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A review of the effects of using fermented agro-industrial by-products for non-ruminants

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ABSTRACT

The world is going through its growing protein demand due to the increased human population. As a result, livestock production is getting accelerated to keep up with the pace with the increasing demand for animal protein. Furthermore, a good amount of animal protein comes from non-ruminants like poultry which mostly depend on cereals and concentrate-based feed as humans. The focus should be given to the agro-industrial by-products as alternative feed sources to reduce competition on human for food and make the low-quality feeds more efficiently digestible. This paper shows the effect of feeding fermented agro-industrial by-products on chicken, pig and fish. Feed quality changes, comparative procedures of fermentation, place of implementation and way forward are also discussed. In general, developing countries face problems with livestock feed scarcity. So, they are more conscious of removing this feed scarcity rather than having high-quality feeds. Therefore, fermentation is the technique best suited for agro-industrial by-products in countries where quality feeds are less available and unaffordable for budget farmers. This review depicts different fermentations to increase the nutrient contents of the agro-industrial by-products (rice bran, wheat bran, maize cob, maize straw, etc.). Additionally, this paper finds amelioration worldwide using this technique to increase nutrient digestibility, gut microbiota stabilization, immunization, and growth development with higher feed efficiency and overall raised performances of non-ruminant animals. In conclusion, this study tries to show the feed nutrient quality change and non-ruminants' performance after fermentation is implemented. Also, it gives evidence about the possibilities of the effective execution of the fermentation procedure.

Introduction

Fermentation has been employed to prepare meals and drinks since Neolithic era (Benninghaus et al., 2021). The existence time of fermentation is assumed to be 10000 years. Previously, during wine and beer production, foaming generation was observed due to carbon-dioxide gas. According to Louis Pasteur, a French scientist, and microbiologist, fermentation with yeast and other microbes not only produces ethyl alcohol but also other changes. (Morigasaki et al., 2020). Method involved for feed quality improvement includes fermentation of various types, bioprocessing with enzymes etc. In one of the fermentation processes like in solid state fermentation, microorganisms are cultured on a medium that is solid, moist and provides carbon and energy source. Value-added products are obtained by using this fermentation (Yafetto et al., 2023). This type of fermentation involves different types of agro-industrial by-products like rice straw, rice bran, sorghum straw, wheat straw, sorghum hay, and maize straw. This method is widely used for its cost efficiency and multifaceted benefits because it gives value addition to the products and removes

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environmental waste by managing the residues by using them in different fields (Shradhdha et al., 2020). World population, income growth, and high demand for animal-sourced products are the major causes to put the human food system under pressure. As a consequence, the number of undernourished people is 821 million and stunted children fewer than five is 613 million worldwide (Mbow et al., 2020). Livestock feeding is getting key concern for global food security as concentrate feeds are common for both animals and humans (Mottet et al., 2017). Specifically, most of the non-ruminant animals rely on concentrate feeds that create competition with human food. At the same time, in highly developed countries animal protein contributes 66% of the total protein demand where it meets around 17 % for the countries of low income (Ederer et al., 2023). To minimize the problems, it is very significant to utilize the by-products obtained after processing in agro-industries rather than main cereal grains. Another reason for using by-products is to minimize the feed cost of livestock rearing. Livestock feeding takes over the highest livestock input cost in the case of non-ruminants especially pigs and poultry which is up to the range of 65% to 70% (Apata et al., 2012). As high-quality protein feed is limited and costly in many developing countries, efforts have been made to improve protein content. In fact, fiber content enhancement is also seen (Debi et al., 2018). Altogether, nutrient augmentation of agro-industrial by-products is more prevalent for livestock feeding. However, agro-industrial by-products are mostly made up of three polymer compounds cellulose 40%-50%, lignin amounts from 20% to 35% and 20% to 30% hemicellulose (Šelo et al., 2021). In general, agro-industrial by-products have lower protein sufficiency from 2% to 6% and improvement can be achieved up to (10%-15%) if fungal growth is carried out (Shojaosadati et al., 1999). Huge amounts of agro-industrial by-products are being produced worldwide. According to Kumar et al., 2024, the practical use of the crop residue can be increased by on-farm management. If proper technology can be involved in agro-industrial by-products for the valorization with nutrient enrichment then it would be a potential solution to the feed shortage worldwide. Moreover, it will provide protein and energy because these are the sources of biomass, bioactive and nutraceutical compounds like carotenoids, polyphenolics and dietary fibers (Ajila et al., 2012). It is well known that soybean hulls contain about 17% fiber higher than wheat bran (Tabibloghmany et al., 2020) and crude protein content as the fed basis is 12.27% (Barbosa et al., 2008). Fermentation of soybean hulls with Aspergillus oryzae and Bacillus subtilis showed enhanced nutritional value (Crude protein increased 19.4% to 63.11% and decreased fiber by 73%) making it suitable for the nutrient source (Egwumah et al., 2023). The use of bioprocessing with the help of enzymes, bacteria, yeast and feed-grade fungi breaks down the lignin, enhances protein quality, utilizes lignin, digests phosphorus. Additionally, it decreases the antinutrients like mycotoxins to change the feedstock composition permanently for sustainable supply of food with reduced phosphorus, carbon and nitrogen footprint (Sun et al., 2024). On the other hand, fermenting low-quality feeds degrades toxins and antinutritional factors, pathogenic microbes and also preserves the feedstuffs for a long time with nutritional quality assurance (Dai et al., 2022). Recently, fermented feeds have been found as functional feeds for the micrology of broiler gut, performance and productivity including health of the broilers and helps for sustainable agriculture (Sugiharto et al., 2019; Dawood et al., 2020).

As a great portion of protein comes out of the meat of non-ruminant animals worldwide for human consumption, their rearing, and feeding should be economic especially in countries of high population so that there will be no competition between human and animal feed materials. Agro-industrial by-products obtained after agricultural products have huge benefits and show improved performance when offered to different non-ruminant animals after fermentation.

Composition of agro-industrial by-products (Nutritional composition and anti-nutritional factors)

Different agro-industrial by-products can supply different nutrients like protein, carbohydrates, energy, etc. (Freitas et al., 2021). Although these nutrients may be low in concentration, efforts have been made to optimize it by fermentation which has been discussed in a later section. Feed palatability and digestibility are affected by antinutritional factors contained by so many agro-industrial by-products (Olukomaiya et al., 2020). Moreover, antinutritional factors can reduce animal performance and toxicity can be caused by increased intake of these substances in the scarcity period of feed. Antinutritional factor hydrocyanic acid is present at an amount 364.2-814.7 ppm in cassava peel (Chauynarong et al., 2009). For example, cyanide ion can inactivate different enzymes that reduce the growth of animals. (Soetan et al., 2009). Therefore, these types of factors should be removed from the feed. Table 1 shows the compositions of agro-industrial by-products, their antinutritional properties and their way of removal.

Benefits of fermentation

Fermentation of feeds not only increases the nutritional value, digestibility and performance of animals but also decreases antinutritional factors of feed. The protein content of cocoa pod husk increases upto 167.6% and 200% while fermenting with the fungi Aspergillus niger and Aspergillus oryzae respectively along with various level of nitrogen treatment increasing the true protein content that shows the chance to be used as the feed for non-ruminant (Rakhman et al., 2018). Fermented cocoa pod husk meal with Rhizopus stolonifer at 12.5% level can be used for best performance and health for Chinchilla and New Zealand White rabbits (Olugosi et al., 2021). A dramatic reduction of phytate has been found in fermented corn cob compared to the control group.

Table 1: Nutritional composition of agro-industrial by-products and elimination methods of antinutritional factors

Name of by-products	Gross energy kcal/kg	Crude protein %	Crude fiber %	Fat %	Ash %	Dry matter %	Antinutritional factors/other obstacles	Mode of elimination	Intended animal	Reference
Cassava leaves	2532.37	29	14.90	6.70	11.6	92.20	Hydrocyanic acid	Fermentation with *Aspergillus niger*	Broiler	Apata et al., 2012, Chauynarong et al., 2009
Cassava peels	2460	8.20	12.50	3.10	5.40	94.90	Hydrocyanic acid (364.2-814.7 ppm)	Fermentation with *Aspergillus niger*	Broiler	Apata et al., 2012, Chauynarong et al., 2009
Coffee skin	3892	8.76	29.65	1.29	8.15	88.92	Tannin, caffeine	Fermentation with local microorganism	Pig	Sudita et al. 2023
Rice bran	3708	15.79	39.06	2.28	12.73	88.25	Fiber, beta-glucans	Two-step fermentation with rumen liquor	Chicken	Fanelli et al., 2023, Debi et al., 2019, Debi et al., 2018
Wheat bran	4538.7	18.01	10.80	-	7.94	87.78	Fiber, beta-glucans	Two-step fermentation with rumen liquor	Chicken	Lebas et al., 2012, Debi et al., 2019, Debi et al., 2018
Coconut dreg	-	5.7	36.7	-	-	-	Phytic acid	Solid-state fermentation by *Aspergillus awamori*	Fish	Sundu et al., 2019. 51. Mohd-Razali et al., 2020
Cassava stem (Saracura variety)	-	4.75	-	1.30	5.70	-	Less alpha-amylase	Solid-state fermentation with *Rhizopus oligosporus*	Poultry	Soares et al., 2024, ojo et al., 2022
Maize cob	-	3.49	37.40	9.55	4.41	94.52	High fiber	Fermented with probiotic MOIYL	Rabbit	Oduguwa et al., 2008, Noviani et al., 2018, olagunjo et al., 2013
Soybean hull	-	7.33	34.24	-	4.09	91.55	Low digestibility	Multienzyme supplementation	Pig	Niño-Medina et al., 2017, Kim et al., 2021

This is the result of the fermentation of the cobs with fungi (mixture of four fungi species namely, Aspergillus niger, Penicillium, Trychoderma and Aspergillus flavus) which produce a phytase enzyme that hydrolyzes the phosphate from the molecule of phytin making phosphorus available to the animals. Aspergillus niger had been reported to degrade the tannin content and phytate of fermented cob due to the production of enzymes (Busari et al., 2013). Moreover, improved nutritional and energy contents are possible when endophytic fungi transformation is done on agro-industrial by-products to convert them into digestible hexose and enhance nitrogen and protein content (Patil et al., 2020). Most importantly, bio-converted agro-industrial residue helps the poultry to mitigate oxidative stress. For example, wheat bran fermented with white rot fungi had been found to decrease the malondialdehyde (MDA) in chicken (Ababor et al., 2023). Feeding fermented agricultural by-products lowered the GHG emission for poultry rearing for increased secretion and activity of enzymes for digestion in the gastrointestinal tract (Sugiharto et al., 2022). If focus goes on the overall benefits and modes of action of fermented feed in poultry and pigs, these points come out - 1) intestinal physiology and microbial development, 2) nutrient utilization improvement, 3) stimulants for the gut immune system, and 4) improved barrier function against pathogens of the gut with lower pH. (Niba et al., 2009). Fermented rapeseed meal with Lactobacillus acidophilus, Bacillus subtilis, and Saccharomyces cerevisiae increases apparent ileal digestibility and standardized ileal digestibility in broiler chicken (Wu et al., 2020). In the countries of the tropics, fermentation is smoothly carried out at the ambient temperature (25-30)^{0}C which helps to reach the desired lactic acid level (>150 mmol/L) and attain low pH (<4) within a day (Geary et al., 1996; Niba et al., 2009). Feed fermentation has been found to increase mineral bioavailability thereby degrading antinutritional factors such as phytic acids, tannins, and trypsin inhibitors that improve the feeding value (Niba et al., 2009). At the same time, unutilized phosphorus has a tremendous influence on environmental pollution in the case of intensive poultry farms (Niba et al., 2009). To overcome this problem, fermentation makes them utilizable before releasing them into the environment. As pathogen contamination and spoilage of feed are of great concern in hot and humid countries, fermentation can bring biosafety and remove the contamination risk in poultry flocks and the food chain for humans. Fermented agro-industrial by products (brewer's dried grain, rice bran, palm kernel meal) with fungi Trichoderma viride were used to see the cost efficiency in layer birds. Cost of egg production was reduced by 28.30%, 11.32% and 24.53% for Brewer's dried grain, rice bran and palm kernel meal respectively (Iyayi et al., 2004). A two-stage fermentation of soybean meal by 2% and 3% replacement with protein feed in broiler reduced feed cost by 2.39% and 2.17% respectively on an average basis compared to control feed (Wang et al., 2012). Fermented mango kernel composite meal reduced the feed cost by 4.4 % when used at 20 % level in broiler (Abang et al., 2018). Most commonly, as fermentation increases the nutrient contents of feedstuffs, removes antinutritional factors, increases enzyme activity etc. which improves animal performance so it proves the viability and sustainability of fermentation for non-ruminant feeding practices.

Methodologies used for fermentation of agro-industrial by-products

Improvement of animal performance and feed quality is possible when a correct methodology is implemented. Different methods are used to serve the purpose. Commonly used methods are -two-step fermentation, solid-state fermentation, biotransformation with microorganisms. In two-step fermentation method, a mixture of feedstuffs, McDougall buffer and rumen liquor were used in the proportion of 1:2:3 for protein content improvement (Debi et al., 2022). In the same way, anaerobic fermentation of rice bran with rumen liquor had been used to improve fiber content (Debi et al., 2022). Most suitable method for fermentation of agro-industrial by-product is solid-state fermentation (Vandenberghe et al., 2021). Solid-state fermentation is done on solid substances which is free from any free-flowing liquid, protein, fatty acids, and lipids and these nutrients have been increased with solid-state fermentation of agricultural by-products (Abu et al., 2000). At the same time, this method has been used to increase protein in cereal grains and potato residues (Ajila et al., 2012). Furthermore, another researcher used solid-state fermentation method for potato processing waste to increase protein content by using yeast (Gélinas and Barrete, 2007). However, researchers are more interested toward the solid-state fermentation due to its low-cost media, minimum production of wastewater, better availability of oxygen, cheap operation process, low moisture, minimum processing steps, lower energy requirement, and maximum productivity (Ababor et al., 2023). Mostly used agro-industrial by-products for solid-state fermentation includes wheat bran, rice bran, oat brans, soybean bran, coffee pulp and husk, fruit pulps, peels, wood shavings, etc. which mostly contain non-starch polysaccharides (NSP) like hemicellulose, lignin, cellulose, pectins and other fibers. Agro-industrial by-products act both as nutrients and carbon for microbes and support biomass growth (Supriya et al., 2023). Sometimes baker's yeast is found to be used as fermented broiler feed for quality improvement (Akhtar et al., 2024). The method fungal fermentation relates depolymerization of enzymes and enrichment of protein with increased degradability of feeds (Manmdebvu et al., 1999). Other than this, fermentation with different microorganisms is carried out. For example, fermentation of coconut pod husk for non-ruminant feeding. Here Solid-state fermentation with Aspergillus oryzae and Aspergillus niger with urea and ammonium sulfate have been used (Rakhmani et al 2018). Table 2 shows different methods of fermentation used in non-ruminant animal.

Table 2: Fermentation methods for non-ruminants

Methods of fermentation	**Used feed**	**Experimented animal**	**Methodology followed**	**Reference**
Solid state fermentation	Maize cob	Poultry	Fermentation with *Rhizopus oligosporus*, room temperature, 72 hours, Phosphate buffer (pH 6, 50 mM)	Ndego et al. 2023

Fermentation with *A. niger, B. licheniformis, C. utilis,* and *L. plantarum*	Wheat bran	Growing pig	Moisture content was adjusted to 45^{0}C, And GE, CP, CF, EE were estimated using AOAC, lactic acid content was determined by liquid chromatography autoanalyzer, twenty pigs were experimented at temperature (26-28)^0 C with (55-60) RH.	Liu et al. 2023
Solid state fermentation with by *Bacillus amyloliquefaciens* and *Saccharomyces cerevisiae*	Wheat bran	Broiler chicken	60% distilled water was mixed with wheat bran added with 10% broth culture of BA, 10% broth culture of SC, and a mixture solution of with a 5% broth culture of BA and a 5% broth culture of SC, respectively. After the procedure at 30 °C for 3 days, the fermented wheat brans were dried at 40 °C for 4 days and mashed to form broiler feed.	Teng et al. 2017
SSF with *Trichoderma pseudokoningii*	Wheat bran	Broiler chicken	Wheat bran was chosen to be the substrate for SSF at 50% moisture, other procedures enzyme extraction assay, determination of reducing sugar content were also followed	Chu et al. 2017
Anaerobic fermentation with rumen liquor with or without urea	Rice bran	Broiler chicken	2% urea was used for anaerobic fermentation by rumen liquor. Broiler chicks of 90 days old were used.	Alam et al. 2023
Fermentation with rumen liquor	Corn straw	Cross breed native chicken	Moisture given is (55-60) % with 7% inoculum of *Trichoderma viride* and then keeping it in plastic bag for incubation for 2 weeks.	Saleh et al. 2020
Two step fermentation with rumen liquor	Wheat bran and rice bran	Laboratory analysis for poultry feed	First fermentation with (3-6) hours and again second step fermentation with buffer solution and rumen liquor then dried at 100^{0}C and finally analysis of nutrients.	Debi et al. 2022
Solid state fermentation with *Aspergillus oryzae* and *aspergillus niger* with urea and ammonium sulphate	Coconut pod husk	This experiment shows the chance of using fermented coconut pod husk without the toxic effect of urea for non-ruminant animal feeding	Cleaned, small pieced and chopped cocoa pod husks were taken of 10% moisture. Dried inoculum of *aspergillus oryzae* and *aspergillus niger* had been used which were grown from the substrate cooked rice for 3-4 days and dried. After that it was stored at 4^0 C in ground form. To make the water content 60% of cocoa pod husk, water had been added and then steamed for half an hour to add inoculum of 8 gm when it was cooled to 40^0 C. It was in room temperature when incubated.	Rakhmani et al. 2018
Fermentation with MOIYL Probiotics (*Trichoderma sp*. YLF8, Bacillus sp. YLB1, *Saccharomyces sp.* YLY3)	Corn Cob	Local rabbit of Indonesia	20 animals (Local rabbits) had been used of about 404.4 ± 9.14 gm weight. Four treatments had been experimented on the animals like P0, P1. P2, P3 with varying level of fermented cobs and unfermented cobs. CRD (Completely randomized Design) with 4 treatments and 5 replications. Different variables like dry matter and organic matter digestibility had been observed.	Noviani et al. 2018
Fermentation with *zymomonas mobilis*	Corn cob	Broiler chicken	*Zymomonas mobilis* extracted from fresh palm wine had been used on crushed Corn cobs using 3.5 cm sieve. In a fermentation vat following ingredients had been taken, 50 kg ground corn cobs, 100 liters water and starter of *zymomonas mobilis* of 5kg. The mixture had been mixed well to ferment for about 20 days at room temperature after that it was sun dried and was ready fot analysis.	Alade et al. 2023
Fermented peanut shell meal	Peanut shell	Broiler chicken	Fermented peanut meal with other feed ingredient had been given to the DOC (Day old chick) broilers four times a day and weight had been checked weekly. After 14 days in starter cage were moved to finisher case. Ad libitum water was being supplied. Completely randomized design with 4 treatments and 6 replications had been used, 6 broilers were there to form each unit.	Armayanti et al. 2021
Biotransformation using endophytic fungi and solid-state fermentation	Groundnut shell, Pigeon pea husk, wheat straw, Groundnut shell got the highest feasibility	Poultry	Endophytic fungi had been found to be isolated from the symptomless leaves and twigs of the plant *Celastrus paniculatus* which transformed agro-residues biologically in solid state fermentation. Maximum nutrient had been found for ground nut shell got the (maximum feasibility due to increased nutritive value which contain maximum carbohydrate content 13.92±0.7 g/100 g) after biotransformation and applied for the trial with 5%, 10% and 20 % supplementation along with commercial poultry diet to observe the body weight gain, feed consumption and feed conversion ratio.	Patil et al. 2020

AOAC = Association of official Analytical Chemists, BA = Bacillus amyloliquefaciens, SC = Saccharomyces cerevisiae, SSF = Solid State Fermentation

Effect of fermentation on nutritional quality of agro-industrial by-products

Fermentation of agro-industrial by-products improves the nutritional quality by increasing crude protein, digestibility and reduces fiber content of feed. Fermented rice bran with rumen inoculants increased the crude protein contents by 17.21% in broiler chicken and also increased growth performance (weight gain increased by 6.45%) and reduced blood cholesterol level by 22.89% (Shuvo et al., 2022). Therefore, crude protein enrichment is necessary for growth performance of broiler. But according to Debi et al., 2022, fermentation of wheat bran and rice bran with rumen inoculants did not increase crude protein content rather decreased crude fiber content. Methionine content of Wheat bran after 3 and 6 hours of fermentation increased by 24.9 %, 25.9 % respectively, and for rice bran it measured 12.2 %, 13.0% respectively in first and second stage of fermentation compared to control. In each case methionine content has been increased in 6 hours of fermentation. This might be an option for poultry feed. The main limitation of agro-industrial by-products is fibrous nature which makes the other nutrients unavailable for animals. Anaerobic fermentation with rumen liquor of rice bran and de-oiled rice bran removed the limitation of these feed ingredients by reducing the fiber components, CF and NDF. The CF and NDF level decreased by 19.09% and 7.79% respectively for de-oiled rice bran after 24-hour fermentation at 50 % moisture level as compared to the non-fermented state. The CF and NDF content of rice bran after 12 hours of anaerobic fermentation at 50% moisture level were 10.41% and 27.70% respectively. Most of the plant phosphorus remains as phytate phosphorus which is less available for non-ruminants. Fermentation process can increase the plant phosphorus availability to the animals. The minimum phytate phosphorus was at 50% moisture level which showed the suitability of feeding non-ruminant animals, especially pigs and poultry (Islam et al., 2022). A desirable chemical change occurred when fermentation was done with de-oiled rice bran, yeast and urea that increased phosphorus availability for broiler (Azrinnahar et al., 2021). Decreased crude fiber by 2.3% and increased crude protein by 7.72% were found when fermenting rice bran with Saccharomyces cerevisiae and urea for broiler (Liza et al., 2022). Fermented maize cob with Rhizopus oligoporus significantly increased glucose and decreased sugars and concentration of soluble protein. At 10 % inoculum, glucose, reduced sugar and soluble proteins were 1.15±0.21, 45.7±0.6 and 12.9±0.3 mg g-1 respectively. In the same way, total flavonoid, phenol, and the activity for antioxidant of 2,2- diphenyl-1-picrylhydrazyl (DPPH) and activity for amylase were found to be increased in fermented maize cob for poultry (Ndego et al., 2023). Substrate consists of 80% palm kernel cake and 20% rice bran with the fermentation of fungi Trichoderma viride enhanced crude protein to 17.34 % from 13.38 % and reduced crude fiber to 23.67% from 30.55% for poultry (Azizi et al., 2021). Fermentation of corn cobs with Zymomonas mobilis (Derived from fresh palm sap) had been proposed to increase crude protein content by 63.90%, crude fiber is decreased by 137.89% for broiler (Alade et al., 2023). The protein content of the fermented coconut dreg with 0.1% sodium selenite increased from 5.7% to 12.8% for broiler feeding. (Sundu et al., 2019). Fermentation of rice bran with or without urea using rumen liquor increased true protein content in the diet of broiler group urea fermented rice bran, UFRB (Isonitrogenous and isocaloric diets contained 7% urea added fermented rice bran) by 16.85%, FRB (Isonitrogenous and isocaloric diets contained 7% fermented rice bran) group by 16.45% and RB (Isonitrogenous and isocaloric diets contained 7% rice bran) group by 16.27% (Alam et al., 2023). Urea-added fermented feed gives higher true protein content. Recommended level should be applied to the non-ruminants. Solid state culture with fungal strain Trichoderma longiobrachiatum increased protein content and decreased cellulose and hemicellulose content in palm kernel cake of fish feed (Iluyemi et al., 2006). Protein content was enhanced with the reduction in fiber of fermented corn cob, rice bran and cowpea husk in rabbit nutrition (Oduguwa et al., 2008). Fermented corn cob with probiotic MOIYL (whose component is made up of fungi, yeast and bacteria having the capability to degrade fiber) at 20% level in feed of rabbit can reduce the fiber content at 14.26% level (Noviani et al., 2018). Therefore, probiotic is also used to ferment feeds of high fiber to give increased dry matter digestibility by reducing the fiber.

Effect of fermented agro-industrial by-products on non-ruminants

Researchers have found different results experimenting with fermented ago-industrial by-products worldwide. Table 3 shows the fermentation effects on the performances of non-ruminants.

Table 3: Effect of fermented agro-industrial by-products on the performances of non-ruminants

Type of fermentation	Used feed	Experimented animal	Effect on animal	Reference
Solid state fermentation	Maize cob	Broiler	No significant difference in weight gain	Ndego et al., 2023
Fermentation with *Aspergillus. niger, Bacillus licheniformis, Candida utilis, and*	Wheat bran	Growing pig	Improved nutrient digestibility, serum antioxidant, gut and fecal microbiota.	Liu et al., 2023

Lactobacillus plantarum				
Solid state fermentation with by *Bacillus amyloliquefaciens* and *Saccharomyces cerevisiae*	Wheat bran	Broiler	Improved FCR, enhanced lactic acid bacteria in ileum, increased ileum villus height, reduced serum cholesterol	Teng et al., 2017
Solid-state fermentation with *Trichoderma pseudokoningii*	Wheat bran	Broiler	Improved FCR, increased ileum villus height and villus height/ crypt depth ratio of ileum, decreased coliform count.	Chu et al., 2017
Anaerobic fermentation with rumen liquor with or without urea	Rice bran	Broiler	Improved growth performance and carcass yield	Alam et al., 2023
Fermentation with *Trichoderma viride*	Corn straw	Cross-breed native chicken	Improved weight gain and feed consumption	Saleh et al., 2020
Fermentation with *zymomonas mobilis*	Corn cob	Broiler	Reduced Viscosity of ileal digesta, improved FCR	Alade et al., 2023
Fermented peanut shell meal with probiotic	Peanut shell	Broiler	Improved body weight gain, FCR and broiler performance	Armayanti et al., 2021
Biotransformation using endophytic fungi and solid-state fermentation	Ground nut shell, Pigeon pea husk, wheat straw	Broiler	Decreased feed consumption and FCR, increased body weight gain	Patil et al., 2020
Fermentation with *Saccharomyces cerevisiae* along with inorganic selenium	Coconut dreg	Broiler	Increased broiler meat selenium level	Sundu et al., 2019

Chicken

A big portion of protein consumption of many developing countries comes from the chicken. To develop this protein source with higher feed efficiency fermentation of fibrous feed is an option. Fermentation of agro-industrial by products increases different production performance of chicken. Profitability is highly expected when growth performance is higher with minimum feed consumption. Fermented corn straw at 10% level in feed increases weight gain by 0.47% and feed consumption is reduced by 6.36% when used at 20% level (Saleh et al., 2020). Shuvo et al., 2022 also finds the increased growth performance of broiler chicken when fed with fermented rice bran with rumen inoculants. But body weight gain is 23% when fermented peanut shell meal is used in broiler which is little bit higher (Armayanti et al., 2021). This study finds negligible effect on feed consumption. So type of substrate for fermentation can alters the body weight gain at varying levels. Different levels or percentages of fermented feed also influence the performance of chicken. Supplementation with 20% fermented biomass showed the highest body weight gain at the end of the trial 1920.3 g which is 0.52% of control group and slight decrease in feed consumption is also found (Patil et al., 2020). Adding non-protein nitrogenous substance can be a beneficial way while fermenting feeds for chickens. 7% urea added fermented rice bran increases final body weight of chicken by 5.04% compared to the fermented rice bran without urea (Alam et al., 2023). Thereby each unit of body weight gain represents the extra amount of protein source for consumption which signifies the fermentation of feeds. But body weight gain is not always higher. Sometimes it is as it is before and after giving fermented feed. According to Ndego et al., 2023, fermented maize cob gives the same weight gain when broiler is fed with 10% inoculum (10% fermented maize cob with Rhizopus oligosporus). In this context, some non-protein nitrogenous substances can be used to see further results. FCR of broiler chicken is one of the most significant parameters to assess the production performance of broiler. FCR of broiler becomes 21% lower while feeding the birds with 5% fermented peanut shell meal along with basal feed compared to the group without fermented feed supplement (Armayanti et al., 2021). This improved FCR goes with the study of Patil et al., 2020 where all over FCR was improved when supplementing feed with 15% bio-transformed agro-industrial waste. Fermented rice bran reduces FCR by 5.14% level compared to the group having no fermented rice bran with increased dressing percentage level upto 73%

(Alam et al., 2023) Similarly, fermented corn cobs with Zymomonas mobilis (Derived from fresh palm sap) has been proposed to lower FCR when fed with 100 % Zymononas mobilis inoculated corn cob (Alade et al., 2023). FCR reduction is one of the common goals of economic broiler farming. Other blood parameters, bone mineral density, selenium contents are also found to ensure the health issues of birds. According to Shuvo et al., 2022, reduced blood cholesterol level has been found. Similarly, Fermented soybean hull with Aureobasidium pullulans (0.5%) reduced total cholesterol by 8.23% and LDL by 32% in the blood of 35 days old broiler (Lee at al., 2017). But fermentation of rice bran with Saccharomyces cerevisiae with urea increased the cholesterol content in blood in poultry (Liza et al., 2022). High level of cholesterol in blood can hamper the metabolic process of chicken affecting growth and feed efficiency and improves meat quality. Wheat bran fermented with white rot fungi is used to increase the activity of lignocellulolytic enzymes, and active components that regulate the antioxidant molecular targets, haem oxygenase-1 and glutathione-S-transferase (antioxidant gene expression) of chicken and peripheral blood mononuclear cells (Wang et al., 2017). But the activities of serum alanine aminotransferase, aspartate aminotransferase and alkaline phosphatase were not significantly induced with fermentation of maize cob (Ndego et al., 2023). Bone strength and mineralization are the key issues to support the rapid growth of broiler and to minimize the stress over the skeletal system. FFermented de-oiled rice bran with yeast and urea strengthens the bone of the broiler by increasing the availability of phosphorus. It also helps in bone mineralization and increasing tibia ash content and decreasing blood cholesterol levels (Azrinnahar et al., 2021). Commercial selenium additives in the diet of the broiler can be replaced by the prior addition of selenium to the fermented coconut dregs to get an equal performance level. 2% coconut dreg along with commercial selenium increased meat selenium level to 1.238 ppm and 2% fermented coconut dregs with 0.1% sodium selenite made it to a level of 1.237ppm, resembling almost the same value (Sundu et al., 2019). Inorganic minerals are toxic for monogastric animals and fermentation makes them organic (Hafsah et al., 2020). Microbes are responsible for transforming inorganic selenite to organic selenium with high nutritional value (Kieliszek et al., 2015; Rayman et al., 2018). Biotransformation is the process where microbes participate to make the inorganic selenium to organic selenium to reduce the toxicity (Thiry et al., 2013). This technique is also useful for layers regarding performance, egg mass and egg storage quality (Hatta et al., 2020). Selenium is one of the bioactive components that is beneficial for consumer health (Kralik et al., 2018). Proper fermentation of palm kernel cake through solid-state fermentation can be used as broiler feed up to (10-15) % without any performance deterioration (Azizi et al., 2021). Crude fiber digestibility is improved at the finisher phase of the broiler when fed with 50%fermented corn cobs with Zymomonas mobilisViscosity of ileal digesta had been reduced in broiler chicken for 50% and 100% fermented corn cobs with Zymomonas mobilis ((Alade et al., 2023). Fermented soybean hull with Aureobasidium pullulans (0.5%) d increases breast meat water holding capacity by 3.62%, breast meat protein by 4.06% and decreased breast meat crude fat by 28.86% (Lee et al., 2017). Therefore, all the meat quality related parameters are improved after fermented feed feeding of chicken which have higher consumer preference.

Pig

Pork meat is highly demanding in most of the countries of the world. Commercial farms for pigs create large impact of using fermented feeds (Niba et al., 2009). The microbial protein produced from fermentation using Candida utilis was found to have the potential to be used as an alternative source of antibiotics for the growth of weaned piglets. This protein increased the overall growth, amplified diversity in cecal microflora, and reduced diarrhea with enhanced intestinal health, and overall richness in piglets (Rasool et al., 2023). Antioxidant activity, immune status and intestinal permeability were improved with the co-fermented defatted rice bran in pig diet. It also increased the gut microbial richness and regulated microbiota with increasing bacteria which can degrade fiber (Clostridium butyricum and Lactobacillus amylovorus) and the dietary fiber of fermented bran improved immunity and gut barrier in finishing pig by butyrate secretion (Su et al., 2022). According to Liu et al., 2023, in the case of growing pigs, nutrient digestibility, capacity of serum antioxidant, microbiota composition in the gut, and growth performance had been improved by replacing 10% wheat bran with fermented wheat bran (Fermented with Bacillus licheniformis). Fecal microbiota (Escherichia coli) count became 5.76 (log10CFU/g) for basal diet in which 10% wheat bran was replaced with Bacillus licheniformis fermented wheat bran as compared to the group where basal diet had been given and the fecal E. coli amounted to 5.85 (log10CFU/g). Therefore, fecal microbiota is reduced by 1.54%. Fermentation of coffee husk with local microorganism (LMO) had been used as a substitute feed for pigs 1-3 months old. At 10% substitution, body weight increased from 7.89 kg to 12.76 kg (Sudita et al., 2023). In the case of piglets, using fermented soybean meal (B. subtilis, Lactobacillus casei, Hydrangea anomala) which increased lactic acid bacteria count, nutrient digestibility, fecal enzyme activity, decreased fecal E. coli, and decreased trypsin inhibitor and antigen protein content, diarrhea and mortality, improves FCR and Average daily gain (Feizi et al., 2022). If piglets are offered fermented soybean meal with Aspergillus oryzae then it increases ADG (Average daily gain) and reduces the feed gain ratio (also called feed conversion ratio, FCR) (Feizi et al., 2022).

Fish

When using fermented coconut waste (With bread yeast) in the case of catfish by 30% with other feed ingredients feed consumption, absolute body weight, the survival rate increased by 3.15% /fish, 11.97% /fish, 4.68%respectively and decreased feed conversion by 3.77%at the treatment of two months (Farizaldi et al., 2017).

Possible strategy for future

Fermentation of agro-industrial by-products has influences on feed nutritional status and animal performance. Different types of fermentation have been found to reduce crude fiber and neutral detergent fiber of feed to increase the availability of other nutrients. As in most cases, agro-industrial by-products have greater structural polysaccharides like lignin, and cellulose content, with lower nutritional value (low CP) and high fiber, they are less available and utilized by the non-ruminant animals due to their stomachs being simple which mostly work by enzymatic digestion. And it becomes a problem to digest them efficiently. For this reason, different types of fermentation, with different durations using microorganisms like fungus, bacteria, and rumen liquor have been used for the upgradation of the feed quality. The commonly used agro-industrial residues for feeding are rice bran, wheat bran, maize cob, soybean hull, coconut dreg, etc. Sometimes mineral supplementation with fermentation has been found to give better results for feed and to avoid commercial selenium supplementation for broilers (Sundu et al., 2019). Some antinutritional factors are found to be removed by this fermentation process which has damaging effects on the animal. Another major issue, that is animal performance is increased at various levels like increasing meat quality by increasing water holding capacity, increased growth rate, increased dressing percentage, improved immune status and gut health, blood cholesterol level, cost efficiency of rearing, reduced FCR, etc. in case of different non-ruminant animals. The beneficial effects on the non-ruminant animals are due to the greater availability of the nutrients which are bound by the lignin content of the agro-industrial residues in the unfermented state rather than fermented state. Side-by-side fermented feed contains different developed acids, and enzymes and bears the potential to be used as an antibiotic. Thus, fermentation process of the agro-industrial by-products may be used for improved broiler farming maximizing all the production performances of the birds and other non-ruminant.

Conclusion

Fermented agro- industrial by-products might be an alternative choice for their high nutrient enrichment and sustainability. The overall performance of the non-ruminant animals was increased at different levels using fermentation of various types. At the same time, the nutritional quality of low-quality feeds was also improved showing the positive effects on animal performance. This can ultimately show a way for livestock farmers and might be an option for feeding to their non-ruminant animals and utilization of low-quality feeds. More research should be done on economic viability, long term health impacts for non-ruminants. Deep knowledge and understanding on fermentation processes are required to improve the performance of non-ruminants in a more efficient way.

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