

Review

Food Security: Nutritional Characteristics, Feed Utilization Status and Limiting Factors of Aged Brown Rice

Xuehong Chai, Xue Sun , Xueyan Qi, Anshan Shan * and Xingjun Feng * 

College of Animal Science and Technology, Northeast Agricultural University, Harbin 150030, China; cxh990906@163.com (X.C.); 18800434060@163.com (X.S.); 13019717322@163.com (X.Q.)

* Correspondence: asshan@neau.edu.cn (A.S.); fengxingjun@neau.edu.cn (X.F.); Tel.: +86-451-5519-0585 (A.S.); +86-451-5519-0685 (X.F.)

Abstract: Rice is one of the most significant food crops for human sustenance. Every year, many countries around the world hoard enormous amounts of rice to avert emergencies and guarantee food security and sufficiency. As a result, the inventory of aged rice is growing as the number of inventory years rises. Aged rice stored over three years loses its nutritional value and is no longer suitable for human consumption. There is a pressing need to find a solution to effectively utilize aged brown rice produced from aged rice after dehulling. Developing and utilizing aged brown rice as feed is economical and efficient due to its massive resources and rich nutritional content, which will also lessen food waste while resolving the problem of excessive hoarding of aged rice. This review mainly summarizes the nutritional value, application in feed, and nutritional limiting factors of aged brown rice. It provides a theoretical basis for solving the overstock of aged brown rice and the feasibility of using aged brown rice as feed in a cost-effective way.

Keywords: aged brown rice; food security; inventory; feed; nutrient value; limiting factors



Citation: Chai, X.; Sun, X.; Qi, X.; Shan, A.; Feng, X. Food Security: Nutritional Characteristics, Feed Utilization Status and Limiting Factors of Aged Brown Rice. *Agriculture* **2024**, *14*, 858. <https://doi.org/10.3390/agriculture14060858>

Academic Editor: Hrvoje Valpotić

Received: 17 April 2024

Revised: 25 May 2024

Accepted: 28 May 2024

Published: 29 May 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Rice is one of the most significant grains in the world. The global annual rice production, especially from 2019 to 2021, has gradually increased due to the rapid development of agricultural planting technology and the continuous increase in rice planting area [1], and the rice production of Asia alone is enough to meet the food consumption of 2 billion people [2]. Many countries store a portion of rice annually as a strategic measure to assure food security and meet emergency requirements to prevent calamities such as wars and natural disasters, or to maintain a balance in international trade. As a result, global rice stock has also been growing year by year, with its stock reaching 275 million tons from 2018 to 2019 [3]. China and India, as the two countries with the largest rice storage reserves in the world, possessed 62% and 19% of the worldwide rice inventories from 2019 to 2021, respectively [4]. In 2017, South Korea's rice reserves reached 1.89 million tons, more than double the government's regular rice stocks [5]. However, with the increase in storage time, aged rice is no longer suitable for human consumption due to changes in its physical, chemical, and nutritional properties [6,7], which will not only affect taste but may also have unpredictable effects on human health. If not effectively utilized, aged rice will cause significant waste and environmental pollution. Seeking effective ways to utilizing a large amount of aged rice will be a crucial measure of great significance in the areas of economy, environmental protection, and resource reuse.

The feed utilization method provides a valuable solution for the high value utilization of a large amount of aged rice due to a huge demand for feed. Using aged rice as feed raw material can effectively consume the inventory of aged rice and solve the huge demand for feed grain sources. As early as 2006, the Chinese government have prohibited storing rice for more than 3 years as food and proposed that aged rice should be used as feed. Aged rice, as a feed ingredient, has certain advantages in terms of nutritional composition, but there

are also some unfavorable factors that limit the application in feed, even having an adverse impact on animal growth and productivity. At present, aged brown rice has not been widely used in animal husbandry. This paper summarizes the nutritional characteristics of aged brown rice, which is the main form of feed material formed after aged rice is ground and husked. In addition, it reviews the influence of storage time on the nutritional properties of brown rice, the application of aged brown rice in feed, and the limiting factors of aged brown rice in animal production application, which would provide technical and theoretical supports for the efficient use of aged brown rice as feed and reducing its inventory pressure.

2. Nutritional Properties of Brown Rice

Brown rice is the product of coarsely dehulling and processing rice grains, consisting of a bran layer, germ, and endosperm. Furthermore, starch is the main component of brown rice [8,9]. Brown rice is further classified as edible brown rice and forage brown rice based on the dehulling rate during dehulling and processing, with the glume content of edible brown rice accounting for 2% of the total weight, while that of forage brown rice accounts for about 7%.

Brown rice is rich in various nutrients, mainly from functional nutrients of the bran layer, such as dietary fiber, lipids, and mineral elements, so consuming brown rice is more beneficial for one's health. Furthermore, the bran layer contains a range of naturally occurring bioactive compounds including B vitamins, glutenin, glutathione, γ -aminobutyric acid, polyphenols, and other chemicals [10]. Dietary fiber is a non-starch polysaccharide with the property of improving intestinal flora balance and ameliorating intestinal peristalsis, and a reasonable amount of dietary fiber is beneficial for intestinal health. The dietary fiber content in brown rice is approximately 3.7 g/100 g. As antioxidants, glutathione and glutenin can scavenge free radicals and other harmful peroxide substances. γ -aminobutyric acid can promote brain metabolism, regulate blood pressure, and alleviate atherosclerosis and other physiological processes [11–13]. Brown rice polyphenols are a natural antioxidant and crucial functional component. Polyphenols, such as phenolic acid, anthocyanin, catechin, and epicatechin, play an important role in the physiological efficacy of improving hypoglycemia, hypolipidemia, and cardiovascular disease [12,14]. The primary phenolic compound found in brown rice is trans-ferulic acid (range: 161.42–374.81 $\mu\text{g/g}$) [15]. In addition, polyphenol present in bound form in brown rice has antioxidant properties and improves the activity of intestinal flora [16].

3. Influence of Storage Time on the Nutritional Properties of Brown Rice

Usually, changes in physical and chemical properties are inevitable when rice is stored for more than three months even under favorable storage conditions. Reduction in nutritional quality undergoes a series of physicochemical and physiological changes brought on by respiration, oxidation, and endogenous enzymes during storage as a result of some external factors (time, temperature, and moisture) [17]. With the extension of storage time, some nutrients in brown rice undergo the following changes: change in starch structure, denaturation of proteins, and decomposition of fats.

3.1. Influence on the Starch Structure of Brown Rice

The starch in brown rice accounts for about 78% of the total weight of brown rice and consists of amylose and amylopectin. During the storage process, the total amount of starch does not change significantly. However, due to the presence of debranching enzyme activity, the content of insoluble amylose increases while the content of amylopectin decreases, resulting in a harder taste and lower viscosity [18,19]. It has been shown that insoluble amylose makes the microcrystalline bundle structure of starch grains more compact, making it difficult for water to penetrate the interior. Moreover, under gelatinization temperature conditions, there are many unbroken hydrogen bonds in the structure, which leads to a decrease in the edible quality and palatability of brown rice [20]. A study showed that the apparent digestibility of nutrients decreased linearly as the content of amylose

increased by feeding rations with amylose/amylopectin ratios of 0.26, 0.37, 0.47, and 0.98 to finishing pigs [21]. Li et al. [22] conducted a study on weaned pigs fed with two diets with amylose/amylopectin ratios of 0.39 and 0.6 and found a negative correlation between the digestibility and the size of the ratio between amylopectin and amylose. The group with a ratio of 0.6 had a 2.67% drop in overall intestinal digestibility of feed digestibility compared with the group with a lower ratio of 0.39.

3.2. Influence on the Protein of Brown Rice

Proteins in brown rice are mainly composed of four types: serum proteins, globulins, alcohol soluble proteins, and gluten proteins, among which the gluten protein content is the highest, accounting for about 80% of the total protein content [23,24]. With the extension of storage time, the total protein content in brown rice decreases slightly under the influence of external factors such as air, light, and heat. The sulfhydryl groups in proteins are easily oxidized into disulfide bonds, which increases the molecular weight of the proteins and the reduce hydrophilic groups and the ability of brown rice to bind with water, resulting in an overall decrease in the solubility of the proteins and an increase in the content of free amino acids [25]. Another study also showed that limiting amino acids such as lysine and tryptophan would be oxidized and reduced in the aging process of rice, leading to a reduction in the nutritional quality of proteins [26]. Proteins can form a firm mesh structure around the starch and limits the expansion and digestion of starch. Because of the oxidation of proteins leads to the increase in the content of carbonyl compounds in brown rice [27]. Liu et al. [28] reported that the carbonyl values of brown rice gradually increased with the increase in storage time at 15 °C and 25 °C, reaching the maximum values of 5.20 and 8.31 meq/kg-1 after 270 days, respectively. The results of Frame et al. [29] showed that the content of carbonyl compounds in feed reached 7.3 nmol/kg and 13.5 nmol/kg after three days of oxidation at 45 °C and 100 °C, respectively, and they found a linear decrease in protein digestibility with the increase in the content of carbonyl compounds.

3.3. Influence on the Crude Fat of Brown Rice

The content of crude fat in brown rice will decrease slightly during the aging period [30,31]. The change in lipids in aged brown rice is mainly through oxidation and hydrolysis. Most of the fatty acids in brown rice are unsaturated, and the double bonds within their molecular structure can be oxidized to generate some carbonyl compounds. Lipids in aged brown rice are hydrolyzed by lipase to produce glycerol and free fatty acids [27,32]. The fatty acid value is one of the most used and core indicators to reflect the freshness of brown rice. Generally, the higher the fatty acid value, the worse the quality of brown rice [33]. The quality of brown rice will be significantly deteriorated when the fatty acid value exceeds 25 mg KOH/100 g. When the fatty acid value of brown rice exceeds 100 mg KOH/100 g, it will give off an unpleasant odor, and the palatability is reduced so that the brown rice cannot be used as a raw material for feeding [8]. In addition, free fatty acids and amylose will react to each other to form some compound molecules with spiral shaped, densely crystalline structure, which will severely constrain the expansion of the starch during cooking [17].

3.4. Influence on the Enzymatic Activity of Brown Rice

Various enzymes, such as α -amylase, protease, fat oxidase, catalase, etc., are present in brown rice, and these enzymes can still function even at low moisture content [34]. Most of the physiological changes occurring in brown rice's nutrients result from enzymatic reactions. Furthermore, with the extension of the storage time, the activities of catalase and α -amylase in brown rice will be gradually diminished, and the activity of lipase will be enhanced, resulting in a gradual increase in the content of free fatty acids in brown rice [35].

4. Application of Aged Brown Rice in Feed

4.1. Advantages of Aged Brown Rice in Feed Applications

It is evident from Table 1 that the nutritional content of husked brown rice is comparable to that of maize, with certain kinds even surpassing their nutritional value of maize. Compared with the conventional nutrients of maize, the content of nitrogen free extract in aged brown rice is higher and the crude fiber content is lower, indicating that the aged brown rice has better palatability than maize [36]. Meanwhile, the content of amylopectin, crude protein, calcium, and phosphorus in aged brown rice is also higher than those of maize. The amino acid composition of aged brown rice, as shown in Table 2, is more balanced than that of maize [27]. Lysine, methionine, and threonine are the top three essential amino acids required for the pig growth and fattening process [37]. The three amino acid contents of aged brown rice were higher than those of maize, as indicated in Table 2. Overall, aged brown rice is expected to be used as an energy feed to replace maize in feed. However, the current usage of aged brown rice in livestock and poultry feed is relatively low, and it needs to be considered whether the storage time of aged brown rice will affect the production and growth performance of animals.

Table 1. Conventional nutrients in aged brown rice and maize.

General Nutrition Facts, %	Aged Brown Rice	Maize
Total Energy, MJ/kg	16.00	16.20
Dry Matter	89.5	86.0
Crude Protein	8.67	8.70
Crude Fat	2.75	3.60
Crude Ash	1.41	1.20
Crude Fiber	0.90	2.30
Neutral Detergent Fiber	2.23	9.30
Acid Detergent Fiber	1.31	2.70
Nitrogen Free Leachate	74.1	70.7
Total Starch	79.6	75.0
Amylose	14.4	18.8
Amylopectin	66.2	56.3
Calcium	0.03	0.02
Total Phosphorus	0.41	0.27
Effective Phosphorus	0.15	0.05

Data on maize are from China Feed Database, version 31; and data on aged brown rice are from Kang et al. [38].

Table 2. Amino acid in aged brown rice and maize.

Amino Acid, %	Aged Brown Rice	Maize
Arginine	0.53	0.39
Histidine	0.17	0.21
Isoleucine	0.30	0.25
Leucine	0.68	0.93
Lysine	0.30	0.24
Methionine	0.20	0.18
Phenylalanine	0.41	0.41
Threonine	0.31	0.30
Tryptophan	0.08	0.07
Alanine	0.53	0.60
Cysteine	0.12	0.18
Tyrosine	0.22	0.33

Data on maize are from China Feed Database, version 31, and data on aged brown rice are from Kang et al. [38].

4.2. Application of Aged Brown Rice in Pig Feed

Starch in plant feedstuffs such as grains and tubers are the primary energy source for pigs [39]. Maize is widely used as a primary energy feed for pigs due to its high content of starch and considerable digestible energy. The total energy and crude protein composition

of brown rice is better than those of maize, and a fresh brown rice diet can provide more digestible energy, crude protein, and dry matter for growing finishing pigs [40]. Aged brown rice also has the potential to be used as feed for pigs. He et al. [37] found that feed brown rice aged for one year or six years had no significant effect on the growth performance indexes, digestibility, and pork quality of weaned piglets and growing pigs. Nevertheless, they have significantly reduced the activities of weaned piglets' duodenum, jejunum, and ileum digestive enzymes. Sarah et al. [41] and Wu et al. [42] also showed that the diet for pigs formulated from brown rice increased amino acid digestibility and practical energy value compared with the other cereal grains, indicating that brown rice is an excellent raw material for feed. Kim et al. [43] found that adding 50% brown rice into the diet had no adverse effect on the slaughter performance of pigs, but long-term feeding of brown rice affected the intestinal microbiota of pigs due to the low fiber content and fewer substrates required for bacterial fermentation in brown rice. The results of Katsumata et al. [44] also indicated that replacement of all of corn contained in feed with brown rice did not significantly impact growth traits and meat quality of fattening pigs.

On the contrary, some studies showed that feeding brown rice was detrimental to the growth performance of pigs [45–47]. The different particle size of brown rice after grinding significantly affected the absorption of nutrients in brown rice by animals [48]. However, for weaned piglets, the diet of brown rice significantly reduced average daily gain and daily feed intake compared to that of maize [49], due to the higher starch content in brown rice, and the weaker ability of weaned piglets to digest starch in the early stages [50]. Hence, the starch content in the diet has a significant influence on the growth performance of weaned piglets. Moreover, the starch in brown rice is more accessible to be digested for growing and fattening pigs and will not cause significant changes in their growth performance [51].

4.3. Application of Aged Brown Rice in Poultry Feed

Poultry occupies an essential position in animal production because its meat, eggs, and feathers have high utilization values and high breeding efficiency [36,52]. However, to obtain quality poultry produce, the energy and protein content of feed are crucial to achieve ideal feeding efficiency for poultry production. Plant vegetable protein is one of the best choices for monogastric animals, such as maize [53], soybeans [54], and other common feed raw materials.

Brown rice contains more protein, fat, and mineral content than white rice [55]. Shih et al. [56] found that there was no significant effect of different proportions of aged brown rice in diet on the growth performance, the number of lactic acid bacteria and *Escherichia coli* in the ileum and cecum of broilers, which suggested that aged brown rice with a short aging time has no adverse effect on broilers. Fujimoto et al. [57] suggested that rice can be used to feed broilers, but it is important to pay attention to the potential adverse effects of the fat in the aged rice on broilers. Excessive fat addition in diet will reduce the feed intake of broilers, thus affecting their growth [58,59].

As herbivorous animals, geese have a more vital ability to digest crude fiber than broilers, which is attributed to the solid digestive capacity of the goose stomach [60]. Yu et al. [61] found that different proportions of paddy in the diet of geese significantly improved the growth indexes of geese ($p < 0.05$) and had no adverse effect on the feed digestibility. A study of feeding mallard ducks with rice found no significant difference in growth traits and serum biochemical indexes compared with the control group [62,63]. These reports demonstrated that rice can be a good energy source in the diet of aquatic poultry.

4.4. Application of Aged Brown Rice in Ruminant Feed

Nikkhah [64] found that brown rice, due to its rich starch and crude fiber content, can effectively promote chewing and digestion, improve buffering and absorption capacity of the rumen, and reduce the risk of rumen acidosis. The study of Scheibler et al. [65] showed that replacing different proportions of corn with brown rice (0%, 33%, 63%, and 100%) had no significant effect on the daily gain, apparent digestibility, milk yield, milk composition,

and feed utilization efficiency of cows. However, Miyaji et al. [66] found that the higher the proportion of brown rice replacement in the diet, the lower the milk yield of cows. Because of the high grain content in dairy cow diets, replacing corn with rice in the diet of cows resulted in an increase in rumen starch digestibility, the dry matter and starch intake decreased. The report of Kim et al. [67] concluded that the maximum amount of paddy replacing corn in the sheep diet cannot exceed 91%. Cattalam et al. [68] found that brown rice can reduce carcass weight, adipose tissue accumulation, and slaughtering performance of cattle compared with maize, indicating that it is not suitable to feed brown rice during cattle's growth and fattening stages. The above reports indicate that the application of rice as feed for ruminants requires further research on its proportion in the diet, and the types and physiological stages of ruminants used.

4.5. Application of Aged Brown Rice in Fish Feed

Fish is considered one of the indispensable sources of protein for humans, and the demand is increasing. By 2020, the production of fisheries and aquaculture reached a historic high of 214 million tons [69]. In the last century, fish feed was mainly composed of expensive fish meal and fish oil, but today's fish feed is mainly vegetable protein and vegetable oil [70]. Brown rice has a rich starch content and can be added to fish feed as a carbohydrate. Studies have shown that adding appropriate carbohydrates to the feed can promote more protein for fish growth, reduce the consumption of protein, and reduce the pollution of aquaculture water by excretion [71]. Sun et al. [72] found that tilapia has a good utilization effect on southern brown rice, which can be used as a high-quality carbohydrate source for tilapia to reduce feed cost. Aged brown rice with good storage conditions also has great potential as a novel fish feed.

5. Limiting Factors of Aged Brown Rice in Feed Application

5.1. Antinutritional Factors in Aged Brown Rice

The bran layer of brown rice contains phytic acid, non-starch polysaccharides, trypsin inhibitory factor, and other antinutritional elements. In addition, brown rice has a rough texture and low palatability due to a certain quantity of crude fiber and antinutritional elements, which affect animal growth and digestion of feed.

5.1.1. Phytic Acid

Phytic acid is mainly concentrated in the bran layer of rice, and with a content of about 9–14%. Phytic acid is difficult to degrade in the animal digestive tract, and can only be degraded under conditions of strong acid, high pressure, or exogenous phytase. Phytic acid can bind divalent and trivalent metal ions in the animal digestive tract to form insoluble chelate compounds, which cannot be absorbed by the digestive tract [73,74]. Simultaneously, the chelate compounds amalgamate with proteins and certain enzymes to generate ternary complexes of phytic acid, metal cation, and protein, reducing the solubility of proteins and the activity of enzymes, consequently reducing the digestion and absorption of proteins and carbohydrates in animal digestive tracts [75–77].

5.1.2. Non-Starch Polysaccharides

Non-starch polysaccharides are one of the main antinutritional factors in brown rice. The antinutritional effects of non-starch polysaccharides are related to their viscosity and effects on the physiology and microbial composition of the digestive tract. Soluble non-starch polysaccharides can increase the viscosity of intestinal chyme, affect the mixing of enzymes and nutrients, and thus reduce the circulation rate of chyme particles in the intestinal cavity and affect the absorption of minerals, amino acids, and fats [78–80].

5.1.3. Trypsin Inhibitors

Trypsin inhibitors have the most significant impact on the digestive and absorption functions of animals among the various protease inhibitors. They can reduce the activity

of trypsin, leading to a reduction in protein digestibility and utilization, hyperplasia, and enlargement of the pancreas, thereby inhibiting animal growth [81,82]. Trypsin inhibitor binds to trypsin and chymotrypsin in the small intestine, forming a stable complex that inactivates enzymes. Trypsin inhibitors also cause enhanced pancreatic secretory activity and excessive secretion of trypsin and chymotrypsin, which externally leads to a significant loss of endogenous nitrogen and sulfur-containing amino acids in the body [35].

At present, there are various means, such as milling, enzyme treatment, extrusion, and germination, which can be used to reduce the content of antinutritional factors in brown rice. Milling is a mechanical processing treatment that can remove the outer layer of the paddy glumes [83]. Extrusion mainly uses high temperature and high pressure to inactivate certain substances in brown rice such as trypsin inhibitors. Enzyme treatment by adding exogenous enzymes, such as phytase and α -amylase, can effectively hydrolyze phytic acid and non-starch polysaccharides, and improve the feeding value [84,85].

5.2. Mycotoxins in Aged Brown Rice

Molds will infect rice and other grains during their whole growth and ripening process in the field. Mycotoxins are toxic fungal secondary metabolites frequently found as contaminants of food and feed [86]. Many mycotoxins, especially aflatoxins (AFT), ochratoxins (OTA), deoxynivalenol (DON), fumonisins (FBs), T-2 toxins, and zearalenone (ZEN), would inevitably contaminate brown rice during storage. These mycotoxins can be severely hazardous to animal bodies and produce additive and synergistic toxic effects. It is necessary to consider the content and hazards of mycotoxins in aged brown rice used as feed.

From 2018 to 2020, Zhao et al. [87] collected 3507 samples from different regions of China and found that the positive rates of AFB1, DON, and ZEN in rice bran were 100%. Lin et al. [88] analyzed 344 grains in the Tianjin area of China and found that the detection rate of new Fusarium toxins (ENN A, ENN B) in rice was 69.0%. The percentage of rice samples contaminated with AFB1 (31%) was higher than that of any other grain and feed samples, with ZEN and DON contamination reaching 34% and 27%, respectively [89]. It presents the limit standards of mycotoxins in China and international organizations in Table 3 [90–92]. By conducting a global survey on mycotoxins from 2018 to 2020 on cereals, Khodaei et al. [93] found that AFB1 in rice is a serious hazard, and 50%, 11.1%, 16.6%, and 25% of rice exceeded the EU standard limits of AFT, ZEN, DON, and FBs, respectively. Iqbal et al. [94] found that the detection rates of AFB1 and OTA of brown rice from the Pakistani market were 54% and 46%, respectively, and the content of AFB1 in 25% of the brown rice samples exceeded the EU limit. The detection rates of 5 types of mycotoxins in rice worldwide are summarized in Table 4. The detection rates of AFT, FBs, and ZEA were the highest in Asian rice, while the detection rates of OTA and DON were the highest in Africa [95]. However, as shown in Table 5, Kang et al. [38] determined the content of DON and ZEN in brown rice stored from 2017 to 2019 for 1–3 years in some regions of China and found that the contents of both mycotoxins were lower than the Chinese limit standards. The average contents of AFT and OTA in the rice in Sichuan Province of China from 2013 to 2018 were 5.93 $\mu\text{g/kg}$ and 1.175 $\mu\text{g/kg}$, respectively, which was lower than the Chinese limit standards [96]. Therefore, mycotoxin content in aged brown rice will be varied and influenced by factors such as storage conditions, storage time, and processing methods.

Table 3. Maximum limit standards of mycotoxins in rice by organizations and countries.

	European Union	America	China
AFB1 ($\mu\text{g/kg}$)	20	-	30
AFT ($\mu\text{g/kg}$)	-	200	-
OTA ($\mu\text{g/kg}$)	250	-	100
DON ($\mu\text{g/kg}$)	8000	5000	5000
ZEN ($\mu\text{g/kg}$)	2000	-	500
FBs ($\mu\text{g/kg}$)	60,000	30,000	60,000

Table 4. Occurrence of mycotoxins in rice worldwide from 2008 to 2016.

Items		Africa	America	Asia	Europe
AFT	Incidence (%)	53	-	63	9
	Range (µg/kg)	20–1642		0.1–308	0.45–3
OTA	Incidence (%)	38	42	18	7
	Range (µg/kg)	0–1164	0–12.5	0.08–4.34	1.0–7.5
FBs	Incidence (%)	10	-	29	2
	Range (µg/kg)	0.4–4.4	-	0–500	-
DON	Incidence (%)	24	-	23	3
	Range (µg/kg)	0–112.2	-	6.2–81.2	71–176
ZEN	Incidence (%)	47	-	19	-
	Range (µg/kg)	0–1169	-	1.5–51.1	-

Table 5. Mycotoxin content in brown rice aged for 3 years in four provinces in China.

Regions	Year	DON (µg/kg)	ZEN (µg/kg)	AFT (µg/kg)	OTA (µg/kg)
Heilongjiang Province	2017	11.3	0.46		
	2018	10.5	0.72	-	-
	2019	13.2	0.49		
Anhui Province	2017	7.20	1.18		
	2018	19.3	1.63	-	-
	2019	52.6	1.78		
Hunan Province	2017	28.4	0.82		
	2018	29.0	1.40	-	-
	2019	26.8	1.15		
Sichuan Province	2016			8.24	1.25
	2017	-	-	8.98	0.985
	2018			4.84	1.17

In recent years, the detoxification methods of mycotoxins in cereals, such as high temperature irradiation, ozone, and probiotic degradation, have been developed relatively maturely, which can effectively reduce the harm of mycotoxins to animal health and solve the limitation of aged brown rice contaminated with mycotoxin as feed.

5.3. High Fatty Acid Content in Aged Brown Rice

With the increase in storage time of brown rice, the content of the free fatty acids in aged brown rice will increase, leading to a continuous increase in the fatty acid value of aged brown rice. A diet composed of aged brown rice with high fatty acid content could affect the antioxidant and immune functions of an animal organism, leading to oxidative stress and delay of the growth and development of animals [97]. As shown in Table 6, the fatty acid values of brown rice from four origins of China were gradually increased with the increase in storage time. The crude fat content of three kinds of brown rice stored at room temperature for 300 days decreased significantly by about 55.5%, and the fatty acid and fatty acid degree increased significantly [98]. Wang et al. [99] found that after 12 weeks of storage at 15 °C or 25 °C, the fatty acid value of red brown rice increased from 38.48 mg/100 g to 44.86 mg/100 g at 15 °C, and 54.86 mg/100 g, respectively. It can be concluded that the fatty acid value increased gradually with the increase in storage time. In the storage process, specific methods such as air-conditioned storage, air-conditioning temperature control, and new drying technology can reduce the fatty acid content produced by fat oxidation and hydrolysis in brown rice. Adding some antioxidants, such as vitamin E, tea polyphenol, and bile acids, to the diet can effectively alleviate the adverse effects of fatty acids in brown rice on animal health [100].

Table 6. Fatty acid values in brown rice aged for 3 years in four provinces in China.

Regions	Year	Fatty Acid Value (mg KOH/100 g)
Heilongjiang Province	2017	20.0
	2018	21.3
	2019	18.3
Anhui Province	2017	31.0
	2018	31.1
	2019	20.8
Hunan Province	2017	30.4
	2018	26.7
	2019	21.5
Sichuan Province	2016	53.9
	2017	57.2
	2018	43.5

6. Summary

Brown rice is rich in nutrients. Compared with fresh brown rice, the nutritional content of aged brown rice slightly decreased, but the overall change is not significant. The application of aged brown rice as feed is subject to limiting factors such as mycotoxins and elevated fatty acid values during storage. In animal production, measures such as improving feed formulas based on the nutritional characteristics of brown rice or adding antioxidants and detoxifiers to feed can eliminate the potential adverse effects of aged brown rice on animals. So, aged brown rice can be used as a feed ingredient in pigs, chickens, ruminants, and aquatic animals. Importantly, the price of aged brown rice is lower than that of corn. The effective utilization of aged brown rice can alleviate the shortage of feed resources in animal husbandry and the problems of food competition between humans and animals, and reduce the cost of feed and the waste of inventory resources in animal husbandry. It has important economic, social, and ecological significance to comprehensively and deeply exploring the efficient utilization technology of aged brown rice as feed. This is of great significance for the formation of a new feeding mode of “corn brown rice” recycling and the promotion of agricultural sustainable development.

Author Contributions: Writing—original draft, X.C.; writing—review and editing, X.C., X.S. and X.F.; methodology, X.C.; data curation, X.S.; visualization, X.S.; resources, X.Q.; investigation, X.Q.; supervision, A.S. and X.F.; project administration, A.S. and X.F. All authors have read and agreed to the published version of the manuscript.

Funding: This review was supported by the National Key R&D Program of China (2022YFD1300604).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

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

References

1. Mohidem, N.A.; Hashim, N.; Shamsudin, R.; Che Man, H. Rice for food security: Revisiting its production, diversity, rice milling process and nutrient content. *Agriculture* **2022**, *12*, 741. [\[CrossRef\]](#)
2. Butt, A.; Yaseen, S.; Javaid, A. Seed-borne mycoflora of stored rice grains and its chemical control. *J. Anim. Plant Sci.* **2011**, *21*, 193–196. [\[CrossRef\]](#)
3. U.S. Department of Agriculture. Available online: <https://fas.usda.gov/> (accessed on 16 April 2024).
4. International Rice Outlook: International Rice Baseline Projections 2022–2032. 2023. Scholar Works @UARK. Available online: [https://scholarworks.uark.edu/cgi/viewcontent.cgi?article=1055&context=aaesrb#:~:text=The%20international%20nominal%20price%20of,reach%20\\$1,172/%20mt%20by%20the](https://scholarworks.uark.edu/cgi/viewcontent.cgi?article=1055&context=aaesrb#:~:text=The%20international%20nominal%20price%20of,reach%20$1,172/%20mt%20by%20the) (accessed on 16 April 2024).

5. Jeong, O.-Y.; Park, H.-S.; Baek, M.-K.; Kim, W.-J.; Lee, G.-M.; Lee, C.-M.; Bombay, M.; Ancheta, M.B.; Lee, J.-H. Review of rice in Korea: Current *status*, future prospects, and comparisons with rice in other countries. *J. Crop Sci. Biotechnol.* **2021**, *24*, 1–11. [\[CrossRef\]](#)
6. Guevara-Guerrero, B.; Fernández-Quintero, A.; Montero-Montero, J.C. Free fatty acids in rice bran during its storage after a treatment by twin-screw extrusion to prevent possible rapid hydrolytic rancidity of lipids. *Dyna* **2019**, *86*, 177–181. [\[CrossRef\]](#)
7. Tamura, M.; Tsujii, H.; Saito, T.; Sasahara, Y. Relationship between starch digestibility and physicochemical properties of aged rice grain. *LWT* **2021**, *150*, 111887. [\[CrossRef\]](#)
8. Cho, D.-H.; Lim, S.-T. Germinated brown rice and its bio-functional compounds. *Food Chem.* **2016**, *196*, 259–271. [\[CrossRef\]](#) [\[PubMed\]](#)
9. Kumar, S.; Mohanraj, R.; Sudha, V.; Wedick, N.M.; Malik, V.; Hu, F.B.; Spiegelman, D.; Mohan, V. Perceptions about varieties of brown rice: A qualitative study from Southern India. *J. Am. Diet. Assoc.* **2011**, *111*, 1517–1522. [\[CrossRef\]](#) [\[PubMed\]](#)
10. Esa, N.M.; Kadir, K.-K.A.; Amom, Z.; Azlan, A. Antioxidant activity of white rice, brown rice and germinated brown rice (in vivo and in vitro) and the effects on lipid peroxidation and liver enzymes in hyperlipidaemic rabbits. *Food Chem.* **2013**, *141*, 1306–1312. [\[CrossRef\]](#)
11. Saikrishna, A.; Dutta, S.; Subramanian, V.; Moses, J.; Anandharamakrishnan, C. Ageing of rice: A review. *J. Cereal Sci.* **2018**, *81*, 161–170. [\[CrossRef\]](#)
12. Shao, Y.; Bao, J. Polyphenols in whole rice grain: Genetic diversity and health benefits. *Food Chem.* **2015**, *180*, 86–97. [\[CrossRef\]](#)
13. Zhang, B.; Zhang, Y.; Li, H.; Deng, Z.; Tsao, R. A review on insoluble-bound phenolics in plant-based food matrix and their contribution to human health with future perspectives. *Trends Food Sci. Technol.* **2020**, *105*, 347–362. [\[CrossRef\]](#)
14. Donkor, O.; Stojanovska, L.; Ginn, P.; Ashton, J.; Vasiljevic, T. Germinated grains—Sources of bioactive compounds. *Food Chem.* **2012**, *135*, 950–959. [\[CrossRef\]](#)
15. Ravichanthiran, K.; Ma, Z.F.; Zhang, H.; Cao, Y.; Wang, C.W.; Muhammad, S.; Aglago, E.K.; Zhang, Y.; Jin, Y.; Pan, B. Phytochemical profile of brown rice and its nutrigenomic implications. *Antioxidants* **2018**, *7*, 71. [\[CrossRef\]](#)
16. Zhao, G.; Zhang, R.; Dong, L.; Huang, F.; Liu, L.; Deng, Y.; Ma, Y.; Zhang, Y.; Wei, Z.; Xiao, J. A comparison of the chemical composition, in vitro bioaccessibility and antioxidant activity of phenolic compounds from rice bran and its dietary fibres. *Molecules* **2018**, *23*, 202. [\[CrossRef\]](#)
17. Keawpeng, I.; Venkatachalam, K. Effect of aging on changes in rice physical qualities. *Int. Food Res. J.* **2015**, *22*, 2180–2187.
18. Matalanis, A.; Campanella, O.; Hamaker, B. Storage retrogradation behavior of sorghum, maize and rice starch pastes related to amylopectin fine structure. *J. Cereal Sci.* **2009**, *50*, 74–81. [\[CrossRef\]](#)
19. Zhou, Z.; Wang, X.; Si, X.; Blanchard, C.; Strappe, P. The ageing mechanism of stored rice: A concept model from the past to the present. *J. Stored Prod. Res.* **2015**, *64*, 80–87. [\[CrossRef\]](#)
20. Gu, F.; Gong, B.; Gilbert, R.G.; Yu, W.; Li, E.; Li, C. Relations between changes in starch molecular fine structure and in thermal properties during rice grain storage. *Food Chem.* **2019**, *295*, 484–492. [\[CrossRef\]](#) [\[PubMed\]](#)
21. Pu, J.; Wang, H.; Chen, D.; Tian, G.; He, J.; Zheng, P.; Mao, X.; Yu, J.; Huang, Z.; Luo, J. Effects of dietary amylose/amylopectin ratio on growth performance, nutrient apparent digestibility, intestinal microflora number and volatile fatty acid concentrations and intramuscular fat content of finishing pigs. *Chin. J. Anim. Nutr.* **2018**, *30*, 4874–4885. [\[CrossRef\]](#)
22. Li, Y.; Zhang, A.; Luo, H.; Wei, H.; Zhou, Z.; Peng, J.; Ru, Y. In vitro and in vivo digestibility of corn starch for weaned pigs: Effects of amylose: Amylopectin ratio, extrusion, storage duration, and enzyme supplementation. *J. Anim. Sci.* **2015**, *93*, 3512–3520. [\[CrossRef\]](#)
23. Sodhi, N.; Singh, N.; Arora, M.; Singh, J. Changes in physico-chemical, thermal, cooking and textural properties of rice during aging. *J. Food Process. Preserv.* **2003**, *27*, 387–400. [\[CrossRef\]](#)
24. Ning, J.; Guo, Y.; Song, R.; Zhu, S.; Dong, P. Spectral Analysis of Glutelin Changes During Rice Aging and Its Effects on Glutelin Functional Properties. *Spectrosc. Spectral Anal.* **2021**, *41*, 3431–3437. [\[CrossRef\]](#)
25. Guo, Y.; Cai, W.; Tu, K.; Wang, S.; Zhu, X. Key proteins causing changes in pasting properties of rice during aging. *Cereal Chem.* **2015**, *92*, 384–388. [\[CrossRef\]](#)
26. Guo, Y.; Cai, W.; Tu, K.; Wang, S.; Zhu, X. Infrared and Raman spectroscopic characterization of structural changes in albumin, globulin, glutelin, and prolamin during rice aging. *J. Agric. Food Chem.* **2013**, *61*, 185–192. [\[CrossRef\]](#) [\[PubMed\]](#)
27. Zhang, M.; Liu, K. Lipid and Protein Oxidation of Brown Rice and Selenium-Rich Brown Rice during Storage. *Foods* **2022**, *11*, 3878. [\[CrossRef\]](#) [\[PubMed\]](#)
28. Liu, K.; Li, Y.; Chen, F.; Yong, F. Lipid oxidation of brown rice stored at different temperatures. *Int. J. Food Sci. Technol.* **2017**, *52*, 188–195. [\[CrossRef\]](#)
29. Frame, C.A.; Johnson, E.; Kilburn, L.; Huff-Lonergan, E.; Kerr, B.J.; Serao, M.R. Impact of dietary oxidized protein on oxidative status and performance in growing pigs. *J. Anim. Sci.* **2020**, *98*, skaa097. [\[CrossRef\]](#) [\[PubMed\]](#)
30. Hu, X.; Fang, C.; Zhang, W.; Lu, L.; Guo, Z.; Li, S.; Chen, M. Change in volatiles, soluble sugars and fatty acids of glutinous rice, japonica rice and indica rice during storage. *LWT* **2023**, *174*, 114416. [\[CrossRef\]](#)
31. Huang, S.; Zhang, D.; Wang, Q.; Shang, B.; Liu, J.; Xing, X.; Hong, Y.; Duan, X.; Sun, H. Shotgun lipidomics reveals the changes in phospholipids of brown rice during accelerated aging. *Food Res. Int.* **2023**, *171*, 113073. [\[CrossRef\]](#)
32. Rashid, M.T.; Liu, K.; Han, S.; Jatoti, M.A. The effects of thermal treatment on lipid oxidation, protein changes, and storage stabilization of Rice bran. *Foods* **2022**, *11*, 4001. [\[CrossRef\]](#)

33. Zhang, D.; Huang, S.; Wang, Q.; Shang, B.; Liu, J.; Xing, X.; Hong, Y.; Liu, H.; Duan, X.; Sun, H. Lipidomics and volatilomics reveal the changes in lipids and their volatile oxidative degradation products of brown rice during accelerated aging. *Food Chem.* **2023**, *421*, 136157. [\[CrossRef\]](#)
34. Bechman, A.; Phillips, R.D.; Chen, J. Changes in Selected Physical Property and Enzyme Activity of Rice and Barley Koji during Fermentation and Storage. *J. Food Sci.* **2012**, *77*, M318–M322. [\[CrossRef\]](#) [\[PubMed\]](#)
35. He, J.; Liu, C.; Fu, C.; Li, J. Effects of extrusion and supplementation of exogenous enzymes to diets containing Chinese storage brown rice on the carbohydrase activity in the digestive tract of piglets. *J. Anim. Physiol. Anim. Nutr.* **2010**, *94*, 146–153. [\[CrossRef\]](#) [\[PubMed\]](#)
36. Asyifah, M.; Abd-Aziz, S.; Phang, L.; Azlian, M. Brown rice as a potential feedstuff for poultry. *J. Appl. Poult. Res.* **2012**, *21*, 103–110. [\[CrossRef\]](#)
37. He, B.; Shi, J.; Liu, K.; Cheng, J.; Wang, W.; Wang, Y.; Li, A. Evaluation of the Available Energy Value and Amino Acid Digestibility of Brown Rice Stored for 6 Years and Its Application in Pig Diets. *Animals* **2023**, *13*, 3381. [\[CrossRef\]](#)
38. Kang, F.; He, B.; Wang, Y.; Aike, L. Research Progress on Application of Rice Resources in Livestock and Poultry Diet. *Chin. J. Anim. Nutr.* **2021**, *33*, 4271–4284. [\[CrossRef\]](#)
39. Tan, F.P.; Beltranena, E.; Zijlstra, R.T. Resistant starch: Implications of dietary inclusion on gut health and growth in pigs: A review. *J. Anim. Sci. Biotechnol.* **2021**, *12*, 124. [\[CrossRef\]](#) [\[PubMed\]](#)
40. Li, X.; Yuan, S.; Piao, X.; Lai, C.; Zang, J.; Ding, Y.; Han, L.; Han, I.K. The nutritional value of brown rice and maize for growing pigs. *Asian-Australas. J. Anim. Sci.* **2006**, *19*, 892–897. [\[CrossRef\]](#)
41. Cervantes-Pahm, S.K.; Liu, Y.; Stein, H.H. Comparative digestibility of energy and nutrients and fermentability of dietary fiber in eight cereal grains fed to pigs. *J. Sci. Food Agric.* **2014**, *94*, 841–849. [\[CrossRef\]](#)
42. Wu, S.; Duan, J.Q.; Xiao, J.; Yong-Teng, S. Evaluation of effective performance and amino acid digestibility of pigs grown from brown rice with different varieties of feed. *J. Anim. Nutr.* **2020**, *13*, 3381.
43. Kim, S.; Cho, J.H.; Kim, Y.; Kim, H.B.; Song, M. Effects of substitution of corn with ground brown rice on growth performance, nutrient digestibility, and gut microbiota of growing-finishing pigs. *Animals* **2021**, *11*, 375. [\[CrossRef\]](#)
44. Katsumata, M.; Ashihara, A.; Ishida, A.; Kobayashi, H. Effects of replacement of all of corn contained in feed with brown rice and feeding brown rice together with sweet potato on growth performance and quality of pork of fattening pigs. *Jap. J. Swine Sci.* **2015**, *52*, 17–28. [\[CrossRef\]](#)
45. Tasaka, Y.; Tachihara, K.; Kagawa, R.; Takada, R. Effects of rice feeding on growth performance and protein (amino acids) metabolism in weanling piglets. *Anim. Sci. J.* **2020**, *91*, e13311. [\[CrossRef\]](#)
46. Tsukahara, T.; Kishino, E.; Inoue, R.; Nakanishi, N.; Nakayama, K.; Ito, T.; Ushida, K. Correlation between villous height and the disaccharidase activity in the small intestine of piglets from nursing to growing. *Anim. Sci. J.* **2013**, *84*, 54–59. [\[CrossRef\]](#)
47. Yagami, K.; Takada, R. Dietary rice improves growth performance, mucosal enzyme activities and plasma urea nitrogen in weaning piglets. *Anim. Sci. J.* **2017**, *88*, 2010–2015. [\[CrossRef\]](#)
48. Li, E.; Zhu, T.; Dong, W.; Huang, C. Effects of brown rice particle size on energy and nutrient digestibility in diets for young pigs and adult sows. *Anim. Sci. J.* **2019**, *90*, 108–116. [\[CrossRef\]](#)
49. Li, T.; Huang, R.; Wu, G.; Lin, Y.; Jiang, Z.; Kong, X.; Chu, W.; Zhang, Y.; Kang, P.; Hou, Z. Growth performance and nitrogen metabolism in weaned pigs fed diets containing different sources of starch. *Livest. Sci.* **2007**, *109*, 73–76. [\[CrossRef\]](#)
50. Medel, P.; Latorre, M.; De Blas, C.; Lázaro, R.; Mateos, G. Heat processing of cereals in mash or pellet diets for young pigs. *Anim. Feed Sci. Technol.* **2004**, *113*, 127–140. [\[CrossRef\]](#)
51. Pluske, J.R.; Siba, P.M.; Pethick, D.W.; Durmic, Z.; Mullan, B.P.; Hampson, D.J. The incidence of swine dysentery in pigs can be reduced by feeding diets that limit the amount of fermentable substrate entering the large intestine. *J. Nutr.* **1996**, *126*, 2920–2933. [\[CrossRef\]](#)
52. Wang, Y.; Zhou, X.; Liu, M.; Zang, H.; Zhang, R.; Yang, H.; Jin, S.; Qi, X.; Shan, A.; Feng, X. Quality of chicken breast meat improved by dietary pterostilbene referring to up-regulated antioxidant capacity and enhanced protein structure. *Food Chem.* **2023**, *405*, 134848. [\[CrossRef\]](#)
53. Onderci, M.; Sahin, N.; Cikim, G.; Aydin, A.; Ozercan, I.; Ozkose, E.; Ekinci, S.; Hayirli, A.; Sahin, K. β -Glucanase-producing bacterial culture improves performance and nutrient utilization and alters gut morphology of broilers fed a barley-based diet. *Anim. Feed Sci. Technol.* **2008**, *146*, 87–97. [\[CrossRef\]](#)
54. Vahjen, W.; Busch, T.; Simon, O. Study on the use of soya bean polysaccharide degrading enzymes in broiler nutrition. *Anim. Feed Sci. Technol.* **2005**, *120*, 259–276. [\[CrossRef\]](#)
55. Vicente, B.; Valencia, D.; Pérez-Serrano, M.; Lázaro, R.; Mateos, G. The effects of feeding rice in substitution of corn and the degree of starch gelatinization of rice on the digestibility of dietary components and productive performance of young pigs. *J. Anim. Sci.* **2008**, *86*, 119–126. [\[CrossRef\]](#)
56. Shih, C.-H.; Lee, T.-T.; Kuo, W.H.-J.; Yu, B. Growth performance and intestinal microflora population of broilers fed aged brown rice. *Ann. Anim. Sci.* **2014**, *14*, 897–909. [\[CrossRef\]](#)
57. Fujimoto, H.; Matsumoto, K.; Koseki, M.; Yamashiro, H.; Yamada, T.; Takada, R. Effects of rice feeding and carnitine addition on growth performance and mRNA expression of protein metabolism-related genes in broiler grower chicks. *Anim. Sci. J.* **2020**, *91*, e13390. [\[CrossRef\]](#)

58. Zhang, J.; Sun, X.; Chai, X.; Jiao, Y.; Sun, J.; Wang, S.; Yu, H.; Feng, X. Curcumin Mitigates Oxidative Damage in Broiler Liver and Ileum Caused by Aflatoxin B1-Contaminated Feed through Nrf2 Signaling Pathway. *Animals* **2024**, *14*, 409. [\[CrossRef\]](#)
59. Li, Y.; Wang, Z.; Yang, H.; Xu, L.; Xie, Y.; Jin, S.; Sheng, D. Effects of dietary fiber on growth performance, slaughter performance, serum biochemical parameters, and nutrient utilization in geese. *Poult. Sci.* **2017**, *96*, 1250–1256. [\[CrossRef\]](#)
60. Guan, P.; Yu, H.; Wang, S.; Sun, J.; Chai, X.; Sun, X.; Qi, X.; Zhang, R.; Jiao, Y.; Li, Z.; et al. Dietary rutin alleviated the damage by cold stress on inflammation reaction, tight junction protein and intestinal microbial flora in the mice intestine. *J. Nutr. Biochem.* **2024**, *130*, 109658. [\[CrossRef\]](#)
61. Yu, J.; Zhang, H.; Yang, H.; Wang, Z. Effects of dietary paddy rice on growth performance, carcass traits, bare skin color, and nutrient digestibility in geese. *Poult. Sci.* **2022**, *101*, 101865. [\[CrossRef\]](#)
62. Dabbert, C.B.; Powell, K.C.; Martin, T.E. Effects of monotypic diets of soybean, rice, and corn on Mallard (*Anas platyrhynchos*) physiological status. *J. Zoo Wildlife Med.* **1996**, *27*, 248–254.
63. Yang, H.; Wang, Y.; Jin, S.; Pang, Q.; Shan, A.; Feng, X. Dietary resveratrol alleviated lipopolysaccharide-induced ileitis through Nrf2 and NF- κ B signalling pathways in ducks (*Anas platyrhynchos*). *J. Anim. Physiol. Anim. Nutr.* **2022**, *106*, 1306–1320. [\[CrossRef\]](#) [\[PubMed\]](#)
64. Nikkhah, A. On Energy Policies in Animal Production: Avoiding Starchy Explosions. *Innov. Energy Policies* **2014**, *3*, 142. [\[CrossRef\]](#)
65. Scheibler, R.; Schafhäuser, J.; Rizzo, F.; Nörnberg, J.; Vargas, D.; Silva, J.; Fluck, A.; Fioreze, V. Replacement of corn grain by brown rice grain in dairy cow rations: Nutritional and productive effects. *Anim. Feed Sci. Technol.* **2015**, *208*, 214–219. [\[CrossRef\]](#)
66. Miyaji, M.; Matsuyama, H.; Hosoda, K. Effect of substituting brown rice for corn on lactation and digestion in dairy cows fed diets with a high proportion of grain. *J. Dairy Sci.* **2014**, *97*, 952–960. [\[CrossRef\]](#) [\[PubMed\]](#)
67. Kim, J.Y.; Lee, B.H.; Chemere, B.; Min, D.H.; Kim, B.W.; Sung, K.I. In vivo nutritive value of rice feed for sheep and its application for cattle feed. *J. Anim. Sci. Technol.* **2019**, *61*, 254. [\[CrossRef\]](#) [\[PubMed\]](#)
68. Cattellam, J.; Argenta, F.M.; Alves, F.; Brondani, I.L.; Machado, D.S.; Pereira, L.B.; Cardoso, G.d.S.; da Silva, M.A.; Adams, S.M.; Viana, A.F.P. Non-carcass components of cattle finished in feedlot with high grain diet. *Biosci. J.* **2018**, *34*, 709–718. [\[CrossRef\]](#)
69. FAO. *The State of World Fisheries and Aquaculture 2022. Towards Blue Transformation*; FAO: Rome, Italy, 2022; p. 211.
70. Zlaugotne, B.; Pubule, J.; Blumberga, D. Advantages and disadvantages of using more sustainable ingredients in fish feed. *Heliyon* **2022**, *8*, e10527. [\[CrossRef\]](#) [\[PubMed\]](#)
71. Kamalam, B.; Medale, F.; Panserat, S. Utilisation of dietary carbohydrates in farmed fishes: New insights on influencing factors, biological limitations and future strategies. *Aquaculture* **2017**, *467*, 3–27. [\[CrossRef\]](#)
72. Sun, Y.; Huang, Y.; Cao, J.; Wang, G.; Hu, J.; Chen, B.; He, F.; Qiu, J. Apparent digestibility of nutrients in six types of carbohydrate ingredients for tilapia (*Oreochromis niloticus*). *Chin. J. Anim. Nutr.* **2015**, *27*, 3577–3586. [\[CrossRef\]](#)
73. Khosravi, M.; Dastar, B.; Aalami, M.; Shawrang, P.; Ashayerizadeh, O. Comparison of gamma-Irradiation and enzyme supplementation to eliminate antinutritional factors in rice bran in broiler chicken diets. *Livest. Sci.* **2016**, *191*, 51–56. [\[CrossRef\]](#)
74. Woyengo, T.; Nyachoti, C. Anti-nutritional effects of phytic acid in diets for pigs and poultry—current knowledge and directions for future research. *Can. J. Anim. Sci.* **2013**, *93*, 9–21. [\[CrossRef\]](#)
75. Pasha, I.; Ahmad, F.; Siddique, Z.; Iqbal, F. Probing the effect of physical modifications on cereal bran chemistry and antioxidant potential. *J. Food Meas. Charact.* **2020**, *14*, 1909–1918. [\[CrossRef\]](#)
76. Selle, P.H.; Macelline, S.P.; Chrystal, P.V.; Liu, S.Y. The contribution of phytate-degrading enzymes to chicken-meat production. *Animals* **2023**, *13*, 603. [\[CrossRef\]](#)
77. Zouaoui, M.; Létourneau-Montminy, M.; Guay, F. Effect of phytase on amino acid digestibility in pig: A meta-analysis. *Anim. Feed Sci. Technol.* **2018**, *238*, 18–28. [\[CrossRef\]](#)
78. Gao, Y.; Zhou, X.; Yu, J.; Jin, Y.; Li, C.; Liu, J.; Zhang, J.; Zhang, L.; Wang, D.; Han, Y. Effects of non-starch polysaccharide enzyme on growth performance, carcass traits and meat quality of growing-finishing pigs. *Chin. J. Vet. Sci.* **2014**, *34*, 820–824.
79. Kwak, M.; Kim, J.; Sung, K.; Whang, K. PSX-31 Effects of Dietary Non-starch Polysaccharide (NSP) and NSP-Degrading Enzyme Complex (Endo-Power™) Supplementation on Growth Performance, Intestinal Environments and Systemic Immune Responses in Growing Pigs. *J. Anim. Sci.* **2018**, *96*, 487–488. [\[CrossRef\]](#)
80. Nisley, M.J.; Gabler, N.K.; Sparks, C.; Vanderbeke, E.; De Keyser, K. In The Impact of Dietary Crude Protein and Non-Starch Polysaccharide Inclusion on Nursery Pig Performance. *J. Anim. Sci.* **2022**, *100*, 180. [\[CrossRef\]](#)
81. Ajita, T. Extrusion cooking technology: An advance skill for manufacturing of extrudate food products. In *Extrusion of Metals, Polymers and Food Products*; Books on Demand: Norderstedt, Germany, 2018. [\[CrossRef\]](#)
82. Datta, S.; Bouis, H.E. Application of biotechnology to improving the nutritional quality of rice. *Food Nutr. Bull.* **2000**, *21*, 451–456. [\[CrossRef\]](#)
83. Zentek, J.; Boroojeni, F.G. (Bio) Technological processing of poultry and pig feed: Impact on the composition, digestibility, anti-nutritional factors and hygiene. *Anim. Feed Sci. Technol.* **2020**, *268*, 114576. [\[CrossRef\]](#)
84. Ferrara, M.; Perrone, G.; Gallo, A. Recent advances in biosynthesis and regulatory mechanisms of principal mycotoxins. *Curr. Opin. Food Sci.* **2022**, *48*, 100923. [\[CrossRef\]](#)
85. Silva, J.V.B.d.; Oliveira, C.A.F.d.; Ramalho, L.N.Z. An overview of mycotoxins, their pathogenic effects, foods where they are found and their diagnostic biomarkers. *Food Sci. Technol.* **2021**, *42*, e48520. [\[CrossRef\]](#)

86. Zhang, L.; Zhang, J.; Zang, H.; Yin, Z.; Guan, P.; Yu, C.; Shan, A.; Feng, X. Dietary pterostilbene exerts potential protective effects by regulating lipid metabolism and enhancing antioxidant capacity on liver in broilers. *J. Anim. Physiol. Anim. Nutr.* **2024**, *108*, 1–13. [CrossRef]
87. Zhao, L.; Zhang, L.; Xu, Z.; Liu, X.; Chen, L.; Dai, J.; Karrow, N.A.; Sun, L. Occurrence of Aflatoxin B1, deoxynivalenol and zearalenone in feeds in China during 2018–2020. *J. Anim. Sci. Biotechnol.* **2021**, *12*, 74. [CrossRef]
88. Lin, X.; Zhang, Q.; Zhang, Y.; Li, J.; Li, F. Further data on the levels of emerging Fusarium mycotoxins in cereals collected from Tianjin, China. *Food Addit. Contam. Part B* **2021**, *14*, 74–80. [CrossRef]
89. Gruber-Dorninger, C.; Jenkins, T.; Schatzmayr, G. Global mycotoxin occurrence in feed: A ten-year survey. *Toxins* **2019**, *11*, 375. [CrossRef]
90. GB 13078-2017; Feed Hygiene Standards. Available online: <http://www.foodmate.net/> (accessed on 16 April 2024).
91. FDA. Available online: <https://www.fda.gov/food/natural-toxins-food/mycotoxins> (accessed on 16 April 2024).
92. EUR-Lex. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32023R0915> (accessed on 16 April 2024).
93. Khodaei, D.; Javanmardi, F.; Khaneghah, A.M. The global overview of the occurrence of mycotoxins in Cereals: A three-year survey. *Curr. Opin. Food Sci.* **2020**, *39*, 36–42. [CrossRef]
94. Iqbal, S.Z.; Asi, M.R.; Hanif, U.; Zuber, M.; Jinap, S. The presence of aflatoxins and ochratoxin A in rice and rice products; And evaluation of dietary intake. *Food Chem.* **2016**, *210*, 135–140. [CrossRef]
95. Lee, H.J.; Ryu, D. Worldwide Occurrence of Mycotoxins in Cereals and Cereal Derived Food Products: PublicHealth Perspectives of Their Co-Occurrence. *J. Agric. Food. Chem.* **2017**, *65*, 7034–7051. [CrossRef]
96. Zheng, Y. Differences in Rice Quality, Mold Flora and Mycotoxins at Different Storage Stages. Master's Thesis, The Nanjing University of Finance and Economics, Nanjing, China, 2020.
97. Wang, X.; Yan, S. Regulation and mechanism of lipid metabolism by polyunsaturated fatty acids of animals. *Chin. J. Anim. Nutr.* **2019**, *31*, 2471–2478.
98. Zhao, Q.; Guo, H.; Hou, D.; Laraib, Y.; Xue, Y.; Shen, Q. Influence of temperature on storage characteristics of different rice varieties. *Cereal Chem.* **2021**, *98*, 935–945. [CrossRef]
99. Wang, T.; She, N.; Wang, M.; Zhang, B.; Qin, J.; Dong, J.; Fang, G.; Wang, S. Changes in Physicochemical Properties and Qualities of Red Brown Rice at Different Storage Temperatures. *Foods* **2021**, *10*, 2658. [CrossRef] [PubMed]
100. Yin, C.; Xia, B.; Tang, S.; Cao, A.; Liu, L.; Zhong, R.; Chen, L.; Zhang, H. The effect of exogenous bile acids on antioxidant status and gut microbiota in heat-stressed broiler chickens. *Front. Nutr.* **2021**, *8*, 747136. [CrossRef] [PubMed]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.