (SDG) 2 (Zero hunger) and SDG 3 (Good health and wellbeing), the negative implications for SDG 12 (Responsible consumption and production) and SDG 13 (Climate action) are concurrently increased through increased resource use and pollution, respectively. Development of circular economies is an effective way to reduce the livestock and poultry pollution, improve the utilization efficiency of resources [3], and to balance economic development and environmental protection [3]. It is well recognised that the potential for extensive environmental impact from poultry production is substantial if a linear model is followed [4] and the key to sustainable development in animal production is conversion of potential waste and pollutants into resources [4]: negative externalities may be transformed into positives ones by identifying potential beneficiaries of waste streams [3].

Historically, circular economy models involving poultry production have focussed on the waste (or, more appropriately, co-product) streams associated with meat or egg production. The scale and speed of bird growth on a modern poultry farms means that a single farm may produce more than 700 tonnes of manure each year. This volume far exceeds the volume that may be safely applied as fertiliser to surrounding arable land, leading to harmful levels of N and P levels in soil if application to land is continued [5] or, if not managed properly, un-needed manure can be dangerous to the health of local waterways and the people who depend on them [5]. The greatest focus of circular economy models involving poultry production has been on converting the litter (mix of manure and bedding) into energy via anaerobic digestion, combustion, pyrolysis and gasification [5]. Waste management is now attracting increasing cooperation between multi-field stakeholders (including governments) to promote circular economy approaches [5], for example through generation of innovative bio-based functional products from feather meal [5] and egg shells [5] and fish processing waste [5]. While the outputs from fish and poultry production are increasingly incorporated into circular economies, the main input, feed, has moved away from a circular approach where by-products from other food production sectors were used to a high natural resource approach where soya beans are grown specifically for inclusion in animal feed. In order for meat production to develop sustainably, feed producers must revert to their traditional of using co-products from other industries.

Soy is one of the most internationally traded agricultural commodities, and is principally used globally as the protein component of animal feed [6]. Brazil and the United States are jointly the world's leading soy producers and exporters, [7]. While the land use change associated with Unite States soy production occurred more than 25 years ago and so incurs no penalties in current greenhouse gas (GHG) emission assessments, expansion of soy production in Brazil is associated with deforestation [8]. The major role of Brazilian deforestation to GHG emissions (Maciel et al., 2016) is now raising concerns among consumers, leading traders and governments to take measures to prevent deforestation [9]. The carbon footprint (CF) of Brazilian soy used in animal feed depends not only on deforestation, but also the GHG emissions associated with transport to the importing country. The required transportation distance for soy used in European countries adds to the CF associated with soy use in European animal feed.

Meat for human consumption is derived from two types of animal: ruminant animals (primarily cattle and sheep) and non-ruminants (primarily fish, pigs and poultry). The ability of ruminants to digest fibre as an energy source and to utilise non-protein nitrogen to meet their amino acid requirements means that ruminant animals such as beef cattle are readily able to consume fibrous products that are not suitable for direct human consumption but their comparatively slow growth and methane gas outputs give a high carbon tariff to beef. In contrast, the high growth rates and extremely efficient feed conversion rate to usable meat of salmon and poultry give them a low carbon footprint but render them extremely sensitive to fluctuations in the quality of feed provided and the density of protein and energy in the feed, which limits the inclusion of many co-products. Each year, more than 30 MT of soybean meal is imported into the EU for inclusion in animal feed due to its high protein content, balance of amino acids and low levels of residual antinutritional factors [7]. Poultry as a whole account for most soy use in the EU [10], but production of soy beans in Europe is limited. Soy has a low yield and long growing season in the European climate and soil, so production cannot compete with the more efficient growth in countries such as Brazil [11]. Soy use often does not fit sustainability objectives [12] particularly as widespread deforestation is common in soy production in many countries.

In order to reduce the use of soy in poultry and fish feed, there is a need to consider novel and alternative proteins associated with lower carbon footprint (CF). Use of some conventional proteins have been limited in the EU, either due to lack of supply [13] or due to EU wide bans [14]. Alongside the mounting pressures to reduce levels of soy used in animal feed, legislatures such as The Renewable Fuel Standard in the USA and The Renewable Transport Fuel Obligation in the UK have driven massive increases in bioethanol production from cereal (first generation bioethanol). In 2011, the estimated global production was around 113 billion litres [15]. Production of bioethanol is a exogenous enzyme and fermentation-based technology using Saccharomyces cerevisiae yeast to produce ethanol and a residual mash co-product known as 'whole stillage' which is subsequently decanted into a fibrous wet portion and a liquid component with only around 60–85 g/kg dry matter [16], 'thin stillage' that contains the majority of the yeast protein and soluble components. In traditional ethanol fermentation systems, the thin stillage is evaporated into a syrup, remixed with the wet grain and dried to form Distiller's Dried Grains with Solubles (DDGS). The evaporative drying of the co-product is an energy-demanding, expensive necessity in order to remove all the "waste" material not required for the production of ethanol from the distillery which, if not removed, would congest the primary process of ethanol production.

DDGS is successfully used in ruminant feed [17] but the high fibre content decreases feed intake and limits nutrient utilization in fast growing species such as pigs, salmon, turkey and broiler (meat-type) chicken [18]. Therefore, the biorefining process associated with bioethanol production has been recently adapted to develop high protein, low fibre biorefinery co-products more suitable for non-ruminant meat species than DDGS [19]. The aim of this study is to assess the nutritional viability of partially replacement of SBM with corn-fermented protein (CFP) in the feed of fast growing meat species and to determine the impact of SBM replacement with CFP on the carbon footprint associated with the feed for each species.

2. Material and Methods

2.1. Study Design

Three animal growth experiments were conducted to evaluate the impact of replacing soy in salmon, turkey and broiler chickens. Institutional and national guidelines for the care and use of animals were followed and all experimental procedures involving animals were approved by the local ethical review committees. For each growth experiments, diets were formulated to meet the need of the age and strain of species used, with partial replacement of high (>44%) protein soy bean meal (SBM) by a high (>50%) protein biorefinery co-product (Corn-Fermented Protein from a Maximized Stillage Co-products™ process, Fluid Quip Technologies, Cedar Rapids, IA, USA) as summarized in Table 1.

Table 1. Replacement levels of soy bean meal with CFP in animal trials.

Species	Treatment	SBM (%)	CFP (%)	% SBM Reduction
Turkeys	control	47.3	0	0
	4% CFP	44.6	4	5.7
	8% CFP	41.9	8	11.4
Broilers	control	34.2	0	0
	5% CFP	28.6	5	16.4
	10% CFP	22.9	10	33
Salmon	control	13.2	0	0
	5% CFP	11.5	5	12.9
	10% CFP	9.8	10	25.8
	15% CFP	8.2	15	37.9
	20% CFP	6.5	20	50.8

2.2. Broiler Study

Male, Ross 308 broilers (n = 324) were obtained from a commercial hatchery at day of hatch. Chicks were weighed individually and allocated to 0.64 m^2 floor pens in groups of 9 birds per pen. Pens contained clean wood shavings as bedding and two nipple drinkers per pen. There were three dietary treatments with CFP inclusions of 0, 4 and 8% (see

Table 1 and Appendix A for more information), and these were each randomly allocated to 12 pens by block. Feed was available from 50 cm troughs in each pen ad libitum. The room was maintained at 31 °C and reduced based on Ross guidelines and bird behaviour to reach approximately 21 °C by D21. The lighting was increased from 23 h on D1 to 18 h by D6, and the 6 h of dark were maintained throughout the rest of the study. Diets were commercially formulated using a wheat, soy bean meal base and were produced by a commercial manufacturing facility (Target Feeds Ltd., Shropshire, UK). Diets were fed in two phases, starter crumb (D0–21) and grower pellet (D21–42), and all diets contained 0.5% TiO_2 as an inert marker for digestibility measures. Nitrogen content of the diets was determined using a combustion analyser (Dumatherm N Pro, Gerhardt Analytical Systems, Germany) then multiplied by 6.25 to derive crude protein content. Dry matter content and ether extractable fat content of diets were analyzed according to [20] (methods 930.15 and 945.16, respectively) was analysed by bomb calorimetry with sucrose as a standard [21]. Diet analysis is available in Appendix A, Table A1.

Birds and feed were weighed weekly on a pen basis to calculate bodyweight gain, feed intake and feed conversion ratio (FCR). On D42, two birds per pen were euthanized by cervical dislocation and butchered by a trained operative to assess carcass yield. Breast, thigh and drumstick (excluding skin) were collected and pooled to give an incomplete estimate of carcass meat yield. Excreta was collected per pen on D42, with a minimum of 10 g collected per pen, and dried in a forced air oven at 105 °C until constant weight. Dried, ground excreta and diets were analysed for titanium dioxide content by the spectrophotometric method described by [22]. Excreta was also analysed for nitrogen content as previously described. Nitrogen retention was calculated using the following equation:

$$\text{N per g diet} - \text{N per g Excreta} \times (\text{Diet TiO}_2/\text{Excreta TiO}_2) \tag{1}$$

Statistical analysis was carried out using R [23]. Data outside 2 standard deviations from the mean for each variable were considered as outliers. Data of the study were analysed according to the following model:

$$Y(ij) = \mu + \text{Diet}(i) + \text{Block}(j) + \varepsilon(ij) \tag{2}$$

where Y is the response variable, μ is the overall mean, Diet is the effect of the experimental diet and ε is the residual. The pen was used as an experimental unit. Means were separated using Tukey's test at $p \leq 0.05$.

2.3. Turkey Study

Male, BUT6 turkey poults (n = 150) were collected on day of hatch and allocated in groups of five to 10 pens per treatment. Pens were 0.64 m^2 and contained two water nipples and clean wood shavings as bedding. The room was maintained at 32 °C from D0 and the temperature was reduced daily to reach 21 °C by D21. Lighting was 23 h of light a day until D2, decreasing by 1 h a day to reach 8 h of darkness, which was then maintained throughout the study. Diets were formulated by a commercial nutritionist to be matched for protein, amino acids and energy (formulations and analysis in Appendix A). Treatments contained 0, 4 and 8% of CFP as detailed in Table 1 (see Appendix A, Table A2 for diet details) and all diets contained 0.5% TiO_2 as an indigestible marker. Each treatment was randomly allocated by block to 10 pens and was feed and water were available ad libitum throughout the study. Diets were provided as starter, sieved crumb (D0–21) and grower, short pellet (D21–42) and manufactured by a commercial mill (Target Feeds, Ltd., Shropshire, UK). Diets were analysed as previously described.

Poults and feed were weighed weekly by pen to calculate bodyweight gain, feed intake and FCR. On D42 3 birds per pen were culled by cervical dislocation and ileal digesta collected from the region between Meckel's Diverticulum and the ileal cecal junction. Ileal digesta was pooled per pen and freeze dried and ground before analysis.

Diets and digesta were analysed for nitrogen content and titanium dioxide marker to assess ileal nitrogen digestibility using the following equation

$$\text{N per g diet} - \text{N per g Digesta} \times (\text{Diet TiO}_2/\text{Digesta TiO}_2) \quad (3)$$

Statistical analysis was carried out using SPSS v.24. After KS testing to confirm normality, data were analysed using one way ANOVA to investigate the effect of dietary treatment on FCR, feed intake (per bird) and individual bodyweight gain for each weigh period of the study, and cumulatively. Where appropriate, Bonferroni post hoc testing was used to elucidate differences between diets/treatments.

2.4. Salmon Study

Atlantic Salmon (n = 525; starting weight 304 g ± 10.7 g) were raised in 15 saltwater (25 ppt) tanks with 35 fish per tank for 84 days. Tanks were maintained in a recirculating aquaculture system using 750 L tanks and temperatures maintained at 14.2 °C (±0.6 °C) with greater than 90% oxygen saturation. A control diet was formulated to meet the needs of Atlantic salmon [24] and four further diets were formulated to contain graded levels of CFP; 5, 10, 15 and 20%. Diets were manufactured and extruded via a twin-screw cooling extruder and vacuum coated in the oil component of the diet (see Table 1 and Appendix A, Table A3). Each diet was fed to three tanks of fish. Salmon were fed by hand to satiety three times a day.

Fish were weighed on D0, 28, 56 and 84 of the study, with 5 fish per tank used to provide a mean fish weight. Five fish per tank were euthanized on D84 for whole body protein composition via the AOAC method (990.03). These results were used to calculate the rate of protein deposition using the following equation [25]:

$$D_j = \frac{F_j - I_j}{\sum_{i=1}^{n}(T_i \times t_i)} \quad (4)$$

where D_j is deposition rate [mg (°C • d)-1] of nutrient j, F_j and I_j are final and initial whole-body mass of nutrient j (mg) at the end and the beginning of the 84-day period, respectively, n stands for the day number covering the period from F_j to I_j, T_i (°C) is mean daily water temperature for day T_i, the product of which results in units of degree-days.

The results were analysed using one-way ANOVA and Tukey's multiple comparison test with GraphPad Prism version 8.1.2 for Windows. Statistical differences were considered significant at $p < 0.05$.

2.5. Carbon Footprint Calculation

Global Food LCA Institute (GFLI) database (version 28-Dec-2018) was used to calculate the carbon footprint of the experimental feed. The carbon footprint of feeds was calculated using ReCiPe 2016 midpoint (H) assessment method with "economic" method of allocation. The GLFI database does not contain the footprint of high protein, ethanol bio-refinery product. Thus, the carbon footprint of high protein, ethanol bio-refinery product was obtained from Tallentire et al. (2018). The carbon footprint (kg CO_2 e/kg feed) was normalized for 1 kg of live weigh growth of Turkey and Salmon and 1 kg of meat yield of broilers.

3. Results

3.1. Broiler Study

Table 2 summarizes the performance of the broiler study and the nitrogen retention measured in the birds at D42. Feed intake increased with increasing levels of CFP in the diets, with intake of 10% CFP-fed birds being significantly higher than the control. FCR was also significantly increased for the 10% CFP diet. Nitrogen retention was significantly improved for the 5% CFP diet over both the control and the 10% diet.

Table 2. Bird weight (BW), feed intake (FI), feed conversion ratio (FCR) and Nitrogen retention for broilers fed graded levels of Corn-Fermented Protein (CFP).

Parameter	Control	5% CFP	10% CFP	SEM	*p* Value
BW/bird D0 (g)	45	45	44	0.2	0.086
BW/bird D42 (g)	3360	3439	3339	32.7	0.144
FI/bird D0–42 (g)	4878 ^{b}	5042 ^{ab}	5151 ^{a}	61.8	0.028
FCR D0–42	1.47 ^{a}	1.49 ^{a}	1.57 ^{b}	0.02	0.005
N retention (%) *	29.4 ^{b}	30.4 ^{a}	28.7 ^{b}	0.27	0.002

SEM; standard error of the mean. Superscript letters denote significant differences within a row. * excreta nitrogen retention.

Table 3 shows the calculated carbon emissions per kg of bird growth, and also per kg of meat production (based on carcass yield of breast, thigh and drum only). It can be seen that all three GHG calculations show a reduction in CO_2 emissions with increasing dietary content of CFP.

Table 3. Greenhouse gas emissions (GHG; calculated) on a per bird, per kg growth and per kg meat basis for broilers fed graded levels of corn-fermented protein (CFP).

Parameter	Control	5% CFP	10% CFP
GHG (kg CO_2 e/bird)	8.22	7.49	6.62
Meat yield (kg)	1.41	1.49	1.45
Weight gain (kg/bird)	3.32	3.39	3.3
GHG (kg CO_2 e /kg growth)	2.48	2.21	2.01
GHG (kg CO_2 e/kg meat)	5.85	5.03	4.57

3.2. Turkey Study

The performance of the turkey poults at D42 is shown in Table 4. Bodyweights at D42 increased numerically with CFP inclusion, but there were no significant differences in any performance measure over the six-week trial period. Nitrogen retention was significantly increased at 10% dietary inclusion of CFP over the control, soy-based diet.

Table 4. Performance of turkey poults fed graded levels of corn-fermented protein (CFP).

Parameter	Control	4% CFP	8% CFP	SEM	*p* Value
BW/bird D0 (g)	66	66	66	1	0.962
BW/bird D42 (g)	2328	2423	2518	52.1	0.122
FI/bird D0–42 (g)	3741	3850	3743	77.3	0.363
FCR d0–42	1.66	1.64	1.61	0.028	0.797
N retention (%)	18.3 ^{b}	21.0 ^{ab}	21.8 ^{a}	0.98	0.001

BW: body weight; FI: feed intake; FCR: feed conversion ratio; N: nitrogen; SEM: standard error of the mean. Superscript letters denote significant differences within a row.

Table 5 shows the calculated GHG emissions of the birds fed graded levels of Corn-Fermented Protein (CFP) on a per bird and per kg growth basis. Both measures show a reduction in CO_2 emissions with increased CFP inclusion.

Table 5. Greenhouse gas (GHG) emissions for turkey poults fed graded levels of Corn-Fermented Protein (CFP).

Parameter	Control	CFP 4%	CFP 8%
GHG (kg CO_2 e/bird)	8.96	8.88	8.34
Weight gain (kg/bird)	2.26	2.36	2.45
GHG (kg CO_2 e/kg growth)	3.96	3.77	3.40

3.3. Salmon Study

The fish performance measures and the protein retention for the trial period (84 days) is shown in Table 6. Final salmon weights were significantly higher for the 10% CFP inclusion diet compared with the 20% inclusion diet (752.1 g vs. 663.7 g, respectively). Feed intake was also highest for the 10% CFP diet and the control diet compared with the 20% CFP diet. There were no significant differences in FCR or protein retention during the duration of this study.

Table 6. Performance and protein deposition in salmon fed graded levels of Corn-Fermented Protein (CFP) over an 84-day trial period.

Parameter	Control	5% CFP	10% CFP	15% CFP	20% CFP	SEM	*p* Value
Initial BW (g) D0	295	301.9	305.7	304.7	305	5.28	0.858
Final BW (g) D84	720.0 ^{ab}	701.1 ^{ab}	752.1 ^{a}	690.8 ^{ab}	663.7 ^{b}	15.96	0.034
FI/fish D0–84 (g)	411.9 ^{a}	370.5 ^{ab}	414.4 ^{a}	377.8 ^{ab}	348.3 ^{b}	11.74	0.016
FCR D0–84	0.98	0.93	0.93	0.97	0.97	0.014	0.288
Protein deposition (%)	19.8	23.1	23.0	22.1	26.0	1.46	0.181

SEM: standard error of the mean. Superscript letters denote significant differences within a row.

Table 7 shows the calculated GHG emissions and CO_2 output for the salmon study. CO_2 output is reported on a per kg feed basis and also per kg of fish growth. Increasing inclusion of CFP reduces GHG emissions in a linear fashion.

Table 7. Greenhouse gas emissions (GHG; calculated) for salmon fed graded levels of Distiller's high protein (CFP).

Parameter	Control	5% CFP	10% CFP	15% CFP	20% CFP
GHG (kg feed)	1.64	1.55	1.47	1.39	1.3
Weight gain (kg)	0.425	0.399	0.446	0.386	0.359
GHG (kg CO_2 e/kg growth)	1.59	1.44	1.37	1.36	1.27

4. Discussion

Previous studies theoretically modelling LCA have suggested that a CFP type product increases nitrogen excretion associated negative environmental impacts [26], but this study showed that nitrogen utilization was significantly improved with CFP for both poultry studies studied and not affected in salmon. Therefore, although the CFP has higher total protein nitrogen than SBM, its improved digestibility mitigates the additional feed nitrogen and reduces excretion to a similar level to SBM. Beyond the positive environmental impact associated with this improved nutrient utilization, further quantifiable effects are incurred earlier in the meat production process; associated with production of the individual feed material. Agricultural land use (ALU) associated with feed material production substantially contributes to CF, so maintaining low ALU values is a key focus in low carbon meat production. In the case of CFP, the ALU comes almost entirely from the production of the cereal crop [26]. However, with multiple product streams deriving from the fermentation process, this ALU tariff is spread across a number of co-products including as corn oil and bioethanol. Therefore, the calculated CF of diets including CFP are substantially reduced compared to diets relying on SBM as the main dietary protein source.

Use of soy as livestock feed outside the Americas incur a high CO_2 cost relating to the long distance of transportation. In addition, South American soy production is associated with high level of deforestation, resulting in particularly high ALU tariffs derived from the additional land use change. Accordingly, decreasing the dependency on soy in livestock nutrition would reduce the negative consequences of soy production and transportation on the environment due to the large penalties associated with land use change. CFP is currently produced at 500 thousand tonnes per annum from six bioethanol plants in the USA, which will increase to an estimated 1 million tonnes a year by the end of 2023. CFP is a co-product with high protein content which is produced from bioethanol generation. Accordingly, it is expected to be a low-GHG replacement of soy in livestock nutrition. Furthermore, it is more cost-effective source of nutrients for livestock compared to conventional feedstuffs [27].

The results of the current study show N retention of broilers fed diets containing 5% CFP in place of SBM, and 8% CFP in turkey diets was higher than the control; which conflicts with previous studies on traditional bioethanol co-product: DDGS. Ref. [28,29] reported that increased manure production and manure N excretion was produced by broilers fed high-protein corn distillers dried grains. This negative effect may be due to the increase in dietary fibre and reduction in protein digestibility resulting from heat damage associated with DDGS production [30]. However, the replacement of soy by CFP in the current study did not introduce sufficient fibre or heat-damaged protein to negatively impact on broiler performance or nitrogen retention. Furthermore, the high digestibility of CFP reduces N excretion in comparison to wholly SBM-based diets. This improvement in N retention of broilers fed 5% CFP would decrease the NH3 emission from broiler production, creating added value from 5% CFP inclusion beyond the quantified parameters reported in the current study. Interestingly, 10% dietary inclusion of CFP improved nitrogen retention of broilers, but also increased feed intake without a concurrent improvement in weight gain, so deleteriously effecting feed conversion ratio and therefore negatively impacting the economic viability of including 10% CFP in broiler diets. However, a 10% dietary inclusion of CFP provides a 19% reduction in CO_2 output compared with the control diet on a basis of per kg growth, and a 22% reduction in CO_2 emissions on the basis of kg of meat produced. This reduction is 11% (per kg meat) and 14% (per kg meat) for the 5% inclusion of CFP. Turkeys may be fed diets including to 8% CFP in place of SBM with no effect on performance but a reduction in GHG emissions of 14% compared to turkeys fed the control diet. Distillers dried grains with solubles were included in broilers (up to 12%) and Turkeys (up to 8% diets) without negative consequences on growth performance [30]. Similarly to the poultry studies, the salmon study showed no improvement in growth related to dietary SBM replacement with FP, and, as with the broilers, the highest CFP level diet led to a small, negative effect on growth. This lack of improved growth response in salmon is surprising as previous studies show DDGS may totally replaces fish meal in fish diets when fishmeal is included at a level of 12% of the diet [31]. The DDGS was used as a protein source in rainbow trout diet without negative effect on digestibility and growth [30]. It has also been reported that DDGS can be used at levels up to 90% of winter diets for channel catfish without amino acids supplementation [32,33]. In alignment with the poultry trials, inclusion of 10% CFP in salmon diets leads to a reduction in CO_2 cost of one kg growth of almost 14% over the control diet.

In all three species assessed, the impacts on growth performance were limited but the positive impacts of including CFP in place of soy on the CF of each species diet were substantial. This initial evidence that partial CFP replacement of dietary soy reduces the carbon footprint of meat production justifies further in vivo studies directly assessing carbon cost of meat from fish and poultry fed CFP-containing diets as predictive modelling approaches (Tallentyre et al., 2018) provide conflicting results.

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Successful circular economies rely on precise alignment of needs between producers and users. Cereal-based bioethanol plants have historically produced a secondary product of low and inconsistent nutrient value that has limited attraction as an animal feed material. The expansion of cereal-based bioethanol production raised initial concerns that the concurrent increased supply of the traditional co-product (DDGS) would exceed feed use potential [34]. However, the reframing of bioethanol production into biorefining, where multiple product streams are empirically scrutinized and modelled for optimum plant design [35], has revolutionized the sustainability of cereal-based bioethanol plants. The new engineering and plant design focus has been on optimizing the generation of high-quality protein from the bioethanol plants [36]. The multiple-species evaluation of CFP reported here shows that the biorefinery approach has created a protein product aligned to the needs of very high-volume users: salmon and poultry meat producers. The economic impact on the bioethanol plants pivoting to a biorefinery approach with multiple high value streams was particularly apparent as demand for transport fuel decreased during the early phase COVID-19 pandemic [37]. The environmental impact of partially replacing soy with a biorefinery product (CFP) in the diet of salmon and poultry has been clearly demonstrated in the reported studies. This shows that the development of circular economies is not only an effective way to reduce the livestock and poultry pollution, but may also be used to improve the utilization efficiency of resources and support environmental protection, thereby allowing meat production to simultaneously supporting a number of UN SDGs without concurrent detriment to others.

5. Conclusions

Inclusion of CFP in broiler, turkey and salmon diets at a rate of 5%, 8% and 10%, respectively improved nitrogen retention while decreasing GHG emissions. This indicates partial replacement of soy with CFP in the diets of fast-growing meat species would reduce the environmental impact of meat production without impacting on growth performance. Corn-fermented protein (CFP) presents a nutritionally viable option for partial replacement of soy in fish and poultry feed. The replacement of 10% of dietary soy with CFP is associated with a 19% and 14% reduction in CO_2 production associated with poultry and salmon production, respectively. Coupling bioethanol production with poultry and salmon production represents a highly effective circular economy.

Author Contributions: Conceptualization, P.W. and E.B.; methodology, P.W., D.S. and A.A., investigation, E.B., P.W. and D.S.; data curation, D.S. and A.A.; manuscript preparation, E.B., A.A. and D.S. All authors have read and agreed to the published version of the manuscript.

Funding: The authors would like to acknowledge the financial support of Fluid Quip Technologies, LLC to cover the cost of completing the three animal experiments.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The datasets generated during the current study are available from the corresponding author on reasonable request.

Acknowledgments: The authors would like to thank the research teams involved at Nottingham Trent University and The Center for Aquaculture Technologies Canada.

Conflicts of Interest: Peter Williams is employed as a consultant by Fluid Quip Technologies, LLC and contributed to the design of the studies but not the interpretation of the findings, which was undertaken by the NTU authors who declare no conflict of interest.

Appendix A

Table A1. Turkey diets formulation, starter and grower phases.

	Starter			Grower		
Ingredient (g/kg)	**Control**	**4% DHP**	**8% DHP**	**Control**	**4% DHP**	**8% DHP**
Corn fermented protein (CFP)	0	40	80	0	40	80
Dicalcium P 18%	41.3	41.1	41	37.5	37.4	37.3
DL Methionine	3.8	3.7	3.6	3.3	3.1	3
Full fat Soya	20	20	20	20	20	20
High protein sunflower meal	30	30	30	30	30	30
Limestone	8.2	8.5	8.8	7.8	8.1	8.3
Lysine mono HCl	4	4.1	4.2	3.5	3.6	3.7
Salt	1.6	1.5	1.5	1.7	1.7	1.6
Sodium Bicarbonate	3.1	3.1	3.2	2.6	2.6	2.7
Hipro soya	473	446.2	419.4	404.6	377.8	351
Soya oil	32.7	30.7	28.6	32.9	30.8	28.8
Vit/Min premix *	4	4	4	4	4	4
Threonine	0.6	0.4	0.2	0.6	0.3	0.1
Maize	377.1	366	355	451	439.9	428.9
Total calculated g/kg						
Dry matter	889.9	891.9	894	889.1	891.2	893.3
Ash	73.1	73.4	73.7	66.7	67	67.3
Protein	276.4	282.4	288.4	249.3	255.4	261.4
EE Fat	58.5	56.3	54.1	60.1	57.9	55.7
Gross energy (MJ/kg)	11.9	11.9	11.9	12.2	12.2	12.2
Calcium	14	14	14	12.8	12.8	12.8
Av Phosphorous	7	7	7	6.4	6.4	6.4
Cysteine	4.3	4.4	4.6	3.9	4.1	4.2
Methionine	7.8	7.9	8.1	6.9	7.0	7.2
Lysine	18.8	18.9	19.0	16.6	16.7	16.8
Threonine	11.1	11.1	11.2	10.0	10.0	10.1
Valine	12.5	12.9	13.2	11.2	11.6	12.0
Isoleucine	11.7	11.9	12.1	10.4	10.7	10.9
Leucine	21.7	22.8	24.0	19.9	21.1	22.2
Tyrosine	8.3	7.8	7.3	7.1	6.6	6.1
Phenylalanine	11.2	11.5	11.9	9.5	9.9	10.3
Arginine	18.8	18.8	18.8	16.8	16.8	16.8

All diets contained 0.6 g/kg coccidiostat; * Premix content (volume/kg diet): Mn 100 mg, Zn 88 mg, Fe 20 mg, Cu 10 mg, I 1 mg, Mb 0.48 mg, Se 0.2 mg, Retinol 13.5 mg, Cholecalciferol, 3 mg, Tocopherol 25 mg, Menadione 5.0 mg, Thiamine 3 mg, Riboflavin 10.0 mg, Pantothenic acid 15 mg, Pyroxidine 3.0 mg, Niacin 60 mg, Cobalamin 30 μg, Folic acid 1.5 mg, Biotin 125 mg.

Table A2. Broiler diet formulations.

	Starter			Grower		
% in Diet	**Control**	**5% DHP**	**10% DHP**	**Control**	**5% DHP**	**10% DHP**
Wheat	60.28	61.41	62.16	67.58	68.68	69.84
Hipro soya	34.24	28.55	22.85	25.58	19.99	14.28
Soya oil	1.95	1.36	1	4.1	3.52	2.93
Limestone	1.12	1.17	1.32	0.89	0.94	0.99
Mono cal P	0.94	0.9	0.86	0.55	0.5	0.46
Salt	0.25	0.19	0.15	0.25	0.23	0.19
Sodium Bicarbonate	0.15	0.22	0.27	0.15	0.17	0.22
Lysine HCL	0.25	0.35	0.45	0.2	0.28	0.37
DL Methionine	0.29	0.28	0.26	0.22	0.19	0.17
L Arginine	0	0.2	0.11	0	0	0.07

Table A2. *Cont.*

	Starter			Grower		
% in Diet	**Control**	**5% DHP**	**10% DHP**	**Control**	**5% DHP**	**10% DHP**
L Threonine	0.12	0.13	0.14	0.07	0.07	0.07
Valine			0.005			
Phytase/Econase	0.02	0.02	0.02	0.02	0.2	0.2
Premix *	0.4	0.4	0.4	0.4	0.4	0.4
Corn fermented protein (CFP)	0	5	10	0	5	10
Nutrient content (% unless stated)						
Oil A (Ether Extract)	4.13	3.99	3.16	5.98	5.18	4.95
Calcium	0.72	0.99	0.93	0.67	0.64	0.64
Copper (mg/kg)	56	48	30	20	16	18
Iron (mg/kg)	563	532	265	113	92	106
Magnesium	0.16	0.16	0.16	0.11	0.12	0.12
Manganese (mg/kg)	128	148	137	117	116	117
Phosphorus	0.56	0.59	0.57	0.42	0.42	0.43
Potassium	0.95	0.93	0.89	0.71	0.7	0.65
Sodium	0.15	0.21	0.18	0.13	0.14	0.15
Zinc (mg/kg)	135	149	137	121	106	117
Crude Protein	21.7	21.9	22.1	16.8	18.6	19.1
Crude Fibre	2.3	2.4	2.2	2.2	2.3	2.4
Dry Matter	88.4	88.9	88.4	88	88.1	88.7
Ash	5.4	6.1	5.4	5	4.9	4.8
Total Oil (Oil B)	4.84	4.74	3.87			
Cystine	0.3	0.33	0.34	0.29	0.3	0.33
Aspartic	1.96	1.83	1.73	1.49	1.48	1.49
Methionine	0.53	0.62	0.57	0.45	0.49	0.49
Threonine	0.86	0.88	0.86	0.67	0.71	0.75
Serine	1.01	0.99	0.98	0.83	0.87	0.93
Glutamic	4.47	4.37	4.44	3.82	3.99	4.23
Glycine	0.91	0.9	0.86	0.69	0.72	0.76
Alanine	0.88	0.93	0.97	0.68	0.76	0.88
Valine	0.89	0.95	0.96	0.75	0.8	0.86
Iso-Leucine	0.86	0.85	0.83	0.67	0.71	0.74
Leucine	1.52	1.58	1.69	1.22	1.39	1.6
Tyrosine	0.48	0.53	0.51	0.35	0.43	0.46
Phenylalanine	1.01	0.99	1.01	0.81	0.85	0.91
Histidine	0.51	0.51	0.52	0.41	0.44	0.48
Lysine	1.24	1.3	1.27	0.92	1.01	1.08
Arginine	1.29	1.24	1.26	1.01	1.18	1.17
Proline	1.36	1.54	1.51	1.14	1.29	1.38

* Premix content (volume/kg diet): Mn 100 mg, Zn 88 mg, Fe 20 mg, Cu 10 mg, I 1 mg, Mb 0.48 mg, Se 0.2 mg, Retinol 13.5 mg, Cholecalciferol, 3 mg, Tocopherol 25 mg, Menadione 5.0 mg, Thiamine 3 mg, Riboflavin 10.0 mg, Pantothenic acid 15 mg, Pyroxidine 3.0 mg, Niacin 60 mg, Cobalamin 30 μg, Folic acid 1.5 mg, Biotin 125 mg.

Table A3. Salmon study diet formulation.

Raw Material (%)	Control	5% DHP	10% DHP	15% DHP	20% DHP
Poultry by product meal	20	19.118	18.237	17.355	16.473
Corn fermented protein (CFP)	0	5	10	15	20
Fish oil herring	19.516	19.516	19.516	19.516	19.516
Fish meal herring	15	15	15	15	15
Soy protein concentrate	13.196	11.522	9.848	8.174	6.5
Wheat Flour	12.002	10.803	9.604	8.404	7.205
Corn protein concentrate	8.662	7.47	6.278	5.085	3.893
Wheat gluten meal	5	5	5	5	5
Rapeseed 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	0.77	0.798	0.826

Table A3. *Cont.*

Raw Material (%)	Control	5% DHP	10% DHP	15% DHP	20% DHP
Vitamin and Mineral Premix *	0.5	0.5	0.5	0.5	0.5
Vitamin C (Stay-C)	0.3	0.3	0.3	0.3	0.3
L-Histidine	0.249	0.242	0.235	0.228	0.221
Carophyll Pink	0.05	0.05	0.05	0.05	0.05
DL Methionine	0.033	0.036	0.038	0.041	0.043
Nutrient content (%)					
Dry matter	92.124	92.205	92.286	92.366	92.447
Crude protein	44	44	44	44	44
Crude lipid	28	28	28	28	28
Gross energy (MJ/kg)	23.93	23.464	22.997	22.531	22.064
Crude fibre	0.754	0.676	0.599	0.521	0.443
Ash	5.891	5.818	5.744	5.671	5.597
Lysine	3.338	3.344	3.349	3.355	3.36
Digestible lysine	3	3	3	3	3
Methionine	1.216	1.219	1.222	1.225	1.228
Digestible methionine	1.095	1.095	1.095	1.095	1.095
Arginine	2.633	2.593	2.553	2.512	2.472
Histidine	1.2	1.2	1.2	1.2	1.2
Isoleucine	1.908	1.899	1.889	1.88	1.87
Leucine	3.676	3.692	3.709	3.725	3.741
Phenylalanine	1.84	1.838	1.835	1.833	1.83
EPA	1.232	1.232	1.232	1.232	1.232
DHA	0.8	0.8	0.8	0.8	0.8
Phosphorus	0.979	0.989	0.999	1.008	1.018
Digestible phosphorus	0.682	0.682	0.682	0.682	0.682
Calcium	0.768	0.747	0.726	0.704	0.683
Astaxanthin	0.005	0.005	0.005	0.005	0.005

* Premix content (volume/kg diet): Mn 100 mg, Zn 88 mg, Fe 20 mg, Cu 10 mg, I 1 mg, Mb 0.48 mg, Se 0.2 mg, Retinol 13.5 mg, Cholecalciferol, 3 mg, Tocopherol 25 mg, Menadione 5.0 mg, Thiamine 3 mg, Riboflavin 10.0 mg, Pantothenic acid 15 mg, Pyroxidine 3.0 mg, Niacin 60 mg, Cobalamin 30 µg, Folic acid 1.5 mg, Biotin 125 mg.

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