fermentation

Review

Enhancement of the Nutritional Composition and Antioxidant Activities of Fruit Pomaces and Agro-Industrial Byproducts through Solid-State Fermentation for Livestock Nutrition: A Review

Olusegun Oyebade Ikusika [1,*], Oluwakamisi Festus Akinmoladun [1,2] and Conference Thando Mpendulo [1]

[1] Department of Livestock and Pasture Science, Faculty of Science and Agriculture, Private Bag X1314, Alice 5700, South Africa; fakinmoladun@ufh.ac.za (O.F.A.); tmpendulo@ufh.ac.za (C.T.M.)
[2] Department of Animal and Environmental Biology, Faculty of Science, PMB 001, Adekunle Ajasin University, Akungba-Akoko 342111, Nigeria
* Correspondence: oikusika@ufh.ac.za

Abstract: The abundance of fruit waste from the food industry and wineries, particularly peels, seeds, and other fruit pomace throughout the year, could lead to health and environmental hazards if not channelled into productive areas. Improving or transforming these waste products for better use in other vital sectors could be achieved via solid-state fermentation (SSF) since most waste products are solid. One such productive and important area is the feeding of livestock, which will guarantee millennium food security goals for many nations of the world. The nutritional and antioxidant composition of abundantly available fruit pomace and agro-industrial byproducts could be improved via solid-state fermentation for overall livestock productivity. They contain substantial dietary fibre, protein, and phenolic compounds; hence, improving them via fermentation could serve the livestock industry in dual capacities, including nutraceutical and conventional feedstuff. This review seeks to provide reinforcing evidence on the applicability and impact of fruit pomaces on livestock nutrition. The significant nutrient improvements, beneficial outcomes in feeding trials, and inconsistencies or areas of research gap were also explored.

Keywords: solid-state fermentation; fruit pomace; agro-allied byproducts; microorganism; animal feeds; livestock production

check for updates

Citation: Ikusika, O.O.; Akinmoladun, O.F.; Mpendulo, C.T. Enhancement of the Nutritional Composition and Antioxidant Activities of Fruit Pomaces and Agro-Industrial Byproducts through Solid-State Fermentation for Livestock Nutrition: A Review. *Fermentation* **2024**, *10*, 227. https://doi.org/10.3390/fermentation10050227

Academic Editor: Mengzhi Wang

Received: 19 March 2024
Revised: 12 April 2024
Accepted: 15 April 2024
Published: 25 April 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

The rise in the global human population would continue to place a higher demand on livestock production, a significant food source for the populace. Based on present and future projections, meat and dairy production will continue to expand to meet the protein and other animal product demands of the ever-growing human population [1]. To meet this demand, it is estimated that livestock feed supply will increase from the present 6.0 billion tonnes of DM to 7.3 billion tonnes of DM by 2030 [2]. Succinctly, especially in monogastric animals, the cost of raising livestock to the market stage could be over 70% of the total cost of production [3]. Many scholars all over the globe have reported that the continual use of conventional feed ingredients such as soybean and maize in formulating feeds for livestock cannot be sustained economically and environmentally in the long term [4]. Therefore, sustaining profitable livestock production could depend largely on nutritional manipulation using alternative sources of feed ingredients that will reduce feed costs while nutritional quality is still maintained [5]. Hence, researchers around the world have investigated several alternative feed ingredients that could entirely or partially replace these conventional feed ingredients with recent attention shifted towards the use of fruit pomace and waste from agro-allied industries [6].

Fruit pomaces are products derivable after pressing or crushing whole fruits to extract their juice. They are waste products in wineries and other fruit processing industries. According to [7], fruit pomace accounts for 40–50% of global waste. Fruits such as mango, berries, grapes, apples, guavas, citrus, carrot, tomatoes, strawberries, peas, pineapple, and many others have often been used in producing juice with large amounts of pomace produced following juice extraction. The volume of this waste would adversely affect the economy and the environment. Hence, inculcating them into livestock feeding will solve part of the world's economic, environmental, and food security problems. Table 1 shows some fruit pomace used in livestock feed and annual quantities generated globally. The pomaces of these fruits are sources of dietary fibres, micronutrients, bioactive compounds, lipids, and protein that could be valuable in livestock production. Fruit pomaces undergo oxidation and fermentation reactions immediately after processing in the presence of light, heat, and oxidants [8].

In the same vein, agro-industrial byproducts are waste products of food processing industries that can be used to feed livestock. These include but are not limited to beet pulp, corn gluten feed, casava peels, cocoa pods, hulls, pomegranate peels, lemon peels, green walnut husk meal, molasses, etc. These industrial byproducts are obtained from different agro-industrial processes, such as oil, sugar, vegetables, roots, and tuber [9]. Despite their important nutritional properties, they are no longer suitable for human consumption [10].

Table 1. Some fruit pomaces used in livestock feeds.

Fruits	Global Availability	Global Production	% Resulted in Pomace	Estimated Pomace Generated Globally per Year	Nutrient Contents	Class of Animals that Consume it	Reference
Apple (*Malus* spp.)	In temperate regions	93.14 Mt	NA	21 Mt	Non-fibre carbohydrates and hemicellulose	Sweeteners and sources of carbon hydrates for ruminants and rabbits	[11]
Citrus pomace	Mostly in Brazil, China, India, Mexico, Spain, and the USA	161.8 Mt	NA	10 Mt	Valuable amounts of free sugars, flavonoids, fats, organic acids, carbohydrate polymers, limonene essential oil, enzymes, and pigments.	All classes of animals	[12]
Grapes (*Vitis* spp.)	Mostly Italy, France, and Spain	28.4 Mt	20–30	8.49 Mt	Bioactive compounds (flavonols, glucosides, gallate esters, anthocyanins, and proanthocyanins)		[13]
Olive pomace	Asia/Europe	16 Mt		2 Mt/year	Rich in sugar, protein, lipids, polyphenols, and 3,4-DHP	All classes of animals	[14]

Table 1. *Cont.*

Fruits	Global Availability	Global Production	% Resulted in Pomace	Estimated Pomace Generated Globally per Year	Nutrient Contents	Class of Animals that Consume it	Reference
Watermelon (*Citrullus lanatus*)	Worldwide	103 Mt		NA	Contains water, carbohydrates, vitamins, fat, protein, minerals, citrulline, pectin, and lycopene	Swine	[15]
Banana peels	China, India Philippines, and Brazil	170.3 Mt	30–40	36 Mt	High in antioxidant capacity and antimicrobial properties.	Ruminant and swine	[16]
Pomegranate (*Punica granatum* L.)		8.1 Mt	40–50	1.5 Mt	Rich in polyphenols such as ellagic tannins, ellagic acid, gallic acid, and punicalagin	Poultry	[17]
Pineapple (*Ananas comosus* L.)	Tropical and subtropical countries	28.65 Mt	40	16.8 M	Rich in vitamin C, calcium, dietary fibre, and soluble carbohydrates. Also, contains a wide range of bioactive compounds, such as polyphenols and carotenoids.	Mostly swine	[18]
Mango (*Mangifera indica* L.)	North India and the Malay Peninsula	57 Mt	35–50	17.1 M	Dietary fibre, vitamins E and C, enzymes, polyphenols, and carotenoids	All classes of livestock	[19]

M, Million; Mt, million tonnes or million metric tonnes, NA; not applicable.

Many of these byproducts are useful when added to animal diets since they alleviate the feeding cost for farmers as well as improve animal health and products in many instances [20]. In addition, some agro-industrial byproducts, such as olive mill vegetation water, could boost bioactive compounds and improve the quality of microbial meat and dairy products [21]. Also, including agro-industrial byproducts to ruminants in the animals' diet could present a way of developing a circular economy and environmental sustainability. However, fruits, pomace, and agro-industrial wastes vary in the composition of proteins, sugars, and minerals. Because of their nutritional composition, these residues could not be referred to as "wastes" but as ingredients for livestock feeds.

The nutrients in these ingredients provide enabling environments for microbial growth, and through a fermentation process, the microbes can reuse these raw materials. Agro-industrial residues are especially often used to support solid-state fermentation processing when making beneficial products [22].

2. Methodology

The materials used in developing this review article were sourced from peer-reviewed papers on the internet using the following keywords: solid-state fermentation, fruit pomaces, agro-industrial wastes, non-conventional feedstuffs for livestock, and waste valorisation. Scopus, PubMed, and Google Scholar were employed in the literature search. The search was expanded in scope to include experimental studies of solid-state fermentation (SSF) on fruit pomaces and agro-industrial byproducts, nutritional composition, and antioxidant activities as influenced by SSF and microbial strains used in SSF. However, the search excluded fermentation methods other than SSF, studies using fermented byproducts for human nutrition, and other applications unrelated to livestock as well as studies on non-fermented byproducts of fruit pomaces and agro-industrial byproducts.

3. Solid-State Fermentation

Scientists define solid-state fermentation (SSF) differently. In this review, the definition shall be harmonized. SSF is defined as a fermentation process in which microorganisms grow on solid or complex materials void of free water or with very low content of free water, thereby converting it into simpler forms, while the solid material acts as a source of energy. However, the moisture level should be sufficient to support microbial growth and metabolic activity [23]. The genesis of solid-state fermentation could be dated back to 2600 BC when Egyptians made bread using a fermentation process.

Similarly, Indonesia, China, and Japan each utilized solid-state fermentation (SSF) techniques at various points in history for the production of traditional Oriental foods, preservation of animal and fish products, and creation of vinegar and gallic acid, stretching back hundreds or even thousands of years.

However, between 1980 and 1990, the period saw a notable surge in research endeavours focusing on SSF techniques. This surge yielded advancements leading to the creation and manufacturing of numerous significant products within the livestock industries. These advancements encompassed various bioprocesses, such as bioremediation and biodegradation of hazardous substances, detoxification of agro-industrial wastes, transformation of crops and crop residues for enhanced nutritional value, and the large-scale production of bioactive secondary metabolites like antibiotics and alkaloids. Additionally, it included the production of enzymes (e.g., cellulase, phytase, proteases, and lipases), organic acids (e.g., citric acid, lactic acid, oxalic acid, fumaric acid, and gallic acid), biopesticides, biosurfactants, biopharmaceuticals, biofuels, and aromatic compounds [24].

3.1. Effect of SSF on the Nutritional Content of Fruit Pomaces and Agro-Allied Byproducts

3.1.1. Effect on Protein Content

The protein content of ingredients, raw materials, or byproducts plays a pivotal role in determining the suitability of such products for consumption by specific animal classes and influences their perceived value. In a study by [25], solid-state fermentation of apple pomace with autochthonous cider yeasts resulted in a substantial protein content increase of 23–49% compared to unfermented pomace. Similarly, ref. [26] noted elevated protein levels in chia and sesame seed wastes following solid-state fermentation with *Pleurotus ostreatus*. Ref. [27] found significant protein content enhancements in soybean and orange-fleshed sweet potato blends subjected to solid-state fermentation using *Rhizopus oligosporus* (2710) and *Lactobacillus plantarum* (B-41621), with increases ranging between 17.10 and 19.02%. During solid-state fermentation, ref. [28] reported considerable protein content increments in fruit pomace with the yeast *Kluyveromyces marxianus* NRRL Y-8281. Ref. [29] observed a 15.7% rise in crude protein content in the fermented substrate due to enhanced fungal cell mass production, leading to reduced sugar production when employing *Rhizopus* sp. Conversely, ref. [30] noted an initial decline in crude protein content during the first 48 h, followed by a significant increase of 4 to 14% during solid-state fermentation of some feed ingredients using *Aspergillus niger* and *Bacillus coagulans*. Tables 2 and 3 detail the effects of solid-state fermentation on selected fruit pomaces and agro-industrial byproducts, respectively.

3.1.2. Effect on Crude Fibre

Crude fibre is a measure of the indigestible plant material present in livestock feed. It consists primarily of cellulose, hemicellulose, lignin, and smaller amounts of pectins and other components. Crude fibre is determined by subjecting a feed sample to acid and alkali treatment to remove soluble carbohydrates, proteins, and ash, leaving behind the insoluble fibrous fraction. It is important to note that while crude fibre is a valuable indicator of the fibre content in the feed, it does not provide a complete picture of the digestibility or nutritional value of the feed. Other measures, such as neutral detergent fibre (NDF) and acid detergent fibre (ADF), are often used with crude fibre analysis to better assess the fibre fraction in feed and its potential impact on animal nutrition and performance. Many researchers have studied the effects of solid-state fermentation on the crude fibre of various agro-allied byproducts and fruit pomace. Ref. [31] reported that solid substrate fermentations of cocoa pod husk, cassava peel, and palm kernel cake using isolated fungal strain *Rhizopus stolonifer* LAU 07 resulted in the reduction of crude fibre content of these byproducts by 44.5, 8.6, and 7.2% respectively.

Similarly, ref. [32] noticed a significant reduction in the crude fibre content of pineapple pomace added with *Trichoderma viride* ATCC 36316 for 96 h at 30 °C under solid-state fermentation. Also, ref. [33] noticed a significant decrease in crude fibre contents in maize bran when subjected to solid-state fermentation using *Lactobacillus plantarum* and *Saccharomyces cerevisiae* and their cocultures. Ref. [34] reported reduced fibre content when cassava bagasse and leaves were subjected to solid-state fermentation using *Lentinula edodes*. These reports were also collaborated by the observation of [35] that crude fibre content of animal feed ingredients decrease by 25% when undergoing solid-state fermentation using *Aspergillus ibericus* MUM 03.29, *Aspergillus niger* CECT 2088, and *Aspergillus niger* CECT 2915. However, ref. [36] observed no difference in the crude fibre content of solid-state fermented and unfermented lupin flour using *Aspergillus sojae*, *Aspergillus ficuum*, and their co-cultures.

3.1.3. Effect on Ether Extract

Ether extract, or crude fat or lipid content, refers to the portion of a feed that is soluble in organic solvents such as ether. It consists primarily of triglycerides (fats and oils), phospholipids, and some waxes.

Table 2. Some fruit pomaces' nutritive value improved via solid-state fermentation.

Pomace Source	Microbes Used	After Biodegradation	Significant Level	Days of Biodegradation and Temp.	Experimental Animal	Effect on Tested Animals	Reference
Mango	*Kluyveromyces marxianus* NRRL Y-8281(Yeast)	Protein and fat content did not increase. Similarly, crude fibre and cell wall constituents remained unchanged. Carbohydrate content decreased.		48 h at 45 °C	In vitro	In vitro	[28]
Mango	*Saccharomyces boulardii*, *Lactobacillus plantarum* (combined)	Enhanced the protein, fat, ash, and minerals (Ca, Mg, K, Fe, Mn) over the control.		48 h at 37 °C	In vitro	In vitro	[37]

Table 2. *Cont.*

Pomace Source	Microbes Used	After Biodegradation	Significant Level	Days of Biodegradation and Temp.	Experimental Animal	Effect on Tested Animals	Reference
Pomegranate	*Aspergillus niger* (ATCC 9142)	Increased protein and fat content and decreased crude fibre content and cell wall constituents.		7d at 30 °C	Broilers chicken	No change in the body weight and feed conversion ratio. Caecal clostridium perfringens count decreased in broiler chickens fed 5 and 10 g/kg of fermented pomegranate. There were detrimental effects on the ileum morphology.	[38]
Orange	*Saccharomyces cerevisiae*	Increased protein and fat content and decreased crude fibre content and cell wall constituents. Carbohydrate content decreased.	Significantly	14 d at 30 °C	Ossimi rams	Digestibility of CF and EE increased with a 15% inclusion rate.	[39]
Grape	*Lactobacillus plantarum*	Increased protein and fat content and decreased crude fibre content and cell wall constituents. Carbohydrate content decreased.		10 d at 30 °C	Finishing pigs	Increased beneficial bacteria and decreased VFA emission in faeces.	[40]
Grape	*Rhizopus oryzae. Pleurotus cornucopiae*	Decreased ash, protein, and sugar content, and increased fat, cellulose, and lignin content.		4 weeks at 27 °C	Steers	Reduced lignin content and improved rumen fermentation and metabolizable energy. However, increasing the fermentation periods with both white-rot fungi reduced the gain of metabolizable energy and ruminal microbial crude protein synthesis.	[6,41]
Citrus pomace	*Lactobacillus plantarum* P10, M14	Reduced organic matter and reduced sugars, but increased crude protein and neutral detergent fibre, acid detergent fibre and neutral detergent insoluble protein.		3 d	Brown beef cattle	Reduced methane emission from the insoluble fraction without modifying the production rate. Increased acetic but decreased propionic and butyric acid proportions.	[42]

Table 2. *Cont.*

Pomace Source	Microbes Used	After Biodegradation	Significant Level	Days of Biodegradation and Temp.	Experimental Animal	Effect on Tested Animals	Reference
Citrus pomace	*Bacillus subtilis* BF2	Carbohydrate content was reduced, and fat and total dietary fibre increased.		3 d	Brown beef cattle	Improved dry matter intake, organic matter, crude protein, ash-free neutral detergent fibre, ether extract, and starch intake. Increased ruminal concentrations of total volatile fatty acids, acetate and isovalerate, and acetate to propionate ratio, and reduced propionate concentration.	[42]
Apple pomace	*Lactobacillus plantarum*			21 d at 9.7–20.1 °C	Finishing pigs	Increased feed efficiency; reduced average daily feed intake but no effect on finished body weight and back fat thickness.	
Apple pomace	*Saccharomyces cerevisiae*	Improved crude protein, fat, total ash, and vitamin content			poultry	Increased weight gain and feed conversion efficiency.	
Red grape	*Rhizopus* sp.	Improved crude protein, fat, total ash, and vitamin content of the diets.		48 h at 30 °C	Broiler chicken	Increased feed conversion efficiency but did not affect body weight gain.	[43]
Mango	*Saccharomyces boulardii* and *S. cerevisiae*	Greatly enhanced protein (7.88%), fat (4.18%), ash (5.74%), and minerals: Ca (0.70%), Mg (0.46%), K (1.30%), Fe (313 ppm), Mn (45.80 ppm) compared to control.		7 d	Broiler chicken	Improve growth performance when 100–150 g/kg was included in the starter phase.	[44]
White mulberry pomace	*Lactobacillus acidophilus*	Rich in phenolic compounds and anthocyanins.		4 d	Laying birds	Increased feed intake, egg yield, and egg general parameters.	[45]
Tomato pomace	*Lactobacillus plantarum*, *A. niger*	Increased dry matter, crude fibre, neutral detergent fibre, acid detergent fibre, acid, crude protein, ether extract and ash.		30 d	Saanen dairy goats	Inclusion of 40% increased feed intake, digestibility, milk yield, and quality. No effect on feed efficiency and feed conversion. Thyroid hormones were significantly affected.	[46]
Olive pomace	*Bacillus subtilis*	Increased EE, OM, and CP while CF, lignin content, and PH levels reduced after fermentation.		2 d at 37 °C	Broiler chicken and laying birds	Increased feed conversion ratio and defence system response. Improved overall egg quality and shell strength in brown laying hens.	[47,48]

Table 2. *Cont.*

Pomace Source	Microbes Used	After Biodegradation	Significant Level	Days of Biodegradation and Temp.	Experimental Animal	Effect on Tested Animals	Reference
Olive pomace	*Lactobacillus casei*	Increased EE, OM, and CP while CF, lignin content, and PH levels reduced after fermentation.		5 d at 25–35 °C	Broiler chicken	Reduced body weight gain, protein efficiency ratio, and nutrient digestibility.	[47]
Olive pomace	*Kluyveromyces marxianus* NRRL Y-8281	Crude fibre decreased by 8.56%, while crude protein, fat, and carbohydrate content increased by 2.74, 2.63 and 3.57%, respectively.		48 h at 45 °C	In vitro	Increased feed intake, feed conversion efficiency, and weight gain. Fat percentage and cholesterol content in breast meat were significantly reduced.	[49]
Strawberry pomace	*Lentinus edodes*	Increased mineral and phenol content.		1 d at 35 °C	Laying birds and pigs	Improved the immunological status of laying hens. Also, the lean tissues of growers' pigs.	[50]
Raisin and popped nuts	*Aspergillus niger*	Reduced phytate and glucosinolate. Increased crude protein and acid soluble protein and ether extract content.		24 h at 30 °C	Quails and laying birds	Increased egg-laying rate, egg weight, albumen, yolk, and shell quality.	[51]

Table 3. Some agro-industrial byproducts improved via solid-state fermentation.

Agro Byproducts	Microbes Used	After Biodegradation	Days of Biodegradation and Temp.	Experimental Animals	Effect on Experimental Animals	Reference
Rice bran	*Penicilium* sp.	Improvement in crude protein, ether extract, ash, and gross energy. Similarly, the percentage reduction in crude fibre.	7 d at 70 °C	In vitro	Reduced abundance in bacterial community in the animal gut.	[52]
Cassava residual pulp	*Rhizopus stolonifer*	Reduction of anti-nutrition factor called cyanide.	8 d at 30 °C	Poultry	Improved feed intake, feed conversion ratio, weight gain, and meat quality.	[53]
Soursop (*Annona muricata*)	*Aspergillus niger* and *Aspergillus flavus*	Decreased cellulose (86%), but increased sugars (335%). Crude protein levels also increased (48%).	144 h at 25–28 °C	In vitro	In vitro	[54]

Table 3. *Cont.*

Agro Byproducts	Microbes Used	After Biodegradation	Days of Biodegradation and Temp.	Experimental Animals	Effect on Experimental Animals	Reference
Palm kernel cake	*Lactobacillus salivarius*	Significant reduction of anti-nutritional factors. Also, reduction of unsaturated fatty acid.	7d at 35 °C	Boars and gilts pig	Improved weight gain feed conversion ratio and feed intake. No effect on fat deposit. No significant difference in internal organ characteristics compared with the control.	[53]
Pineapple peels	*Aspergillus flavus* *Aspergillus niger*	Improved protein content and digestibility. It also Decreased cellulose.	7 d at 25–28 °C	In vitro	In vitro	[54]
Sesame oil cake	*Bacillus subtilis*	Nutrient enrichment and reduction of anti-nutritional factors.	96 h at 37 °C	Swine	Greater concentrations of crude protein, ash, and total phosphorus (P) compared to the control. While the concentrations of neutral detergent fibre (NDF), hemicellulose, and phytate P in fermented inoculated feed declined	[55]
Wheat bran	*A. ficuum*	Production of enzymes inulinase.	2d at 40 °C	Broiler chicken	Improved availability of more soluble sugar for metabolism activities.	[56]
Wheat bran	*Trichoderma pseudokoningii*	Total phenolic content increased after fermentation. Production of xylanase and cellulase enzymes.	7 d at 25 °C	Broiler chicken	Improved broiler performance and enhanced antioxidative status, while also providing an optimal intestinal environment.	[57]
Sugarcane bagasse	*Kluyveromyces marxianus*	Production of enzymes laccase.	5 d at 40 °C	Cattle	Improved availability of more soluble sugar for metabolism activities.	[58]
Castor bean waste	*Paecilomyces variotii*	Production of xylanase enzymes. Reduction of phytate and tannin.	7 d at 45 °C	Cattle	Breakdown of hemicellulose and other complex carbohydrate rumen.	[59]
Soybean waste	*A. niger*	Production of protease enzymes.	48 h at 37 °C	Sheep	Production of rumen protein.	[60]
Jatropha curcas seed cake waste	*Pseudomonas aeruginosa*	Production of lipase enzymes.	7 d at 25 °C	Swine	Improved the utilization of fats. Reduced back fat thickness.	[61]

Ether extract plays a vital role in livestock nutrition by serving as a concentrated source of energy, providing essential fatty acids and fat-soluble vitamins, enhancing palatability, influencing rumen function, and facilitating the formulation of balanced diets for optimal animal performance and health [6]. The effect of SSF on the ether extract of fruit pomace can be variable and depends on the specific conditions of the fermentation process. While SSF may lead to the degradation of lipids and a decrease in ether extract content, it can also result in the formation of bioactive lipid-derived compounds and the utilization of lipid substrates by microorganisms for metabolic activities. There were differences in the ether extract profile due to the solid-state process. SSF of grape and apple pomace produced more acetate and less propionate with a concomitant greater acetate/propionate ratio. Similarly, ref. [52] reported a significant increase in ether extract content when rice bran, cassava residual pulp, sawdust, and palm oil fibre were subjected to SSF using *Penicillium* sp. for 7 days. Ref. [28] likewise observed a 5.63% increase in fat content when orange pomace was subjected to SSF using *Kluyveromyces marxianus*. The increase in ether extract content observed by these authors could be due to the degradation of lipids, biotransformation of lipid compounds, production of extracellular lipolytic enzymes, and modulation of fermentation conditions.

3.1.4. Effect on Hemi-Cellulose, Lignin, and Cell Walls

In livestock nutrition, understanding the composition and characteristics of hemicellulose, lignin, and cell walls in feed ingredients is crucial for formulating balanced diets that meet the nutritional requirements of animals while optimizing digestibility and feed efficiency. Strategies to enhance the utilization of fibrous feed components, such as fermentation with fibrolytic enzymes or microbial additives, can help improve the nutritional value of fibrous feeds for livestock production. SSF with both bacteria and fungi can effectively degrade lignocellulosic biomass components such as hemicellulose, lignin, and cellulose, resulting in the release of fermentable sugars and other metabolites that can be utilized in various biotechnological applications, including biofuel production, bioremediation, and the production of value-added chemicals [41]. Fungi, such as species of the genera *Aspergillus*, *Trichoderma*, and *Penicillium*, are known to produce a variety of hemicellulases, including xylanases, mannanases, and arabinofuranosidases, which can efficiently hydrolyse hemicellulose [39]. Bacterial species like *Bacillus*, *Lactobacillus*, and *Streptomyces* also produce hemicellulases that can contribute to hemicellulose degradation [38]. This was corroborated by the study of [54] on pineapple and soursop pomace using *Aspergillus niger* and *Aspergillus flavus* in a solid-state fermentation process. In this research, a decrease between 69 and 86% in cellulose and an increase of 219 to 335% in sugars after 144 h of fermentation was observed. This is because the fungi can produce enzymes that degrade cellulose as they grow on the substrate, thereby degrading polysaccharides in the starch to soluble sugars within the period of fermentation.

3.1.5. Effects on Anti-Nutritional Factors

Anti-nutritional factors (ANFs) are compounds present in feeds that can interfere with the digestion, absorption, or utilization of nutrients by animals, thereby reducing the nutritional value of the feed. Fruit pomace and agro-allied byproducts can contain various ANFs, which may differ depending on the specific type of fruit or agro-byproduct. Some common ANFs found in these materials include:

(i) Tannins: Tannins are polyphenolic compounds found in various fruit pomace and agro byproducts. This includes pomace from grapes, cranberries, strawberries, blueberries, apples, apricots, and barley. They bind to proteins and other nutrients, making them less available for digestion and absorption by animals [41].

(ii) Phytates: Phytates, or phytic acid, are present in grains and oilseeds, which may be components of agro-allied byproducts. This includes olive pomace, soya bean and maize byproducts. Phytates chelate with minerals such as calcium, magnesium, zinc, and iron, reducing their bioavailability to animals [49].

(iii) Oxalates: Certain fruits and byproducts may contain oxalates, which can form insoluble complexes with calcium, leading to the formation of calcium oxalate crystals, and reducing calcium availability. Such fruit pomace includes citrus, apple, strawberry, and pineapple [62].

(iv) Glycosides: Some fruits and byproducts may contain glycosides, which can release toxic substances upon hydrolysis, affecting animal health and performance. Byproducts from tuber crops, soursop, and orange pomace have high levels of glycosides [63].

(v) Alkaloids: Alkaloids are nitrogen-containing compounds found in some plants. They can have toxic effects on animals, affecting various physiological processes. Legume byproducts have a high level of these anti-nutritional factors [55].

(vi) Saponins: Saponins are compounds found in various plant materials, including certain fruits and byproducts. They can disrupt cell membranes in the gut, affecting nutrient absorption and causing gastrointestinal disturbances [6].

(vii) Cyanogenic glycosides: Some fruits and agro byproducts contain cyanogenic glycosides, which release cyanide upon hydrolysis, posing a risk of toxicity to animals if consumed in large quantities. Prominent are cassava peel and other cassava byproducts [52].

Subjecting fruit pomace and agro-allied byproducts to SSF would help to reduce the levels of ANFs in feeds and improve their nutritional value for livestock. SSF is an effective strategy for lowering anti-nutritional factors in agricultural byproducts and improving their nutritional quality for livestock feeds. The efficacy of SSF in reducing specific ANFs may vary depending on factors such as the type of substrate, microorganisms used, fermentation conditions, and duration of fermentation. In a study conducted by [64], it was reported that using *Aspergillus niger* ATCC 52172 on olive oil pomace in SSF resulted in a reduction in the levels of tannin concentration. This is because *A. niger* can degrade tannins enzymatically during fermentation, thereby lowering their concentration in the feed. In a more recent study, ref. [65] reported that SSF with fungi (*Aspergillus* spp. and *Rhizopus* spp.), bacteria (*Bacillus subtilis* and lactic acid bacteria (LAB) spp.) and yeast (*Saccharomyces cerevisiae*) significantly reduce the level of tannins in some fruit pomace and agricultural byproducts. In another study, ref. [34] reported that using *Rhizopus stolonifera* under a solid-state fermentation on cassava peels significantly reduced the anti-nutrition factor in cassava byproducts called cyanide, thereby making it fit for feeding pigs. During this process, *Rhizopus stolonifera* produces cyanide-degrading enzymes, such as cyanide hydratase and cyanide dihydratase, which convert cyanide into less toxic forms, such as thiocyanate. Therefore, it can be concluded that SSF through fungi and bacterial organisms can enhance the nutritional value of fruit pomace and agricultural byproducts by reducing anti-nutritional factors, thereby making the products beneficial to livestock. The effect of solid-state fermentation on the antioxidant composition of some fruit pomace is shown in Table 4.

Table 4. Effects of solid-state fermentation on the antioxidative composition of some fruit pomace.

Fruit Pomace	Organism/ Microbes	After Biodegradation	Levels	Experimental Animal	Effects on Experimental Animals	Reference
Citrus	*Lactobacillus plantarum* P10, M14	Converts the conjugated phenolics into free phenolics that are released and owing to this, the antioxidant activity of citrus pomace is enhanced.		In vitro	Increases digestibility, feed intake, and reduces methane emission.	[42]

Table 4. *Cont.*

Fruit Pomace	Organism/ Microbes	After Biodegradation	Levels	Experimental Animal	Effects on Experimental Animals	Reference
Cocoa meal	*Penicillium roqueforti*					
Grape	*Rhizopus oryzae*	Increases the content of 11 individual phenolic compounds (from 1.1 to 2.5-fold).	12 d at 28 °C	Sheep	Animals: Increases antioxidant defence system response, average daily gain, growth of facultative probiotic bacteria, and LAB; reduces oxidative stress and pathogen. Meat: Increases omega-3 fatty acid content. Reduces n-6/n-3 ratio, and meat quality.	[41]
Olive pomace	*Kluyveromyces marxianus* NRRL Y-8281 yeast	A sharp decrease in tannin content by 96.75% with 2.8 times increase in gallic acid concentration.			Increases feed conversion ratio, relative average daily feed intake, leukocyte count, and carcass composition.	[49]
Apple	*Aspergillus niger*	Produces a balanced profile of enzymes (cellulase, tannase, and pectinase)	72 h at 30 °C		In vitro	[62]
Apple	*Aspergillus oryzae*	Increases the antioxidant activity of the extracts, reaching maximum values of 109.2 ± 0.5 mmol of Trolox equivalents/100 g of grape pomace. Promotes the growth of Lactobacillus casei cultures.	72 h at 30 °C		In vitro	[62]
Apple	*Actinomucor elegans*	Increases in carotenoids and phenolic antioxidant productivity. Total phenolics increase significantly (27%) by day 4				
Apple	*P. chrysosporium*	Increases in carotenoids and phenolic antioxidant productivity and β-glucosidase.	10 d at 37 ± 1 °C	In vitro	In vitro	[63]

4. Impact of Solid-State Fermented Fruit Pomace and Agricultural Byproducts on Animal Performance and Health

One of our greatest problems in the future decades will be to feed the globe sustainably. Globally, consumption and demand for animal products have progressively increased and are expected to increase by 50–70% by 2050 [66,67]. This is especially important for developing nations, where recent shocks in food prices have brought to light the challenges of feeding the undernourished, and sustained price increases in food are expected [68]. Therefore, rearing livestock is deemed of utmost significance in promoting food security as they provide nutrients, stable income, and other benefits [69]. Nevertheless, one of the foremost obstacles to increasing livestock production is high feed costs, driven by increased global feed prices and competition for conventional feed ingredients between humans and animals [70,71]. Hence, exploring alternative feed ingredients for livestock production using various fruit pomaces and agricultural byproducts has been greatly sought. Solid-state fermentation (SSF) has been recognized for its multifaceted benefits in animal nutrition, encompassing the production of enzymes, bioactive compounds, organic acids, vitamins, feed additives, bio-transformed products, as well as biological degradation and detoxification of fruit pomace and agricultural byproducts [72]. These contributions have significantly influenced the nutritional composition of feed, animal performance, hemobiochemical status, gut morphology, gut microbiota, carcass attributes, rumen fermentation, and the reduction of enteric methane emissions in animals and poultry birds through SSF. Hereafter, we delineate some of the impacts of SSF on fruit pomace and agricultural byproducts in livestock production.

4.1. Impact on Enteric Gut and Health

Microbial communities of livestock and poultry gut play a significant role in maintaining their gut health. Solid-state fermentation improves digestibility and nutrient availability of feed ingredients, leading to better absorption of nutrients in the small intestine. This improved nutrient absorption can stimulate the growth of intestinal villi, increasing their height. Taller villi provide a larger surface area for nutrient absorption, enhancing the overall efficiency of the digestive process [38]. In addition, some fermentation byproducts, such as short-chain fatty acids (SCFAs), produced during solid-state fermentation can promote the development and maintenance of a healthy intestinal barrier. Short-chain fatty acids (SCFAs) have been demonstrated to stimulate mucin and tight junction protein production, reinforcing the integrity of the gut barrier. This reinforcement can mitigate the risk of intestinal inflammation and enhance overall gut health [37]. Through solid-state fermentation, beneficial microorganisms are introduced into the gastrointestinal tract, affecting the composition and diversity of the gut microbiota. A balanced and diverse gut microbiota is crucial for preserving gut health and functionality. Fermented feed ingredients can stimulate the growth of beneficial bacteria while suppressing harmful pathogens, fostering a more favourable microbial community in the gut [42]. Additionally, fermentation of feed ingredients can yield organic acids like lactic and acetic acid, which can reduce the gastrointestinal tract's pH, creating an environment conducive to beneficial bacteria growth while inhibiting pathogenic bacteria proliferation. In summary, solid-state fermented ingredients possess the potential to enhance gut morphology in livestock by promoting a healthier intestinal epithelium, bolstering gut barrier function, modulating gut microbiota composition, and supporting immune function.

4.2. Effects on Animal Overall Performance

Feeding solid-state fermented ingredients to livestock has been suggested by many researchers to have a positive effect on production efficiency and general performance while also promoting sustainable and environmentally friendly livestock and poultry production practices. Nevertheless, the impacts may vary depending on factors such as the type of feed ingredients fermented, the fermentation process used, and the species and management practices of the livestock. For example, ref. [73] observed that feeding solid-state fermented wheat bran to broiler chicken significantly increased average weight gain and feed conversion efficiency. This is because solid-state fermentation enhances the digestibility of feed ingredients by breaking down complex carbohydrates, fibres, and anti-nutritional factors. This improvement in digestibility allows for better nutrient absorption in the gut, leading to improved feed efficiency and overall performance.

In a similar vein, ref. [74] documented enhancements in average daily gain, gain: feed ratio, and overall performance of weaner and grower pigs when fed solid-state fermented ingredients. Likewise, ref. [75] noted that solid-state fermented apple pomace improved the profitability index of Landrace and York swine breeds during the growing phase. The impact of feeding solid-state fermented ingredients was investigated by [6,76,77]. Ref. [77] observed that solid-state fermentation of grape pomace with white-rot fungi improved rumen fermentation, dry matter, and fibre digestibility, consequently enhancing volatile fatty acid and ammonia-nitrogen concentration in the rumen, thus contributing to improved microbial crude protein synthesis and metabolizable energy by ruminants. Similarly, ref. [6] observed significant improvements in performance, nutrient digestibility, and nitrogen utilization of West Africa Dwarf goats when fed water hyacinth fermented with *Pleurotus sajor caju* via solid-state fermentation. Likewise, ref. [76] reported enhanced nutrient digestibility and reduced enteric methane emissions in crossbred cattle fed a wheat straw-based diet supplemented with solid-state fermented groundnut straw biomass.

4.3. Effects on Blood Parameters

The blood profile serves as a critical indicator in livestock production, offering valuable insights into the health, nutritional status, productivity, food safety, and overall management of animals. Ref. [78] conducted an experiment with weaner pigs, noting a significant increase in albumin and superoxide dismutase levels by 8.98 g/L and 2.9 U/mL, respectively, while concentrations of aspartate aminotransferase and malondialdehyde decreased by 23.59 U/L and 2.33 nmol/mL in the solid-state fermented apple pomace group. In poultry, the incorporation of fermented dried black chokeberry and black currant pomace positively influenced the immune system of laying hens, evidenced by changes in white blood cell smear and higher spleen percentage [79]. Similarly, ref. [80] observed significantly improved antibody titres against Newcastle, Influenza, and IDV with incremental levels of fermented, dried apple pomace in broiler chickens. In ruminants, ref. [81] reported increased plasma ethanol, lactate, β-hydroxybutyrate, and lipid components, along with decreased glucose levels in Suffolk ewes fed fermented apple pomace.

The effects of fermented fruit pomace and agro-industrial byproducts on blood parameters may vary depending on the specific characteristics of the fruit, fermentation process, and animal species. Conducting controlled studies and monitoring blood parameters in response to fermented agricultural byproducts and fruit pomace supplementation can provide valuable insights into its impact on livestock health and production.

4.4. Effect on Quality of Meat and Milk from Livestock

Meat and milk production in livestock are essential for meeting global food demand, promoting economic development, alleviating poverty, and ensuring the nutritional well-being of populations worldwide. Hence, anything leading to their high quantity and quality should be considered. Feeding fermented apple pomace to sheep did not affect the meat's lightness and redness, but more meat's yellowness was noticed with increased storage time. The authors also observed no impacts on the pH, water-holding capacity (WHC), drip loss (DL), and meat shear force. However, lipid oxidation in stored meat was lower than that in the control group.

Similarly, ref. [82] found no discernible differences in carcass characteristics, tenderness, adipose and lean colour values, and chemical composition in steers fed fermented mulberry fruit pomace compared to those in the control group. However, the fermented mulberry groups exhibited lower levels of intramuscular fat. In poultry production, ref. [79] noted paler yolk colour and slightly diminished shell quality in laying birds that were fed diets containing fermented raspberry and black currant fruit pomace. Conversely, ref. [83] observed enhanced slaughter efficiency, reduced drip loss in leg muscles, and decreased crude fat levels in breast muscles of broilers consuming fermented cherry pomace. In dairy production, ref. [84] found that incorporating 20 g/kg DM of solid-state fermented Emblica officinalis fruit pomace (Indian gooseberry) into the diet of buffaloes for 120 days improved milk yield, production efficiency, milk protein, solid-not-fat content, and reduced somatic cell counts in milk. Similarly, ref. [85] reported increased milk production, protein, and fat content in ewes fed fermented grape marc pomace at 100 g/day for 120 days, while fermented tomato pomace supplementation resulted in decreased milk yield in the same experiment. It is important to note that the effects of fermented fruit pomace and agricultural waste products on meat and milk quality can vary based on numerous factors, including the specific of fruit used, the fermentation process, the inclusion level in the diet, and the animal species and breed.

4.5. Effects on Greenhouse Gas Emissions

Methane emissions from livestock, primarily ruminants, significantly contribute to greenhouse gas emissions globally. Ruminant animals like cows, sheep, and goats produce methane as a byproduct of their digestive process, known as enteric fermentation. According to various estimates, ruminants contribute approximately 25% to 30% of total methane emissions globally [86]. This has been one of the significant causes of climate change, adversely affecting our ecosystems. Therefore, it is imperative to consider their effects on methane emissions.

Ref. [87] noticed that supplementation of 500 g kg^{-1} dosage of fermented pomegranate pomace in a short-term in vitro experiment using the Hohenheim Gas Test significantly lowered methane formation by about 28% without impairing digestibility. In an in vivo experiment with Buffaloes, ref. [84] reported that feeding 20 g/kg DM of fermented Indian gooseberry pomace to Buffalo decreases methane production and intensity without impacting buffaloes' health and milk production profiles. Similarly, ref. [88] reported a significant decrease in methane emission when fermented apple pomace was fed to dairy cows. Based on the facts above, solid-state fermented feed ingredients can be a valuable, sustainable, and environmentally friendly dietary component for livestock production.

5. Conclusions and Future Direction

Solid-state fermentation in various biotechnological processes using fruit pomaces and agro-industrial byproducts as sources of nutrients and biologically active substances in livestock diets could enhance efficient, sustainable, and environmentally friendly production systems. As discussed in this review paper, solid-state fermentation adds value to agricultural wastes and fruit pomace, making them useful for ever-demanding livestock feeds. This would mitigate over-dependence on traditional feed ingredients for livestock. Because fruit pomace and agro-industrial byproducts have no direct food value for human beings, modifying them via solid-state fermentation will help contribute to global food security. This review has shown that livestock fed SSF diets had an improved growth performance, gut health status, hematobiochemical profile, nutritional status, and meat and milk quality of livestock. It also shows that supplementation in livestock diets can help reduce greenhouse gas contribution from livestock, especially ruminants. However, research is needed to establish the cost implications of using various organisms, and commercialization, and the toxicology impact of fruit pomace and agro-allied byproducts for animal use, especially in commercial livestock farms. Likewise, optimum usage levels of various microbes in solid-state fermentation for various fruit pomace and agro-industrial byproducts for different classes and breeds of animals need to be established.

Author Contributions: Conceptualization, O.O.I.; Methodology, O.O.I.; Validation, O.O.I. and O.F.A.; Investigation, O.O.I.; Resources, O.O.I. and C.T.M.; Data curation, O.F.A. and O.O.I.; Writing—original draft preparation, O.O.I.; Writing—review and editing, O.O.I. and O.F.A.; Visualization, O.F.A. and

O.O.I.; Supervision, C.T.M.; Project administration, O.O.I. and C.T.M.; Funding acquisition, C.T.M. All authors have read and agreed to the published version of the manuscript.

Funding: Research and Innovation Office, University of Fort Hare, South Africa.

Acknowledgments: The authors acknowledged the members of our research group and the Research and Innovation Office, University of Fort Hare, South Africa.

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

References

1. OECD-FAO. *Organization for Economic Co-operation and Development/Food and Agriculture Organization of the United Nations Agricultural Outlook 2021*; OECD Publishing: Paris, France, 2021.
2. Kim, S.W.; Less, J.F.; Wang, L.; Yan, T.; Kiron, V.; Kaushik, S.J.; Lei, X.G. Lei Meeting global feed protein demand: Challenge, opportunity, and strategy. *Annu. Rev. Anim. Biosci.* **2019**, *7*, 221–243. [CrossRef] [PubMed]
3. Borkar, V.D.; Motghare, A.B.; Bawaskar, S.S.; Wankhade, B.R. Studies on feeding of Azolla meal on growth performance of Ka-daknath poultry. *Int. J. Fauna Biol. Stud.* **2021**, *8*, 105–108.
4. Akinmoladun, O.F.; Sabi, R.S.; Adedayo, O.T. Toxicological evaluation of graded levels of freshly harvested bamboo *(Bambusa arundinacea*) and Tridax (*Tridax procumbens*) leaves on blood chemistry of rabbits. *Niger. J. Anim. Prod.* **2018**, *45*, 183–197.
5. Alhotan, R.A. Commercial poultry feed formulation: Current status, challenges, and future expectations. *World's Poult. Sci. J.* **2021**, *77*, 279–299. [CrossRef]
6. Mako, A.A.; Ikusika, O.O. Pleurotus sajor-caju biodegraded water hyacinth (*Eichhornia crassipes*) was utilized in solid-state fermentation by West African Dwarf goats in the humid tropics. *J. Trop. Agric.* **2021**, *97*, 1–13.
7. FAO. Food and Agriculture Data. 2021. Available online: http://www.fao.org/faostat/en/ (accessed on 8 February 2021).
8. Lou, S.-N.; Lin, Y.-S.; Hsu, Y.-S.; Chiu, E.-M.; Ho, C.-T. Soluble and insoluble phenolic compounds and antioxidant activity of immature calamondin affected by solvents and heat treatment. *Food Chem.* **2014**, *161*, 246–253. [CrossRef] [PubMed]
9. Pappas, A.; Tsiplakou, E.; Papadomichelakis, G.; Mitsiopoulou, C.; Sotirakoglou, K.; Mpekelis, V.; Haroutounian, S.; Fegeros, K.; Zervas, G. Effects of olive pulp addition to broiler diets on performance, selected biochemical parameters and antioxidant enzymes. *J. Hell. Vet. Med. Soc.* **2019**, *70*, 1687–1696. [CrossRef]
10. Pinotti, L.; Ferrari, L.; Fumagalli, F.; Luciano, A.; Manoni, M.; Mazzoleni, S.; Govoni, C.; Rulli, M.; Lin, P.; Bee, G.; et al. Review: Pig-based bioconversion: The use of former food products to keep nutrients in the food chain. *Animal* **2023**, *17*, 100918. [CrossRef] [PubMed]
11. Mnisi, C.M.; Mhlongo, G.; Manyeula, F. Fruit pomaces as functional ingredients in poultry nutrition: A review. *Front. Anim. Sci.* **2022**, *3*, 883988. [CrossRef]
12. Zannini, D.; Poggetto, G.D.; Malinconico, M.; Santagata, G.; Immirzi, B. Citrus Pomace Biomass as a Source of Pectin and Lignocellulose Fibers: From Waste to Upgraded Biocomposites for Mulching Applications. *Polymers* **2021**, *13*, 1280. [CrossRef] [PubMed]
13. Munekata, P.E.S.; Domínguez, R.; Pateiro, M.; Nawaz, A.; Hano, C.; Walayat, N.; Lorenzo, J.M. Strategies to Increase the Value of Pomaces with Fermentation. *Fermentation* **2021**, *7*, 299. [CrossRef]
14. Sönmüş, A.; Aslan, M.H. Comparative Advantage of Turkish Olive Oil in Global Markets: An Empirical Analysis. *Turk. J. Agric.—Food Sci. Technol.* **2021**, *9*, 1114–1119. [CrossRef]
15. Assefa, A.D.; Hur, O.-S.; Ro, N.-Y.; Lee, J.-E.; Hwang, A.-J.; Kim, B.-S.; Rhee, J.-H.; Yi, J.-Y.; Kim, J.-H.; Lee, H.-S.; et al. Fruit Morphology, Citrulline, and Arginine Levels in Diverse Watermelon (*Citrullus lanatus*) Germplasm Collections. *Plants* **2020**, *9*, 1054. [CrossRef] [PubMed]
16. Sial, T.A.; Khan, M.N.; Lan, Z.; Kumbhar, F.; Ying, Z.; Zhang, J.; Sun, D.; Li, X. Contrasting effects of banana peels waste and its biochar on greenhouse gas emissions and soil biochemical properties. *Process Saf. Environ. Prot.* **2019**, *122*, 366–377. [CrossRef]
17. Pienaar, L. *The Economic Contribution of South Africa's Pomegranate Industry*; AgriProbe: Elsenburg, UK, 2021.
18. Rico, X.; Gullón, B.; Alonso, J.L.; Yáñez, R. Recovery of high value-added compounds from pineapple, melon, watermelon and pumpkin processing by-products: An overview. *Food Res. Int.* **2020**, *132*, 109086. [CrossRef] [PubMed]
19. FAOSTAT. Food and Agriculture Organization of the United Nations. 2019. Available online: http://faostat.fao.org (accessed on 10 February 2024).
20. Cubero-Cardoso, J.; Trujillo-Reyes, Á.; Serrano, A.; Rodríguez-Gutiérrez, G.; Borja, R.; Fermoso, F.G. High-Value-Added Compound Recovery with High-Temperature Hydrothermal Treatment and Steam Explosion, and Subsequent Biomethanization of Residual Strawberry Extrudate. *Foods* **2020**, *9*, 1082. [CrossRef] [PubMed]
21. Brenes, A.; Viveros, A.; Chamorro, S.; Arija, I. Use of polyphenol rich grapes by-products in monogastric nutrition. A review. *Anim. Feed Sci. Technol.* **2016**, *211*, e17. [CrossRef]
22. Nguyen, M.-V.; Lee, B.-K. Removal of Dimethyl Sulfide from Aqueous Solution Using Cost-Effective Modified Chicken Manure Biochar Produced from Slow Pyrolysis. *Sustainability* **2015**, *7*, 15057–15072. [CrossRef]
23. Wu, C.; Zhang, F.; Li, L.; Jiang, Z.; Ni, H.; Xiao, A. Novel optimization strategy for tannase production through a modified solid-state fermentation system. *Biotechnol. Biofuels* **2018**, *11*, 92. [CrossRef] [PubMed]

24. Costa, J.A.; Treichel, H.; Kumar, V.; Pandey, A. Advances in solid-state fermentation. In *Current Developments in Biotechnology and Bioengineering*; Elsevier: Amsterdam, The Netherlands, 2018; pp. 1–17.
25. Madrera, R.R.; Bedriñana, R.P.; Valles, B.S. Production and characterization of aroma compounds from apple pomace by solid-state fermentation with selected yeasts. *LWT Food Sci. Technol.* **2015**, *64*, 1342–1353. [CrossRef]
26. Calvo-Lerma, J.; Asensio-Grau, A.; García-Hernández, J.; Heredia, A.; Andrés, A. Exploring the Impact of Solid-State Fermentation on Macronutrient Profile and Digestibility in Chia (*Salvia hispanica*) and Sesame (*Sesamum Indicum*) Seeds. *Foods* **2022**, *11*, 410. [CrossRef] [PubMed]
27. Okoronkwo, N.C.; Okoyeuzu, C.F.; Eze, C.R.; Mbaeyi-Nwaoha, I.E.; Agbata, C.P. Quality Evaluation of Complementary Food Produced by Solid-State Fermentation of Fonio, Soybean and Orange-Fleshed Sweet Potato Blends. *Fermentation* **2023**, *9*, 250. [CrossRef]
28. Mahmoud, A.E.; Omer, H.A.A.; Mohammed, A.T.; Ali, M.M. Enhancement of Chemical Composition and Nutritive Value of Some Fruits Pomace by Solid State Fermentation. *Egypt. J. Chem.* **2020**, *63*, 3713–3720. [CrossRef]
29. Ibarruri, J.; Goiri, I.; Cebrián, M.; García-Rodríguez, A. Solid State Fermentation as a Tool to Stabilize and Improve Nutritive Value of Fruit and Vegetable Discards: Effect on Nutritional Composition, In Vitro Ruminal Fermentation and Organic Matter Digestibility. *Animals* **2021**, *11*, 1653. [CrossRef] [PubMed]
30. Imelda, J.; Paulraj, R.; Bhatnagar, D. Effect of solid-state fermentation on nutrient composition of selected feed ingredients. *Indian J. Fish.* **2008**, *55*, 327–332.
31. Lateef, A.; Oloke, J.K.; Gueguim Kana, E.B.; Oyeniyi, S.O.; Onifade, O.R.; Oyeleye, A.O.; Oladosu, O.C.; Oyelami, A.O. Improving the quality of agro-wastes by solid-state fermentation: Enhanced antioxidant activities and nutritional qualities. *World J. Microbiol. Biotechnol.* **2008**, *24*, 2369–2374. [CrossRef]
32. Aruna, T. Production of value-added product from pineapple peels using solid state fermentation. *Innov. Food Sci. Emerg. Technol.* **2019**, *57*, 102193. [CrossRef]
33. Terefe, Z.K.; Omwamba, M.N.; Nduko, J.M. Effect of solid state fermentation on proximate composition, antinutritional factors and in vitro protein digestibility of maize flour. *Food Sci. Nutr.* **2021**, *9*, 6343–6352. [CrossRef] [PubMed]
34. Morales, E.M.; Zajul, M.; Goldman, M.; Zorn, H.; Angelis, D.F. Effects of Solid-State Fermentation and the Potential Use of Cassava By-products as Fermented Food. *Waste Biomass Valorization* **2018**, *11*, 1289–1299. [CrossRef]
35. Filipe, D.; Vieira, L.; Ferreira, M.; Oliva-Teles, A.; Salgado, J.; Belo, I.; Peres, H. Enrichment of a Plant Feedstuff Mixture's Nutritional Value through Solid-State Fermentation. *Animals* **2023**, *13*, 2883. [CrossRef]
36. Olukomaiya, O.O.; Adiamo, O.Q.; Fernando, W.C.; Mereddy, R.; Li, X.; Sultanbawa, Y. Effect of solid-state fermentation on proximate composition, anti-nutritional factor, microbiological and functional properties of lupin flour. *Food Chem.* **2020**, *315*, 126238. [CrossRef] [PubMed]
37. Munishamanna, K.; Suresha, K.; Veena, R.; Subramanya, S. Solid State Fermentation of Mango Peel and Mango Seed Waste by Different Yeasts and Bacteria for Nutritional Improvement. *Int. J. Food Ferment. Technol.* **2018**, *7*, 111. [CrossRef]
38. Gungor, E.; Altop, A.; Erener, G.; Coskun, I. Effect of raw and fermented pomegranate pomace on performance, antioxidant activity, intestinal microbiota and morphology in broiler chickens. *Arch. Anim. Nutr.* **2021**, *75*, 137–152. [CrossRef] [PubMed]
39. Ali, M.M.; Nayel, U.A.; Abdel-Rahman, K.M. Use of tomato pomace and/or orange pulp supplemented corn silage for animal feeding. *Menoufia J. Anim. Poult. Fish Prod.* **2015**, *40*, 643–654. [CrossRef]
40. Cho, S.; Cho, J.H.; Hwang, O.H.; Yang, S.H.; Park, K.H.; Choi, D.Y.; Yoo, Y.H.; Kim, I.H. Effects of Fermented Diets Including Grape and Apple Pomace on Amino Acid Digestibility, Nitrogen Balance and Volatile Fatty Acid (VFA) Emission in Finishing Pigs. *J. Anim. Vet. Adv.* **2012**, *11*, 3444–3451. [CrossRef]
41. Šelo, G.; Planinić, M.; Tišma, M.; Martinović, J.; Perković, G.; Bucić-Kojić, A. Bioconversion of Grape Pomace with *Rhizopus oryzae* under Solid-State Conditions: Changes in the Chemical Composition and Profile of Phenolic Compounds. *Microorganisms* **2023**, *11*, 956. [CrossRef] [PubMed]
42. Hu, X.; Zeng, J.; Shen, F.; Xia, X.; Tian, X.; Wu, Z. Citrus pomace fermentation with autochthonous probiotics improves its nutrient composition and antioxidant activities. *Food Sci. Technol.* **2022**, *157*, 113076. [CrossRef]
43. Kumanda, C.; Mlambo, V.; Mnisi, C.M. From Landfills to the Dinner Table: Red Grape Pomace Waste as a Nutraceutical for Broiler Chickens. *Sustainability* **2019**, *11*, 1931. [CrossRef]
44. Orayaga, K.T.; Oluremi, O.I.A.; Tuleun, C.D.; Carew, S.N. Utilization of Composite Mango (*Mangifera indica*) Fruit Reject Meal in Starter Broiler Chicks Feeding. *J. Exp. Agric. Int.* **2017**, *17*, 1–9. [CrossRef]
45. Şengul, A.Y.; Şengul, T.; Çelik, Ş.; Şengül, G.; Daş, A.; İnci, H.; Bengu, A.Ş. The effect of dried white mulberry (*Morus alba*) pulp supplementation in diets of laying quail. *Rev. MVZ Cordoba* **2021**, *26*, e1940. [CrossRef]
46. Mizael, W.C.F.; Costa, R.G.; Cruz, G.R.B.; de Carvalho, F.F.R.; Ribeiro, N.L.; Lima, A.; Domínguez, R.; Lorenzo, J.M. Effect of the Use of Tomato Pomace on Feeding and Performance of Lactating Goats. *Animals* **2020**, *10*, 1574. [CrossRef] [PubMed]
47. Ibrahim, D.; Moustafa, A.; Shahin, S.E.; Sherief, W.R.I.A.; Abdallah, K.; Farag, M.F.M.; Nassan, M.A.; Ibrahim, S.M. Impact of Fermented or Enzymatically Fermented Dried Olive Pomace on Growth, Expression of Digestive Enzyme and Glucose Transporter Genes, Oxidative Stability of Frozen Meat, and Economic Efficiency of Broiler Chickens. *Front. Vet. Sci.* **2021**, *8*, 644325. [CrossRef] [PubMed]

48. Dedousi, A.; Kritsa, M.-Z.; Stojčić, M.; Sfetsas, T.; Sentas, A.; Sossidou, E. Production Performance, Egg Quality Characteristics, Fatty Acid Profile and Health Lipid Indices of Produced Eggs, Blood Biochemical Parameters and Welfare Indicators of Laying Hens Fed Dried Olive Pulp. *Sustainability* **2022**, *14*, 3157. [CrossRef]
49. Fathy, S.A.; Rashad, M.M.; Ezz, M.K.; Mohammed, A.T.; Mahmoud, A.E. Enhanced tannase production by *Kluyveromyces marxianus* NRRL Y-8281 under solid-state fermentation of olive oil cake. *Res. J. Pharm. Biol. Chem. Sci.* **2017**, *8*, 1698–1708.
50. Islam, R.; Hassan, Y.I.; Das, Q.; Lepp, D.; Hernandez, M.; Godfrey, D.V.; Orban, S.; Ross, K.; Delaquis, P.; Diarra, M.S. Dietary organic cranberry pomace influences multiple blood biochemical parameters and cecal microbiota in pasture-raised broiler chickens. *J. Funct. Foods* **2020**, *72*, 104053. [CrossRef]
51. Pereira, A.A.; de Alcântara, R.S.; de Moura, A.S.; Júnior, D.N.G.; Vieira, G.M.N.; Almeida, J.R.d.S. Passion fruit waste in diets for quail in the laying phase. *Acta Sci. Anim. Sci.* **2020**, *42*, e48281. [CrossRef]
52. Omoikhoje, S.O.; Animashaun, R.A.; Edokpayi, M.I. Enhancement of the nutritive values of some agro-industrial waste products by solid state fermentation. *Niger. J. Anim. Prod.* **2014**, *41*, 81–85. [CrossRef]
53. Aladi, N.O.; Okpaliko, F.C.; Ikpamezie, L.; Omede, A.A.; Emenalom, O.O.; Okoli, I.C.; Okeudo, N.J. Solid-state fermentation improves the nutritive value of grated cassava roots and palm kernel cake mix for growing pigs. *Niger. J. Anim. Prod.* **2021**, *48*, 106–120. [CrossRef]
54. Egwim, D.; Evans, C. Production of Animal Feed Concentrates From Sour Sop and Pineapple Peels Using Solid State Fermentation. *J. Biol. Agric. Healthc.* **2014**, *4*, 22–29.
55. Shi, C.; Zhang, Y.; Lu, Z.; Wang, Y. Solid-state fermentation of corn-soybean meal mixed feed with *Bacillus subtilis* and *Enter-ococcus faecium* for degrading antinutritional factors and enhancing nutritional value. *J. Anim. Sci. Biotechnol.* **2017**, *8*, 50. [CrossRef] [PubMed]
56. Nambi, V.E.; Chandrasekar, V.; Karthikeyan, S. Value addition of grains using solid state fermentation. *Nutr. Food Sci. Int. J.* **2017**, *3*, 6. [CrossRef]
57. Canedo, M.S.; de Paula, F.G.; Da Silva, F.A.; Vendruscolo, F. Protein enrichment of brewery spent grain from *Rhizopus oli-gosporus* by solid-state fermentation. *Bioproc. Biosyst. Eng.* **2016**, *39*, 1105–1113. [CrossRef]
58. Dwivedi, M.; Yajnanarayana, V.K.; Kaur, M.; Sattur, A.P. Evaluation of anti nutritional factors in fungal fermented cereals. *Food Sci. Biotechnol.* **2015**, *24*, 2113–2116. [CrossRef]
59. Godoy, M.G.; Gutarra, M.L.; Maciel, F.M.; Felix, S.P.; Bevilaqua, J.V.; Machado, O.L.; Freire, D.M. Use of a low-cost methodology for biodetoxification of castor bean waste and lipase production. *Enzym. Microb. Technol.* **2009**, *44*, 317–322. [CrossRef]
60. Yafetto, L. Application of solid-state fermentation by microbial biotechnology for bioprocessing of agro-industrial wastes from 1970 to 2020: A review and bibliometric analysis. *Heliyon* **2022**, *8*, e09173. [CrossRef]
61. Gemar, G.; Soler, I.P.; Sanchez-Teba, E.M. Waste management: Valorization is the way. *Foods* **2021**, *10*, 2373. [CrossRef]
62. Meini, M.-R.; Cabezudo, I.; Galetto, C.S.; Romanini, D. Production of grape pomace extracts with enhanced antioxidant and prebiotic activities through solid-state fermentation by *Aspergillus niger* and *Aspergillus oryzae*. *Food Biosci.* **2021**, *42*, 101168. [CrossRef]
63. Ajila, C.M.; Gassara, F.; Brar, S.K.; Verma, M.; Tyagi, R.D.; Valéro, J.R. Polyphenolic Antioxidant Mobilization in Apple Pomace by Different Methods of Solid-State Fermentation and Evaluation of Its Antioxidant Activity. *Food Bioprocess Technol.* **2012**, *5*, 2697–2707. [CrossRef]
64. Altop, A. Effect of Solid-State Fermentation on Main Nutritional Components, Some Minerals, Condensed Tannin and Phenolic Compounds of Olive Leaves. *Turk. J. Agric.-Food Sci. Technol.* **2019**, *7*, 115–119. [CrossRef]
65. De Villa, R.; Roasa, J.; Mine, Y.; Tsao, R. Impact of solid-state fermentation on factors and mechanisms influencing the bioactive compounds of grains and processing by-products. *Crit. Rev. Food Sci. Nutr.* **2023**, *63*, 5388–5413. [CrossRef]
66. Ingram, J.S.I. A food systems approach to researching food security and its interactions with global environmental change. *Food Secur.* **2011**, *3*, 417–431. [CrossRef]
67. Alexandratos, N.; Bruinsma, J. *World Agriculture Towards 2030/2050: The 2012 Revision*; FAO: Rome, Italy, 2012.
68. Smith, J.; Sones, K.; Grace, D.; MacMillan, S.; Tarawali, S.; Herrero, M. Beyond milk, meat, and eggs: Role of livestock in food and nutrition security. *Anim. Front.* **2013**, *3*, 6–13. [CrossRef]
69. Jodlowski, M.; Winter-Nelson, A.; Baylis, K.; Goldsmith, P.D. Milk in the Data: Food Security Impacts from a Livestock Field Experiment in Zambia. *World Dev.* **2016**, *77*, 99–114. [CrossRef]
70. Mengesha, M. The Issue of Feed-Food Competition and Chicken Production for the Demands of Foods of Animal Origin. *Asian J. Poult. Sci.* **2012**, *6*, 31–43. [CrossRef]
71. Mtolo, M.; Ikusika, O.O.; Mpendulo, T.C.; Haruzivi, C. Consumers' perception of poultry meat from insect-fed chickens: University students focus study. *Cogent Food Agric.* **2022**, *8*, 2140471. [CrossRef]
72. Parmar, A.B.; Patel, V.R.; Usadadia, S.V.; Rathwa, S.D.; Prajapati, D.R. A solid-state fermentation, its role in animal nutrition: A review. *Int. J. Chem. Stud.* **2019**, *7*, 4626–4633.
73. Zhang, A.; Wei, M.; Yan, L.; Zhou, G.; Li, Y.; Wang, H.; Yang, Y.; Yin, W.; Guo, J.; Cai, X.; et al. Effects of feeding solid-state fermented wheat bran on growth performance and nutrient digestibility in broiler chickens. *Poult. Sci.* **2022**, *101*, 101402. [CrossRef]
74. Xu, B.; Li, Z.; Wang, C.; Fu, J.; Zhang, Y.; Wang, Y.; Lu, Z. Effects of fermented feed supplementation on pig growth performance: A meta-analysis. *Anim. Feed. Sci. Technol.* **2020**, *259*, 114315. [CrossRef]

75. Chamorro-Ramírez, F.H.; García-Macías, J.A.; Durán-Meléndez, L.A.; Peña-González, E.M.; González-Sánchez, J.F. Productivity of pigs fed with solid-state fermented apple pomace and an enzymatic complex. *Ecosistemas Recur. Agropecu.* **2017**, *4*, 453. [CrossRef]
76. Sherasia, P.; Pandya, P.; Parnerkar, S.; Prajapati, M.; Murty, S. Influence of Supplementing Solid State Fermented Biomass on Digestibility, Microbial Nitrogen Supply and Enteric Methane Emissions in Cattle. *Indian J. Anim. Nutr.* **2018**, *35*, 138. [CrossRef]
77. Abid, K.; Boudagga, S.; Abid, O.; Najar, T.; Jaouani, A. Bioconversion of grape pomace waste into suitable alternative feed for ruminants with *Pleurotus cornucopiae* and *Ganoderma resinaceum* via solid-state fermentation bioprocess. *Biomass-Convers. Biorefinery* **2023**, 1–10. [CrossRef]
78. Ao, W.; Cheng, M.; Chen, Y.; Sun, J.; Zhang, C.; Zhao, X.; Liu, M.; Zhou, B. Fermented Apple Pomace Improves Plasma Biochemical and Antioxidant Indicators and Fecal Microbiota of Weaned Pigs. *Agriculture* **2022**, *12*, 1603. [CrossRef]
79. Sosnówka-Czajka, E.; Skomorucha, I. Effect of supplementation with dried fruit pomace on the performance, egg quality, white blood cells, and lymphatic organs in laying hens. *Poult. Sci.* **2021**, *100*, 101278. [CrossRef]
80. Aghili, A.H.; Toghyani, M.; Tabeidian, S.A. Effect of incremental levels of apple pomace and multi enzyme on performance, immune response, gut development and blood biochemical parameters of broiler chickens. *Int. J. Recycl. Org. Waste Agric.* **2019**, *8*, 321–334. [CrossRef]
81. Islam, S.; Islam, M.; Matsuzaki, M. Effect of apple pomace silage on blood parameters in Suffolk ewe. *Bangladesh J. Anim. Sci.* **2018**, *47*, 51–60. [CrossRef]
82. Zhou, Z.; Zhou, B.; Ren, L.; Meng, Q. Effect of Ensiled Mulberry Leaves and Sun-Dried Mulberry Fruit Pomace on Finishing Steer Growth Performance, Blood Biochemical Parameters, and Carcass Characteristics. *PLoS ONE* **2014**, *9*, e85406. [CrossRef]
83. Sosnówka-Czajka, E.; Skomorucha, I.; Obremski, K.; Wojtacha, P. Performance and meat quality of broiler chickens fed with the addition of dried fruit pomace. *Poult. Sci.* **2023**, *102*, 102631. [CrossRef]
84. Singla, A.; Hundal, J.S.; Patra, A.K.; Wadhwa, M.; Nagarajappa, V.; Malhotra, P. Effect of dietary supplementation of *Emblica officinalis* fruit pomace on methane emission, ruminal fermentation, nutrient utilization, and milk production performance in buffaloes. *Environ. Sci. Pollut. Res.* **2021**, *28*, 18120–18133. [CrossRef]
85. Nudda, A.; Buffa, G.; Atzori, A.; Cappai, M.; Caboni, P.; Fais, G.; Pulina, G. Small amounts of agro-industrial byproducts in dairy ewes diets affects milk production traits and hematological parameters. *Anim. Feed. Sci. Technol.* **2019**, *251*, 76–85. [CrossRef]
86. Ikusika, O.O.; Mpendulo, C.T. Effects of dietary fossil shell flour supplementation on a basal diet, relative feed values, in vitro true digestibility, and rumen fermentation parameters of Dohne-Merino wethers. *J. Appl. Anim. Res.* **2022**, *50*, 629–634. [CrossRef]
87. Giller, K.; Bossut, L.; Eggerschwiler, L.; Terranova, M. In vitro ruminal fermentation, methane production and nutrient degradability as affected by fruit and vegetable pomaces in differing concentrations. *J. Anim. Physiol. Anim. Nutr.* **2022**, *106*, 957–967. [CrossRef]
88. Gadulrab, K.; Sidoruk, P.; Kozłowska, M.; Szumacher-Strabel, M.; Lechniak, D.; Kołodziejski, P.; Pytlewski, J.; Strzałkowska, N.; Horbańczuk, J.O.; Jóźwik, A.; et al. Effect of Feeding Dried Apple Pomace on Ruminal Fermentation, Methane Emission, and Biohydrogenation of Unsaturated Fatty Acids in Dairy Cows. *Agriculture* **2023**, *13*, 2032. [CrossRef]

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.