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Review

Solid-State Fermentation of Fruit Pomace and its Effects on Broiler Growth Performance, Meat Quality, and Gut Health: A Review

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Abstract: The food and beverage industry generates a significant amount of fruit waste, especially in the form of peels, seeds, and various components of fruit pomace. The mismanagement of fruit pomace, particularly when dumped in landfills, poses significant health and environmental risks. Therefore, it is crucial to redirect these byproducts to productive applications, such as broiler nutrition, where they have substantial potential to contribute to reducing feeding costs. The pomace is, however, often unsuitable as broiler feed ingredients due to their high crude fiber and tannin contents. In recent years, solid state fermentation (SSF) with bacteria, fungi, and yeast has been applied to valorize pomace through breaking down complex materials into simpler, more digestible compounds, enhancing the bioavailability of nutrients, and boosting the antioxidant activity. It is envisaged that the utilization of fruit pomace as broiler feed ingredients is expected to alleviate pressure on conventional feed ingredients, optimize broiler production systems, and promote both environmental and economic sustainability. This review aims to gather supporting evidence on the applicability and potential of SSF of fruit pomace, as well as the impact of the resulting fermented fruit pomace on broiler nutrition, focusing on growth performance metrics, meat quality attributes, and gut health.

Keywords: Broiler; fruit pomace; growth performance; solid state fermentation

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1. Introduction

The global human population is anticipated to reach 9.1 billion by 2050 [1], intensifying the demand for livestock production as a crucial food source for this growing population. In the poultry sector, the affordability and accessibility of poultry products exacerbate the current situation [2]. The industry predominantly relies heavily on conventional feed resources such as maize and soybean meal [3], which is economically and environmentally unsustainable [4,5]. Additionally, the increasing demand from both humans and livestock for these two products poses significant, untenable competition [6]. High feed costs, exceeding 70% of total production costs [7], further constrain sustainable poultry production. Interestingly, the development of sustainable alternatives to partially or completely replace maize and soybean meal is gaining attraction. Current attention is focusing on novel feed resources such as agro-waste by-products, fruit pomace, and insects [8–11].

Fruit pomace, a by-product of fruit processing, contributes to the significant food loss in the fruit and vegetable sector, which FAO estimates at 40–50% globally [12]. Large quantities of pomace are generated from juice extraction of cultivated fruits (apples, berries, citrus, grapes, guavas, strawberries, mangoes, pineapple) and wild fruits such as wild loquat (*Uapaca kirkiana*), baobab (*Adansonia digitata*), and wild berries. Utilizing fruit pomace as broiler feeds could address feeding costs while offering a long-term strategy to protect the environment, as they are typically disposed of in landfills, resulting in environmental concerns such as water, soil, and air pollution. However, fruit pomace are characterized by elevated levels of dietary fiber and condensed tannins, which impair feed digestibility and nutrient bioavailability, necessitating pre-processing before safe incorporation in poultry diets [13–15]. Therefore, inexpensive and efficient processing methods are needed to allow higher dietary inclusion levels. Recently, valorization of fruit pomace through SSF has been done to enhance pomace nutritional value [9,16,17]. The process uses various microorganisms, including fungi (*Aspergillus* spp, *Trichoderma* spp, and *Rhizopus* spp), yeasts (*Saccharomyces cerevisiae*, *Candida* spp), and bacteria (*Lactobacillus* spp and *Bacillus* spp), which break down complex substrates, enhancing nutrient availability and bioactive compounds in the fermented pomace [9,18–20].

Several studies have shown that the incorporation of SS fermented fruit pomace in broiler diets has a positive impact on broiler growth performance [21], meat quality [22], and gut morphology [23] as well as overall health [24] and these benefits could be attributed to the presence of phytochemicals. This review therefore seeks to provide supporting evidence regarding the applicability and effects of SSF of fruit pomace along with the effects fermented fruit pomace on broiler nutrition with emphasis on growth performance, meat quality, and overall health based on insights from recent scientific studies. The beneficial outcomes observed in feeding trials, along with inconsistencies or areas which need further research were also explored.

2. Methodology

Scientific articles used in this review were sourced from reputable scientific scholarly electronic databases (Figure 1) following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach. In addition to the scientific scholarly electronic databases, Google Search and Research Gate were also used to obtain relevant published articles. According to the PRISMA guidelines, a broad Boolean search string "fruit pomace" AND "broiler production" was used. In addition to the broad search string, a combination of multiple phrases such as "solid state fermentation", "nutrient" AND/OR "chemical composition", "dietary fiber", "feed intake", "digestibility", "broiler", "growth performance", "meat quality", "blood parameters", "intestinal morphology", and "broiler performance" were added to the broad string.

Only articles published in the English language were used, and only literature from 2000 to 2025 was considered for the review to ensure the relevance of findings and capture recent advancements in the field. All the gathered literature was screened for potential bias systematically, as shown in Figure 1. Articles that were not relevant to the topics under discussion, theses, books, duplicates, non-scientific reports, along with those having unclear methodology and results, were excluded from this review.

The inclusion criteria were strictly limited to core articles specific to SSF and fruit pomace, and core articles specific to broiler feeding trials with SS fermented fruit pomace. Articles on fermentation methods other than SSF, broiler feeding trials using unfermented fruit pomace, fermented fruit pomace for human nutrition, agro-industrial byproducts other than fruit pomace, and other applications unrelated to broiler nutrition were excluded. The acquired literature was analyzed, described, summarized, and critiqued. The review included a total of 107 research articles. The core of the review consisted of 51 articles specific to SSF and fruit pomace, and 19 articles specific to broiler feeding trials with SS fermented fruit pomace.

3. Fruit Pomace

Fruit pomace is the residual solid material left after extracting juice, oil, or other valuable components from fruits. Fruit processing into value-added market products such as juices, wines, and jams generates pomace in the form of peels, stalks, stems, or seeds. Fruit pomace yield per fruit and nutritional composition are variable, depending on the fruit type, as shown in Table 1. In 2020, global production of fruit pomace from processing apples, grapes, watermelons, bananas, citrus fruits, avocados, mangoes, pineapples, and pomegranates was estimated at 900 million metric tons [25].

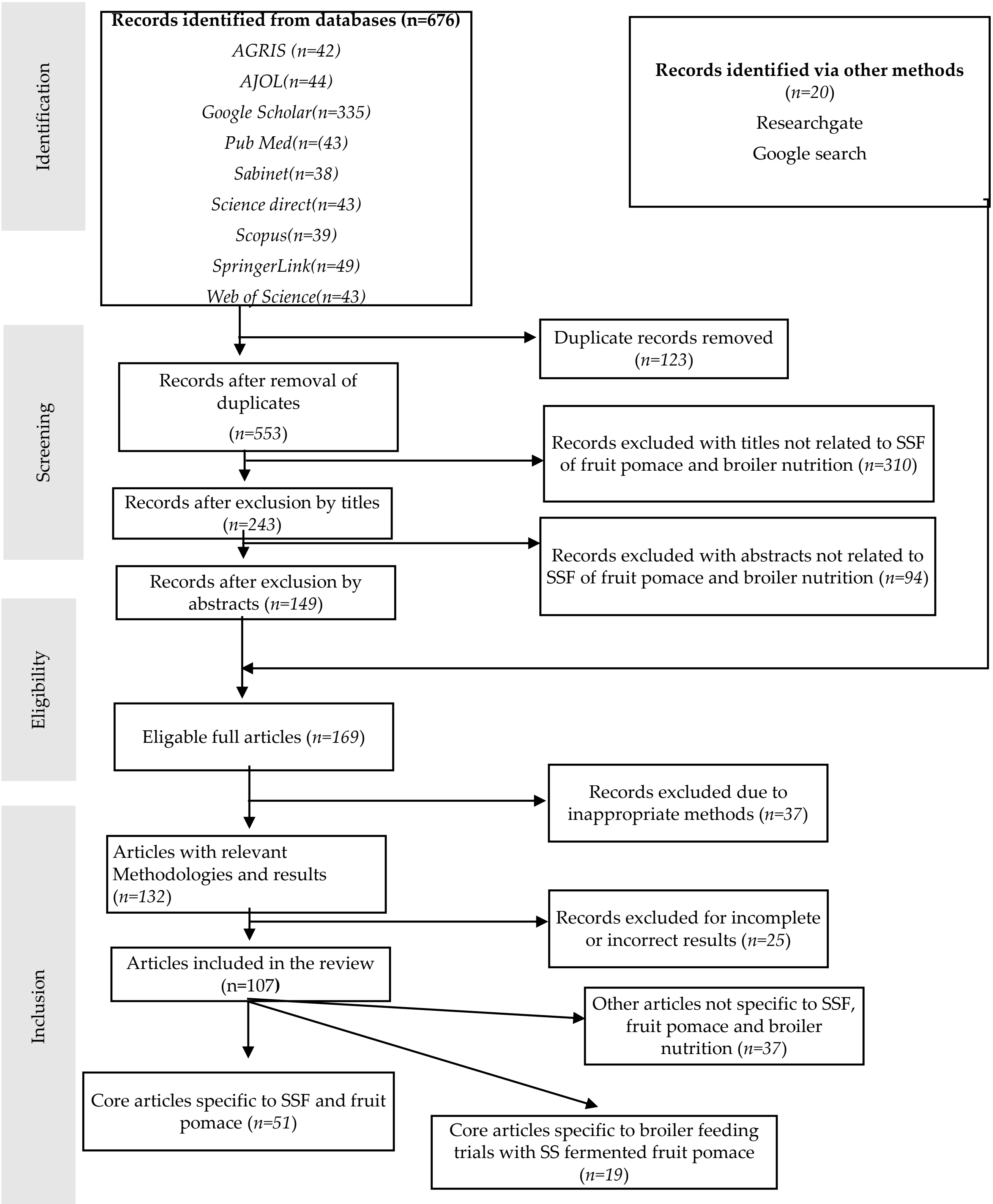

Figure 1. PRISMA flow stages.

Fruit pomace contains some nutrients such as non-fiber carbohydrates, minerals, and a wide range of bioactive compounds such as polyphenols and carotenoids with potent antioxidant, antimicrobial, and anticancer activities [26,27]. Nutraceuticals would not only improve poultry growth performance but would also enhance product quality [28,29]. However, fruit pomace also contains high fiber content and anti-nutritional factors (ANF) [9], which limit their inclusion levels in broiler nutrition as they will result in adverse effects on growth parameters and intestinal morphology [10].

Mismanagement of fruit pomace can result in significant environmental issues, primarily due to its contribution to greenhouse gas emissions. When fruit pomace is not properly disposed of or utilized, it can decompose in landfills, releasing carbon dioxide and methane into the atmosphere [5,30]. This increase in carbon footprint not only exacerbates climate change but also poses risks to local ecosystems and public health.

Table 1. Common fruit pomaces and their nutritional composition.

Fruit pomace	**Proportion (%) of the pomace to the whole fruit**	**Nutritional composition**	**Reference**
Apple (*Malus spp.*)	24–30	Non-fiber carbohydrates (sugars); minerals; dietary fiber (pectin, cellulose, hemicellulose); and bioactive compounds (flavanones, flavones, flavanols, and phenolic acids)	[5] [7]
Banana peels	30–40	Antioxidants; antimicrobial properties	[5,31]
Citrus pomace	45–60	Free sugars; fats; organic acids; dietary fiber (pectin, cellulose, hemicellulose); bioactive compounds (flavanones, flavones, flavanols, and phenolic acids); limonene essential oils; enzymes; pigments	[5,26,32]
Grapes (*Vitis spp.*)	20–30	Polysaccharides; amino acids; dietary fiber; fatty acids; bioactive compounds	[7,33]
Olive pomace		Sugars; proteins; lipids; polyphenols (3,4-DHP); tannins	[34,35]
Pineapple (*Ananas comosus L.*)	40	Dietary fiber; bioactive compounds (polyphenols and carotenoids)	[7,36]
Pomegranate (*Punica granatum L.*)	40–50	Dietary fiber; tannins; polyphenols	[5,7,37]
Mango (*Mangifera indica L.*)	35–50	Dietary fiber; vitamins E and C; enzymes; polyphenols and carotenoids	[5,12]

3.1. Environmental Concerns Caused by Fruit Pomace

Almost one-third of fruit pomace is disposed of as waste in landfills [38], making up to 40–50% of global waste [12]. Large-scale dumping in landfills may give rise to environmental concerns, including water, soil, and air pollution. Water in landfills carries various organic and inorganic compounds, along with heavy metals [39], which can compromise groundwater quality and pose health risks to humans and animals [40, 41]. Heavy metals are non-biodegradable, leading to the depletion of soil resources and negatively impacting plant growth and yield. They also have detrimental consequences for the ecosystem [30, 42].

Landfills also produce some emissions in form of carbon dioxide (90–98%), ammonia, hydrogen sulfide, nitrogen (10%), due to bacterial decomposition, significantly contributing to the global anthropogenic greenhouse gas (GHG) emissions, which eventually result in global warming [43]. Moreover, continuous exposure to methane (CH4), carbon dioxide (CO2), and unpleasant odors can lead to serious health effects in humans [44].

To reduce the environmental carbon footprint, fruit pomace is valorized to enhance their utility in poultry nutrition and the biofuel industry. Solid state fermentation is used to improve the digestibility and nutrient bioavailability of fruit pomace for large-scale broiler production [35].

4. Solid State Fermentation

Solid-state fermentation is an ancient practice that emerged around 2600 BC in Egypt where it was used for bread-making [45]. The process was subsequently utilized for centuries in regions like Indonesia, China, and Japan to produce traditional foods, preserve animal and fish products, as well as create vinegar and gallic acid [7]. However, a significant surge in SSF research occurred between 1980 and 1990, driving advancements that led to the development of numerous important products for the livestock industry, such as fermented feeds, probiotics, enzymes, and bioactive compounds [46,47]. Recently SSF has been used to valorize fruit pomace and agro-industrial waste products for livestock nutrition [10].

Solid state fermentation is defined as a bioprocess in which microorganisms grow on moist solid materials/substrates in the absence of free-flowing water [7,48]. SSF mimics natural microbial habitats, enabling the breakdown of complex substrates like fruit pomace, agricultural byproducts such as wheat bran and rapeseed cakes into nutrient-rich feed ingredients [16,49].

Microorganisms primarily used in solid-state fermentation are mainly filamentous fungi of the genera Aspergillus, Fusarium, Penicillium, Rhizopus, and Trichoderma [49]. Yeasts such as Saccharomyces sp and Candida sp, along with actinobacteria species like Streptomyces sp are also utilized in solid-state fermentation [18,19,20,49]. Bacteria, especially Bacillus megaterium, Bacillus mycoides, and Lactobacillus spp, are also utilized in solid-state fermentation [10,51,52]. Filamentous fungi and yeasts are mainly used in SSF because they release enzymes (hemicellulases, xylanases, pectinases, and tannases) that can break down solid organic substrates in low moisture environments [7,10,53]. Notably, Streptomyces spp., which are gram-positive mycelial bacteria, are used in SSF due to their ability to withstand harsh environmental conditions and efficiently colonize and digest solid organic materials [49,54].

4.1. Solid State Fermentation of Fruit Pomace

The SSF of fruit pomace comprises a sequence of steps divided into upstream, midstream, and downstream processes [48,55,56]. The upstream process includes preparing substrates using mechanical, chemical, and enzymatic methods, as well as selecting microorganisms for use (Figure 2). The midstream process involves the inoculation of the substrate and incubation (fermentation). The downstream process involves obtaining the final products and preparing them for packaging. While the steps in SSF are commonly employed in industry, there are variations in the methods used to obtain the final desired product.

Pretreatment techniques such as mechanical (chopping, grinding), chemical (chemical hydrolysis) and biological (commercial enzymes) are applied to break down the lignin's resistant structure, thus increasing the accessibility of non-crystalline cellulose and hemicellulose to microbes [10,57–59]. Selecting microbial strains is also a crucial step in the SSF of fruit pomace. To ensure an effective fermentation process, selecting microorganisms depends on several factors: their growth behavior, specific product yield, ability to degrade certain substrates, tolerance to temperature and pH, suitability for genetic manipulation, and the safety of the final product for animal consumption [49,60,61].

Research on SSF has shown that microorganisms can be employed singly as monocultures, co-cultures, or a consortium of mixed cultures to facilitate optimum fermentation of solid substrates [48,62,63]. The most used co-cultures are (i) filamentous fungi and bacteria, (ii) filamentous fungi and yeast, or (iii) yeast and bacteria [48]. Meini *et al*. [64] demonstrated that monoculture of *Aspergillus oryzae* improves the bioactive compounds of grape pomace. Similarly, Orayanga *et al*. [65] demonstrated that a co-culture of *Saccharomyces boulardii and S. cerevisiae* improve the crude protein, crude fat, vitamin, ash and mineral content of of Mango pomace. In another study, Liu *et al*. [66] demonstrated that co-cultures of *Aspergillus niger*, *Candida tropicalis*, *Bacillus subtilis*, and *Lactobacillus plantarum* improve the nutritional value of citrus pomace. Similar studies have also been conducted and referenced in the literature [35,50,66–71]. These studies affirm that different microorganisms can be used to improve the nutritional composition of different fruit pomaces for utilization as broiler feed ingredients (Tables 2–7).

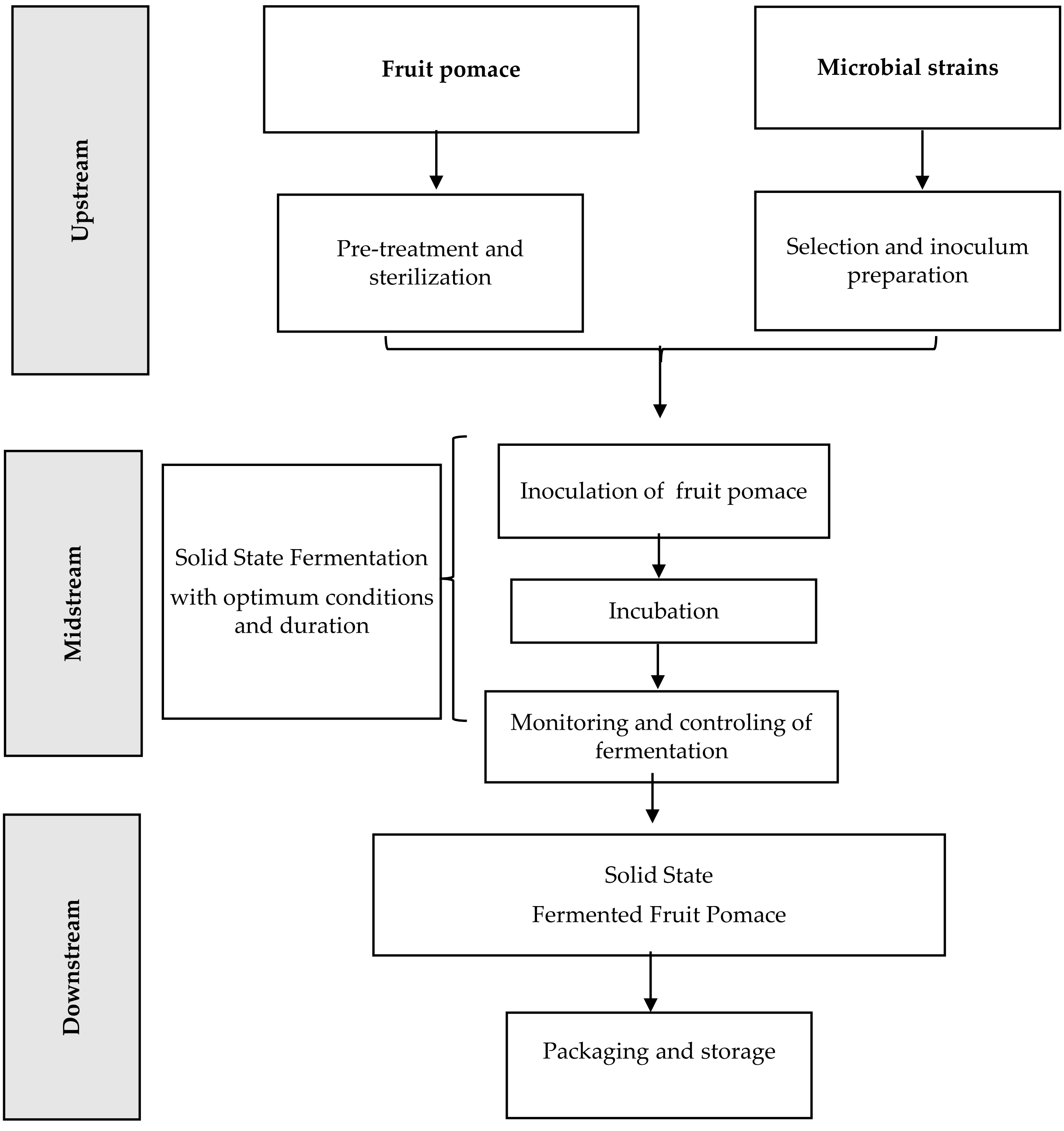

Figure 2. Solid-state fermentation of fruit pomace.

5. Effects of SSF on the Nutritional Composition of Fruit Pomace

Fruit pomace usually contains low crude protein (CP) levels, high fiber content, hemicellulose, glucosinolates and tannins [26,35], which limits their inclusion levels in broiler feeds. SSF fermentation has proven to increase the CP content [63,72,73], reduce the fiber content [7], improve ether extract [72], reduce antinutritional factors [74], and enhance antioxidant capacity [75] of fruit pomace, thereby improving their suitability in broiler nutrition. Table 2 shows the effects of SSF on the nutritional composition of various fruit pomaces. There is, however, little research on the nutritional composition of pomace from wild fruits as well as their valorization through SSF.

Table 2: Effects of SSF on the nutritional composition of various fruit pomaces.

Fruit Pomace	Fermentation conditions	Effects on Nutritional Composition	References
Apple	*Actinomucor elegans*, 4 d	Increased carotenoid content; antioxidant production; phenolic content	[7]
Apple	*Saccharomyces cerevisiae*	Increased total ash; crude protein; fat; vitamin content	[7]
Apple	*Phanerochaete chrysosporium*, 10 d at 37 °C	Increased antioxidant production; β-glucosidase	[69]
Citrus	*Bacillus subtilis* BF2, 3 d	Reduced carbohydrate content; increased fat content; enhanced antioxidant activity	[75]
Grape	*Rhizopus sp.*, 48 h at 30 °C	Improved crude protein; crude fat; total ash; vitamin content	[62]
Grape	*Aspergillus oryzae*, 72 h at 30 °C	Increased antioxidant activity	[64]
Grape	*Saccharomyces cerevisiae*, 48 h at 30 °C	Increased acid-soluble protein; crude protein; free amino acid content; decreased acid detergent fiber; neutral detergent fiber	[76]
Grape	*Rhizopus oryzae*, 28 d at 28 °C	Increased phenolic compounds (1.1–2.5-fold)	[16]
Mango	*Saccharomyces boulardii* and *S. cerevisiae*, 7 d	Increased crude protein; crude fat; ash; minerals (Ca, Mg, K, Fe, Mn)	[65] [7]
Olive	*Kluyveromyces marxianus* NRRL Y-8281 yeast	Increased gallic acid concentration (2.8-fold); decreased tannin content (−96.75%)	[35]
Olive	*Bacillus subtilis*, 2 d at 37 °C	Increased extract; crude protein; reduced crude fiber; lignin content	[63] [7]
Pineapple Pomace	*Trichoderma viride* ATCC 36316, 96 h at 30 °C	Reduced crude fiber	[76]
Yam peels	*Saccharomyces cerevisiae* (BY4743), 96 h at 27 °C	Crude protein increased (6.60 → 15.54%); true protein increased (4.38 → 13.37%); fat content increased (1.12 → 2.09%); ash content increased (4.45 → 8.02%)	[77]

5.1. Effects of SSF on Crude Protein of Fruit Pomace

The CP content of feed ingredients, raw materials, or byproducts is essential for assessing their appropriateness for feeding broiler chickens [7]. Solid state fermentation has been proven to improve the CP content of fruit pomace, as an example, a study by Orayanga *et al.* [65], showed that SSF of mango pomace with *S. boulardii* and *S. cerevisiae* enhanced crude protein by 7.88%. SSF of yam peels with *Saccharomyces cerevisiae* increased the CP from 6.60 to 15.54% while the true protein increased from 4.38 to 13.37% [77]. Similarly, a study by Mandrena *et al*. [72], showed that solid state fermentation of apple pomace using *autochthonous cider* yeasts led to significant increase in protein content, ranging from 23% to 49%. Additionally, SSF of red grape pomace increased the CP content [62]. Therefore, SSF of fruit pomace improves their crude protein content, making them more suitable for broiler nutrition.

5.2. Effects of SSF on Crude Fiber of Fruit Pomace

Crude fiber (CF) content indicates the indigestible or slowly digestible plant material present in feeds. Broilers require low levels of crude fiber in their diets to reduce adverse effects on the digestive system and overall growth performance [78]. Crude fiber mainly comprises cellulose, hemicellulose, lignin, and lesser quantities of pectins and other constituents. Bacterial species like Bacillus, Lactobacillus, and Streptomyces produce cellulases and hemicellulases, which aid in the degradation of fiber [79]. Fungi, including species from the genera Aspergillus, Trichoderma, and Penicillium, are recognized for producing various cellulases and hemicellulases, such as xylanases, mannanases, and arabinofuranosidases, which can effectively hydrolyse cellulose and hemicellulose [7,80]. SSF has proven to reduce the CF of various fruit pomaces, as shown in Table 2. Fermentation of olive pomace with Bacillus subtilis has been shown to reduce lignin and hemicellulose content [7]. Similarly, Aruna et al. [77] noticed that fermentation of pineapple pomace with Trichoderma viride leads to a substantial decrease in the crude fiber content. The reduction of CF of fruit pomace through SSF makes them suitable for broiler nutrition.

5.3. Effect of SSF on Crude Fat of Fruit Pomace

Ether extract, also known as crude fat or lipid content, primarily comprises triglycerides (fats and oils), phospholipids, and certain waxes [7]. Crude fat is the energy source in feeds, providing more than twice the energy per gram compared to carbohydrates and proteins [81]. Crude fat is required to increase nutrient absorption, palatability, essential fatty acids, and feed efficiency in broilers [82,83]. The influence of SSF on the ether extract of fruit pomace is inconsistent and depends on the particular conditions and the microbial strain involved in the fermentation process. Usually, SSF reduces the ether extract of fruit pomace since lipid substrates are utilized by microbial strains to form bioactive lipid-derived compounds. However, conflicting findings has been reported in other research, for instance, Mahmoud et al. [73] reported a 5.63% increase in fat content following the fermentation of orange pomace with Kluyveromyces marxianus. Similarly, Orayanga et al. [65] observed enhanced crude fat content (4.18%) of mango pomace after fermentation with Saccharomyces boulardii and S. cerevisiae for 7 days. Kumanda et al. [62] also observed that fermenting red grape pomace with Rhizopus sp. increased the crude fat content. Fermentation of yam peels with Saccharomyces cerevisiae increased the fat content from 1.12% to 2.09% [77]. The increase in ether extract (crude fat) content noted by these authors may be attributed to microbial lipid synthesis (de novo), effects of substrate concentration, and enhanced extractability, amplified by the unique metabolism of the microbial strains used. This highlights the strain-substrate specificity in fermentation applications.

5.4. Effects of SSF on Anti-Nutritional Factors (ANFs)

ANFs are compounds found in animal feeds that can hinder the digestion, absorption, or utilization of nutrients, thereby diminishing the feed's nutritional value [84]. According to Ikusika et al. [7], fruit pomace can contain a variety of ANFs, which may vary based on the specific type of fruit, the common are tannins (grapes, cranberries, strawberries, blueberries, apples, and apricots), phytates (olive pomace), oxalates (citrus, apple, strawberry, and pineapple) and glycosides (orange pomace).

Solid-state fermentation has been shown to decrease the anti-nutritional factors in fruit pomace, although its effectiveness can vary based on factors such as the type of substrate, fermentation duration, microorganisms utilized, and specific fermentation conditions. A study conducted by Atlop et al. [74], demonstrated that fermentation of olive pomace with Aspergillus niger reduced the tannin concentration. Similarly, fermentation of olive pomace with Kluyveromyces marxianus yeast led to a significant reduction in tannin content, achieving a decrease of 96.75% [35]. Additionally, De Villa et al. [85] reported that SSF of fruit pomace using fungi (Aspergillus spp. and Rhizopus spp.), bacteria (Bacillus subtilis and lactic acid bacteria), and yeast (Saccharomyces cerevisiae) significantly reduced tannin levels. Therefore, SSF using fungi, yeast, and bacterial organisms can improve the nutritional value of fruit pomace by diminishing anti-nutritional factors, making the products viable ingredients for broiler feeds.

5.5. Effect of SSF on Bioactive Compounds of Fruit Pomace

Bioactive compounds are known for their antioxidant, anti-inflammatory, and antimicrobial properties [86]. They include phenolics, flavonoids, carotenoids, alkaloids, and terpenoids [87]. Bioactive compounds improve broiler performance, boost the immune system, and enhance meat quality, making them a valuable addition to broiler nutrition

[88]. SSF of fruit pomace improves the content of bioactive compounds via enzymatic liberation and microbial biotransformation. SSF of citrus pomace with Lactobacillus plantarum P10, M14 converted the complex phenolics into free phenolics, thereby enhancing the antioxidant activity [75]. Similarly, fermenting apple pomace with P. chrysosporium for 10 d at 37◦C increased the carotenoid and phenolic antioxidant productivity and β-glucosidase [69]. According to Ikusika et al. [7], fermenting Grape pomace with Rhizopus oryzae resulted in improved phenolic compounds. In a related study, fermenting grape pomace with Aspergillus oryzae increased the antioxidant activity of the extracts [64]. Optimizing strain selection, temperature, and duration can yield nutraceutical-grade extracts. Future focus should address scalability and in vivo efficacy to unlock commercial potential in feed, food, and pharmacy sectors.

6. Effects of SS Fermented Fruit Pomace on Growth Performance of Broilers

The nutritional composition and feed quality greatly influence broiler growth performance [89]. It is proven that SSF improves the nutritional composition of fruit pomace and reciprocally improves broiler growth performance [21,66,90]. Fermented pomace inclusion in broiler diets has resulted in improved feed intake, growth rates, and FCE in broiler chickens (Table 3).

Fermented fruit pomace improves broiler growth performance at optimum inclusion levels, while higher inclusion levels seem to have detrimental effects. Ibrahim et al. [63] have shown that fermented olive pomace increased feed conversion ratio and immune response of broiler chickens at 7.5% and 15% inclusion levels, with a higher inclusion level (30%) regressing growth performance. Similarly, fermented banana pomace resulted in increased weight gain and feed intake at 10% inclusion levels, while the 15% inclusion did not increase feed intake [21]. Additionally, fermented mango pomace improved broiler growth performance at 10–15% inclusion level (100–150 g/kg) in the starter diets, while the 20% inclusion (200 g/kg) reduced weight gain and feed intake [65]. In contrast, higher inclusion of some fermented fruit pomace still improved broiler growth performance; for instance, up to 20% incorporation rates of cocoa pod husk for broiler finisher diets improved the feed conversion efficiency as well as growth [68]. Additionally, 50% inclusion of fermented apple pomace improved the weight gain of broilers while maintaining liver and kidney function [90]. Some studies did not observe significant improvements in growth performance, for example, fermented pomegranate did not alter the feed conversion ratio and body weight at 5 and 10 g/kg (0.5–1%) inclusion [91]. However, the same pomace when subjected to 2 two-stage fermentation with 9 different microbial strains improved broiler growth performance [92]. The improved growth performance observed by the above authors shows that fermentation with multispecies probiotics is more efficient than a single microbial strain.Controversially, other studies have revealed that fermented pomace can have detrimental effects on broiler growth; for example, fermented sweet orange pomace depressed body feed intake, weight gain, and slaughter weight of broilers [67]. This could be due to inadequate fermentation procedure; hence, it is essential to select the most suitable microbes, combined with optimal fermentation conditions, to ferment fruit pomace and achieve desirable effects on the broiler growth performance.

Overall, the observed variations in optimal inclusion levels and their effects suggest that different types of fermented pomaces have unique nutrient profiles and bioactive compounds, which can significantly influence digestive efficiency and overall health in broilers. Furthermore, the contrasting outcomes at higher inclusion levels indicate that while some pomaces may yield beneficial effects even in larger quantities, others can adversely impact growth performance due to factors such as increased fiber content or nutrient imbalances. Consequently, these findings underscore the need for tailored fermentation procedures for specific fruit pomace.

Table 3. Effects of SS fermented fruit pomace on broiler growth performance.

Fruit pomace	Fermentation conditions	Impact on broiler growth performance	References
Apple	*Saccharomyces cerevisiae*, *Candida utilis*, *Torula utilis*, *Schizosaccharomyces pombe*, *Kloeckera* sp.	Up to 50% inclusion: improved weight gain; no mortality; no abnormalities in liver or kidneys	[90]
Banana peel	*Rhizopus oligosporus*	10% inclusion: increased weight gain and feed intake; 15% inclusion: no effect on feed intake; improved weight gain and feed conversion; 10–15% inclusion: increased pectoral and thigh muscle percentages	[21] [22]
Citrus	*Aspergillus niger*, *Candida tropicalis*, *Bacillus subtilis*, and *Lactobacillus plantarum* (1:1:1:1), 8 d at 30 °C	10% inclusion: increased average daily gain (ADG) and slaughter weight; decreased feed-to-gain ratio (F:G)	[66]
Citrus	24 and 48 h	30% maize replacement (starter diet): depressed feed intake, body weight gain, and slaughter weight	[67]
Cocoa	*Pleurotus ostreatus*	Up to 20% inclusion (finisher diet): improved growth rate and feed conversion efficiency	[68]
Dragon fruit peel	*Saccharomyces cerevisiae*	3–7% inclusion: improved feed conversion efficiency and body weight gain	[93]
Grape	*Rhizopus* sp., 48 h at 33 °C	5.5–7.5% inclusion (55–75 g/kg): increased feed conversion efficiency; no effect on body weight gain; 7.5% inclusion (75 g/kg): depressed feed intake	[24]
Grape	*Aspergillus niger*	Improved live weight and serum catalase levels	[79]
Grape	*Saccharomyces cerevisiae*, 48 h at 30 °C	2–6% inclusion: increased average daily gain (ADG); decreased feed conversion ratio (FCR)	[70]
Mango Pomace	*Saccharomyces boulardii and S. cerevisiae*, 7 d	10–15% inclusion (100–150 g/kg, starter diet): improved growth performance; 20% inclusion (200 g/kg, starter diet): reduced weight gain and feed intake	[65]
Olive Pomace	*Bacillus subtilis* var. natto N21 (BS), 2 d at 37 °C, then *Lactobacillus casei*, 25–35 °C	15% inclusion: increased feed conversion ratio; improved defense system response 30% inclusion: depressed body weight gain; reduced protein efficiency ratio	[63]
Pomegranate	*Aspergillus niger* (ATCC 9142), 7 d at 30 °C	5–10 g/kg inclusion: no effect on body weight or feed conversion ratio	[91]
Pomegranate	*Bacillus subtilis* (KCTC 1022, KCTC 1103, KCTC 3239) and *Saccharomyces cerevisiae* (KCTC 7107, KCTC 7915, KCTC 7928), 72 h at 40 °C anaerobic fermentation	1–2% inclusion (finisher phase): increased average daily weight gain	[92]

7. Effects of SS Fermented Fruit Pomace on Meat Quality of Broilers

Broiler meat quality is determined by evaluating the fatty acid profile, pH levels, malondialdehyde content, color, texture, tenderness, juiciness, cooking loss, and flavor compounds of the breast muscle [94,95]. Good quality broiler meat has a balanced fatty acid composition, with a higher proportion of unsaturated fatty acids, optimal pH levels post-slaughter, lower levels of malondialdehyde, desirable color, and desirable flavor compounds [96,97].

The studies indicate that fermented fruit pomace is natural source of antioxidants in broiler feeds, promoting better meat quality and safety (Table 4). According to Li et al. [22], fermented banana peels resulted in superior meat flavor profiles at 10 and 15% inclusion levels. The same authors also indicated that 10 and 15% inclusion improved the total fatty acid content of breast meat. This indicates enhanced nutritional value, although fatty acid profiling is a necessity to determine the saturated and unsaturated fatty acids, as well as the overall fatty acid balance. Gungor et al. [79] showed that 5 and 10 g/kg inclusion of fermented pomegranate decreased malondialdehyde (a marker for lipid oxidation) in breast meat, suggesting improved shelf life. Similarly, 10% inclusion of fermented citrus pomace increased the meat pH and color, increased the levels of inosine monophosphate and intramuscular fat [66]. In the same study, the same authors also reported that 10% inclusion increased the malondialdehyde. The study indicates improved broiler meat quality by fermented citrus pomace. In another study, 15 and 30% inclusion of fermented of olive pomace increased the phenolic and flavonoid contents in breast meat, and even after a long period of frozen storage [63]. This indicates improved broiler meat quality and enhanced shelf life.

Conversely, 15 g/kg inclusion of fermented grape pomace did not change the pH, color and malondialdehyde level of the breast meat [79]. This raises questions on the microbes that were used, fermentation time as well as temperature as they affect fermentation products.

Table 4. Effects of SS fermented fruit pomace on broiler meat quality.

Fruit pomace	Fermentation conditions	Impact on meat quality	Reference
Banana peel	*Saccharomyces cerevisiae* (yeast)	10–15% inclusion: improved fatty acid content of breast meat; improved flavor profiles	[22]
Banana peel		Up to 15% inclusion (finisher diet): increased lightness (L*); decreased redness (a*)	[98]
Banana peel	*Rhizopus oligosporus*, 48 h	10% inclusion: no effect on abdominal fat percentage	[21]
Citrus	*Aspergillus niger*, *Candida tropicalis*, *Bacillus subtilis*, and *Lactobacillus plantarum* (1:1:1:1), 8 d at 30 °C	10% inclusion: increased pH (45 min) and b* (24 h) in breast muscle; increased inosine monophosphate and intramuscular fat; increased polyunsaturated fatty acids (PUFAs) and n-6 PUFAs; decreased malondialdehyde content	[66]
Grape	*Aspergillus niger*, 7 d	15 g/kg inclusion: no effect on pH, color, or malondialdehyde in breast meat	[79]
Olive	*Bacillus subtilis* var. natto N21 (BS), 2 d at 37 °C, then *Lactobacillus casei*, 25–35 °C	15–30% inclusion: increased total phenolic and flavonoid contents in breast meat, maintained after prolonged frozen storage	[63]
Pomegranate	*Aspergillus niger* (ATCC 9142), 7 d at 30 °C	5–10 g/kg inclusion: decreased malondialdehyde in breast meat	[91]

8. Effects of SS Fermented Fruit Pomace on Blood Parameters

Monitoring blood parameters such as glutathione (GT), catalase (CAT), triglycerides (TG), and blood urea nitrogen (BUN) can provide insights into the metabolic health and oxidative status of broilers, helping producers optimize nutrition and management practices for better growth and welfare [99,100]. High levels of glutathione, elevated CAT levels, moderate TG and BUN levels indicate good oxidative status and overall broiler health

[101]. High triglyceride levels can indicate excessive fat deposition and poor energy metabolism, while low levels might suggest inadequate energy intake or metabolic issues [102]. Elevated BUN levels can indicate high protein intake or kidney dysfunction, while low levels may suggest inadequate protein consumption or liver issues [103].

The effects of fermented fruit pomace on the blood parameters of broilers are presented in Table 5. Fermented fruit pomace did not negatively affect the blood parameters, even at higher inclusion levels; for instance, 50% inclusion of fermented apple pomace maintained the optimum levels of ALT, AST, and AKPase [90]. Additionally, inclusion up to 30 % of fermented cocoa pod husk in the broiler finisher diet had no detrimental effects on the blood parameters of the broiler chickens [68]. In another study, inclusion of fermented sweet orange peels up to 20% did not alter Hb, RBC, PCV, MCV, and MCH values but increased WBC and MCHC values [103], indicating an improved immune system.

Interestingly, fermented citrus pomace increased the antioxidant capacity and catalase activity in serum at a 10% inclusion level [66]. This indicates protected tissues against antioxidant stress, thereby improving the overall broiler health. Additionally, fermented grape pomace also increased the serum catalase (CAT) level at 15 g/kg inclusion in broiler diets [79]. In a similar study, fermented grape pomace increased the TP and BUN content while reducing the serum TG content at 2, 4, and 6% inclusion level [70], implying improved nutritional status, high protein intake and improved lipid metabolism. Overall, fermented fruit pomace improves the oxidative status as well as the overall health of broiler chickens.

Table 5. Effects of SS fermented fruit pomace on blood parameters of broilers.

Fruit pomace	Fermentation conditions	Effects on blood parameters	References
Apple	*Saccharomyces cerevisiae, Candida utilis, Torula utilis, Schizosaccharomyces pombe, Kloeckera spp.*	50% inclusion: ALT, AST, and AKPase within normal limits	[90]
Citrus	*Aspergillus niger*, *Candida tropicalis*, *Bacillus subtilis*, and *Lactobacillus plantarum* (1:1:1:1), 8 d at 30 °C	10% inclusion: increased antioxidant capacity and catalase activity in serum; increased glutathione peroxidase and catalase in breast muscle	[66]
Citrus (sweet orange peels)	Rumen filtrate (RF), 48 h	Up to 20% inclusion: no effect on Hb, RBC, PCV, MCV, or MCH; increased WBC and MCHC	[104]
Cocoa	*Pleurotus ostreatus*	Up to 30% inclusion (finisher diet): no detrimental effects on blood parameters	[68]
Grape	*Saccharomyces cerevisiae*, 48 h at 30 °C	2–6% inclusion: increased serum total protein (TP); decreased blood urea nitrogen (BUN); reduced serum triglycerides (TG)	[70]
Grape	*Aspergillus niger*, 7 d at 30 °C	15 g/kg inclusion: increased serum catalase	[79]
Olive	*Bacillus subtilis*, 2 d at 37 °C	Improved defense system response	[63]

9. Effects of SS Fermented Fruit Pomace on Broiler Gut Morphology and Nutrient Absorption

Gut morphology is critical for nutrient absorption and feed efficiency. The villi height and the villus height-to-crypt depth ratio (VH) are indicators of gut health and efficient nutrient uptake [10]. Good gut morphology is characterized by well-developed villi, an intact epithelial layer, and optimal crypt depth, with high villus height-to-crypt depth. Research has shown that fermented fruit pomace improves broiler gut morphology, although few studies were carried out in this area (Table 6). Sugiharto et al. [98] indicated that inclusion of fermented banana peels up to 15% in finisher diets increased the ileal and villi height. However, some other studies reported no changes in ileal morphology; for instance, Gungor et al. [79] indicated that fermented grape pomace did not alter the ileal morphology of broiler chickens at 15 g/kg inclusion. Similarly, Dewi et al. [93] reported that fermented dragon fruit pomace did not alter the caecum and the villi height [93]. Consequently, fermented fruit pomace can result in adverse effects on gut morphology, as seen in pomegranate pomace which decreased villus height as well as the villus height-to-crypt ratio at 5 and 10 g/kg inclusion levels [91], implying impaired gut health, potential inflammation, or damage leading to reduced nutrient absorption. This affects the growth performance, and hence, considerations should be made on the inclusion levels. More research needs to be done to determine the effects of fermented fruit pomace on broiler gut morphology and nutrient absorption.

Table 6. Impact of SS fermented fruit pomace on gut structure.

Fruit pomace	Fermentation conditions	Impacts on gut structure	References
Banana peels		Up to 15% inclusion: increased ileal villus height	[98]
Pomegranate	*Aspergillus niger* (ATCC 9142), 7 d at 30 °C	5–10 g/kg inclusion: decreased villus height and villus height-to-crypt ratio; detrimental effects on ileum morphology	[91]
Grape	*Aspergillus niger*, 7 d at 30 °C	15 g/kg inclusion: no effect on ileal morphology	[79]
Sour cherry	*Aspergillus niger*, 7 d at 30 °C	1% inclusion: increased villus height-to-crypt depth ratio	[23]

10. Effects of SS Fermented Fruit Pomace on Broiler Gut Microbiome and Health

The gut microbiome influences nutrient absorption, immune function, and pathogen resistance. The composition of the gut microbiome is influenced by several factors, including feed, age, and feeding method, with feed having the most significant impact [70]. Fermented feed components improve gut microbial ecosystems by promoting beneficial bacteria, such as lactic acid bacteria, and inhibiting pathogens like coliforms and Salmonella [10,105]. Fermented diets also lower gut pH, creating an optimal environment for beneficial microbes [106]. The effects of SS fermented fruit pomace on the intestinal microbiome of broiler chickens are presented in Table 7.

Inclusion up to 15% of fermented banana peels in finisher diets decreased the coliform population in the ileum [97]. Additionally, fermented grape pomace increased the abundance of Firmicutes, reduced the relative abundance of Bacteroidetes, and altered cecal microbiota composition at 2, 4, and 6% inclusion levels [70]. Cecal Clostridium perfringens was also reduced by adding fermented grape [79] and fermented pomegranate [91]. The alteration in microbiota, as reported by the above authors, results in improved nutrient utilization and results in enhanced growth performance. Additionally, the studies have shown that fermented fruit pomace reduces the disease pressure due to lowered Clostridium perfringens count.

Table 7. Effects of SS fermented fruit pomace on gut microbiome.

Fruit pomace	Fermentation conditions	Impact on gut microbiota	References
Banana Peels		Up to 15% inclusion (finisher diet): decreased ileal coliform population	[98]
Grape	*Saccharomyces cerevisiae*, 48 h at 30 °C	2–6% inclusion: increased Firmicutes abundance; reduced Bacteroidetes abundance; altered cecal microbiota composition	[70]
Grape	*Aspergillus niger*, 7 d at 30 °C	15 g/kg inclusion: reduced cecal Clostridium perfringens count	[79]

Pomegranate	*Aspergillus niger* (ATCC 9142), 7 days at 30 °C	5–10 g/kg inclusion: decreased cecal Clostridium perfringens count	[91]
Sour cherry	*Aspergillus niger*, 7 days at 30 °C	1% inclusion: increased cecal Lactobacillus spp.; no effect on Enterococcus spp. or Escherichia coli counts	[23]

11. Effects of SS Fermented Fruit Pomace on Feeding Cost

Generally, fruit pomace has little or no commercial value. Their valorization through SSF with microbial strains is a cost-effective bioprocess [107], making the ingredient a cheaper option. Therefore, the higher inclusion levels of SSF fruit pomace in broiler diets, the lower the feeding costs, although little research has been done on this aspect.

Nevertheless, Ibrahim et al. [63] reported that, SS fermented olive pomace increased the net profit and profitability ratio while lowering the cost feed/kg body gain at 7.5 and 15% inclusion levels. Additionally, 1 and 2% inclusion of fermented pomegranate pomace reduced the feed cost per unit of weight gain [92].

Given these findings, a comprehensive cost-benefit analysis of SSF fermented fruit pomace in broiler nutrition is essential to identify optimal inclusion levels and the most economically viable options. This exploration will contribute to more sustainable poultry practices, thereby supporting the overall profitability of the industry.

12. Conclusions

Valorization of fruit pomace through SSF helps to sustainably manage waste disposal and its environmental consequences while reducing the feeding costs, improving growth performance, meat quality, and overall health in broiler production to meet the demands of the ever-growing world population. Studies have shown that up to 15% inclusion of fermented fruit pomace can enhance broiler performance without compromising growth, meat quality, and overall health. However, some fermented pomaces, such as sour cherry and pomegranate, are fed at <2% inclusion levels. Therefore, it is essential to establish and adhere to optimum inclusion levels to prevent any adverse effects on broiler health and well-being.

Future research should also focus on developing standardized, scalable, and cost-effective SSF protocols supported by robust techno-economic analyses for fruit pomace. Collaboration between researchers and industry stakeholders (fruit processors, feed manufacturers, poultry farmers, and regulatory agencies) can help bridge the gap between scientific findings and practical applications of the SSF of fruit pomace. This will develop sustainable supply chains, promote the adoption of SSF pomace in broiler diets, and address any regulatory hurdles.

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