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Review

The Use of Biologically Converted Agricultural Byproducts in Chicken Nutrition

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Abstract: This article aims to uncover the current knowledge on using bioconverted agricultural byproducts in the chicken diet and the impact of these byproducts on performance, product quality, and health status. Agricultural and agro-industrial activities generate thousands of tons of byproducts. Converting these agricultural byproducts into valuable entities would be an environmentally friendly, sustainable, and viable part of byproduct management. Upon recycling to make new products, the process contributes to socio-economic value and maintaining environmental health and paves the way for realizing energy security and a circular economy. The current paper identifies that solid-state fermentation has attracted more research attention than other fermentation counterparts because it requires minimal moisture, good oxygen availability, cheap media, low wastewater generation, low cost, a low processing scheme, low energy demand, and high productivity. This paper illustrates the role of proteolytic and lignin-degrading enzymes present in bacteria and fungi in the bioconversion process of complex polymers into smaller molecules of amino acids and simple sugar with a profound improvement in the palatability and bioavailability of agricultural products. In addition, the paper gives more detailed insights into using bioconverted agricultural products in chickens to improve performance, product quality, gut microbiota and morphology, and chicken welfare. In conclusion, the bioconversion of agricultural byproducts is an encouraging endeavor that should be supported by governments, research centers, universities, and non-governmental entities to improve the productivity of animal source foods by ensuring environmental sustainability and expanding food security efforts for national development.

Keywords: anti-nutritional factor; bioconversion; broilers; fermented feed; laying hens

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1. Introduction

To date, world population growth has been a severe challenge for food availability, with a tremendous increment to over 7.91 billion in 2021, and it is projected to increase further by well over 9 billion by 2050 [1]. Poultry production is vital to the food supply of the ever-growing world population, and it is estimated that poultry meat and eggs account for about a third of the animal protein consumed worldwide [2]. According to F.A.O. data, the poultry sector contributed 40.6 percent (337.3 million tons) of meat availability in 2020. The global egg yield increased from 1.528 billion in 2018 to 1.577 billion in 2019 [3].

The Food and Agriculture Organization (F.A.O.) estimated the global production of agricultural byproducts in 2019 at about 5.2 billion tons [4]. The amounts of agricultural byproducts produced vary by region and country, with developing countries producing the majority of byproducts due to their reliance on traditional farming methods and limited access to modern technologies for product management. Agricultural byproducts can pose both an environmental hazard and a valuable resource for manufacturing valuable products. As a result, there is growing interest in developing sustainable and efficient methods of managing and utilizing agricultural byproducts [4]. A sustainable method of managing agricultural byproducts is to process them for animal feed production [5].

Converting agricultural byproducts into utilizable ingredients in the chicken diet would be a noble, economical, and viable option for byproduct management. Bioconversion fermentation contributes to nutrient recycling, ultimately realizing energy security and a circular economy [6]. However, the utilization of agricultural byproducts is restricted due to legal prohibitions, anti-nutritional factors (A.N.F.s), high fiber, and low protein content that would affect nutrient availability and digestibility. However, it is reported that the fermentation process that involves lignin-degrading and proteolytic enzymes from fungi and bacteria can significantly improve agricultural residues' digestibility and palatability [7].

Bioconversion can improve the nutritional quality of feedstuffs by reducing dietary fiber and anti-nutritional factors and enhancing lipids and protein levels. Moreover, it improves amino acid composition, protein digestibility, vitamin availability, calcium, and organic matter digestibility [8,9], ultimately boosting the diet's palatability [10]. It has been reported that bacterial fermentation results in the production of a considerable amount of lactic acids, which would retard harmful bacterial multiplication in the gut, minimize nutrient and dry matter (D.M.) loss during storage, and boost the palatability of the diet to the animal [11,12].

In poultry, meanwhile, wider research attention has been put in place to integrate microbially fermented ingredients into the chicken diet to boost the nutritive value of the diet, enhancing the growth traits [13], product quality, and health of both broilers and laying hens [14,15]. In terms of cost-effectiveness, it is a profitable venture to use readily available and cheaper microbially fermented diets than expensive ones (such as yellow corn) in chicken diets, with a profound improvement in the performance and health of chickens [16,17]. Therefore, this paper aims to uncover the current knowledge on using bioconverted agricultural byproducts in chicken feed and the impact of these byproducts on chicken performance, product quality, and health status.

2. Agricultural Byproducts and Their Nutritional and Anti-Nutritional Factors

2.1. Volume of Biomass of Agricultural Byproducts

Agricultural and agro-industrial activities result in the production of large quantities of byproducts. These byproducts amount to approximately 998 million tons yearly [18]. They have different types and can be categorized based on their source and composition. One type of agricultural byproduct is field residue, composed of plant parts such as leaves, stalks, seed pods, and culms [19–21]. Agricultural byproducts are materials generated in large quantities during the processing of primary agricultural products. These byproducts can include materials from various industries, such as milling, oil, sugar, starch, fruit and vegetable, and fermentation industries. Byproducts from the milling industry, for example, can include bran, byproduct flour, residues from grain cleaning processes, wheat, corn, and rye germ. In addition, husks from certain seeds, such as pea, barley, and buckwheat, can be considered byproducts of the milling industry. These are examples of various byproducts from different industries that can be used in animal feed production. For instance, the residual materials of the oil industry, like cakes obtained from soybean and oil-producing rapeseed, sunflower, and flax products, along with lecithin and fatty acids resulting from the refining of vegetable oils, can be used in the production of animal feed. Similarly, residual materials from the sugar industries and starch industries, including beet pulp, molasses, potato pulp, potato cell juice, and other seed residues after starch extraction, as well as byproducts from the fruit and vegetable industry, such as products that result from the peeling of vegetables, apples, avocados, grapes, pomace, and fruit stones, can also be used in animal feed production. Additionally, byproducts of the fermentation industry, including grain, molasses, soluble potato distillery, brewer's and wine's yeast, bacterial and fungal biomass, spent grains, and malt germ in breweries, can be used in animal feed production [19].

2.2. Nutritional Composition of Agricultural Byproduct

Commonly found anti-nutritional factors are presented in Table 1. Anti-nutritional factors (A.N.F.s) are chemical substances in some feed ingredients that can negatively affect animal health, feed conversion, and production. A.N.F.s can impair the uptake, availability, or metabolism of nutrients in an animal and affect feed palatability, voluntary feed intake, and physiological control processes [22,23]. A.N.F.s are classified into two main categories: those impairing protein digestion and utilization (such as tannins, protease inhibitors, and lectins) and those that interfere with the utilization of minerals (such as gossypol, phytates, and glucosinolates). Other A.N.F.s include antivitamins and substances such as alkaloids, cyanogens, mycotoxins, mimosine, saponins, and phytoestrogens [24,25].

Gossypol is a toxic compound found in the cotton plant, with the highest concentration being in the cotton seeds. While cottonseed meals can be used as components of poultry diets, their use is often restricted due to gossypol and their low lysine content [26]. Free gossypol can bind to lysine and reduce its availability, harming growth performance and increasing broilers' mortality. Therefore, it is essential to carefully consider the use of cottonseed meals in poultry diets and take measures to mitigate the potential adverse effects of gossypol [27,28].

Chitin is a complex carbohydrate that the digestive enzymes of poultry cannot break down. Nutrients in feed ingredients containing chitin can be limited in some products, such as shrimp byproducts, for poultry [29–31]. Shrimp byproducts are rich in nutrients, particularly protein, comparable to quality fishmeal, and relatively inexpensive. However, the presence of chitin in shrimp byproducts can be problematic as it binds to proteins and minerals in a way that limits availability [30,32].

Glucosinolates are a group of sulfur-containing phytochemicals commonly found in cruciferous vegetables and vegetables. In R.S.M. (rapeseed meal), the main glucosinolates are glucosamine, glucobrassicin, progoitrin, gluconapoleiferin, and glucobrassicin. These compounds can have positive and negative effects on animal health, depending on their level and the animal species being fed [33,34]. Phytic acid, or myoinositol hexaphosphoric acid, is a compound found in grains, legumes, nuts, and seeds [35]. It is the stored form of phosphorus in these foods. However, phytic acid is considered an anti-nutritional factor since it can form insoluble complexes by binding with proteins and minerals. This interaction can lead to alterations in protein solubility and structure, making them less available for absorption in the gut in both humans and animals [36].

Tannins are polyphenolic compounds with high molecular weights that can be grouped into condensed or hydrolyzable tannins. The majority of tannins in canola are condensed tannins [37]. Tannins can decrease nutrient bioavailability by forming indigestible and bitter-tasting complexes with proteins [38]. Rapeseed meal (R.S.M.) contains anti-nutritional components such as glucosinolates, phytic acid, and fiber, which can limit its nutritional value and palatability. As a result, R.S.M. is used in limited amounts in animal feed [39]. Similarly, rapeseed meal contains nutritionally inhibiting factors, including phytates, glucosinolates, tannins, and crude fibers, which can affect a broiler's feed utilization [40].

Cyanogenic glycosides (C.G.s) comprise a type of organic compound, containing cyanide, commonly found in various plants such as almonds, wheat, barley, sorghum, cassava, apples, and flaxseed [41]. Linseed meal (F.S.M.) is a novel protein source in animal farming that contains several beneficial nutrients. However, it also contains nutritional inhibitors, such as cyanogenic glycosides, phytic acid (P.A.), and antivitamin B6 (VB6), that can adversely affect animal health and limit the use of F.S.M. in animal nutrition. The antivitamin B6 in F.S.M. is a dipeptide composed of glutamine and proline with a concentration of approximately 177,437 g/g. This antivitamin B6 factor can bind to the enzyme formed after VB6 phosphorylation, which causes the enzyme to lose its physiological role and impairs the utilization and absorption of vitamins by animals, leading to Vitamin B6 insufficiency [42].

Non-starch polysaccharides (N.S.P.s) such as mannan, xylan, and cellulose in poultry feed limit the digestibility of the basal diet. Palm kernel cake (PKC) use in monogastric animal feeds has been limited due to high N.S.P. concentrations and high content of coarse texture, crude fiber, and sandy appearance. It is also stated that PKC comprises 35.2% mannan [43,44]. The indigestible portions comprise N.S.P.s, consisting of mannan (78%), cellulose (12%), arabinoxylans (3%), and water-insoluble glucoxylans (3%) [45]. Because of the adverse effects observed in poultry, palm-kernel-cake dietary intake should not exceed 40% [45,46]. Feedstuffs such as soybeans, wheat, barley, and rapeseed meal contain vast amounts of N.S.P.s, but poultry lacks endogenous N.S.P. hydrolase. The soluble N.S.P. in the feed increases the digestive viscosity of the small intestine broiler and decreases the digestibility of nutrients [47].

Phytate is a compound that serves as the primary storage form of phosphorus in many plants, particularly in bran and seeds. However, phytate can also hinder the absorption of other minerals in addition to phosphorus. Soy meal, a byproduct of soybean oil extraction, is a commonly used animal feed, particularly for poultry. This meal contains a variety of anti-nutritional factors, including protease inhibitors, phytic acid, lectins, saponins, phytoestrogens, and antivitamins [25].

Table 1. Anti-nutritional compounds found in agricultural byproducts.

Feedstuffs	Ant Nutritional Factors	Reference
Soybean meal	Trypsin inhibitors, Lectins, Phytic Acid, Protease inhibitors, Saponins, Antivitamin	[25]
Rapeseed meal	Glucosinolates, tannins, phenolic acids, phytic acid, and fiber	[33,34,39]
Canola meal	Glucosinolates, tannins, crude fiber, and phytate	[40]
Cassava peels	Cyanide and phytate	[48]
Cotton seed meal	Gossypol	[26,27]
Shrimp by product	Chitin	[30,31]
Flaxseed Meal	Cyanogenic glycosides, phytic acid, and antivitamin B6	[41,42]
Mulberry leaf	Protease inhibitors, tannin tannic acid	[49,50]
Groundnut shells, pigeon pea husk	Phytate and tannin	[7]
Wheat straw and bran	Tannin, phytic acid	[51,52]
Rice bran	Phytic acid	[53,54]

2.3. Methods for Reducing Anti-Nutritional Factors

Table 2 presents the role of biological treatments on reducing antinutritional factors from agricultural byproducts. The nutrient availability and digestibility of feed and agro-industrial byproducts can be impaired by the presence of anti-nutritional factors (A.N.F.s) such as hydrocyanic acid, oxalates, phytates, tannins, polyphenols, and saponins [55]. Different methods, such as biological (microbial) processes, have been used to enhance the nutritional quality and decrease the quantities of A.N.F.s. Chemical and mechanical processes are costly and labor-intensive, whereas microbial fermentation is a more affordable and safer alternative for improving the nutrient content of agro-industrial byproducts. The abundance and composition (cellulose, hemicellulose, and lignin) of agro-industrial byproducts make them an attractive option for recycling and fermentation through microbial fermentation as a viable alternative for product management [55]. Solid-state fermentation (S.S.F.) is a type of biological fermentation that involves cultivating microorganisms on humid, compact, insoluble biological ingredients. These materials serve as nutrient bases for the microorganisms to grow, and the process occurs in the absence or near-nonexistence of free-flowing water [32,56].

S.S.F. has been found to reduce A.N.F.s, which are bioactive compounds that affect the bioavailability and bio-digestibility of nutrients in feed, thereby improving the bioavailability and digestibility of nutrients in agro-industrial byproducts [57]. *Both filamentous fungi* such as *Trichoderma reesei*, *Trichoderma viride*, *Rhizopus oligosporus*, *Aspergillus niger*, *Mucor racemosus*, *Rhizopus arrhizus*, *Rhizopus oryzae*, *Mucor rouxii*, *Penicillium oxalicum*, *Penicillium viridicatum*, and *Fusarium oxysporum* as well as yeasts such as *Saccharomyces boulardii*, *Saccharomyces cerevisiae*, *Candida sphaerica*, *Candida tropicalis*, *Candida stellate*, and *Candida* are commonly used in S.S.F. Bacteria such as *Bacillus mycoides*, *Bacillus megatherium*, *Lactobacillus acidophilus*, *Lactobacillus bulgaricus*, *Lactobacillus plantarum*, and *Lactobacillus rhamnosus* have also been used in S.S.F. [32,56].

Several studies have demonstrated the effectiveness of S.S.F. in the biological detoxification of and reduction in the quantities of A.N.F.s in agro-industrial byproducts using filamentous fungi, yeast, and bacteria [58]. However, it has been reported that fermentation can also increase the levels of A.N.F.s in feedstuff components, such as glucosinolates in rapeseed meal; lectins and trypsin inhibitors in soybean meal; tannins, hemagglutinins, and prosopin in prosopean meal; and phytate in corn [59,60]. Despite this, some studies have shown that S.S.F. can decrease the levels of A.N.F.s in animal feed. For example, Oboh [48] found S.S.F. using a mixed culture of *Lactobacillus* spp and Saccharomyces cerevisiae, significantly decreased phytate and cyanide levels in fermented cassava peel compared to not-fermented peel, which contained higher concentrations of these A.N.F.s. In another study, *Bacillus subtilis, Candida utilis*, and *Enterococcus faecalis* were found to degrade phytic acid, glucosinolate, and tannin in rapeseed meal under S.S.F., resulting in reductions of 20%, 96%, and 36%, respectively [61]. Overall, S.S.F. is a practical approach to reducing A.N.F. quantities in animal feed production. It can significantly benefit both the animals and the farmers who rely on them for their livelihoods.

Aspergillus niger is known to produce Phytase during fermentation, which releases the protein trapped in rice bran by hydrolyzing the phytic acid and making it easier to digest. Additionally, anti-nutritional factors (A.N.F.s) in animal feed can produce intermediate products that decrease the presence of essential nutrients [62]. However, solid-state fermentation (S.S.F.) treatment with microorganisms can reduce the harmful effects of A.N.F.s. For instance, S.S.F. with *Lactobacillus fermentum*, *Enterococcus faecium*, *Saccharomyces cerevisiae*, and *Bacillus subtilis* reduced the amount of isothiocyanate in rapeseed meals from 119 to 14 mmol/kg after 30 days [63]. Similarly, other studies have documented a reduction in isothiocyanate levels after S.S.F. [64]. In one study, glucosinolates, isothiocyanate, phytic acid, and tannins were reduced from 41.91 to 23.86 mol/g, 2.48 to 1.10 mg/g, 2.66% to 0.37%, and 1.32% to 0.84%, respectively [65]. The reductions in glucosinolate content may have been due to the utilization of glucose and the sulfur portions of these compounds by microbial enzymes [66,67]. The reduction in phytic acid can be attributed to microbial enzymes such as Phytase produced during S.S.F.

S.S.F. with the bacterial degradation of A.N.F.s in rapeseed flour using the enzyme myrosinase can degrade glucosinolates and release several derivatives [67]. Additionally, in some studies, S.S.F. significantly decreased the amount of free gossypol and A.N.F. Tang et al. [68] found that free gossypol was reduced from 0.82 to 0.21 g/kg in solid fermented cottonseed meal. Similarly, in another study, free gossypol decreased from 90 to 30 mg/kg [69]. The reduction in free gossypol content during S.S.F. may have been due to the binding of free gossypol to proteins or amino acids produced by microorganisms, the degradation of gossypol by microbial enzymes, or both mechanisms.

The fermentation process for shrimp byproducts can be carried out using a stepwise fermentation technique with *Bacillus licheniformis*, *Lactobacillus* sp., and yeast in the form of *Saccharomyces cerevisiae*. *Bacillus licheniformis* bacteria produce chitinase and protease enzymes with deproteinizing properties that release nitrogen or protein from chitin bonds [30,31]. *Saccharomyces cerevisiae* is a yeast that produces enzymes such as amylase, lipase, protease, and others that can aid in the digestion process of feed in the digestive organs [70]. After deproteinization and demineralization, proteins and minerals bound to chitin can be broken down, allowing a chicken's digestive system to digest this protein [70,71]. In a study, the phytate and tannin content of biotransformed peanut shells was also significantly reduced [7]. The decrease in tannin and phytate content in the byproduct material during S.S.F. may have been due to the ability of the test fungi to produce Phytase. Phytase is an enzyme that breaks down phytate, i.e., phosphorus, in many plant-based foods. Conversely, tannins can also be degraded by certain microorganisms or their enzymes during S.S.F.

Table 2. Effect of biological treatments on reducing anti-nutritional factors from agricultural byproducts.

Types of Agricultural Byproducts	Treatment	Reduced Anti-Nutritional Factors								Reference
		Tannins		Glucosinolates		Phytic Acid		Cyanide		
		Before	After	Before	After	Before	After	Before	After	
Rapeseed meal	SSF by *R. oligosporus*	N.A.	N.A.	63.4	36.3 (−42.8%)	29.3	16.9 (−42.3%)	N.A.	N.A.	[66]
	S.S.F. by *A. niger*	N.A.	N.A.	16.45	9.37 (−43.0%)	N.A.	N.A.	N.A.	N.A.	[65]
	S.S.F. by *A. niger*	N.A.	N.A.	23.79	16.51 (−30.6)			N.A.	N.A.	[72]
Rapeseed Cake	S.S.F. by *A. niger*	N.A.	N.A.	NA	NA	2.78 (%)	1.54 (−44.60%)	N.A.	N.A.	[73]
	SSF by *L. delbrueckii* and *B. subtilis*	N.A.	N.A.	64.56 µmol/g	3.47 (−94.6%)			N.A.	N.A.	[74]
Wheat straw	S.S.F. by *E. fungi*	702 µg/100 g	502 (−28.5%)	N.A.	N.A.	200 µg/100 g	175 (−12.5%)	N.A.	N.A.	[7]
Pigeon pea	S.S.F. by *E. fungi*	665 µg/100 g	589 (−11.4%)	N.A.	N.A.	611 µg/100 g	298 (−51.2%)	N.A.	N.A.	[7]
Groundnut	SSF by *E. fungi*	454 µg/100 g	314 (−30.8%)	N.A.	N.A.	465 µg/100 g	303 (−34.3%)	N.A.	N.A.	[7]
Cassava peels	Mixture of *Lactobacillus delbruckii* and *Lactobacillus coryneformis* and *Saccharomyces cerevisae*	N.A.	N.A.	N.A.	N.A.	1043.6 mg/100 g	789.7 (−24.3%)	44.6 mg/kg	6.2 (−86.1%)	[48]
Canola meal	S.S.F. by *Aspergillus sojae*, *Aspergillus ficuum*, and their co-cultures	N.A.	N.A.	9.31	6.52 (−30.0%)			N.A.	N.A.	[75]
Cotton seed meal	S.S.F. by L.A.B.	N.A.	N.A.	77.18 µmol/g	54.05 (−30.0%)	7.71 µmol/g	3.9 (−49.4%)	N.A.	N.A.	[76]
Olive cake	S.S.F. by *Filamentous fungi*	4.78 mg/g	3.23 (−32.4%)	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	[77]
Cassava peels	SSF	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	14.7	1.4 (−90.5%)	[78]

N.A., not analyzed; L.A.B., Lactic Acid Bacteria.

2.4. Nutritional Composition of Bioconverted Agricultural Byproducts

Table 3 presents the role of microbial fermentation in improving the chemical composition of agricultural byproducts. Biotransforming microorganisms have been shown to enhance chicken feed's chemical composition and nutritional value [79]. Purwadaria et al. [80] also reported that the fermentation of agricultural byproducts improved their nutritional value. Nutrient bioavailability has been improved using solid-state fermentation (S.S.F.) while reducing anti-nutritional agents. For S.S.F. to increase nutrition, several microbes have been used, primarily Lactobacillus, Bacillus, and Aspergillus strains. Aspergillus can produce enzymes such as hemicellulase, pectinase, protease, lipase, amylase, tannase [81,82], and Phytase [83,84]. The bacterium Lactobacillus produces Phytase, cellulase, xylanase, and glucanase [85]. Bacillus can synthesize cellulase and Phytase [86]. In a study utilizing *Aspergillus niger* to determine the impact of S.S.F. on the nutrient content of rice bran, Hardini [87] found that the nutrient composition of fermented rice bran had significantly increased. For determining the nutritional value of fermented feed, it is vital to consider the crude protein content, pH level, and the number of bacteria [88].

Lu et al. [89] reported that microbial fermentation increased levels of organic acids (citric, succinic, and butyric), amino acids (Ser, Gly, Cys, Leu, Lys, His, and Arg), crude protein, and levels of neutral and acidic Detergent fibers in soybeans and other flour types. The findings demonstrated that fermentation by microorganisms altered the feed's chemical makeup and boosted certain nutrients.

Guo et al. [79] showed that microbial fermentation increased the C.P. content of the substrate substantially. This could have been because the relative concentration of other nutrients rises due to the dry matter loss in fermented feed, particularly the loss of carbs. The breakdown of macromolecular proteins, primarily antigenic proteins, may have contributed to the rise in C.P. [90]. The microbial fermentation of S.B.M. eliminates A.N.F.s and increases nutritional value [79,91]. It was noticed that the quantity of glucan, phytic acid, and crude fiber decreased following fermentation with the probiotic agent. This might have been because those antinutrient substances are broken down by similar enzymes, like Phytase and cellulase, that are produced. The crude protein level was doubled in the biotransformed crop residues using endophytic fungi [7]. The rise in crude protein could be attributed to the fungi's production of mycelial proteins or the fermenting fungus's growth, breaking down complex polysaccharides into single-cell proteins (S.C.P.) [92].

The extracellular enzymes—amylases, cellulases, xylanases, and pectinases—secreted by fungi to use complex polysaccharides may be the reason for the processed material's higher protein concentration [93,94]. It was also found that the quantities of total carbohydrates are increased, showing that hexoses are released due to Togninia spp—an example of extracellular protease synthesis [7].

Crude protein in rapeseed meals rose from 37.1% to 58.4% after solid-state fermentation (S.S.F.) with *Lactobacillus plantarum* and *Bacillus subtilis* [95]. Similarly, *Bacillus subtilis, Candida utilis,* and *Enterococcus faecalis* inoculation increased the crude protein level from 42.11% to 44.63% [61]. The drop in T.S. content and the extra microbial protein produced during S.S.F. were responsible for the rise in crude protein levels. Likewise, S.S.F. caused a decrease in rapeseed meal's dry matter content (D.M.) [63]. The decrease in the T.S. content could be due to the sugar consumption of the microorganisms. Adding *Lactobacillus plantarum* and *Bacillus subtilis* to S.S.F. rapeseed meal improved its crude fat content [95]. A similar result was observed by [64] when *Bacillus subtilis* and *Lactobacillus fermentum* were tried out. The increase in fat can be partly attributed to the reduction in the quantity of carbohydrates during S.S.F. In contrast to these studies, the authors of [65] reported that the S.S.F. of rapeseed meals employing *Aspergillus niger* resulted in lower crude fat. Overall, variations in the solid fermented rapeseed meal's crude fat content may occur due to factors like oil processing techniques, feed source, and microorganisms utilized.

According to Bidura et al. [53], fermentation increased rice bran's crude protein content and metabolizable energy. Fermented rice bran has a more excellent crude protein content and ether extract due to Phytase and microbial biomass. Hardini [96] conducted a study using *Aspergillus niger* to determine the effect of fermentation in the soil on the nutrient content of rice bran and discovered a considerable enhancement of fermented rice bran's nutritional profile. The nutritional and energy profile of agricultural wastes is improved by fungal bioconversion. *Endophytic fungi* can convert the selected residues of agriculture into digestible hexoses, considerably increasing the concentration of protein and nitrogen. The most significant amounts of total carbs, total proteins, and digestible lipids are found in biotransformed peanut shell residue [7].

Shrimp waste products treated by fermentation showed increased quality and palatability in rations [82,97]. Haddar et al. [83] and Saleh et al. [31] also reported that the processing of shrimp waste products and olive cake flour using the microorganism *Bacillus licheniformis* and yeast in the form of *Saccharomyces cerevisiae* makes protein independent of the limiting factor in the form of chitin, increasing the nutritional value—namely, increasing the protein content in shrimp as a product and improving its palatability.

Table 3. Chemical compositions of agricultural byproducts before and after microbial conversion.

Agricultural Byproducts	Unfermented						Fermented					Reference
	CP	CF	Ash	Ca	P	Reference	CP	CF	Ash	Ca	P	
Palm kernel cake	16.47	16.96	4.74	N.A.	N.A.	[43]	16.7 (+1.6)	14.09 (−16.9)	4.82 (+1.6)	N.A.	N.A.	[43]
	19.7	22.5	5.0	N.A.	N.A.	[78]	26.3 (+33.3)	12.5 (−44.5)	8.6 (+72)	N.A.	N.A.	[78]
Pineapple peel	4.52	13.95	6.79	N.A.	N.A.	[98]	14.7–21.0	N.A.	N.A.	N.A.	N.A.	[98]
Dried Yam peel	6.60	9.02	4.45	N.A.	N.A.	[98]	6.6–14.7	N.A.	N.A.	N.A.	N.A.	[98]
Cassava pulp	3.0	N.A.	N.A.	N.A.	N.A.	[99]	22.6	N.A.	N.A.	N.A.	N.A.	[100]
	2.02	14.6	N.A.	N.A.	N.A.	[101]	11.82	10.6	N.A.	N.A.	N.A.	[101]
Cassava peels	5.36	N.A.	6.05	3.47	1.60	[102]	21.5	11.7	7.2	0.03	N.A.	[48]
	8.2	12.5	6.4	0.03	N.A.	[48]						
	12.3	14.7	9.4	N.A.	N.A.	[78]	19.0 (+55.4)	13.5 (−8.6)	11.8 (+26.0)	N.A.	N.A.	[78]
Cocoa pod husk	8.2	18.3	11.3	N.A.	N.A.	[78]	16.0 (+94.8)	16.9 (−7.2)	20.8 (+83.1)	N.A.	N.A.	[78]
Wheat straw	3.45	N.A.	5.23	N.A.	N.A.	[7]	10.20	N.A.	5.2	N.A.	N.A.	[7]
Pigeon pea	8.41	N.A.	1.95	N.A.	N.A.	[7]	16.41	N.A.	2.95	N.A.	N.A.	[7]
Groundnut	4.35	N.A.	2.01	N.A.	N.A.	[7]	24.95	N.A.	3.06	N.A.	N.A.	[7]
Corn stover	4.75	N.A.	2.61	N.A.	N.A.	[103]	7.65	N.A.	9.93	N.A.	N.A.	[103]
Olive cake mg/g DW	42.65	N.A.	N.A.	N.A.	N.A.	[77]	82.83	N.A.	N.A.	N.A.	N.A.	[77]
Shrimp by product							48.5%	N.A.	N.A.	7.57%	3.14%	[104]
	43.41	18.25%	N.A.	5.54%	1.31%	[71]	39.29	7.79	N.A.	6.81	2.83	[105]
							48.5%	N.A.	N.A.	7.57%	3.14%	[106]
Rice bran	11.4–17.4	10.4–20.0	N.A.	N.A.	N.A.	[19]		N.A.	N.A.	N.A.	N.A.	
	14.8%	N.A.	9.4	N.A.	N.A.	[107]	26.6 (+49%)	N.A.	13.9 (+48%)	N.A.	N.A.	[107]
	8.8	8.3	7.4	N.A.	N.A.	[108]	15.3	6.7	7.0	N.A.	N.A.	[108]
	14.52	12.05	9.8	N.A.	1.74	[54]	16.58	9.35	13.7	N.A.	1. 88	[54]
Rice straw	5.60	N.A.		N.A.	N.A.	[109]	5.91–6.34%	N.A.	N.A.	N.A.	N.A.	[109]
	N.A.	N.A.	15.69%	N.A.	N.A.	[110]	N.A.	27.84–32.63%	20.53%	N.A.	N.A.	[110]
	5.63	34.7	14.60	N.A.	N.A.	[111] [112]	N.A.	7.92%	N.A.	N.A.	N.A.	[113]

Table 3. *Cont.*

Agricultural Byproducts	Unfermented						Fermented					Reference
	CP	CF	Ash	Ca	P	Reference	CP	CF	Ash	Ca	P	
Wheat bran	15.5 18.36	42.8 15.67	5.46	N.A. N.A.	N.A. N.A.	[19] [5,51]	20.79	18.0	5.68	N.A.	N.A.	[5,51]
Sugarcane bagasse	1.57%			N.A.	N.A.	[109]	2.57–3.01%	N.A.	N.A.	N.A.	N.A.	[109]
	3.75	36.8	2.4	N.A.	N.A.	[111] [112]	N.A.	N.A.	N.A.	N.A.	N.A.	[111] [112]
Sweet sorghum	4–8%			N.A.	N.A.	[114]	35.7%	N.A.	N.A.	N.A.	N.A.	[115]
sugar beet leaves	10.94	7.9	12.50	N.A.	N.A.	[111] [112]	14.2%	N.A.	N.A.	N.A.	N.A.	[113]
sugar beet pulp	14.31	27.7	5.5	N.A.	N.A.	[111] [112]	17.9%	N.A.	N.A.	N.A.	N.A.	[113]
Tomato leaves	15.13	14.5	13.56	N.A.	N.A.	[111] [112]	18.53%	N.A.	N.A.	N.A.	N.A.	[113]
Yam Peels	7.72–11.33	9.50	9.80	N.A.	N.A.	[58,116]	14.44%	5.49	4.85	N.A.	N.A.	[58]

N.A., not analyzed; CP, crude protein; CF, crude fiber; Ca, Calcium; P, Phosphorous.

3. Effects of Feeding Bioconverted Agricultural Byproducts to Chickens

3.1. The Impact of Feeding Bioconverted Byproducts on Performance and Product Quality in Broilers and Layers

Table 4 shows the performance and product quality of broilers and layers fed bioconverted agricultural byproducts. Fermentation has been demonstrated to improve the feed's palatability [10,30,117] and the digestibility of numerous nutrients, including calcium, nitrogen, amino acids, fiber, and organic matter [47]. Broilers fed 10% or 15% solid-fermented palm kernel cake (S.S.P.K.C.) digested nutrients better than those fed non-fermented palm kernel cake [118]. S.S.P.K.C. had significantly higher apparent ileal crude protein and amino acid digestibility than non-fermented palm kernel cake [119].

The improvement in the digestibility of amino acids and crude protein in S.S.P.K.C. is attributed to the reduction in N.D.F., A.D.F., crude fiber, hemicellulose, cellulose, and N.S.P. content during S.S.F. Despite the increased digestibility of proper amino acids, metabolizable energy levels decreased in broilers fed Aspergillus-treated palm kernel meal compared to the unfermented palm kernel meal group in [120]. This might be because, during S.S.F., the microbe consumes the energy supply of the substrate, especially the nitrogen-free extract (N.F.E.).

Lu et al. [89] reported that feeding 4% fermented soybean meal increased the average daily feed intake (A.D.F.I.), and feeding 4% other fermented meal increased A.D.F.I., in laying hens. Additionally, laying hens' apparent digestibility of dry matter, crude protein, and N.D.F. was increased when fed 2 to 8% fermented soybean meal or 2 to 4% fermented non-soybean meal. However, 8% fermented mixed meal decreased A.D.F.I. and increased F.C.R. among older laying hens, probably because mixed meal contains more dietary fiber and A.N.F.s than S.B.M., even if the fermentation result of S.B.M. contains indigestible or toxic components [89].

Fermented feed increases nutrient digestion and absorption by increasing broiler duodenum and jejunum and the villi-height-to-crypt-depth ratio (V.H.:CD) [121–123]. According to Chiang et al. [63], broilers fed solid fermented rapeseed meal (S.S.F.R.M.) had higher apparent total digestibility coefficients for D.M., calorie, and calcium at day 42 than birds fed unfermented rapeseed meal. A digestibility study was conducted on 42-day-old broilers fed either canola meal or S.S.F.C.M. as their only source of protein and energy by Ahmed et al. [124]. Rapeseed meal infected with *Lactobacillus salivarius* had a higher crude protein digestibility than unfermented rapeseed meal, rising from 77.44% to 81.56%. Amino acid digestibility coefficients in S.S.F.C.M. improved significantly compared to non-fermented rapeseed meals. This might have been because microorganisms secrete cellulase, Phytase, and xylanase enzymes that convert fibrous materials into monosaccharides. More research on broilers' nutrient digestibility is needed to comprehend how they respond to dietary S.S.F.R.M. and S.S.F.C.M. Nutrient digestion and absorption, which affect health and performance in broilers, are greatly influenced by the gut lining. The primary site of nutrient absorption is in the intestinal villi. The villous epithelial cells are functional digestive and absorptive cells useful in increasing enzyme activity and nutrient absorption [61]. Compared to broilers fed S.B.M. control diets, those provided SSFRM-containing diets showed improvements in the height of the villus and the ratio of the villus'-height-to-crypt-depth in the ileum and jejunum [63].

A similar observation was observed in the study reported in [64]. In addition, Hu et al. [61] reported that the dietary intake of S.S.F.R.M. improved the structure and function of the small intestine in broilers compared to unfermented canola meals. This result implies that feeding S.S.F.R.M. can influence intestinal epithelial cell proliferation, increase the surface area of the gut mucosa for nutrient uptake, and improve nutrient utilization efficiency in broilers.

To promote sustainable agricultural practices, researchers have been looking into the use of alternative feed ingredients for poultry. One strategy is using bioconverted residues as feed components for layer and broiler chickens. The impacts of several bioconverted meal types and their inclusion amounts on growth efficiency, carcass production, and meat and egg quality are summarized in Table 4. Kim and Kang et al. [125] found that broilers can safely consume up to 3% of bioconverted pig manure without this negatively affecting their growth performance or meat quality. Similarly, fermented shrimp waste products can be used as feed ingredients for local chickens at a level of up to 15% without any negative impact on their growth performance or meat quality. Using bioconverted residues as feed components can help minimize waste and promote sustainable agriculture.

A study also looked into how broiler growth performance, the metabolism of nutrients, and gastrointestinal health were affected by fermented feed [126]. The fermented feed was made by mixing the bran of wheat, corn, soybean meal, and water and fermenting with lactic acid bacteria for 48 h. The outcomes demonstrated that the broilers' growth performance and nutrient metabolism were enhanced by the addition of the fermented feed to their diet. The 10%- and 15%-fermented-feed groups had the highest body weight gain and feed conversion ratio. The broilers' fecal microbiota were also changed by the addition of a fermented feed, with more significant abundances of good bacteria like Lactobacillus and Bifidobacterium in the 10%- and 15%-fermented-feed groups. The inclusion of fermented feed, on the other hand, did not affect carcass yield or meat quality. It is important to note that adopting alternative feed ingredients for poultry poses significant issues and constraints. For instance, additional processing and handling may be required to assure safety and quality when employing bioconverted byproducts as feed ingredients. Also, fermented feed may require careful monitoring to ensure proper fermentation and prevent contamination. Despite these challenges, using alternative feed ingredients for poultry can contribute to sustainable agricultural practices and reduce waste. The studies suggest that bioconverted residues and fermented feed can be used as broilers' feed without affecting growth performance or meat quality [80,127–129].

Feeding laying hens fermented feed has been shown to positively affect the quality of the eggs produced. Studies have demonstrated that fermented feed prepared from *Lactobacillus salivarius*, *Bacillus subtilis*, *Lactobacillus butyricum*, and yeast can reduce feed conversion and improve performance and protein quality in laying hens [79]. Fermented feed supplementation has also been shown to significantly improve the hen laying rate and the quality of the eggs while reducing the percentage of broken eggs and feed conversion rates. Furthermore, after fermented feed intake, both albumin levels and Haugh unit values increase significantly in hens.

Supplementing the laying hen feed with S.S.F. wheat bran feed (10% and 15%) also improves egg quality. In a study, eggshell hardness was significantly higher in eggs from laying hens treated with 10% and 15% S.S.F. feed made from the low-fiber fungus strain Mortierella alpina CCF 2861 than in eggs made from chicken feed and ground feed. The antioxidant activity of egg yolk also increased when fermented feed was added to laying hen feed. With a 15% addition of a fermented diet, the lightness of the egg yolk color in laying hens is enhanced. Yolk color is a crucial biophysical characteristic frequently linked to egg quality. In a study, raising the amount of polyunsaturated fatty acid (P.U.F.A.) in the yolk also increased the quality and nutrition content of the eggs produced. Feeding 4% fermented soybean meal and other fermented meal increased egg mass and production, but feeding 8% other fermented meal reduced productivity and egg production. Feeding 4% fermented S.B.M. increased eggshell strength and weight, egg protein content, and Haugh unit values. However, 8% fermented non-SBM meal decreased average egg mass and production rate and improved the F.C.R. in old laying hens. This was likely because non-SBM meal contains more dietary fiber and A.N.F.s than S.B.M. Even though the fermentation results in S.B.M. are high in indigestible or harmful components. Laying hens demonstrate a noticeable decline in egg quality, nutrient absorption capacity, and disease resistance in the late stage [130,131]. As a result, it is critical to promote laying chicken well-being through effective feeding strategies in the face of protein feed shortages [130–132].

Feeding fermented wet food (F.W.F.) increased egg weight, the number of unsaleable hatching eggs, and, consequently, the number of chicks—the ultimate product of breeders—in [133]. Using fermented feed for 14 weeks at rates of 3%, 6%, and 9% in the diet of laying hens

(BabcockB380) showed that doing so results in the digestive tract becoming acidic because it contains volatile fatty acids. According to Gonzalez-Esquuerra and Leeson [134], the ensuing acidic environment of the lumen could lower the breeder's serum triacylglycerol and, as a result, the volume of lipids required for yolk processing and the number of yolks in the ovary. This could explain the considerable increase in egg weight obtained with the fermented wet food treatments of 50% and 75%.

Numerous studies on egg quality have found that fermented feeds, like fermented cottonseed meals, help increase egg quality [135]. Lu et al. [89] reported that fermented feed effectively improved albumen consistency, albumin level, eggshell strength, the Haugh unit value, and yolk color. The color of the yolk is also greatly influenced by nutrients in the feed, like fat, vitamins, and calcium [136]. In the study by Kidd et al. [137], a fermentation product from *Saccharomyces cerevisiae* was found to reduce egg contamination and improve the hatchability of fertilized eggs. The offspring of layers fed *Saccharomyces cerevisiae* showed superior feed conversion percentages.

Table 4. The impact of feeding bioconverted byproducts on performance and product quality in broilers and layers.

Bioconverted Meal	Inclusion Level	Growth/Laying Performance	Carcass Yield	Meat/Egg Quality	Reference
Feather meal	10%	Highest body weight gain, feed intake, and feed conversion ratio	Highest carcass yield	Highest protein content and the lowest fat content	[129]
Corn, soybean meal, fish meal, and rice bran	10%, 20% and 30%	The 30% level resulted in the highest feed intake and egg production	N.A.	Feeding of 30% increased yolk color and reduced egg cholesterol	[138]
Plant fraction (corn, soybean meal, cottonseed meal, and rapeseed meal)	5%, 10%, and 15%	Adding 5% significantly improved A.D.G. and A.D.F.I. in 1–42 days and also enhanced growth performance	N.A.	Fermented feed improved the meat quality, reduced the cholesterol content	[15]
Rice bran	1%	Improved egg-laying performance	N.A.	Reduced the levels of cholesterol in egg yolk	[139]
Ginkgo-leaves	0.5%	Improved laying rate and feed conversion ratio	N.A.	There was a decrease in cracked egg rate and egg-yolk cholesterol, while the concentrations of total polyunsaturated fatty acids were increased with F.G.L. supplementation	[140]
Tea residues	1%, 3% and 5%	Including 1% resulted in a significant increase in the egg-laying rate and average egg weight in birds	N.A.	Supplementation of 1% significantly improved the Haugh unit, whereas 3% improved the content of essential amino acids and total omega-3 polyunsaturated fatty acids in the eggs	[141]
Corn and soybean meal	250, 750, and 1500 g	N.A.	There was no effect on the carcass yield; however, the inclusion of 1500 g/t increased leg yield and reduced P.H.	There was no effect on the color, water holding capacity, cooking loss, and shear force, while the inclusion of 750 g/t decreased the lipid oxidation of breast meat	[142]

N.A., not analyzed; A.D.G., average daily gain; A.D.F.I., average daily feed intake.

3.2. Effects of Feeding Bioconverted Residues on Chicken Health

The effect of feeding bio-converted agricultural products on chicken health is indicated in Table 5. The presence of lactic acid bacteria (L.A.B.) in large numbers and high lactic acid concentrations are two characteristics of fermented feedstuffs [143]. In one study, L.A.B. use increased productivity, boosted immunological function, and enhanced antioxidant capacity in poultry [144]. The dietary supplementation of 2 to 4% fermented soybean meal and other fermented meals had beneficial effects on gut health and barrier function in [89]. Teng et al. [145] fed broilers 10% wheat bran fermented with *Saccharomyces cerevisiae and Bacillus amyloliquefaciens* for 35 days and found that it improved broiler health by improving growth performance and gut microbiota and increasing tiny intestinal lactic acid bacteria (L.A.B.) counts. A comparable study by Jazi et al. [146] found that utilizing fermented cottonseed meal (F.C.S.M.) instead of unfermented C.S.M. considerably enhanced broiler growth performance and gut health. In broilers fed C.S.M. fermented with *Aspergillus oryzae, Aspergillus niger,* and *Bacillus subtilis* for forty-two days and seven days, a substantial reduction in crude fiber and free gossypol enhanced crude protein content, but an increase in small-intestinal L.A.B. counts was observed. According to studies on boosting the microbe population of L.A.B., the lower the animal's gut pH is, the better the conditions are for L.A.B. growth in the gut [63,147]. L.A.B. use also enhances the antioxidant capacity and immune system, which improves broiler meat quality [144,148]. Feeding fermented rapeseed meals can increase broiler serum immunoglobulin IgG and immunoprotein IgM levels [64]. In addition, giving fermented feed to broilers can considerably raise their secretory IgA (S-IgA) levels [123]. The ratio of heterophile cells to lymphocytes in broilers can be reduced [125] as a result of the fermented diet, which also reduces oxidative stress [17], induces recirculating antibodies, and improves the immunity of the gastrointestinal mucosa [149]. Small peptides found in fermented feed can potentially produce broiler immunological globules. The broiler protein content is raised to promote immunological function [64]. Changes in broiler gut flora also affect their immune response [121].

A fermented feed could improve the environment of broiler gastrointestinal tracts, for example, by lowering pH, reducing the proliferation of pathogenic microbes, and increasing the generation of short-chain fatty acids [82]. The levels of pollutants and harmful microbes can be reduced in the body by the intestinal mucosa [150]. In the same way that the addition of fermented rapeseed meal to broiler feed can significantly increase the height of the ileum, jejunal villi, and broilers' V.H.:CD ratios, the groups fed 4% fermented soybean meal and the fermented miscellaneous meal had higher villi heights, crypt depths, and villi:crypt ratios [89]. Small peptides, low toxins, antigenic compounds [64], and low A.N.F. levels favorably impact broilers' intestinal mucosal morphology [60].

The fermented feed containing *Bacillus subtilis*, *Lactobacillus butyricum*, *Lactobacillus salivarius*, and yeast improves gut morphology, epithelial barrier functions, and immune status and also improves the gut health of laying hens [79]. This improvement may be related to the structure of the cecal microbiota. Fermented feed increases the villi height of the duodenum, jejunum, and ileac. In a study, layers fed fermented feed had higher levels of immunoglobulin (Ig)A, IgG, and IgM and higher quantities of interferon, tumor necrosis, interleukin 6, and interleukin two than the control. According to research on the microbiota of laying hens, alpha diversity was unaffected by the addition of fermented feed. Comparing cecal samples from F.F. hens to those from control hens, fewer Firmicutes were present (30.61% vs. 35.12%). A fermented diet was found to be related to increasing relative Lactobacillus abundance and decreased Campylobacter abundance in laying hens at the genus level. These findings imply that adding fermented feed supplementation to laying-hen feed may improve egg quality, laying performance, immune system health, intestinal villi growth, and the microecological environment during the final laying cycle [14]. Similarly, fermented feed improves immune function and gut integrity and is an ideal functional feed to improve gut health in poultry [14].

Table 5. Effects of feeding bioconverted byproducts on the health of chickens.

Types of Byproducts	Organism	Birds	Effect on Intestinal Morphology	Effect on Gut Microbiota	Reference
Palm Kernel Cake	L.A.B.	Broilers	Significantly increases duodenal V.H. and CD of jejunum and ileum		[151]
Basal diet (corn, soybean meal, corn gluten meal, dried distiller's grain, and wheat bran)	Enzyme-bacteria co-fermented feed	Broilers		M.O.s and their metabolites could improve the gut microecological environment, increase disease resistance, and help maintain gut health.	[126]
Mixed substrate (corn, soybean meal, and wheat bran)	*Clostridium butyricum*, *Lactobacillus crispatus*, and *Lactobacillus salivarius*	Layers	Duodenal V.H. and VH/CD, jejunal V.H., and ileal VH/CD were significantly increased, while the jejunal CD was significantly decreased. The study found improved gut health by improving gut morphology.	Feeding fermented feed did not alter the major bacterial species in the cecum in laying hens. However, fermented dietary supplementation with *Lactobacillus salivarius* could improve gut health by altering the microbial composition and increasing microbial community richness.	[152]
Soybean meal and miscellaneous meal (cottonseed meal: coconut meal at a 1:1 ratio)	Multistrain cultures (Bacillus, Saccharomyces, Lactobacillus, and *Clostridium butyricum*)	Layers	Dietary supplementation with 2 to 4% F.S.B.M. or F.M.M. had beneficial effects on gut health. V.H. and CD were significantly improved, resulting in a larger V.H. to CD ratio.		[89]
Dry basal feed (corn, soybean meal, wheat bran) with distilled water	*Bacillus subtilis* and *Saccharomyces cerevisiae*	Layers	They increased the V.H. of the duodenum, jejunum, and ileum in laying hens. Ileac CD also trended up for hens. However, there were no differences in the VH/CD ratio of the duodenum, jejunum, and ileum between the F.F. and CON groups; there were improvements in immune function and gut integrity.	The microecological environment of the cecum was also improved by increasing the abundance of Lactobacillus and decreasing the abundance of Campylobacter.	[14]

Table 5. *Cont.*

Types of Byproducts	Organism	Birds	Effect on Intestinal Morphology	Effect on Gut Microbiota	Reference
Mixed diet (corn, wheat bran, and soybean meal)	Compound bacteria (*Bacillus* subtilis, Lactobacillus, yeast, *Clostridium butyricum*, and *Lactobacillus salivarius*)	Layers	Improved the intestinal immunity of laying hens.	The cecal microflora structure was improved.	[79]
Astragalus	*Lactobacillus plantarum* (CGMCC 1.557)	Layers		There was an increased ileal bacterial community diversity with an increasing feeding time. At the strain level, Firmicutes, Bacteroidetes, and Proteobacteria were the most dominant strains in the chicken gut microbiota.	[153]

N.A., not analyzed; L.A.B., lactic acid bacteria.

3.3. Effects of Feeding Bioconverted Byproduct on Oxidative Stress in Chickens

Table 6 indicates the detailed researches showing ameliorative effect of bio-converted agricultural products against oxidative stress. One of the most significant factors influencing broiler growth performance and profitability in intensive poultry production is oxidative stress [154,155]. It can also lower disease resistance, which induces mortality, and impairs meat quality, including color, flavor, texture, and nutritional value [156]. Free radicals have been shown to produce reactive oxygen species (R.O.S.) in cells, which can lead to cell and tissue damage [157]. The first-line antioxidant defense system is made up of the functions of glutathione peroxidase (G.P.X.), superoxide dismutase (S.O.D.), and catalase (C.A.T.), which are crucial in shielding cells and tissues from the harmful effects of free radicals. As a result, elevated concentrations of such enzymes in the blood or tissue imply a high antioxidant capability [158]. The broiler diet containing 15% fermented feed tended to have lower serum M.D.A. levels and higher T-AOC, indicating a greater capacity for overall antioxidants. This might be because probiotics and peptides resulting from the microbial breakdown of proteins during fermentation increase the feed's antioxidant capabilities [15]. The antioxidant potential of feed or feed components is increased by fermentation; consequently, the harmful effects of free radicals on broilers are reduced [159]. Egg production capacity and egg quality in laying hens may decline due to stress brought on by high-density feeding settings. Antioxidants included in fermented feed, like malic acid and lactic acid, may help mitigate these stress reactions [89].

In addition to the secretion of fiber-degrading enzymes [160,161], active substances from Pleurotus eryngii have also been demonstrated to accumulate a variety of secondary metabolites, including polysaccharides, phenolic compounds, and steroids, which are significant antioxidants and synergists and can enhance animals' oxidative status [162–164]. The fundamental explanation is that these metabolites may activate antioxidant transcription factors such as Keap1 and Nrf2 and induce self-defense and antioxidant gene expression to boost antioxidant capacity [165].

Aspergillus niger is preferred in solid-phase fermentation because it can grow successfully in arid environments [166]. *Aspergillus niger* may generate digestive enzymes such as tannase, lipase, xylanase, cellulase, protease, and amylase [167] and is also employed as a probiotic fungus in chicken nutrition [168]. It can boost the substrate's antioxidant and antibacterial activities by increasing polyphenolic substances' number and potency [169].

Previous research revealed that *Pleurotus eryngii* stem residues are abundant and include a variety of potent compounds, including phenolic compounds and crude polysaccharides [170], that are considered crucial elements influencing antioxidant activity [163,169]. The expression of antioxidant molecular targets in poultry may be further regulated by wheat bran fermented by white-rot fungus by increasing the activities of lignocellulolytic enzymes and the concentration of active ingredients [171].

Alfalfa meal chickens treated and fermented with fermented Astragalus showed significantly increased serum catalase (C.A.T.), glutathione peroxidase (G.P.X.), superoxide dismutase (S.O.D.), and total antioxidant capacity (T-AOC) and decreased serum malondialdehyde (M.D.A.) Supplementing with fermented Astragalus led to a notable improvement in ileal microbiota. Feeding *Lactobacillus plantarum*-fermented Astragalus to laying hens improves production, antioxidant capacity, immunity, and ileal microbiota. Astragalus fermented with *Lactobacillus plantarum* is projected to be a novel chicken feed ingredient [153,172].

Table 6. Effects of feeding bioconverted byproduct on oxidative stress in chickens.

Types of Recycled Byproducts	Microorganism	Oxidative Stress					Reference
		Malondialdehyde (M.D.A.)	**Glutathione Peroxidase (G.P.X.)**	**Superoxide Dismutase (S.O.D.)**	**Total Antioxidant Capacity (T-AOC)**	**Catalase (C.A.T.)**	
Grape pomace	*Aspergillus niger*	Not changed	N.A.	N.A.		Increased	[155]
Astragalus	*Lactobacillus plantarum* (CGMCC 1.557)	Reduced	Increased	Increased	Increased	Increased	[153]
Pine needles	*Aspergillus niger*	Decreased		Increased	Increased		[167]
Plant fraction (corn, cotton seed meal, soybean meal, and rapeseed meal)	*Lactobacillus plantarum* and *Bacillus subtilis*	Adding 15% fermented feed to broiler feed reduced serum M.D.A. levels.	N.A.	N.A.	Adding 15% fermented feed to broiler feed increased their T-AOC	N.A.	[15]
Wheat bran	White-rot fungi	Decreased					[171]
Rapeseed meal	*Bacillus subtilis*, *C. utilis* and *Enterococcus faecalis*	N.A.	N.A.	It increases the levels of serum total S.O.D.	Increased the levels of serum T-AOC	N.A.	[61]
Alfalfa meal	*Bacillus subtilis*	Decreased M.D.A. in serum	Increased the activities of G.P.X.	Increased the activities of total S.O.D.	N.A.	Increased the activities of C.A.T.	[172]
Cottonseed meal	*Bacillus subtilis* ST-141 and *Saccharomycetes* N5	Decreased M.D.A. in serum and liver	Increased levels of G.P.X.	Increased levels of total S.O.D.	Increased levels of T-AOC	N.A.	[173]

N.A., not analyzed.

3.4. Effects of Feeding Bioconverted Byproduct on Chicken Welfare

One key reason for the limited use of fermented feed in broiler feeding is the belief that such diets can result in wet litter and impair chicken behavior and welfare [121]. According to Skrede et al. [174], the amount of fermented wheat or barley in chicken feed caused a considerable decline in litter quality. However, Missotten et al. [121] found no visual changes in litter quality between birds fed fermented and non-fermented feed. In fact, Ref. [175] observed that broilers' paw lesions were less common and that feeding corn silage with crimped grains enhanced bedding quality, measured by the amount of dry matter.

There are limited data on the impact of fermented feed on broiler welfare. In the study by Steenfeldt et al. [176], silage (corn or barley-pea silage) was given to chickens as a supplement, reducing their tendency to pick at their feathers while improving their plumage quality. Compared to birds fed dry feed, Engberg et al. [177] found that providing wet-fermented feed (feed-to-water ratio—1:1.2 to 1:1.4) led to more excellent aggressive behavior and poorer plumage conditions. The water content, other characteristics of some fermented bird feed, and other factors, like the environment during rearing, could explain these disparate results. Further research is needed to determine fermented feed's effects on broilers' welfare and behavior.

4. Conclusions and Prospects

By utilizing all available unconventional feed resources to generate fermented meals, feed costs can be reduced while the production of eggs and meat increases. The use of agricultural residues not only serves to support a poultry farm financially but also improves environmental sustainability. Bioconversions of agricultural residues into high-quality fermented, nutrient-dense chicken feed have been used to supplement or replace nutrient-poor feed sources. *Filamentous fungi*, yeasts, and bacteria are mainly used in the bioconversion of agricultural residues to increase the content of amino acids, proteins, vitamins, and minerals; improve nutrient availability and digestibility; improve gastrointestinal health; and minimize anti-nutritional factors. Bioconverted feed has high lactic acid and lactic acid bacteria content and a low pH. It is essential in improving production efficiency and gut health in chickens and regulating immune function.

Agricultural byproducts remain a significant bioresource and an essential ingredient in the biological conversion of fermented chicken feed, particularly as the cost of producing conventional animal feed continues to grow year after year, and they have the potential to be used in developing high-quality feed. The current review illustrates that biologically converted agricultural byproducts could be exploited as a potential ingredient in poultry nutrition. As a result, feeding chickens a sufficient amount of biologically fermented feed will increase feed conversion and production.

The bioconversion of agricultural residues is a profitable business that should be supported by governments, research institutions, universities, and their development partners to improve the prospects of increasing animal protein sources for human consumption and expanding food security initiatives for national development. Research should be conducted in depth on the selection of strains, fermentation technology, product nutritional factors, optimum dosages in the diets for various breeds of chicken at various growth stages, and the economic viability of various kinds of unconventional feeds.

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