

Review

By-Product Feeds: Current Understanding and Future Perspectives

Kaili Yang ^{1,2}, Yiqing Qing ^{1,2}, Qifang Yu ^{1,2}, Xiaopeng Tang ³, Gang Chen ^{1,2}, Rejun Fang ^{1,2,*}  and Hu Liu ^{1,2} 

- ¹ College of Animal Science and Technology, Hunan Agricultural University, No. 1 Nongda Road, Furong District, Changsha 410128, China; ykelly@stu.hunau.edu.cn (K.Y.); qingyq@stu.hunau.edu.cn (Y.Q.); zly0430@stu.hunau.edu.cn (Q.Y.); SX20190026@stu.hunau.edu.cn (G.C.); liuh2018@lzu.edu.cn (H.L.)
- ² Hunan Co-Innovation Center of Animal Production Safety, Changsha 410128, China
- ³ School of Karst Science, Guizhou Normal University, Guiyang 550001, China; 201811001@gznu.edu.cn
- * Correspondence: fangrj63@hunau.edu.cn; Tel.: +86-(0)731-8618177

Abstract: Recently, industrial and agricultural by-products, resulting from crops, fruit and vegetable processing which can be used in animal diets have become a hot topic in the animal feed industry. This review focuses on the agro-industry by-products as feeds, not only for the nutritional values, but also for their nutritive contribution. In this review, we described the chemical composition of some by-products as feeds and their limiting factors in animal feeding.

Keywords: straws; residues; spent mushroom substrate; pig; hens; cattle; sheep



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Citation: Yang, K.; Qing, Y.; Yu, Q.; Tang, X.; Chen, G.; Fang, R.; Liu, H. By-Product Feeds: Current Understanding and Future Perspectives. *Agriculture* **2021**, *11*, 207. <https://doi.org/10.3390/agriculture11030207>

Academic Editors: Vito Laudadio and Vincenzo Tufarelli

Received: 27 December 2020

Accepted: 22 February 2021

Published: 3 March 2021

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1. Introduction

With the continuously increasing global population, large margin foods are needed and it is estimated that agricultural production should also be improved by 70–100% to meet global food demand in the future [1]. Unfortunately, more than 820 million people suffered from hunger in 2018, and about 2 billion people undergo moderate or severe food insecurity globally [2]. However, the Food and Agriculture Organization (FAO) has estimated that approximately one-third of the food produced globally for human consumption is lost or wasted, representing a significant loss of the resources spent making, processing and transporting food and a threat to food security [3]. The reduction of food waste is, therefore, a potential strategy for closing the gap between the supply and demand of food.

Based on corn and soybean meal as energy and protein sources, livestock provides meat, eggs, milk (as shown in Figure 1) and so on, contributing 1/5 of protein intake to human beings [4]. Consequently, livestock production between 2010 and 2025 has been projected to expand by 21% [5]. If feed efficiency remains the same, this expected expansion will require the world feed supply to increase from 6.0 to 7.3 billion tons of dry matter [6]. Competition between humans and animals for grains (corns, wheat, bean and others) is increasing. Therefore, global food security is at risk due to increasing pressure on natural resources threatening food systems' sustainability in general. It has become imperative to consider the development of new ingredients especially non-conventional feedstuffs which might be used in the animal feed industry. Initial estimates made by FAO for the Food Loss Index indicate that around 14% of the world's food is lost from post-harvest up to (but not including) the retail level [3]. Moreover, halophytes [7], straw [8], and residues [9] also can be used as feedstuffs.

By-product feedstuffs can be categorized into different classifications including stalks and residues. The residues contain several categories, such as by-products from residues of fruit and vegetable, by-products from grain- and legume-milling industry and oil industry. The agro-industry by-products are rich in nutrients, and they can reduce costs for animal products. The sharp increase in the processed foods will make industrial by-products and co-products more available. Systems of feedstuff manufacture from wastes make a

vertical, mutually complemented synthesis of animal production feasible and resolve the problem of waste and environmental pollution. Moreover, the utilization of new typical agro-industry by-products like fruit and vegetable by-products as feeds which supports sustainable development in feedstuffs. These agro-industry by-products will be of real value as an outlet for the leading products from which they have been derived and relieved food crisis to a certain degree. This review discusses and summarizes nutrition and the methods to improve the quality of agro-industry by-products as unconventional feeds.

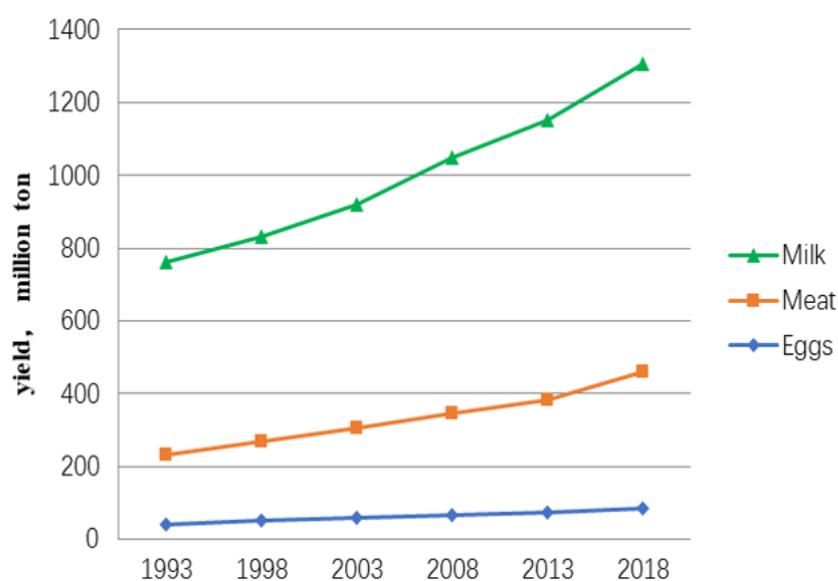


Figure 1. The yield of milk, meat, eggs in the past 30 years (FAO).

2. The Nutritional Components of the Agro-Industry By-Products

Most agro-industry by-products as feedstuffs are enriched in protein, fiber (as shown in Table 1), and other nutrients, which play vital roles in the feed industry's ingredients [10–12]. Plenty of agro-industry by-product protein sources have been used in animal feed [13].

Table 1. The chemical composition of straws and residues from food (%).

Items	DM	CP	NDF	ADF	CF	EE	Ash	Reference
Stalks								
Corn	86.60	5.90	74.10	39.70	-	-	-	Wang et al., 2014 [14]
Rice	89.90	7.26	71.30	44.80	-	1.46	-	Wei et al., 2018 [15]
Wheat	88.60	5.45	81.40	58.10	-	1.14	-	Wei et al., 2018 [15]
Chickpea	89.60	6.50	69.40	51.60	39.00	1.20	6.80	Bampidis et al., 2011 [16]
Cotton	-	6.85	58.86	40.60	-	2.39	7.77	Zhang et al., 2018 [17]
Pepper	-	15.77	41.16	37.43	-	-	-	Zhou et al., 2016 [18]
Soybean	94.62	3.67	67.34	51.162	-	-	3.69	Shen et al., 2019 [19]
Rape	93.62	5.79	67.87	55.52	-	2.51	7.58	Lan et al., 2019 [20]
Fennel	92.17	4.33	-	-	36.41	1.00	-	Yuan et al., 2018 [21]
Sunflower	90.73	5.72	53.09	-	30.15	0.89	-	Yuan et al., 2018 [21]
Residues								
Soya-bean Meal	93.85	44.56	13.84	7.35	5.60	5.69	5.70	NRC, 2012 [22]
Rapeseed Meal	93.11	35.19	23.77	17.57	9.77	9.97	6.39	NRC, 2012 [22]
Cottonseed Meal	90.69	39.22	25.15	17.92	13.96	5.50	6.39	NRC, 2012 [22]
Fishmeal	93.70	63.28	-	-	0.24	9.71	16.07	NRC, 2012 [22]
Blood Meal	93.23	88.65	-	-	-	1.45	5.82	NRC, 2012 [22]
Feather Meal	94.24	80.90	-	-	-	5.97	5.08	NRC, 2012 [22]
Meat Meal	96.12	56.40	31.60	8.30	-	11.09	21.59	NRC, 2012 [22]
Apple Pomace	92.35	6.62	39.03	20.78	14.48	5.53	-	Xiong et al., 2020 [23]

Table 1. Cont.

Items	DM	CP	NDF	ADF	CF	EE	Ash	Reference
Mango Pulp	92.06	16.38	-	-	18.90	5.50	6.43	Pluschke et al.,2018 [24]
Orange Pulp	22.10	15.10	26.50	17.20	7.70	19.10	-	Minguez et al., 2018 [25]
Potato Pulp	100.00	8.21	22.30	17.53	-	-	4.05	Shen et al., 2019 [19]
Fennel Shell	91.17	7.61	-	-	23.31	2.92	-	Yuan et al., 2018 [21]
Sunflower Plate	89.63	11.84	23.51	-	12.48	2.13	-	Yuan et al., 2018 [21]
Cotton Shell	91.57	10.53	45.77	-	53.52	2.04	-	Yuan et al., 2018 [21]
Grape Seed	97.40	9.30	53.90	-	-	10.90	2.70	Correddu et al., 2015 [26]
Winery Sediment	31.20	2.80	6.40	4.30	-	28.00	21.40	Ishida et al., 2015 [27]
Olive Cake	94.70	7.90	58.4	45.9	-	9.20	13.60	Abbeddou et al., 2011 [28]
Cassava Residue	90.16	2.58	75.34	24.48	-	0.22	-	Lv et al.,2017 [29]
Bean Curd Residue(Air-dried)	93.25	18.14	42.99	28.69	-	3.34	-	Lv et al.,2017 [29]
Pistachio	90.00	15.30	25.90	-	-	5.80	-	Ghasemi et al., 2012 [30]
Pomegranate Pulp	91.20	6.90	31.40	22.80	-	2.60	3.60	Valenti et al., 2019 [31]
Citrus Pulp	90.40	7.70	19.40	12.80	-	4.90	16.80	Fegeros et al., 1995 [32]
Exhausted Myrtle Berries	97.00	8.00	67.00	53.30	-	2.60	9.00	Castrkca et al., 2019 [33]
Coffee Grounds	91.10	11.80	-	-	42.50	23.1	7.00	Campbell et al., 1976 [34]
Pumpkin Peel	-	1.65	-	-	2.240	0.86	-	Valdez-Arjona et al.,2019 [35]
Pumpkin Pulp	-	1.13	-	-	1.09	0.42	-	Valdez-Arjona et al.,2019 [35]
Pumpkin Seed	-	27.50	-	-	16.20	52.4	-	Valdez-Arjona et al.,2019 [35]
Bitter Gourd	9.27	22.30 ^a	45.10 ^a	35.80 ^a	-	-	-	Das et al., 2018 [36]
Brinjal	7.85	17.2 ^a	47.20 ^a	42.10 ^a	-	-	-	Das et al., 2018 [36]
Cabbage	9.97	17.3 ^a	33.70 ^a	20.90 ^a	-	-	-	Das et al., 2018 [36]
Cauliflower	10.40	27.0 ^a	58.40 ^a	30.40 ^a	-	-	-	Das et al., 2018 [36]
Snake Gourd	4.30	18.4 ^a	48.0 ^a	37.70 ^a	-	-	-	Das et al., 2018 [36]
Sweet Gourd	5.40	9.40 ^a	43.10 ^a	31.20 ^a	-	-	-	Das et al., 2018 [36]
Tomato	5.20	20.0 ^a	50.40 ^a	36.90 ^a	-	-	-	Das et al., 2018 [36]
Cucumber	4.00	20.1 ^a	42.70 ^a	37.50 ^a	-	-	-	Das et al., 2018 [36]
Sugar Cane Residues	85.04	10.62	31.58	27.77	18.12	1.50	12.82	Zhang et al., 2017 [37]
Pleurotus Eryngii Spent Mushroom Substrate	93.12	12.34	64.33	44.41	-	0.22	14.22	Li et al., 2019 [38]
Ganoderma Lucidum Bran	90.07	17.77	40.83	28.73	14.76	9.65	14.09	Zhang et al., 2017 [37]
Faba Bean	89.8	4.9	78.80	69.10	-	-	5.50	Wegi et al., 2018 [39]
Phragmites Hay	-	7.18 ^a	73.05 ^a	38.11 ^a	-	2.59 ^a	8.05 ^a	Zhang, 2019 [40]
Mulberry Leaves	-	18.08	43.23	29.87	24.34	0.82	9.53	Cai, 2019 [41]
Bottle Gourd Leaf	8.10	33.6	-	-	11.20	4.20	18.2	Hossain, 2016 [42]
Castor Bean Leaf	24.20	21.0	-	-	25.00	1.60	9.30	Hossain, 2016 [42]
Broussonetia Papyrifera	91.12	12.80	46.91	35.73	-	3.50	8.84	Hao et al.,2020 [43]
Leucagena	32.00	20.5	31.60	-	-	-	6.40	Halmemies-Beauchet-Filleau et al., 2018 [44]
Moringa	33.00	25.1	21.90	-	-	-	11.50	Halmemies-Beauchet-Filleau et al., 2018 [44]
Pine Bark	-	2.8	66.70	-	-	4.70	2.20	Halmemies-Beauchet-Filleau et al., 2018 [44]
Willow	26.40	16.7	57.30	-	-	-	7.10	Halmemies-Beauchet-Filleau et al., 2018 [44]

Note: DM: Dry matter; CP: Crude protein; NDF: Neutral detergent fiber; ADF: Acid detergent fiber; CF: Crude fiber; EE: Ether extract; ^a: Based on DM.

2.1. Stalks

The structural portion of most plants, such as the stalks, leaves, and stems, are high in acid detergent fiber (ADF) and neutral detergent fiber (NDF) but low in protein and minerals [45]. Some dietary fiber may be essential for young ruminants (like calves) to sustain attrition in their rumen and keep away from abnormal growth of the rumen [46]. As feedstuff, straw is a by-product of crops, including rice, wheat, corn, and vegetables [47]. For example, millet straw is a crucial coarse fodder provenience for ruminants in many areas [47]. Straws can be not only supplemented with grains or by-products of grains but also as individual ingredients. Stalks are mixtures of pasture used in ruminant feedstuff frequently and the raw materials of ensiling [48]. Chen et al. (2020) investigated that the combinational utilization of millet straw and corn straw could accelerate the metabolism ability of blood biological chemistry in fattening lambs. The growth performance of fattening lamb was improved by the substitute of 50% corn straw with millet straw [48]. Silage-formed stalks include a moderate quantity of protein (9.3–13.0%) and a high content

of NDF (48–59%), which may be a possible source of roughage for ruminant animals [49,50]. Straw is rarely used for monogastric animal feeding. Few research studies investigated that straws were provided to pigs, which could decrease gastric ulcers [51]. In Jensen et al.'s study, the straws were delivered to pigs on a concrete floor, which increased the daily weight gain, the improvement of intestinal tract health and increased stimulation of exploratory behavior with the straws provided need to explore [52]. Ruminants traditionally grazed on pastures, however, with more intensive systems, pasture availability and grazing as a source of nutrients is decreasing. One of the effective ways is that straws are used as feed to ruminant animals. Feeding protein supplements is one of the most expensive and limiting feed sources [13,53]. Some stalks are with typically high moisture content, leading to a decrease in the shelf-life and making their collection and incorporation in animal feed more difficult. In the past years, crop straws fired on the farm not only have significantly impaired air quality but have also wasted sources [54]. Many researchers have been attempting to find methods to improve the nutrition of stalks, such as ensiling. In general, the utilization of stalks, which are human-inedible resources, as a source of animal feedstuff would help to solve the problem of feed inadequacy in a way, potentially decreasing feed costs, and reducing the relevant problems of waste resources.

2.2. Residues

The residue feeds contain agro-industry by-products of plants (oil-seed-meals, plant shell, seed, fruit pulp, fruit pomace, and others), animal (whey, fishmeal, meat and bone meal, blood meal, and so on), and mushroom substrate. The NDF and ADF of residue feeds are lower, while crude protein is higher than straw. Most residues are abundant with crude protein, dietary fiber and phenolic compounds. Agro-industry by-products as feedstuff of plant include conventional feed (soya bean meal, cottonseed meal, rapeseed meal, and others) and unconventional (oil-seed-meals, plant shell, seed, fruit pulp, fruit pomace, etc.) feed.

Soya-bean meal is mainly used in the livestock feed as a protein source, moreover, it is palatable. However, people are exploring a protein substitute that will displace soya-bean in the livestock diets because of its dependence on imports and high prices [55]. Rapeseed meal and cottonseed meal, oil industry by-products, are generally acknowledged as alternative protein feed for animals. Rapeseed meal is a feed component with huge economic potential. It is the second used raw protein material worldwide (after soybean meal) in feeding livestock [56]. The crude protein of rapeseed meal can vary from 33.9–36% of dry matter and this protein supplies less lysine than soybean meal protein but contains more sulfur-containing amino acids [56], and this material is restricted as fodder in livestock due to high levels of anti-nutritional ingredients (particularly tannins, glucosinolates and phytic acid). The utilization of cottonseed meal as feedstuff is also limited because of the presence of high free gossypol (a toxic polyphenolic compound), crude fiber and low lysine level [57].

Agro-industry by-products as unconventional feed sources can be defined as those not traditionally used in animal feeding and commercially prepared feedstuffs for farm animals. The agro-industry by-products as unconventional feedstuffs consist of various food resources, such as palm press fiber (oil palm by-products), by-products from the processing of sugar, cereal grains, citrus fruits and vegetables from the food processing for human consumption [58]. Nutritional ingredients of partial agro-industry by-products as unconventional feeds are listed in Table 1. Agro-industry by-products as unconventional feedstuffs have been exploited for farm animals mainly including peanut meal, olive oil cake, mulberry leaves, orange pulp, as shown in Table 1. Concerning the crude protein, contents and large values can be observed for all by-products or new feed ingredients like *broussonetia papyrifera*, mulberry leaves or mango pulps. Fruit pomace also contains bioactive ingredients including vitamins, polyphenols (especially anthocyanins), dietary fiber, and essential unsaturated fatty acids [59]. Fruit pulp is a good source of the beneficial active compounds: gallic acid, phenolic compounds (anthocyanins, etc.) [60], carotenoids, and dietary fiber [61], and so on. Moreover, dietary fiber is described as supporting

laxation, attenuating blood glucose responses and assisting with cholesterol-lowering, and influencing gut microbiota [62]. The biological activities of polyphenols have been primarily observed and proved the antioxidant abilities, positive consequences on health like anti-inflammatory effects [63,64]. These natural compounds were considered and they can replace antibiotics in the agro-industry by-product as feeds are used all over the world [12]. In the past few decades, a hot point to develop functional foods has emerged, which contains diverse ingredients (protein, specific fatty acids, selenium-riched, low cholesterol), protecting chronic diseases of cancer [65,66]. Khan et al. (2012) indicated that flaxseed cake improved omega-3 fatty acid and vitamin of eggs [67]. However, particularly high protein content of agro-industry by-products has much more phenols including chlorogenic and caffeic acids, which decreases its nutritional value by combining with proteins, particularly to essential amino acids such as lysine and methionine [68]. Hence, seeking methods to improve the nutritional value of agro-industry by-products is indispensable.

Feedstuffs of animal-by-product are generally better than that of plants for the health and performance of livestock and poultry because of the greater quantity of proteinogenic amino acids (AAs) and higher quality (the proportions and digestibility of AAs) [69]. Moreover, animal-derived feedstuffs contain taurine, creatine and creatine phosphate that are effective anti-oxidants and partake in energy metabolism in the brain, skeletal muscle, heart, and gonads of animals [70]. Additionally, animal-derived feedstuffs may involve polyamines that are fundamental for DNA and protein syntheses in most animals [71]. Common animal-by-product feedstuffs contain fishmeal, feather meal, blood meal, meat and bone meal, and meat meal. Among animal-by-product feedstuffs, fishmeal was most used which generally exchanged at 65% crude protein, but the crude protein content can change from 57% to 77%, relying on the species of fish processed [69]. Varieties of fish species can be used in fishmeal, while the most general is Menhaden that occupies about 90% of U.S. fishmeal production [72]. Feather meal is superior to soybean meal in total cysteine, valine, and threonine content. It is cheaper as a protein source. On the other hand, feather meal has not been widely used as a protein source in livestock and poultry diets due to the modifiability in quality and digestibility [73]. Animal-by-products are not widely used as protein sources in feedstuffs compared with plant-by-products. One of the most important reasons is that if pathogenic bacteria would be unsuccessful in being inactivated during the processing of animal carcasses under these altered conditions, and that feeding such polluted material to animals spread the pathogen to animals, causing disease [74]. By-products of animals as protein sources in diets for livestock are forbidden in Europe (European Commission Decisions No. 98/272/CE and 2000/374/CE). According to the report of Hahn, the following steps of the processing of animal meal include that cutting up the carcasses, sterilization of the material, drying the material to a water content of around 5%, removal of fat, and grinding and sieving of the material. Every step should be performed carefully to guarantee the quality of animal meal [75].

A mushroom substrate is a co-product of composted organic medium from the mushroom growth process which is usually the production of renewable agricultural residues including sugarcane bagasse, cottonseed meal, cocoa shells, oil palm empty fruit bunch, and others [76]. After mushrooms are harvested, the mushroom substrates which are enriched in cellulose, lignin and protein could be more easily digested by animals due to enzymolysis of mushroom cultivating [77]. The mushroom substrate contains many bioactive ingredients such as secondary metabolites, extracellular enzymes and carbohydrates produced [78]. The mushrooms industry is one of the incredible drivers in the world and has plentiful mushroom substrates which face storage and disposal issues [79]. One method to solve the problem is to feed animals with the mushroom substrate.

It is worth noting that the chemical compositions of by-products depend on soil varieties, agroclimatic conditions, stage of ripening, or other facts [35,43,80]. Several factors, including protein concentration and its biological value, digestibility, level of energy, fats and carbohydrates, concentration of amino acids, vitamin and mineral, and the amount of fiber and the existence of toxic substances, influence the quality of by-product feedstuffs.

3. The Measures to Improve Agro-Industry By-Product Quality

Lots of agro-industry by-products have low quality, and some of them contain anti-nutritional factors (Table 2) which influence feed palatability, digestibility, and impaired animal production performance [81–83]. Bampidis et al. (2011) reviewed that chick-peas contain a variety of secondary compounds (protease and amylase inhibitors, lectins, polyphenols and oligosaccharides) which impair nutrient absorption on animal health and growth [16]. The agro-industry by-products as feeds are also limited by high fiber [84,85]. Ruminants generally can endure a much higher content of toxic factors than nonruminants [86]. However, there are new and available technologies emerging to degrade or remove anti-nutritional factors and improve the quality of by-products.

Table 2. Anti-nutritional factors on agro-industry by-products ingredients.

Anti-Nutritional Factors	Sources
Protease inhibitors	Beans
Lectin	Beans, Gramineae, Solanaceae, Amaryllidaceae J. St.-Hil.
Tannin	Sorghum, Brassica napus L, beans
Non-starch polysaccharide (NSP)	All plants
Gaseous distention factor	Beans
Antigenic protein	Beans

3.1. Physical Processing

Physical processing, including crushing, peeling, soaking, extruding, and expanding, does not have effects on the chemical composition of biomass, but changes physical characteristics such as surface area, bulk density, and specific porosity [87]. Physical processing is used as pretreatment for destroying the by-products' stubborn structure to facilitate the following processing more effectively. As Akobi et al. indicated, the extrusion decreased particle size and crystallinity and enhanced surface area of biomass sugar availability of lignocellulosic [88]. Heat-treating rapeseed products is a straightforward, effective way to deactivate myrosinase. This approach, currently the most popular, degrades up to 70% of the glucosinolates contained in rapeseed meal [56].

3.2. Chemical Processing

Chemical processing includes alkalinization, acidification, oxidation and ammonification. Alkalinization, acidification and oxidation have not been widely used because of pollution, high cost, etc. Ammoniation is commonly used in chemical processing. However, liquid ammonia and ammonia water transport are very inconvenient. Additionally, the ammonia loss rate is high, and there is a certain degree of insecurity. However, the methods mentioned can be combined in their utilization. For example, lignocellulose is a mass of content in straws of about 80–95%. It has bad hydrolysis performance which hinders the absorption and degradation of energy recovery and volatile concrete degradation which can treatment with mesophilic anaerobic digestion and urea plus nitrate pretreatment [89,90].

3.3. Biological Processing

Biological processes include enzymolysis technology, microbial fermentation, and so on. The enzymes commonly used by the feed industry are the glycanases involved in the splitting decomposition of NSP in viscous cereals (wheat and triticale) and microbial phytases that aim at phytate-complexes in plant components [91]. Moreover, relatively abundant literature examples (papers and patents) have introduced the utilization of typical enzymatic hydrolysis treatments (proteases, glycosyl hydrolases) on by-products for enhancing the nutritional value and digestibility of protein hydrolysates [92]. Microbial fermentation can improve the nutritional ingredient of particular by-products [93]. Fermentation can enrich the nutrition of residues by biotransformation which implements several microorganisms, mainly *Bacillus*, *Saccharomycetes*, fungi, *Lactobacillus* spp [94,95]. Fermentation enhanced

crude protein concentration and other nutriment but reduced many anti-nutritional factors, crude fiber content and toxic ingredients. Organic acid, several amino acids and metabolite of Okara were increased by fermentation [96]. Wang et al. (2020) showed that the crude protein content of corn straw reached the maximum value of 13.23% when fermented by *Trichoderma koningiopsis*, *Phanerochaete chrysosporium* and *Saccharomyces cerevisiae* [97] and Wu et al. (2020) reported that the corn stalk fermented by fungi and enzyme mix (cellulose, xylanase and *Phanerochaete chrysosporium* were 0.2 g/kg, 0.1 g/kg and 20% respectively) were degradable, with NDF and ADF to 51.61% (vs. 67.44%) and 31.77% (vs. 39.79%) [98]. Zhu et al. (2018) showed the content of 17 kinds of amino acids and total AA content was increased in tea residue when fermentation by *Aspergillus niger*. Moreover, the total tanning, NDF, ADF were decreased to 2.42% (vs. 11.63%), 32.96% (vs. 39.85%) and 12.28% (vs. 15.70%) respectively [99]. The ensiling process is an available conservation technology that is known to acidify biomass, and it restrains the development of spoilage bacteria, thus providing safe and long-term preservation for humid fodder [100]. Inoculation with lactic acid bacteria (LAB) or supplementation with easily fermentable carbohydrates (readily metabolizable by LAB) like molasses, certified to be successful in increasing the availability of the ensiling process. This supplies an additional source of simple sugars for the growth and multiplication of LAB, thereby accelerating the silage acidification and avoiding microbial deterioration, especially when the ensiling biomass has a low concentration of soluble carbohydrates. In general, agro-industry by-products as feeds can be improved by fermented, silage, enzyme and other ways [101].

The feedstuffs are commonly manufactured by a combination of technologies to improve nutrition. For example, lignocellulosic biomass can be changed into fermentable sugars. This process needs pretreatment to decrease the recalcitrance of lignocellulosic biomass by opening or partially breaking up the recalcitrant structure to enhance the enzymes' accessibility to the cellulose during the enzymatic hydrolysis step. These pretreatment methods are usually divided into physical, chemical, physical–chemical and biological categories, such as steam explosion, dilute acid pretreatment, organosol pretreatment, and alkali pretreatment [86].

4. The Application of Agro-Industry By-Products as Feeds in Animals

There is a considerable amount of research studies on the roles of agro-industry by-products as feeds in animals. Moreover, agro-industry by-products as feeds have an influence on growth performance, immune function and product quality. However, it is quite difficult and risky to clarify the contribution of each by-product on feed intake and animal performance by considering the attribution of nutrients, due to the complexity of chemical compositions in by-products. In addition, several agro-industry by-products have negative effects when supplied too much in the feed.

4.1. The Application of Agro-Industry By-Products as Feeds in Monogastric Animals

The applications of agro-industry by-products as feeds in monogastric animals (particularly pigs and poultry) are especially prudent for their direct competition with humans for edible energy and protein sources due to the common diet is corn-soybean in the pig and poultry industry. Monogastric animal feeding is more and more challenged by feedstuff in the diets, immune traits, and meat quality. Currently, numerous studies focus on feedstuffs from agricultural by-products on pigs and poultry [102,103]. Moreover, over the last decade, the interest in entirely natural, plant-derived antioxidants has increased greatly [104,105]. Many agro-industry by-products as feeds can improve the feed conversion ratio, body weight, antioxidant capacity, immunity, gut morphology and intestinal microflora of pigs [78,106] and poultry [37,107]. The research studies of agro-industry by-products as feedings of pigs and poultry are shown in the following subparagraphs.

4.1.1. Pigs

Agro-industry by-products as pig feedings can enhance growth performance, meat quality of piglets and growing pigs, and improve production performance, milk, and quality of sows. Dong et al. (2019) assessed the nutrient profiles, the apparent total tract digestibility of nutrients, digestible energy, and metabolizable values of the five feeds: highland barley, buckwheat, glutinous broomcorn millet, non-glutinous broomcorn millet, and Chinese naked oat in the feeding of growing pigs. The results indicated that the five feeds, and particularly the broomcorn millets, could replace the corn in growing pig diets [108]. Numerous beneficial effects of mulberry were identified, including antibacterial and antitumor effects, reducing blood sugar, and improving immunity [109]. Several studies reported that mulberry and *Broussonetia papyrifera* are effective feedstuffs to improve meat quality and the chemical composition of muscle without negative effects on growth performance [110,111]. Most experiments of dietary fiber mainly on the sows confirmed improve production performance, milk quality, immunity traits, and sow's welfare [112–114]. The inulin and cellulose as fiber sources were used in the above studies. Several research studies reported the use of brans or straws which have high fiber content and low cost as fiber in sow production but few studies are observed on the finishing pig. Fan et al. (2020) showed that rice bran replacing corn decreased the inflammatory biomarkers of serum and have the potential function in modulating the intestinal barrier by upregulating the mRNA expression levels of MUC2 and downregulating Nrf2, NQO1, and HO-1 in the colon [115]. More attention should be paid to the fiber source from agro-industry by-products. The results of agro-industry by-products used in pigs are partly demonstrated in Table 3. The research studies of abnormal by-product feeds of oil-seed-meals (like olive cake processing waste, cassava peel meal, brewers dried grain, mango pulp) were supplied for the diets of pigs, and could decrease the backfat thickness and intramuscular fat [116], reduce Insulin-like growth factor (IG-2) expression in liver and duodenum [117], and increase starch and protein digestion [24]. By-product feeds of forestry decreased meat b* value, increased CP and concentrations of Ala, Thr, Ile, Lys and Pro in longissimus thoracis, increased final BW, ADFI and ADG, decreased F/G ratio, improved slaughter weight, carcass weight, and carcass yield and meat a* value, decreased shear force, drip loss, such as mulberry leaf and *moringa oleifera* [106].

Most agro-industry by-products are of lower quality as pig diet feedstuffs. However, they can be improved through chemical, physical and especially biological technology. Rho et al. (2018) investigated treating corn and DDGS with a mixture of β -glucanase and xylanases improved feed efficiency in growing pigs [118]. Sehm et al. (2007) concluded that the flavonoid-rich feeding regiment (polyphenol-rich apple pomace or red wine pomace) has positive effects on villi morphology and gut-associated lymphoid tissue activation, improving pig health [119]. Fang et al. (2016) supplemented apple pomace-mix silage (APMS) to neutered male pigs, and the results demonstrated no difference in average daily gain (ADG), carcass weight, backfat thickness or dressing ration with the control group, but average daily feed intake (ADFI) was lower and feed efficiency was higher when feeding APMS. Moreover, the APMS improved the moisture, linoleic acid, linolenic acid and arachidic acid and decreased the water holding capacity, palmitic acid, palmitoleic acid, and heptadecenoic acid content [120].

Table 3. Applications of agro-industry by-products as feeds in pigs.

Items	Levels	Monogastric	Main Influences	References
Olive Cake Processing Waste	5, 10%	Growing-finishing pig	Decreased backfat thickness and intramuscular fat and modified their fatty acid composition, increasing the concentration of MUFA and PUFA and improving quality indices.	Liotta et al., 2019 [116]
Brewers dried grain, cassava peel meal, Plantain peel meal, corn husk meal	35%	Growing pigs	Decreased Insulin-like growth factors (IG-2) expression in liver and duodenum	Sorhue et al., 2020 [117]
Mango pulp	15%	Grower pigs	Increased starch and protein digestion to a certain extent Decreased meat b* value, MyHCIIx mRNA levels, increased MyHCIIa, CP and concentrations of Ala, Thr, Ile, Lys and Pro in longissimus thoracis.	Pluschke et al., 2018 [24]
Moringa oleifera	4%	Finishing pig	increased final BW, ADFI and ADG, decreased F/G ratio, improved slaughter weight, carcass weight, carcass yield and meat a* value, decreased shear force, drip loss, MyHCIIx and MyHCIIb mRNA levels, and increased MyHCI and MyHCIIa mRNA levels.	Chen et al., 2021 [106]
Mulberry leaf	4%	Finishing pig	Increased loin-eye area and contents of crude protein, inosine monophosphate and several amino acids in muscle tissues.	Chen et al., 2021 [106]
Mulberry leaves	3, 6, 9, 12%	Finishing pig	Improved growth performance, immunoglobulin secretion, and anti-oxidant capacity, decreased leukocyte percentage, cholesterol, and MDA concentrations	Liu et al., 2019 [110]
C. militaris spent mushroom substrate	2 g/kg	Growing pig	Improving anti-oxidant and decreasing inflammatory response of mothers and their offspring through modulating the composition of gut microbiota.	Boontiam et al., 2019 [78]
Dietary fiber (Ratio of insoluble to soluble)	3.89, 5.59, 9.12, 12.81%	Sow	Increased body weight (BW) at weaning and piglet BW gain, the crypt depth of the jejunum in weaned piglets.	Li et al., 2019 [113]
Dietary fiber (Ratio of insoluble to soluble)	3.89, 5.59, 9.12, 12.81%	Sow	Wheat straw increased postprandial IGF-1 and prolactin, oat straw increased lactation feed intake and piglet weaning weight.	Li et al., 2019 [113]
Wheat or oat straw	10%	Sow		Agyekum et al., 2019 [90]

Note: b*: yellowness; a*: redness.

4.1.2. Poultry

Poultry production is developing fast all over the world [22]. Therefore, agro-industry by-products as feedstuffs are in favor of the development of poultry production. The by-product of grape improves gut morphology and intestinal microflora, increases the biodiversity degree of intestinal bacteria and enhances the percentage of unsaturated fatty

acids [121,122]. There is a difference in growth performance when adding high levels of grape seed, but no unifying data of the maximum values exist [123,124]. Zhai et al. (2020) indicated that moringa stem meal, afforded at a rational level (no more than 60 g/kg), could be exploited as a feedstuff for geese in the finisher period [125]. Lombardi et al. (2020) indicated ancient wheat line by-products (consisting 50:50 of *triticum aestivum* var. *spelta* and *Triticum durum dicoccum* L.) could improve feed conversion ratio, reduce the level of cholesterol, triglycerides, ATL and GGT in the blood of laying hens, and increase the amount of butyrate acid in the caecal content of hens. The ancient grain diet could support production performances with positive effects on animal health and on environmental sustainability. [126].

Eggs are ubiquitous in human diets. However, previous studies showed high cholesterol in eggs will impair peoples' health by causing cardiovascular disease [127]. A high number of studies reported that agricultural by-products could reduce cholesterol in eggs [107,128–130]. Cayan et al. (2015) reported olive leaf powder improved the final body weight of laying hens, yellowness in yolk color, reduced the concentration of yolk cholesterol [107]. In the study of Gurbuz et al. (2017), sumac (*Rhus coriaria* L.) seed powder and ginger (*Zingiber officinale*) root powder could decrease powder yolk and blood cholesterol content and low-density lipoprotein, improved acid composition, ginger root powder. Dehydrated bo-caiuva pulp revealed a potential anti-oxidant capacity and reduced the lipid oxidation in egg yolk [129].

Heat stress is one of the major environmental factors which may reduce growth performance, nutrient availability, immunity and welfare in the poultry industry particularly in tropical and arid regions of the world [131–133]. The addition of by-product feed in the diet for laying hens under heat stress can be beneficial for hen health and can exert positive effects on performance and egg quality [134,135]. Tomato pomace diluted the negatively decreased influence of heat stress on the activities of serum enzymes, oxidative status, immune response, and bone ingredients [136]. The above-mentioned studies of by-product feed in poultry are exhibited in Table 4.

Table 4. Applications of agro-industry by-products as feeds in poultry.

Items	Levels	Monogastric	Main Influences	References
Moringa stem meal (MSM)	20, 40, 60, 80, 100%	Geese	Dietary MSM levels of no more than 60 g/kg had no effects on the growth performance and slaughter performance, while diets with 100 g MSM/kg increased the F/G and serum ALT enzyme activity, as well as decreasing the serum GLU level.	Zhai et al., 2019 [125]
Tomato pomace	3, 5%	Broilers	Attenuated the detrimental effects of heat stress on the activities of serum enzymes, oxidative status, immune response, and bone composition	Hosseini-Vashan et al., 2015 [136]
Grape pomace	60 g/kg	Broilers	Modify the gut morphology and intestinal microflora and increase the biodiversity degree of intestinal bacteria.	Viveros et al., 2011 [121]
Grape seed extract	7.2 g/kg	Broilers	Modify the gut morphology and intestinal microflora and increase the biodiversity degree of intestinal bacteria.	Viveros et al., 2011 [121]
Grape seed	5%	Broilers	Higher percentage of unsaturated fatty acids due to linoleic acid, more nutty smell, a more metallic flavour and more stringiness.	Francesch et al., 2015 [122]
Olive leaf powder	1, 2, 3%	Laying hens	Increased final body weight, yellowness in yolk color, decreased yolk cholesterol content.	Cayan et al., 2015 [107]

Table 4. Cont.

Items	Levels	Monogastric	Main Influences	References
Sumac (<i>Rhus coriaria</i> L.) seed powder	10, 20, 30%	Laying hens	Reduced yolk/blood cholesterol concentrations and low-density lipoprotein, improved acid composition.	Gurbuz et al., 2017 [129]
Ginger (<i>Zingiber officinale</i>) root powder	10, 20, 30%	Laying hens	Reduced yolk/blood cholesterol concentrations and low-density lipoprotein, improved acid composition.	Gurbuz et al., 2017 [129]
Dehydrated bocaiuva pulp	0.1, 0.2, 0.3, 0.4%	Quail	Exhibited a potential antioxidant capacity and reduced the lipid oxidation in egg yolk.	Nunes et al., 2018 [130]
Ancient wheat lines by-products (consisting in 50:50 of <i>Triticum aestivum</i> var. <i>spelta</i> and <i>Triticum durum dicoccum</i> L.)	36.3%	Laying hens	Improved feed conversion ratio, decreased egg length and width, egg weight, shell thickness and strength, reduced level of cholesterol, triglycerides, ATL and GGT in blood, increased the amount of butyrate acid in the caecal content of hens.	Lombardi et al., 2020 [126]

4.2. The Use of Agro-Industry By-Products as Feeds in Ruminants

Ruminants take advantage of high fiber feed because they have substantial microorganism populations in the rumen [137]. Indeed, to produce the equivalent amount of animal protein products (meat, milk or eggs) much less human-edible feed is needed in ruminant systems than in monogastric systems (6 vs. 16 kg of human-edible feed dry matter (DM) per kilogram of protein products) [5]. The strengths inherent to ruminant animals in the food production chain could be further developed by more diverse and efficient exploitation of side streams and increased exploitation of fibrous feeds not suitable for the nutrition of humans and monogastric livestock. In the past few decades, animal production systems have undergone radical changes that have led to the concentration of large herds in fewer specialized intensive farms, where animals, especially ruminants, are usually kept indoors. Then the feed costs can contribute up to 70% of total production costs in the ruminant industry due to the lack of grazing on pastures.

Rice straws, wheat straws and other high fiber feeds are commonly used in ruminants [138]. However, energy is crucial to dietary provision for animal production. The data of energy utilizability of untraditional feedstuff formulated are largely unknown. ME and NE values (dry matter basis) are 6.76 and 3.42 MJ/kg for rice straw and 6.43 and 3.28 MJ/kg for wheat straw, respectively [15]. Moreover, the straws treated by fermentation, enzyme, silage, and other methods were proved to exhibit improved quality before application in ruminant feedstuff recently [139,140]. The agro-industry by-products like grape pomace or cassava residues used in ruminants are shown in Table 5. Several studies reported that by-products of cassava and grape could improve the production of lambs, dairy ewes and cows [141–150]. Moreover, grape by-products were also able to reduce approximately 20% of CH₄ emissions and CH₄ yield of dairy cows [146].

Indeed, there are many other agro-industry by-products of fruits and vegetables like dried citrus pulp and grape pomace that have exhibited a positive relationship in the performance of ruminants [151–154]. It is common to supplement by-product materials to ruminant feeds, however, there is no uniform addition standard. Greenhouse gas emissions have gained world attention because of their effect on the global climate. This comes from the fact that cattle take up more than 11% of all human-induced greenhouse gases [155]. The nutritive activities which form agro-industry by-products as feeds have been largely investigated in greenhouse gas emissions [154,156–158].

Table 5. Applications of agro-industry by-products as feeds in ruminants.

Items	Levels	Ruminants	Main Influences	References
Grape by-product	0, 100, 200, 300 g/kg	Lambs	Hay replacement by grape by-product at up to 300 g/kg in the DM was satisfactory to weight gain and not impair ADFI and ADG	Amaral et al., 2019 [141]
Grape seed and skin	20%	Dairy ewes	Improved milk production, calcium, free iron and urea content, no influence on milk fat and protein	Mokni et al., 2016 [142]
Grape pomace	0, 5, 10, 15, 20%	Lamb	The optimum inclusion of 12.2% grape pomace improved lamb productivity, without compromising meat quality	Chikwanha et al., 2019 [143]
Grape pomace	5, 10%	Suckling lambs	No negative effects on meat quality besides the water holding capacity improved. Ruminant microbial N decreased and un-degradable protein and N retention increased. Suggested not exceeding 10% of the diet	Gómez-Cortés et al., 2018 [144]
Distillers' grape residue	3.85, 7.70, 11.55, 15.41%	Lamb	Decreases of approximately 20% in CH ₄ emissions and CH ₄ yield	Gao et al., 2019 [145]
Grape marc	5 kg/day	Dairy cow	No negative influence on blood constituent metabolism and the fat, protein and caseins in milk, but increase other components.	Moate et al., 2014 [146]
Grape pomace	15%	Dairy cow	Reflects antioxidant activity	Chedea et al., 2016 [147]
Grape pomace	10%	Cattle	Improve growth performance, damage antioxidant capacity and kidney function, suggested less than 20%	Iannaccone et al., 2018 [148]
Cassava residue	5, 10, 20%	Lambs (21 kg)	The maximum average daily gain (174 g/day) was estimated with a 22.4 % replacement level	Ly et al., 2017 [29]
Cassava residue(Liquid)	Replacement of 25, 50, 75% corn	Lambs (19.5 kg)	replacement of cassava chip in the concentrate with FCSR decreased feed digestibility; not impact negatively on growth performance and carcass traits	Dos Santos et al., 2015 [149]
Cassava chips or fermented cassava starch residue	100%	Thai native-Lowline Angus crossbred steers	No negative influence on ADFI and milk yield but improve milk quality.	Pilajun et al., 2016 [150]
Fruit and vegetable waste	6, 8, 12, 18%	Lactating Holstein cows	GP is a better fiber source than DCP to enhance growth performance, carcass attributes and economic viability	Angulo et al., 2012 [151]
Fruit by-products (dried citrus pulp(GDP), Grape pomace(DGP))	150 g/kg	Angus steer	44% of feed ingredients in the concentrate replaced without negative growth performance and animal health	Tayengwa et al., 2020 [152]
DDGS, dried citrus pulp (DCP), exhausted olive cake (EOC)	18, 18, 8% respectively	Lamb	Increase DM intake and energy and TDN digestibility	De Evan et al., 2020 [153]
Grocery by-product feed	18, 36, 54%	Cattle		Froetschel et al., 2014 [154]

DDGS: corn distiller's dried grains with solubles; DCP: dried citrus pulp; EOC: exhausted olive cake.

5. Developmental Strategies for Agro-Industry By-Products

The agro-industry by-products have great potential for animal feedings. However, the utilization has different limits due to the large variability in their chemical compositions and physical status, their seasonal production, short shelf-life, high moisture, and fat levels. To increase the by-products' shelf-life, some precautions could be adopted, such as treating by-products rich in water with a hygroscopic substance (e.g., lime) or adding anti-oxidants to the by-products rich in fats. More attention should be paid to the pesticide residue in fruit and vegetable by-products that impair animal health [159]. Agro-industry by-product as feedstuffs should be promoted because of heavy demand for intensification in the future. A change from the traditional to more intensive systems of production is likely to result from different factors such as scarcity of grazing land, need for more control over animals, and higher returns from the stall-feeding system. The quantity of usage of agro-industry by-products relies on the availability of the resources and the technical facility utilized for its preparation, reservation, and improvement. Many countries are in the direction of making the most of all products which are adequate for animal feed. Moreover, the appropriate

methods of collection, transportation, and processing contribute to decrease the expenses and further the nutritive value. The following tactics are recognized to be significant to improve productivity from the animal resources through more efficient utilization of agro-industry by-products [58]:

1. More intensive use in stall-feeding systems.
2. Development of complete rations.
3. Strategic supplementation.
4. Wider use of by-products.
5. Nutrient enrichment of by-products.

6. Conclusions

Most agro-industry by-products including stalks and residues are rich in nutrients as raw materials that are particularly well suited to serve as the base of animal feeds. Stalks are high in dietary fiber but low in protein and minerals while residues are high in protein and other nutrients. Unfortunately, agro-industry by-products also have many shortcomings such as the presence of anti-nutritional ingredients. However, modern processing methods, new sorts, and appropriate developmental strategies are expanding the applications of agro-industry by-products as animal feeding including pigs, poultry and ruminants. That said, the processing methods and developmental strategies still need further improvement. The utilization of agro-industry by-products for animal production will become a sound foundation for sustained development technology and the management of animal farming.

Author Contributions: Investigation, K.Y.; writing—original draft preparation, K.Y., Y.Q., Q.Y.; writing—review and editing, X.T., G.C. and H.L.; project administration, R.F.; funding acquisition, R.F. All authors have read and agreed to the published version of the manuscript.

Funding: We greatly appreciate of the funding support of the Division of Animal Nutrition and Feed Science, Hunan Herbevores Industry Technological System, and National Key R&D Program of China (2018YFD0500605, 2018YFD0501403).

Data Availability Statement: The data presented in this study are available on request from the authors.

Conflicts of Interest: The authors declare no conflict of interest.

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