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REVIEW
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Fruit Pomaces as Functional Ingredients in Poultry Nutrition: A Review

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Sustainable poultry intensification is economically constrained by several factors including high feed costs, which constitute more than 70% of total production costs. Functional feed ingredients such as fruit pomaces can be incorporated into poultry diets as natural sources of nutrients and biologically active substances to deliver sustainable production. Fruit pomaces are agro-industrial waste by-products that have no direct food value for humans. Their utilization as feed ingredients would reduce feed-food competitions, optimize poultry production systems, and promote environmental, economic, and social sustainability. Large quantities of fruit pomaces are generated and disposed in landfills or through incineration with little regard to the environment. Thus, their inclusion in poultry feeds could offer a long-term strategy to protect the environment. Valorising fruit pomaces to enhance poultry production would also contribute toward sustainable development goals and food security through the provision of affordable high-quality protein to the rapidly growing human population. Moreover, the use of fruit pomaces complements food production systems by ensuring that food animals are reared on human inedible feedstuffs. Thus, this review explores the nutritional composition and subsequent feeding values of various fruit pomaces, while examining their environmental benefits when used as feed ingredients in poultry nutrition. Furthermore, strategies that can be employed to negate the effect of anti-nutritional factors in the pomaces are presented. We postulate that the use of fresh or valorised fruit pomaces would improve poultry production and significantly reduce the amounts of waste destined for incineration and/or direct deposition in landfills.

Keywords: agro-fruit industry, bioactive compounds, food security, fruit pomace, nutrients, poultry

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INTRODUCTION

For many years now, the formulation of least cost diets to maximize poultry production has been the focus area for feed compounders and animal producers around the world. Formulating inexpensive high-quality feeds requires highly nutritious ingredients that are easily accessible and whose market prices are low. However, over-reliance on maize and soybeans as major ingredients during diet formulation contributes to high feed costs due to their exorbitant market prices (Masenya et al., 2021). The prices of these two ingredients are influenced by many factors including production cost, climate change, and increased demand by the feed, food, and biofuel sectors among others (Marareni and Mnisi, 2020). Several scholars have agreed that the continued use of maize and soybean in poultry diets is economically and environmentally unsustainable (Mengesha, 2012; Mahlake et al., 2021).

Consequently, many researchers all over the world have investigated various alternative feed ingredients that can partially or completely replace maize and soybean meal, with more recent attention directed to the use of agro-waste by-products (Iqbal et al., 2021). Substantial amounts of agro-wastes are generated by various agricultural industries including wineries and breweries, and due to the lack of proper disposal channels, they are discarded in landfills or disposed through incineration causing severe environmental damages (Kumanda et al., 2019a,b; Iqbal et al., 2021). Gassara et al. (2011) reported that only a small fraction from the million tons of waste pomace produced globally is utilized in other applications. The use of agro-wastes in animal feeds has been another strategy to manage their wanton disposal to the environment. From these agro-wastes, fruit pomaces have attracted the most attention because they contain biologically active compounds with putative antioxidative, antibacterial, antiviral, immune-modulatory and anti-inflammatory activities (Kotsampasi et al., 2014; Islam et al., 2020). Fruit pomaces contain a variety of polyphenolics, essential amino acids, vitamins, minerals, and complex carbohydrates (Islam et al., 2020). Several studies have shown that the incorporation of pomaces from apples, citrus, grapes, mangoes among others has positive impact on poultry performance and meat quality (Ebrahimi et al., 2013; Bostami et al., 2015; Kumanda et al., 2019a,b), which could be attributed to the presence of phytochemicals with growth-stimulating, health-promoting, and meat-boosting properties (Islam et al., 2020; Iqbal et al., 2021).

Unfortunately, large-scale usage of fruit pomaces in poultry feeds is lagging due to their low protein value, presence of anti-nutritional factors, and issues relating to availability, accessibility, transportation, and processing (Campos et al., 2020). Indeed, fruit pomaces contain high moisture content (70–80%) and high levels of dietary fiber and condensed tannins that require pre-processing before they can be safely incorporated in poultry diets. High levels of anti-nutrients in the pomaces could limit their utilization by poultry birds, therefore, it is crucial that inexpensive, yet efficient pre-processing methods be evaluated to allow their utilization at higher dietary inclusion levels. This review is, therefore, designed to explore the potential feed value of prominent fruit pomaces as functional ingredients in poultry nutrition. Feeding strategies that can be employed to valorise their utilization in poultry diets and ultimately protect the environment are presented. We believe that efficient utilization of various fruit pomaces would not only protect the environment but would also contribute toward sustainable development goals and global food and nutrition security.

GENERATION, DISTRIBUTION, AND NUTRITIONAL PROFILE OF FRUIT POMACES

Global fruit production was estimated at 900 million metric tons (Mt) in 2020 with almost one-third disposed as waste (Iqbal et al., 2021). This includes a variety of fruits such as apple, grape, watermelon, banana, citrus, avocado, mango, pineapple, pomegranate etc. The processing of these fruits into value-added market products results in the production of fruit pomace in the form of skin or peels, stalks, stems and seeds, which can be valorised to enhance their utility in poultry nutrition (**Figure 1**). This section examines the quality and amount of waste generated by the agro-fruit industry from the processing of various fruits. We also discuss the potential of fruit pomaces to be used as a source of dietary nutrients and functionally active compounds in poultry feeds.

Apple Pomace

Apple (*Malus* spp.) is one of the earliest known fruits to humankind and is widely cultivated in temperate regions (Musacchi and Serra, 2018). Global apple production has doubled almost from 47 million tons in 1990 to 87 million tons in 2019 (FAO., 2021). The highest producer of apple is Asia accounting for 65.4% of global production, with China producing 41.4 million Mt. Other major producers include countries such as the United States, Turkey, and Poland, which accounts for 6.2, 3.6, and 2.9% of total global production, respectively. Lyu et al. (2020) reported that nearly 70–75% of the world's apples are consumed as fresh fruits while the remaining 25–30% is processed to various value-added products such as juices, jams, ciders, wine, vinegar, distilled spirit, jelly, and dried products. However, this processing generates vast amounts of apple pomace. In addition, apples that are not suitable for the market such as rotten, bruised, or damaged ones are subsequently discarded as waste. The disposal in landfills causes harmful environmental issues such as land, air, water, and soil pollution, as well as health risks to humans and animals. On a lighter note, apple pomace contains high concentrations of carbohydrates, minerals, dietary fiber, and phytochemicals like phenolics (4.22–8.67 mg/g), total flavonoids (0.45–1.19 mg/g), and total flavan-3-ols (2.27–9.51 mg/g) with strong antioxidant properties (Cetkovic et al., 2007). Thus, its incorporation in poultry feeds would not only serve a source of valuable nutrients and active biocompounds but would also reduce its harmful effects on the environment.

Grape Pomace

Grapes (*Vitis* spp.) are one of the most widely grown fruit crops in the world, with an estimated production of more than 79 million tons in 2018 (Antonic et al., 2020). Grapes can be consumed as fresh fruits but can be also processed to produce wine, jam, juice, jelly, raisins, vinegar, and seed oil. Approximately 75% of grapes are used in wine production, which generates almost 20–30% of grape pomace, which consists of the skin, pulp, seeds, and stalks (García-Lomillo and González-SanJosé, 2017). The major producers of grape wine are Italy, France,

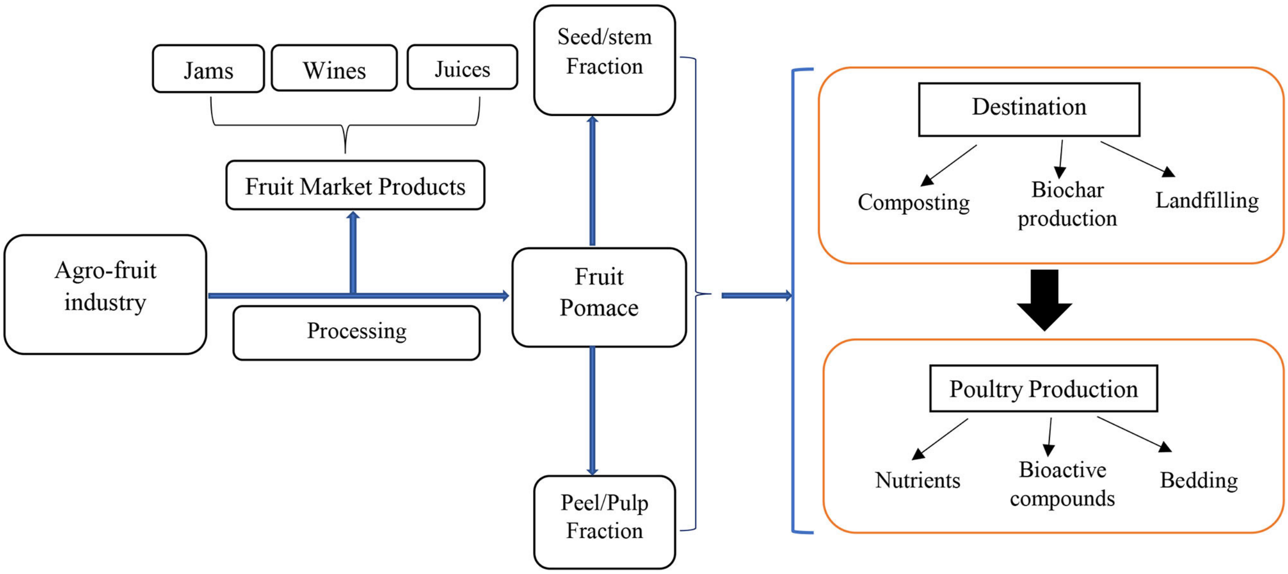

FIGURE 1 | Valorization of fruit pomace waste into value-added products.

and Spain, which are each estimated to generate around 1200 t/year of the pomace (Beres et al., 2017; Kalli et al., 2018). Similarly, Dwyer et al. (2014) reported that the disposal of grape pomace has detrimental environmental effects such as the contamination of ground and surface water, the attraction of disease-spreading vectors, and high oxygen demand. Thus, the re-channeling of grape pomace into poultry feeds as a source of bioactive compounds (flavonols, flavonols glucosides, gallate esters, anthocyanins, and proanthocyanins) could help reduce that negative impact it has on the environment while allowing sustainable poultry intensification (Khan et al., 2015). Other scholars have investigated the potential recycling of grape pomace for other applications such as enzyme, bio-surfactant, and biofuel production, and resin formulation (Munekata et al., 2021), as an attempt to reduce its waste levels. Recently, Mhlongo et al. (2021) indicated that the grape pomace substrate can be used to cultivate edible mushrooms, while the spent substrate can be used as a functional ingredient in animal feeds.

Watermelon Pomace

Watermelon (*Citrullus lanatus*) is a cucurbit crop that is cultivated worldwide for its delicious and sweety taste (Assefa et al., 2020; Manivannan et al., 2020). Watermelons are grown in countries with long, warm growing seasons, such as South Africa, China, India, and the United States (Ahmad and Chwee, 2008). Asian countries account for ∼81% of total watermelon production in the world. In 2018, the Food and Agricultural Organization United Nations reported that 3.2 million hectares of land were used to produce 103 million tons of watermelon over the world (Manivannan et al., 2020). Watermelon fruits can be eaten raw or processed into smoothies, jellies, sauces, sweets, and drinks (Perkins-Veazie et al., 2012). Watermelon is a source of valuable phytochemicals with strong nutritional and medicinal properties. However, massive volumes of its waste are produced and discarded in the fields during harvesting and processing (Arocho et al., 2012). The watermelon flesh, rind, and seed contain a lot of water, carbohydrates, vitamins, fat, protein, minerals, citrulline, pectin and lycopene (Çerçi et al., 2020), which can be beneficial to poultry birds when included in their diets. Perkins-Veazie et al. (2006) reported that watermelon pomace is a high source of lycopene, a potent antioxidant that has been shown in studies to lower the risk of chronic diseases like cancer and cardiovascular disease (Omoni and Aluko, 2005). The available literature on the nutritive value of watermelon pomace shows that it can be potential source of nutrients and active biocompounds in poultry diets. However, more studies are required to determine their optimum dietary inclusion level in poultry feeds.

Pomegranate Pomace

Pomegranate (*Punica granatum* L.) is an ancient fruit crop that is grown in various geographical regions due to its high adaptability to a wide range of soil and climatic conditions (Kara et al., 2018). Pomegranate is grown on approximately 835,950 hectares worldwide, producing almost 8.1 million tons of fruit (average yield of 9.69 tons per hectare) (Pienaar, 2021). India is by far the world's largest pomegranate producer, with nearly 3 million tons produced on 262,000 hectares. China and Iran are the world's second and third largest producers, with 1.2 million and 915,000 tons, respectively (Yuan and Zhao, 2019). The global pomegranate market was valued at USD 8.2 billion in 2018 and is expected to reach USD 23.14 billion by 2026, with a compound annual growth rate of 14% (Conidi et al., 2020). Pomegranates are consumed as fresh produce and/or in a form of juices, jellies, jams, and have been reported to have pharmacological benefits (Dominguez et al., 2019). However, the processing of pomegranate generates large volumes of the pomace (primarily the arils, peels and seeds), which is traditionally dumped as waste (Alexandre et al., 2019). Pomegranate peels constitute about 40–50% of the total fruit weight and are good sources of phenolic compounds (flavonoids, phenolic acids, and tannins), protein and bioactive peptides, and polysaccharides (Smaoui et al., 2019). Over the years, pomegranate by-products have attracted worldwide research attention due to their significant amounts of polyphenols such as ellagic tannins, ellagic acid, gallic acid and punicalagin (Jami et al., 2012), which have antimicrobial, antioxidant, anti-inflammatory, antimitotic, and immunomodulatory properties (Kotsampasi et al., 2014). It is, therefore, clear that poultry birds reared on pomegranate-containing feeds could benefit from these biologically active substances.

Pineapple Pomace

Pineapple (*Ananas comosus* L.) crops are grown mostly in tropical and subtropical countries such as Brazil, Thailand, Costa Rica, Kenya, Malaysia, and Philippines because they adapt well in mild climatic conditions (Rico et al., 2020). The world pineapple production was reported to be more than 28 million tons in 2019 (FAO., 2019). Asia is reported as the largest producer of pineapples with 11.8 million tons (41%) followed by America with 10.4 million tons (38%), and Africa with 5.7 million tons (20%) of global pineapple production (FAO., 2019). Upon harvesting and processing, 60% of pineapples are processed into fruit salads, juices, and jams, and the remaining 40% is discarded as waste consisting of the peels, pulp, stems and leaves (Selani et al., 2014). The utilization of this waste for other applications is limited by its proneness to microbial spoilage. Thus, the use of fresh or valorised pineapple pomace as a functional ingredient in poultry diets could be an ingenious and sustainable strategy to reduce the massive pineapple waste levels and the negative impact it has on the environment. Pineapple pomace is a rich source of vitamin C, calcium, dietary fiber, and soluble carbohydrates (Montalvo-González et al., 2018), and contains a wide range of bioactive compounds such polyphenols and carotenoids with potent antioxidant, antimicrobial and anticancer activities. These nutraceuticals would not only increase poultry production but would also enhance product quality.

Mango Pomace

Mango (*Mangifera indica* L.) is a tropical and subtropical fruit native to North India and the Malay Peninsula and is one of the world's favorite fruit due to its delicate flesh and high nutritional value (Chen et al., 2012). Global mango production was reported to be 55.85 million Mt in 2019, with India and China being the top producers (FAOSTAT., 2019). Mangos are usually eaten fresh (ripe) and almost 20% is processed into shelf-stable products such as pickles, puree, nectar, fruit leather, and canned slices (Ashoush and Gadallah, 2011). However, significant volumes of the pomace are generated annually during the processing of mangoes (Gurumeenakshi et al., 2015). Indeed, over 50% of postharvest losses we45re reported in Asia and Africa during the main harvest season (Owino and Ambuko, 2021). Jahurul et al. (2015) reported that mango pomace account for up to 35–50% of fresh fruits and typically consists of peels, seed kernels and residual pulp, which is commonly dumped as agricultural waste, aggravating environmental pollution (Maran et al., 2015). Thus, the use of the pomace in poultry diets could be a sustainable strategy to manage its deposition into landfills. This approach would allow large-scale poultry production since the pomace has excellent amounts of dietary fiber, vitamin E and C, enzymes, polyphenols, and carotenoids, all of which have a variety of functional and antioxidant properties (Iqbal et al., 2021). Furthermore, mango pomace has been reported to increase anti-lipid peroxidation, alvine peristalsis, and reduce cholesterol levels, and thereby provide health-beneficial effects to humans.

Citrus Pomace

Citrus fruits are one of the world's largest and most commercially produced fruit crops (Castro, 2014), with an estimated global production of 146.6 million tons reported in 2018 (FAO., 2019). Among citrus crops, oranges (*Citrus sinensis*) are the most widely grown accounting for 70.7 million tons, followed by mandarins (*Citrus reticulata*) at 25.5 million tons, and lemons (*Citrus limon*), limes (*Citrus latifolia*) and grapefruit (*Citrus paradisi*) all accounting for 12.9 million tons (Ledesma-Escobar et al., 2015). Over two-thirds of the world's citrus fruits are produced in Brazil, China, India, Mexico, Spain, and the USA (Sataria and Karimia, 2018), and 33% is used for juice and essential oil manufacturing (Castro, 2014). The fruits are used for a variety of applications such as additives, cosmetic ingredients and chemoprophylactic drugs in the food, cosmetic and pharmaceutical industries, respectively (Lv et al., 2015). Unfortunately, citrus processing generates annual waste of 110 million tons worldwide (Zannini et al., 2021). Citrus waste (peels, seeds, and membrane residues) is highly degradable, and has a significant impact on the ecosystem because the large organic and water load of landfilled biomass leads to the generation of greenhouse gases (Zannini et al., 2021). There is, therefore, a growing interest to recycle citrus waste as a potential animal feed ingredient with nutraceutical benefits. Citrus residues contain valuable amounts of free sugars (glucose, fructose, and sucrose), flavonoids, fats, organic acids, carbohydrate polymers (cellulose, hemicellulose, and pectin), limonene essential oil, enzymes (phosphatase, pectinesterase, and peroxidase), and pigments (Sataria and Karimia, 2018), which can be beneficial to the poultry industry.

THE BENEFITS AND LIMITATIONS OF FRUIT POMACES IN POULTRY NUTRITION

Over the last decades, poultry (chicken, quail, ostrich, turkey, ducks etc.) production has increased tremendously throughout the world. In the year 2020, chicken meat alone accounted for 89% of total poultry meat with a global production of about 134 Mt (OECD-FAO., 2021). Moreover, a total of 87 Mt of eggs were produced in 2017, of which 92% were from laying chicken hens (FAOSTAT., 2020). By 2030, the global poultry meat consumption is projected to increase to 152 Mt, accounting for 52% of all additional meat consumed. The expected growth rate in poultry consumption on a per capita basis reflect the important role it plays in the national diets of several developing countries

(OECD-FAO., 2021). This also demonstrates the significant role poultry products play toward achieving sustainable development goals and global food security. However, one of the major constraints in increasing poultry production is high feed costs, which is driven by the increase in global feed prices (Mengesha, 2012). This has led to greater efforts in exploring alternative feed ingredients such as the utilization of various fruit pomaces in poultry production in recent years. However, the use of fruit pomaces in feed ingredients can yield different outcomes (**Table 1**) in poultry birds.

For example, Ebrahimi et al. (2013) reported that broiler chickens fed diets with 15 g/kg of dried orange peel waste had higher carcass yields, and breast, thigh and pancreas weights compared to those reared on the control diet. Similarly, Pereira et al. (2020) observed an increase on egg laying rate, egg weights, and albumen, yolk and shell quality in quail hens fed with 25 and 35 g/kg of passion (*Passiflora edulis* Sim.) fruit waste. Likewise, the inclusion of 20 g/kg dietary levels of pomegranate waste in diets of broiler chickens increased body weight gain (Bostami et al., 2015). Moreover, eggs from birds fed diets with 120 g/kg tomato pulp had improved yolk color (Mansoori et al., 2008). This finding agreed with Knoblich et al. (2005), who reported that feeding laying hens with diets containing tomato by-products may transfer up to 5.8% of the dietary lycopene to the egg yolk. This is important because consumers associate yolk color with good quality eggs, and prefer yellow-orange yolks (Hernandez et al., 2005). Eggs from laying quails fed with 120 g/kg white mulberry in the ration were reported to have reduced yolk cholesterol levels (Sengul et al., 2021), which is good for human health. Inclusion of grape pomace in the broiler diets improved thigh meat oxidative stability (Aditya et al., 2018), and omega-6 polyunsaturated fatty acids (PUFA) (Turcu et al., 2019). Similarly, blackcurrant, strawberry, seedless strawberry pomaces promoted higher concentrations of omega 3 and omega 6 PUFA in turkey meat (Juskiewicz et al., 2017). These positive outcomes could be attributed to the pomaces' functionally active compounds such as anthocyanins, flavonoids, carotenoids, minerals, polysaccharides, vitamin E and unsaturated fatty acids which have growth-stimulating, health-boosting, and meat-enhancing properties.

However, there is a need to first establish an optimum inclusion level for each fruit pomace to avoid compromising the performance and well-being of the birds, especially when included at higher dietary levels. This is because fruit pomaces also contain anti-nutritional factors such condensed tannins, trypsin inhibitors, oxalates and phytates, non-starch polysaccharides (pectin, cellulose, hemicellulose, beta-glucans, xylans etc.), among others. Several studies have reported that high dietary fiber in poultry diets reduce the birds' capacity to absorb and utilize nutrients, while the presence of secondary plant metabolites interfere with the digestion of nutrients (Brenes et al., 2016). For example, Kumanda et al. (2019a) showed that 100 g/kg of grape pomace compromises broiler chicken's performance. In other reports, the inclusion of polyphenolic grape extracts in poultry diets reduced the digestibility of fat (Brenes et al., 2008) and protein (Chamorro et al., 2015). This could be due to the presence of tannins, which are known to bind proteins and form indigestible complexes (Heidarisafar et al., 2016).

STRATEGIES TO IMPROVE THE UTILIZATION OF FRUIT POMACES IN POULTRY

Several strategies such as the application of feed additives, mechanical treatment, thermal treatment, and solid-state fermentation among others have been employed to improve the utilization and feed value of fruit pomaces in poultry diets. Although these strategies have been shown to be efficient in improving the feed value of some feedstuffs, some studies have reported inconsistent results. Moreover, it is important that the cost-effectiveness of each strategy be considered so as not to add to the already high production costs. This section examines the potential strategies than can be used to enhance the utilization of fruit pomaces in poultry nutrition.

Exogenous Feed Enzymes

Exogenous feed enzymes have been increasingly employed in animal nutrition to improve the nutritional qualities of feedstuffs (Ebrahimzadeh et al., 2018). Bedford and Partridge (2010) observed that the use of a multi-enzyme mixture in animal feeds is more efficient in improving nutrient utilization because they target various substrates compared to a single enzyme. Thus, multi-enzymes supplementation can be a viable strategy to better induce the cell wall breakdown of fibrous fruit pomaces and improve the bioavailability of entrapped bioactive compounds. For example, pre-treating 50 g/kg of dried apple pomace with 1,000 ppm Grindazym, an enzyme mixture containing hemicellulase, pentosanase, beta-glucanase, pectinase, protease, and amylase, in layer rations improved egg production and feed efficiency (Yildiz et al., 1998). Chamorro et al. (2015) also found that supplementing grape pomace with carbohydrases and tannase enzymes at 500 mg/kg in chicken diets increased concentrations of gallic acid, catechin, epicatechin, procyanidins, and epicatechin gallate in the lower gastro-intestinal tract (GIT) of the birds. Blandon et al. (2015) found that subjecting air-dried banana peels with 1 g/kg allyzyme boosted feed intake and maintained growth and economic efficiency. Moreover, Aghili et al. (2019) reported that the pre-treatment of 100 g/kg of apple pomace with 0.05 g/kg Safyzym multi-enzyme improved the performance, egg traits and blood parameters in laying hens. It is evident, therefore, that the use of exogenous enzymes can be a viable strategy to improve the utilization of fruit pomaces in poultry feeds.

Solid-State Fermentation

Solid-state fermentation (SSF) is a biological process that promotes the growth of microorganisms on solid substrates in the absence or near absence of free water. However, adequate moisture is needed to support the microbial growth and metabolic activity on the solid substrate (Thomas et al., 2013). Fungal SSF is widely recognized as an economically and environmentally sustainable strategy for lignin-rich substrate bioconversion (Mhlongo et al., 2021), because of their ability to degrade lignocellulolytic components in plant cell walls (Saratale et al., 2008). Gungor et al. (2021) reported that the pre-treatment of pomegranate pomace with 100 g *Aspergillus niger*

TABLE 1 | Effect of incorporating various fruit wastes in poultry diets.

Fruit pomace	Benefits	Limitations	References
Apple	Dietary inclusion of 70 g/kg improved the egg laying ability, hatchability, and vitality of goslings.	Similar dietary level reduced the egg and yolk weight of the birds.	Fiialovych and Kyryliv (2016)
Cranberry	Dietary inclusion between 10 and 20 g/kg positively influenced levels of linolenic and lignoceric acids, blood metabolites and caecal microbial community composition in broilers.	Dietary level of 20 g/kg reduced carcass weights at d 65, blood carbohydrates at d 35 and triglycerides at d 25.	Islam et al. (2020)
Black chokeberry and currant	Dietary inclusion of 30 g/kg improved the immunological status of laying hens.	Similar dietary level had adverse effects on eggshell quality and yolk color.	Sosnowka-Czajka and Skomorucha (2021)
Red grape	Dietary levels of 55 and 75 g/kg promoted higher feed conversion efficiency but had no effect on overall body weight gain in broilers.	Dietary level 75 g/kg reduced feed intake and meat hue angle of the birds.	Kumanda et al. (2019a,b)
Mao	Dietary inclusion of 15 g/kg enhanced meat redness but reduced meat lightness and yellowness in broiler chickens.	Similar dietary level increased meat drip loss of the birds.	Lokaewmanee and Promdee (2018)
Dried olive pulp	Dietary inclusion between 50 and 60 g/kg improved overall egg nutrition quality by increasing PUFA:SFA ratio, shell strength and health lipid indices in brown laying hens.	Similar dietary levels had no improvement on growth performance parameters and serum biochemical indices of the birds.	Dedousi et al. (2022)
White mulberry	Dietary inclusion of 80 g/kg boosted feed intake, egg yield, external and internal egg quality parameters, and low-density lipoprotein levels in laying quails.	Dietary level of 120 g/kg reduced daily feed intake in three- and four-week old birds and resulted in poor overall egg yield.	Sengul et al. (2021)
Passion fruit waste	Dietary inclusion of up to 35 g/kg increased egg laying rate, egg weights, albumen, yolk, and shell quality in quails.	Low feed intake and egg weight was observed in laying quails reared on 80 g/kg dietary level.	Pereira et al. (2020)
Pomegranate waste	Supplementation of a basal chicken diet with 10 and 20 g/kg of fermented pomegranate by-product improved overall weight gain during the finisher phase.	Similar levels had no effect on feed intake and feed conversion ratio of the birds.	Bostami et al. (2015)
Mango	Improved broiler growth performance when included between 100 and 150 g/kg in broiler starter diets.	Reduced broiler weight gain, and protein and feed intake at 200 g/kg inclusion in the starter phase.	Orayaga et al. (2017)
Dried sweet citrus	Significantly increased growth performance in the grower phase, and blood metabolites, humoral immunity, and cecum microbial population when included at 20 g/kg in broiler diets.	Inclusion levels between 10 and 20 g/kg reduced feed intake, weight gain, and feed utilization efficiency in the starter period, and reduced liver, abdominal fat and carcass percentage.	Aghili et al. (2019)

had no effect on feed intake, body weight, feed conversion ratio, carcass characteristics, antioxidant defense system response, and muscularis mucosa thickness. However, the fermented diet increased the crypt depth while reducing lipid oxidation, *Clostridium perfringens* in cecum and villus heights. Moreover, supplementing a basal broiler diet with 15 g/kg *Aspergillus niger*-fermented grape pomace improved live weights, serum catalase levels, and reduced the cecal *Clostridium perfringens* count (Gungor et al., 2021). However, no dietary effects were observed on ileal morphology, carcass parameters, malondialdehyde level, and breast meat color and pH. The available literature shows that SSF can be adopted to valorize and enhance the feed value of fruit pomaces for large-scale poultry production, however, more research is required to determine the optimum SSF treatment for each poultry species.

Tannin-Amelioration

The addition of tannin-binding compounds such as polyethylene glycol (PEG) and polyvinylpyrrolidone (PVP) to ameliorate the antinutritional activities of tannins has been extensively investigated (Besharati and Abdi, 2017). However, research on their use and application in poultry ingredients, particularly fruit pomaces, is lagging behind. Nonetheless, a recent study by Van Niekerk et al. (2020) reported an improvement in body weight gains of broiler chickens reared on grape pomace pre-treated with graded levels (0, 2.5, 5, 10 and 15%) of PEG. This positive outcome could be attributed to the ability of PEG to breakdown tannin-protein complexes, and thus increasing protein utilization for muscular development (Besharati and Abdi, 2017). This approach also has the potential to promote a higher intake of beneficial non-tannin phenolics and other bioactive compounds that are present in fruit pomaces. Furthermore, Kumanda et al. (2019b) revealed that pre-treating 100 g/kg of grape pomace with PEG promoted similar body weight gains and carcass weights as the standard control diet. This confirmed the ability of PEG to successfully inactivate the anti-nutritional effects of condensed tannins. However, the use and application of PVP on fruit pomaces in poultry production has not been investigated. Moreover, the use of wood ash as one potential strategy to ameliorate the negative effects of tannins (Van Ryssen, 2018) requires further investigation in poultry nutrition.

Thermal Processes

One of the major problems with the utilization of fruit pomaces is their susceptibility to microbial decomposition (Iqbal et al.,

TABLE 2 | Potential environmental impacts of direct landfill disposal and incineration of fruit pomaces.

System	Landfill pollutants and their generation	Environmental, Human and Animal Health Outcomes	References
Water	Landfills are subject to either groundwater underflow or precipitation infiltration. Precipitation water percolates through the waste, picking up a variety of organic (biodegradable and non-biodegradable), inorganic compounds and heavy metals that flow out of the waste and accumulate at the landfill's bottom, resulting in contaminated water known as leachate.	When leachate containing higher concentrations of nitrates and phosphates is mixed with surface water, the most widespread threat is eutrophication. In the open sectors of lakes, eutrophic conditions invariably result in excessive production of planktonic algae and cyanobacteria. This excessive algae production harms the marine life in the lakes by limiting light penetration. Furthermore, landfill leachates damage the quality of groundwater systems, posing health risks for humans and animals.	Lehane (1999), Lin et al. (2009)
Air	Bacterial decomposition produces landfill emissions (methane, carbon dioxide, and nitrogen) and odor gases (ammonia and hydrogen sulfide). The decomposition happens when organic waste is broken down by bacteria naturally present in the waste and the soil used to cover the landfill. The methane, carbon dioxide makes up about 90 to 98% of the landfill emissions, while ammonia, hydrogen sulfide, nitrogen and other gases make the 10% of landfill emissions.	Landfills contribute significantly to the world's anthropogenic greenhouse gas (GHG) emissions because vast amounts of methane (CH_4) and carbon dioxide (CO_2) are produced during the degradation process of deposited waste in landfills, which eventually contributes to global warming. Moreover, continuous inhalation of CH_4, CO_2 and the bad odor by humans can induce adverse health effects such as loss of coordination, headache, cancer, respiratory illness, nausea, vomiting, shortness of breath, and death at high concentrations.	Kumar et al. (2004), Shen et al. (2020)
Soil	The presence of high levels of nutrients, heavy metals, and soluble salts in waste leachates found in landfills has been proven to have detrimental impacts on soil quality. Heavy metals have been identified as a significant determinant of soil quality and long-term viability. These metals are non-biodegradable environmental contaminants that can deplete soil resources and have negative impacts on plant growth and yield.	Heavy metals and other leachate elements retained by the soil can have negative consequences for the ecosystem. As a result, the metals stored by the soil are taken up by plants, providing a critical route for metals to enter the food chain. Trace metal deposition in plants can impact crop development and yield, as well as posing a larger risk to animal health. Furthermore, lateral migration of gas pollutants via soil beyond landfill borders causes oxygen to be displaced from the soil. This promotes vegetation dieback and a fall in soil faunal numbers and burrowing animals.	Crowley et al. (2003), Yeilagi et al. (2021)
Natural Environment	The soil structure may be compromised in rehabilitated landfill areas because it might be saturated with chemicals or hazardous substances from the degradation of putrescible waste. In addition, the breakdown of putrescible waste produces hydrogen sulfide and ammonia, which produce a foul smell and strong pungent odor that can cause health effects over time.	Landfills have a significant influence on land value, deterioration, and availability. Depending on the distance from the landfills, leachate and gases have a detrimental influence on house prices. Potential hazards such as flies, odor, and smoke are mentioned as reasons why the general public does not want to live near landfills.	McKendry et al. (2002); Akinjare et al. (2011)

2021). Thus, the use of thermal processes like hydrostatic pressure, extrusion, pelleting, autoclaving as well as irradiation on fruit pomaces has the potential to increase their preservation and ensure safe utilization by destroying a wide range of microorganisms (Khattab and Arntfield, 2009). Rechkemmer (2007) reported that thermal processes alter the structure of plant cell walls, resulting in a significant increase on nutrient bioavailability. This could be due to their potential to deactivate trypsin inhibitors and other antinutrients (Khattab and Arntfield, 2009). Nonetheless, some studies have reported that thermal treatments tend to cause protein denaturation especially at high temperatures (Avilés-Gaxiola et al., 2018). It is worth noting that some thermal processes require advanced machinery, which automatically makes them less cost-effective. Avilés-Gaxiola et al. (2018) stated that thermal processes incur high cost and have a negative impact on both the environment and on the full protein functionality. This could be the reason why a limited number of research studies have sought to valorise the feed value of fruit pomaces using thermal processes.

CONTRIBUTION TO SUSTAINABLE DEVELOPMENT GOALS AND FOOD SECURITY

The sustainable development goals (SDG) by the United Nations revolves around the notion: "no farmer, no food." Sustainable development entails 17 goals some of which seek to achieve global food and nutrition security for all persons. Accordingly, the goals to combat poverty in all its forms, eradicate hunger, and improve nutrition can be achieved using fruit pomaces to support poultry production. Aili Hamzah et al. (2021) stated that sustainable waste management practices could be an antidote to the attainment of SDG since 12 of the goals are interconnected to solid waste management. Thus, the incorporation of fruit pomaces in poultry feeds would fulfill SDG and contribute to economic, social, and environmental sustainability by redirecting the waste from landfills to animal agriculture and subsequently reduce the cost of managing the waste. The presence of bioactive agents in the pomaces could also ensure that the goal to achieve good health and well-being is catered for because consumers would have direct access to organically produced high-quality poultry products. Indeed, several studies have shown that the use of dietary fruit pomaces improve the health status of the birds as well as their product quality (Islam et al., 2020; Sengul et al., 2021), which can potentially improve public health. More importantly, the use of fruit pomaces would reduce feed-food competitions which arise due to the use of human edible products such as maize, sorghum, soybean, and sunflower oils in animal feeds (Marareni and Mnisi, 2020). Thus, the use of fruit pomaces as ingredients with no direct food value for humans would ensure that both animal and crop food systems complement each other in achieving food and nutrition security worldwide.

Furthermore, some fruit pomaces have anti-methanogenic activities (Alexandre et al., 2019), which could be useful in an era where the entire world is battling the negative effects of climate change. This indicates the potential of fruit pomaces to lower carbon footprint in animal production systems by reducing the amount of methane emitted to the environment and, as a result, contribute to the goal to combat climate change and its impacts. In the past decades, there had been increasing concerns about the use of prophylactic antibiotics in animal feeds due to the risk posed by the development of pathogenic bacterial resistance and the presence of antibiotic residues in meat products that can compromise human health (Mahlake et al., 2021). Thus, fruit pomaces can be used to control the growth of pathogenic bacteria in poultry because they possess phytochemicals with antimicrobial activities (Gazalli et al., 2014; Kotsampasi et al., 2014). A recent study indicated that the use of red grape pomace promoted similar growth performance and meat quality attributes as the antibiotic (olaquindox and salinomycin) containing control diets (Mnisi et al., 2021). This reveals the potential of fruit pomaces to simulate organic or antibiotic-free poultry production systems that would meet the demands for organically produced poultry products. However, it remains important that an optimal inclusion level be determined for each fruit pomace in every poultry species to avoid compromising production performance and health status of the birds.

ENVIRONMENTAL BENEFITS OF FRUIT POMACES IN POULTRY NUTRITION

Over the years, agricultural producers have relied on first generation disposal strategies such as incineration and landfill deposition to manage waste with little regard to environmental consequences. This is exacerbated by the fact that fruit pomaces are currently not used for any significant commercial purposes, thus their management remains a major problem experienced by the agro-fruit industry. The disposal of fruit pomaces directly into landfills or through incineration causes serious environmental burden, as shown in **Table 2**. This is because fruit pomaces have high chemical and biological oxygen demands as well as biodegradable organic contents that results in ecological pollution, eutrophication, unwanted fermentation or microbial decomposition, and severe human and animal health hazards (Iqbal et al., 2021). To manage the waste, contemporary concepts such as the circular bio-economy and sustainable development goals indicate a global desire to reduce and re-use agro-wastes for environmental, economic, and social sustainability. Indeed, the vision of the bio-based economy is to unlock the full potential of all types of sustainably sourced biomass including fruit pomace and transform it into value-added products (FAO., 2019).

Garcia-Garcia et al. (2019) stressed out that reducing waste levels and identifying sustainable ways to manage the remaining waste are two main strategies that are required to implement a circular economy by agro-industries. Valorising fruit pomaces to support animal production is an ingenious strategy to protect the environment from wanton pollution caused by the traditional waste disposal methods and enhance food and nutrition security through the provision of meat and eggs to the ever-growing human population. This approach complements food production by ensuring that food animals are reared on feed ingredients that have no direct food value for humans. As already discussed above, fruit pomaces can be used either with minimal modification or after valorisation as dietary ingredients or as bedding in poultry production systems. The use of fresh or valorised fruit pomace in poultry production would, in the long run, reduce the amounts of waste destined for incineration and/or direct deposition in barren lands.

CONCLUSION

The utilization of fruit pomaces as sources of nutrients and biologically active substances in poultry diets could deliver efficient and sustainable poultry production systems, while reducing over-reliance on major conventional feed ingredients. Their large-scale incorporation into poultry feeds would also ensure that both animal and crop food systems complement each other in contributing to sustainable development goals and global food and nutrition security because fruit pomaces have no direct food value for humans. Although their dietary inclusions have been shown to improve growth performance, blood parameters, and meat and egg quality traits in various poultry birds, it is prudent that an optimum inclusion level is established for each poultry strain so as not to compromise their performance and well-being. Several feeding strategies can also be employed to valorise their feed value especially when included at higher dietary levels, however, the cost-effectiveness of each strategy should be considered. It can be concluded that the use of fresh and/or valorized fruit pomace in poultry nutrition can be long-term and sustainable strategy to manage and reduce their wanton disposal to the environment. Future studies should be designed to evaluate the cost-effectiveness of adding fruit pomaces as nutraceuticals in poultry diets.

AUTHOR CONTRIBUTIONS

CM conceptualized the study. CM, GM, and FM were equally involved in writing the first and final draft. All the authors read and approved the final version of the manuscript.

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