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Review Article

Fruit pomaces—their nutrient and bioactive components, effects on growth and health of poultry species, and possible optimization techniques

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ABSTRACT

The ever-growing human population, coupled with the exigent need to meet the increasing demand for poultry meat and egg, has put the onus on poultry nutritionists and farmers to identify alternative feed ingredients that could assure the least-cost feed formulation. In addition, the public desire for non-antibiotic-treated poultry products has also necessitated the ultimate search for potent antibiotic alternatives for use in poultry production. While some identified alternatives are promising, their cost implications and technical know-how requirements may discourage their ease of adoption in poultry. The use of plants and/or their by-products, like fruit pomaces, present a pocket-friendly advantage and as a result, are gaining much interest. This is traceable to their rich phytochemical profile, nutritional composition, ready availability, and relatively cheap cost. The fruit juice and wine pressing industries generate a plethora of fruit wastes annually. Interestingly, fruit pomaces contain appreciable dietary fibre, protein, and phenolic compounds, and thus, their adoption could serve the poultry industry in dual capacities including as substitutes to antibiotics and some conventional feedstuff. Thus, there is a possibility to reduce fruit wastes produced and feed-cost in poultry farming from environmental and economical standpoints, respectively. This review seeks to provide reinforcing evidence on the applicability and impact of fruit pomaces in poultry nutrition.

1. Introduction

Poultry is one of the commonest livestock species in animal husbandry, with chickens being one of the most popularly consumed (Agyare et al., 2018), particularly in Canada and the United States (Bedford, 1998; Economic Research Service/USDA, 2021). Globally, the chicken industry produces more than 9 trillion kilograms of chicken meat annually (Agyare et al., 2018). Current and future projections show that the poultry industry is continuously expanding in meat production (OECD/FAO, 2020) with the need to meet the protein demand of the ever-growing human population. To meet this increasing demand, the livestock feed supply is estimated to increase from 6.0 to 7.3 billion tonnes of DM (Kim et al., 2019). Interestingly, the cost of feeding birds dictates approximately 70 percent of the total cost of production (Thirumalaisamy et al., 2016; Borkar et al., 2021; de Oliveira et al., 2021). Thus, the sustainability and profitability of the poultry industry could partly and largely be dependent on nutritional manipulation. The use of agro-industrial waste as functional feed materials could be a promising strategy that could reduce feed costs while the nutritional qualities of the feed are still maintained (Matoo et al., 2001; Alhotan, 2021; de Oliveira et al., 2021). Fruits are considered an essential part of a healthy and balanced diet (Shahbandeh, 2021) because of their rich vitamins, minerals, polyphenols, and dietary fibre profiles (Wargovich, 2000). A measurable amount of the above-mentioned nutrients in fruits are also found in their by-products, including pomaces (Juśkiewicz et al., 2015; Kruczek et al., 2016).

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Fruit pomaces are intermediate products derivable after pressing or crushing whole fruits to extract their juice, especially in the fruit processing industries and wineries. Fruits, including but not limited to apple, carrot, orange, and berries, have been employed in the production of juice with large amounts of pomace produced following juice extraction (Kruczek et al., 2016). In the presence of oxidants, light, and heat, fruit pomaces undergo oxidation and fermentation reactions almost immediately after processing (Bhushan et al., 2008; Lou et al., 2014) and may degrade valuable compounds within them (Gowman et al., 2019). Currently, their disposals pose an environmental health risk due to their high volume and moisture content, thus becoming a suitable substrate for obnoxious microbes to thrive. However, appropriate processing, including drying of pomace following juice extraction, could solve the disposal predicament. Drying or storing pomaces up in less than 0 °C is a reported method to slow down oxidation and fermentation. Fruit pomaces usually comprise the combination of residual seeds, skin or peel, and stalk or stem of the fruit. Reports have shown that the available amount of pomace in orange, apple, carrot, berries, and grape include 45%–60%, 25%, 30%–50%, 20%–30%, and 20%–25%, respectively (O'Shea et al., 2015; Struck et al., 2016; Kodagoda and Marapana, 2017; Yu et al., 2018; Gowman et al., 2019). Most of these by-products are underexploited and are thus mostly discarded or used for unproductive purposes like landfills (Gowman et al., 2019). It would be a worthwhile approach to adopt these relatively cheap by-products in a dual-capacity as dietary fibre ingredients and antioxidants in poultry nutrition, which could consequently reduce feed cost (Colombino et al., 2020). Unfortunately, complementary studies on the cost implication of the adoption of fruit pomaces in poultry nutrition and production are lacking or do not exist.

The nutritional application of dietary fibre has gained increasing attention due to its identified beneficial capacities on bowel health and calorie reduction in humans (Stephen and Cummings, 1980) and promoting satiety (Buttriss and Stokes, 2008). Dietary fibre substances including polysaccharides, oligosaccharides, cellulose, hemicellulose, and lignin have been implicated in causing laxation, hypocholesterolemic propensity and/or blood glucose attenuation (AACC, 2000; Fuller et al., 2016). These beneficial physiological effects might depend on the fibre type, chemical structure, viscosity, processing, and inclusion levels in poultry diets (Svihus, 2011; Choct, 2015). Interestingly, non-viscous low-molecular-weight dietary fibres, such as oligosaccharides and fructans, are soluble in water and well-fermented and have a prebiotic effect in the poultry gut (Carre et al., 1995; Choct, 2015) leading to the domination of the gut by lactobacilli and bifidobacteria (Elia and Cummings, 2007). In some studies, increase in number and size of villi throughout the small intestine of geese, turkey, broiler chickens, and quail have been reported following the increase in the dietary fibre content of isonitrogenous and isocaloric diets (Chiou et al., 1996; Sklan et al., 2003; Rezaei et al., 2018). There are burgeoning shreds of evidence that fruit pomaces contain about 50%–70% of dietary fibre and a considerable amount of polyphenolics—known substances with a wide spectrum of beneficial bioactivities (Schieber et al., 2001; Ajila et al., 2007; Okonogi et al., 2007; Vieira et al., 2009; Juśkiewicz et al., 2015).

It is, therefore, noteworthy that fruit pomaces could also be tapped in addressing the increasing public concerns about food security and safety through the provision of antibiotic-free poultry products, namely meat and eggs. The polyphenolic compounds present in fruit pomace could exert positive effects in the modulation of gastrointestinal microbial activity, histomorphology, and functionality of the gut (Chamorro et al., 2017, 2019; Fotschki et al., 2015; Kumanda et al., 2019), as well as ceca short-chain fatty acid production in broiler chickens (Colombino et al., 2020; Erinle et al., 2021). The incorporation of different fruit pomaces into the diets of different poultry species is now innovatively studied (Colombino et al., 2020). In studies that involve feeding fruit pomace derived from berries, a maintained growth performance and increased oxidative balance in the meat of turkey was reported (Juśkiewicz et al., 2015; Juskiewicz et al., 2017). Supplementation of maize–soybean diet with dietary fruit pomace derived from grape has also been considered effective without adverse effects on broiler chickens (Sáyago-Ayerdi et al., 2009; Brenes et al., 2016). Although dietary polyphenols have been reported to interfere with nutrient metabolism (Yilmazer-Musa et al., 2012), polyphenols in fruit pomaces could maintain birds' performance at certain threshold inclusion levels. Besides the in vivo application of fruit pomaces, their polyphenols have also been implicated in the augmentation of oxidative stability of foods by preventing lipoxidation and salvaging body tissues from harmful radical species (Makris et al., 2007). It is believed that routine use of these products in poultry nutrition will improve the profitability of chicken farmers and create value-added market opportunities for fruit processors, reduce the ecological burden of disposing of pomaces, and provide suitable alternatives for antibiotics use.

While several studies have demonstrated the use of fruit pomaces in poultry nutrition, their varying inclusion levels have enormously contributed to the inconsistent results, especially on the growth performance of poultry species. With regards to the impact of fruit pomaces reported in some poultry research, possible threshold inclusion levels where optimal performance is afforded could be identified. The present review aims to provide a more aggregated information on the nutrient and phenolic content of some fruit pomaces, their effects on the growth and health of poultry birds with critical evaluation of their inclusion levels, and how they could be optimized for poultry feeding.

2. Some fruit pomaces, their polyphenols, and nutrient composition

The content and composition of nutrients and polyphenols in fruit pomaces vary depending on certain factors, including the fruit type, fruit cultivar, and perhaps edapho-climatic conditions from where they are harvested. The corresponding obtainable quantity of some fruit pomaces following juice extraction is reported in Table 1. Since different fruit pomaces contain varying concentration levels in their phenolic components, total phenolic content (TPC) and antioxidant assay would be sufficient to guesstimate their efficacy. Juskiewicz et al. (2017) demonstrated that the total concentration of polyphenols was lowest in apple pomace compared to blackcurrant, strawberry, and seedless strawberry using a high-performance liquid chromatography system. However, when these pomaces were supplemented into poultry diets, their polyphenol content, antioxidant activity, as measured using 2,2′-azinobis-(3-ethylbenzothiazoline-6-sulfonic acid (ABTS), and the antioxidant capacity of diets were potentiated compared to the non-supplemented corn–soya–wheat diet (Juskiewicz et al., 2017; Colombino et al., 2020). Wang et al. (1996) and Tsao and Deng (2004) have reported that phenolic acids from fruits have antioxidant activities that exceed the values exhibited by vitamins C and E. Thus, fruit pomaces could be a cheap alternative to vitamins C and E not only for their antioxidant capacity but also for the incurred cost associated with such vitamin use in poultry production. It should be noted that the polyphenolic profile of fruit pomaces is multifactorially influenced depending on the types of fruit species and cultivars, edapho-climatic factors, and processing and extraction methods.

In addition to the polyphenol content, it is remarkable that fruit pomaces contain a considerably high amount of crude protein and

Table 1
Fruits and their corresponding yieldable quantity of pomace in percentage.

Fruit pomace	Quantity (% of fruit weight)	References
Apple	25	Kodagoda and Marapana (2017)
	30	Vendruscolo et al. (2008)
	25 to 35	Joshi and Attri (2006)
Orange	45 to 60	O'Shea et al. (2015), Ugwuanyi (2016), Papoutsis et al. (2018a)
Grape	20 to 30	Dwyer et al. (2014), Kalli et al. (2018), Muhlack et al. (2018), Gowman et al. (2019), Kumanda et al. (2019)
Strawberry	50 to 63	Jaroslawska et al. (2011), Juśkiewicz et al. (2015)
Wild blueberry	20	Hoskin et al. (2019)
Pineapple	50	Ugwuanyi (2016)
Cranberry	42 to 53	Harrison et al. (2013)
Olive	30	Rodríguez-Gutiérrez et al. (2012)

dietary fibre and thus could be sought as a possible alternative for both antibiotics and some conventional feed ingredients in the poultry industry. However, the recovery of polyphenols from plant materials is influenced by the solubility of the phenolic compounds in the solvent used for the extraction process. The nutrient composition of some fruit pomaces is presented in Table 2. In addition, the TPC and total antioxidant activity of some fruit pomaces are shown in Table 3. There are a number of fruit pomaces that are available for use in poultry feed. They include but are not limited to those discussed below.

2.1. Strawberry (Fragaria ananassa) pomace

There has been a remarkable interest in berries that contain polyphenols due to their color. Strawberry is one of the most sought and consumed regardless of the form (fresh or processed) (Jaroslawska et al., 2011). The estimated global yield of strawberries is about 224,142 hectograms per hectare in 2019 (FAOSTAT, 2021). The beneficial impacts of strawberries have been reported in in vitro and animal studies and are attributed to their polyphenol constituents. Some of the major phenolic compounds in strawberries include ellagic acid, quercetin, cyanidin glucosides, and complex phenolic polymers including ellagitannins (Puupponen-Pimiä et al., 2005; Heinonen, 2007; Basu et al., 2009). The total amount of extractable polyphenols is dependent on the type of solvent used, their polarity, and time of extraction. According to Felix et al. (2021), the TPC in strawberry by-products, particularly bagasse, was highest when the solvent used is 80% water + 20% acetone mixture compared to ethanol or acetone. In the same study, the maximum total phenolic in strawberry pomace was 1,067.45 ± 10.7 mg gallic acid equivalent (GAE)/100 g. Cultivated varieties of strawberries have also shown variations in the amounts of polyphenols contained in their pomaces. Strawberry pomaces contain an equal amount of anthocyanin profile including 2 pelargonidin glucosides (Šaponjac et al., 2015). The principal anthocyanin compound is pelargonidin-3-glucoside accounting for over 70% of the total anthocyanins in strawberry pomace (Zhao, 2007; Giampieri et al., 2012). Strawberry pomaces have been reportedly confirmed to possess more antioxidant activity compared to some other fruit pomaces which is attributable to their higher 2,2-diphenyl-1-picrylhydrazyl (DPPH) assay values when compared to some other fruit pomaces.

2.2. Wild blueberry (Vaccinium corymbosum) pomace

Wild blueberry, also called low-bush blueberries in the Atlantic and Quebec provinces of Canada. From the available reports of FAOSTAT (2021), the mean yield of blueberries fruit in 2019 is estimated to be 68,914 hectograms per hectare on a global scale. Blueberries have been consistently rated among the top of many health foods for their good taste and high antioxidant capacity (Kalt and Dufour, 1997; Prior et al., 1998; Kalt et al., 1999). Blueberry pomace is one of the major by-products of the juice industry. Ross et al. (2017) reported that the pomace contains carbohydrates, proteins, lipids, minerals, and abundant polyphenols, including flavonoids like anthocyanins and flavonols. The phenolic compounds in blueberry pomace vary with their cultivars (Bhatt and Debnath, 2021; Mallik and Hamilton, 2017) and storage and increases from early to late harvest (Mallik and Hamilton, 2017). The phenolic compounds have been demonstrated to have a wide range of beneficial health effects, including anti-oxidative stress, anti-ageing, anti-fever, anti-diabetic, anti-inflammatory, hypocholesterolemic, and anti-cancer bioactivities (Gouw et al., 2017; Hoskin et al., 2019; Al Hasani et al., 2021). Identified polyphenols in blueberry include delphinidin-3-galactoside, delphinidin-3-glucoside, cyanidin-3-galactoside, delphinidin-3-arabinoside, cyaniding-3-glucoside, petunidin-3-galactoside, peonidin-3-galactoside, malvidin-3-galactoside, and peonidin-3-glucoside (Mi et al., 2004; Esposito et al., 2014; Debnath-Canning et al., 2020). An in vitro study on wild berry polyphenol-protein matrix shows it could hinder gluconeogenesis by inhibiting phosphoenol pyruvate carboxykinase and fibroblast migration activity (Jiang et al., 2011; Welch et al., 2018; Hoskin et al., 2019).

2.3. Olive (Olea europaea) pomace

The olive industry also produces a substantial amount of solid biomass derived following oil extraction. This solid waste is referred to as oil pomace. In comparison with other fruits, the global production of olives is relatively low, given the estimated global mean yield of 18,400 hectograms per hectare. However, about 3 million tonnes of oil pomace are generated annually and globally (Simonato et al., 2019). Like other pomaces, the pomace contains a high amount of dietary fibre, in addition to the minerals and fatty acids and polyphenol contents (Christoforou and Fokaides, 2016; Alvarez Serafni and Tonetto, 2019). The nutrient composition for olive pomace has been reported in the literature, as presented in Table 2. One of the significant limitations peculiar to olive pomace is that it suffers rancidity because its oil component undergoes oxidative reaction in the presence of oxygen and moisture (Mozuraityte et al., 2016); however, proper drying prior to feeding to poultry birds would help to slow this chemical reaction. Concentrations of polyphenols in olive pomace are largely dependent on the extraction methods employed. During the extraction process, crushing, malaxation, and drying are considered as the pivotal pressure points which reduce or inactivate bioactive compounds in olive pomace (Servili and Montedoro, 2002; Yorulmaz et al., 2011; Clodoveo, 2012; de Oliveira et al., 2021). Bioactive constituents in olive pomace include oleuropeoside compounds (oleuropein and verbascoside), flavonoids (luteolin, luteolin-7-glucoside, apegenin-7-glucoside, diosmetin, diosmetin-7-glucoside, and rutin), flavanols (catechins), simple

Table 2
Nutrient composition and fibre fractions of some dried fruit pomaces reported in literature.

Fruit pomaces	Nutrient composition						Fibre fractions					References
	ME, kcal/kg	DM, %	CP, %	EE, %	CF, %	Ash, %	TDF, %	IDF, %	SDF, %	NDF, %	ADF, %	
Apple	–	92.4	6.6	2.6	22.0	1.1	56.5	–	–	41.2	30.3	Juskiewcz et al. (2015)
	–	92.4	6.6	2.6	22.0	1.1	56.5	51.7	9.1	–	–	Colombino et al. (2020)
	–	–	–	–	–	–	–	29.1	2.5	–	–	Gouw et al. (2017)
	–	98.4	6.4	13.7	–	–	79.3	68.1	11.2	–	–	Swanson et al. (2001)
	–	93.2	–	–	–	–	60.1	–	–	–	–	Nawirska and kwasniewska (2005)
	–	89.6	2.7	1.5	–	1.8	–	–	–	–	–	Sato et al. (2010)
	–	89.2	2.1	2.7	–	0.5	51.1	36.5	14.6	–	–	Sudha et al. (2007)
	1,379	89.6	5.5	4.8	18.0	3.4	–	–	–	–	–	Ayhan et al. (2009)
	–	90.0	37.0	29.0	9.0	5.3	–	–	–	–	–	Aghili et al. (2019)
	–	96.4	0.5*	–	–	1.8*	53.1*	47.0*	6.1*	–	–	Wang et al. (2019)
	–	92.4	6.6	5.5	14.5	–	–	–	–	39.0	20.8	Xiong et al. (2020)
	–	88.9	6.9	3.3	25.7	1.5	–	–	–	42.1	34.3	Pieszka et al. (2015)
	–	–	7.9	3.0	20.0	4.3	–	–	–	47.7	–	Ganai et al. (2006)
	2,950	95.3	5.1	3.7	26.7	–	–	–	–	–	–	Joshi and Attri (2006)
Apple cultivars												
'Royal Gala'	–	–	–	–	–	–	78.2	63.9	14.3	–	–	Figuerola et al. (2005)
Granny Smith	–	–	–	–	–	–	60.7	56.5	4.1	–	–	Figuerola et al. (2005)
'Liberty'	–	–	–	–	–	–	89.8	81.6	8.2	–	–	Figuerola et al. (2005)
Strawberry	–	93.2	16.4	10.4	31.4	8.0	63.0	–	–	–	–	Juskiewcz et al. (2015)
	–	93.2	16.4	10.4	31.4	8.0	63.0	52.5	0.4	–	–	Colombino et al. (2020)
	–	91.0	16.2	11.6	35.8	3.7	–	–	–	45.4	40.7	Pieszka et al. (2015)
Seedless strawberry	–	94.8	17.8	9.6	26.3	5.9	59.6	–	–	–	–	Juskiewcz et al. (2015), Colombino et al. (2020)
	–	94.8	17.8	9.6	26.3	5.9	59.6	–	–	–	–	
Olive cake	1,600	–	5.2	11.8	14.1	20.4	–	–	–	–	–	Al-Harthi and Attia (2016)
	2,463	–	9.1	9.0	18.5	7.5	–	–	–	39.3	22.0	El-Galil et al. (2017)
	–	87.2	9.7	10.7	20.0	8.0	–	–	–	–	–	El-Moneim and Sabic (2019)
	3,751	90.0	10.7	12.0	24.0	7.5	–	–	–	34.0	–	Ibrahim et al. (2019)
	–	87.8	6.4	3.0	27.7	7.7	–	–	–	49.3	39.2	Rebollada-Merino et al. (2019)
	–	67.2	7.8	15.5	–	–	–	–	–	58.1	–	Iannaccone et al. (2019)
	4,400	94.1	9.8	18.3	21.5	7.1	–	–	–	–	–	Nasopoulou et al. (2018)
	2,675	94.5	8.6	17.5	27.5	–	–	–	–	–	–	Papadomichelakis et al. (2019)
	2,675	93.0	6.1	7.6	48.2	7.4	–	–	–	–	–	Pappas et al. (2019)
	–	87.0	10.2	–	24.0	–	–	–	–	26.0	34.0	Zarei et al. (2011)
	–	93.0	6.1	7.6	48.2	7.4	–	–	–	–	–	Afsari et al. (2013)
Processed olive	2,980	93.5	10.7	13.0	25.6	8.5	–	–	–	71.6	55.0	Sayehban et al. (2016, 2020)
Unprocessed olive	1,250	93.6	7.1	8.5	35.0	6.2	–	–	–	74.4	58.4	Sayehban et al. (2016, 2020)
Olive pulp	1,600	95.0	6.1	7.1	48.2	–	–	–	–	–	–	Zangeneh and Torki (2011)
Olive pulp	2,230	91.5	10.4	13.5	23.8	–	–	–	–	–	–	Elbaz et al. (2020)
Citrus												
Orange	–	89.5	6.0	1.9	–	3.7	40.5	–	–	–	–	O'Shea et al. (2015)
Sweet orange	–	83.3	8.5	2.1	–	2.7	–	31.8	14.1	–	–	Nagarajaiah et al. (2016)
Sweet lemon	–	80.4	7.3	2.2	–	4.2	–	24.2	19.7	–	–	Nagarajaiah et al. (2016)
Raspberry	–	–	–	–	–	–	–	38.1	0.34	–	–	Gouw et al. (2017)
	5,746	93.9	10.3	11.5	46.5	–	–	–	–	–	–	Sosnówka-Czajka and Skomorucha (2021)
Cranberry	–	–	–	–	–	–	–	57.9	0.45	–	–	Gouw et al. (2017)
	–	95.4	5.2*	–	–	0.6*	59.3*	56.2*	3.0*	–	–	Wang et al. (2019)
	–	–	5.8	4.4	–	1.1	61.8	–	–	46.3	15.5	Ross et al. (2017)
	–	–	5.8	4.4	–	1.1	61.8	–	–	46.3	15.5	Islam et al. (2020)
Blueberry	–	–	–	–	–	–	–	49.0	0.97	–	–	Gouw et al. (2017)
	–	94.8	13.0*	–	–	1.1*	59.1*	56.7*	2.4*	–	–	Wang et al. (2019)
		–	8.4	5.4	–	1.2	–	–	–	–	–	Ross et al. (2017)
Cherry	–	91.4	–	–	–	–	71.4	–	–	–	–	Nawirska and kwasniewska (2005)
Chokeberry	–	90.8	–	–	–	–	95.8	–	–	–	–	Nawirska and kwasniewska (2005)
	–	90.2	10.8	5.2	21.8	2.0	–	–	–	34.7	35.6	Pieszka et al. (2015)
	4,858	93.0	9.6	5.2	20.0	–	–	–	–	–	–	Sosnówka-Czajka and Skomorucha (2021)
Grape												
Red grape	–	93.3	10.4	10.1	–	–	–	–	–	46.3	48.4	Erinle et al. (2021)
Grape	–	–	13.8	10.3	32.5	2.4	–	–	–	–	–	Goñi et al. (2007)
Grape	–	–	13.9	1.0	15.2	2.4	–	–	–	–	–	Brenes et al. (2008)
Grape	–	–	13.9	1.0	15.2	2.4	–	–	–	–	–	Sáyago-Ayerdi et al. (2009)
Grape	–	91.0	9.5	8.7	–	2.7	–	–	–	–	–	Baumgärtel et al. (2007)
White grape	4,466	30.5	9.3	4.8	19.9	–	–	–	–	30.6	25.7	Baumgärtel et al. (2007)
Red grape	4,968	27.3	15.5	7.0	31.2	–	–	–	–	50.7	36.5	Swanson et al. (2001)
Grape	–	86.8	15.9	7.7	–	–	54.7	50.2	4.5	–	–	Nagarajaiah et al. (2016)
Blue grape	–	85.5	3.6	1.8	–	1.7	–	28.2	12.8	–	–	Nagarajaiah et al. (2016)
Red grape	–	–	13.9	1.0	34.3	2.4	–	–	–	–	–	Chamorro et al. (2015)
Fermented grape	–	–	28.3	3.8	22.2	8.5	–	–	–	–	–	Gungor et al. (2021)
Grape	–	–	12.6	5.9	18.8	4.1	–	–	–	–	–	Gungor et al. (2021)
Red grape	–	96.6	11.4	71.0	–	–	–	–	–	40.9	32.3	Jonathan et al. (2021)
Grape[1]	–	93.9	10.1	9.2	18.2	3.9	–	–	–	38.3	32.5	Hanušovský et al. (2019)
Grape pomace	–	–	13.9	9.1	14.3	23.7	–	–	–	–	–	Alm El-Dein et al. (2017)

Table 2 (*continued*)

Fruit pomaces	Nutrient composition						Fibre fractions					References
	ME, kcal/kg	DM, %	CP, %	EE, %	CF, %	Ash, %	TDF, %	IDF, %	SDF, %	NDF, %	ADF, %	
Grape pomace	–	89.9	12.3	6.0	35.2	2.8	–	–	–	–	–	Vlaicu et al. (2017)
Grape pomace	4,398	91.5	8.9	7.0	30.2	3.3	–	–	–	–	–	Ebrahimzadeh et al. (2018)
Grape pomace	2,433	–	13.3	8.4	19.3	4.5	–	–	–	–	–	Hosseini-Vashan et al. (2020)
Pineapple	–	84.5	4.3	1.4	–	1.2	–	30.3	0.4	–	–	Nagarajaiah et al. (2016)
	_	96.2	4.7	0.6	–	2.2	45.2	44.4	0.8	–	–	Selani et al. (2014)
	_	96.6	4.7	0.6	–	2.2	44.4	43.5	0.6	–	–	Kumar et al. (2018)
	_	95.6	6.0	1.4	–	–	79.8	62.2	17.6	–	–	Saikia and Mahanta (2015)
	_	90.7	4.0	1.3	–	4.5	75.8	75.2	0.6	–	–	Martínez et al. (2012)

*Values of nutrient composition expressed on wet weight basis.

ME = metabolizable energy; DM = dry matter; CP = crude protein; EE = ether extract; CF = crude fibre; TDF = total dietary fibre; IDF = insoluble dietary fibre; SDF = soluble dietary fibre; NDF = neutral detergent fibre; ADF = acid detergent fibre.

[1] Average nutrient composition of grape pomace obtained in 2 different locations in Slovakia.

Table 3

Total phenolic content (TPC) and radical scavenging activity of dried fruit pomaces.

Fruit pomace	TPC[1]	Total antioxidant activity				References
		DPPH[2]	RSA[3]	ABTS[4]	ORAC[5]	
Apple	5.5	32.0	–	–	–	Juskiewicz et al. (2017)
	8.4	–	–	–	–	Colombino et al. (2020)
	≃7.5	–	≃4.0	–	–	Gouw et al. (2017)
	_	47.3[6]	–	–	–	Pieszka et al. (2015)
	5.75	–	–	–	–	Juskiewicz et al. (2015)
Strawberry	10.3	84.7	–	–	–	Juskiewicz et al. (2017)
	28.9	–	–	–	–	Colombino et al. (2020)
	_	39.3[6]				Pieszka et al. (2015)
Seedless strawberry	43.1	256.4	–	–	–	Juskiewicz et al. (2017)
Olive (processed)	3.7	–	–	–	–	Sayehban et al. (2016)
	1.9	–	–	–	–	Sayehban et al. (2016)
Olive (unprocessed)	12.5	–	–	–	–	Nasopoulou et al. (2018)
Raspberry	≃25.0	–	≃43.0	–	–	Gouw et al. (2017)
Cranberry	≃2.5	–	≃4.0	–	–	Gouw et al. (2017)
	24.9	–	–	144.1	–	Ross et al. (2017)
Wild blueberry	91.3 to 156.3	488.3 to 714.1	–	–	–	Hoskin et al. (2019)
Blueberry	0.11[7]	3.67[7]	–	–	–	Bhatt et al. (2021)
	≃8.0	–	≃9.0	–	–	Gouw et al. (2017)
	31.1	–	–	24.2	–	Ross et al. (2017)
Citrus						
Dried lemon	14.4 to 17.2	0.12 to 0.13	–	–	–	Papoutsis et al. (2018b)
Lemon (microwave-treated)	62.8	–	–	–	–	Papoutsis et al. (2018c)
Lemon (untreated)	40.9	–	–	–	–	Papoutsis et al. (2018c)
Grape						
Red grape	12.3	–	–	–	–	Erinle et al. (2021)
	12.4	–	–	–	–	Kasapidou et al. (2016)
Red grape cultivars						
Touriga Nacional	69.3	0.52	–	–	1,054	Tournour et al. (2015)
Touriga Franca	100.1	0.87	–	–	1,343	Tournour et al. (2015)
Tinta Roriz	131.7	1.09	–	–	2,337	Tournour et al. (2015)
Pineapple	368.5	68.4	–	–	–	Saikia and Mahanta (2015)
	129[8]	4.8[8]	–	7.7[8]	–	Martínez et al. (2012)

≃ Approximately.

[1] TPC = total phenolic content, mg gallic acid equivalent (GAE) per gram dry weight.

[2] DPPH = 1,1 diphenyl-1-picryl hydrazyl assay, µmol trolox equivalent per gram.

[3] RSA = radical scavenging activity, mg ascorbic acid equivalent per gram dry weight.

[4] ABTS = 2,2′-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid), µmol trolox equivalent per gram.

[5] ORAC = oxygen radical absorbance capacity, µmol trolox equivalent per gram.

[6] DPPH, total antioxidant activity reported as percentage (%).

[7] Values with unit as mg GAE per gram fresh leaf.

[8] Methanol-acetone extracted TPC value reported in mg GAE per 100 g dry weight.

phenolic compounds (tyrosol, hydroxytyrosol, vanillin, vanillic acid, and caffeic acid), etc (Ryan et al., 2002). However, olive pomace has also been shown to contain xyloglucans, a non-starch polysaccharide that possesses antinutritional effects in monogastric animals (Al-Harthi, 2014) particularly poultry. Notwithstanding, some studies have shown that olive pomace has been incorporated into poultry's diets without negative outcomes on performance (El Hachemi et al., 2007; Zarei et al., 2011; Sayehban et al., 2016).

2.4. *Citrus (Citrus spp.) pomaces*

Citruses are some of the most abundant and widely distributed crops in the world and are rich in vitamin C, folic acid, potassium, and pectin. Citruses include oranges, lemons, limes, tangerines, grapefruit, and mandarin, etc. According to the estimated values reported by FAOSTAT (2021), the global mean yield of oranges, lemons, and limes, and tangerines are approximately 193,835, 163,455, and 128,566 hectograms per hectare in 2019. Citrus pomaces are derived from the industrial production of orange and/or lemon juice and it constitutes all the residue following juice extraction. The residue could account for approximately 60% of the citrus fruit itself (Ugwuanyi, 2016). Remarkably, the citrus processing plants generate more than 15 million tonnes of citrus peel alone on an annual basis (Morinaga et al., 2021). The surface and inner white layers of citrus peels are rich in flavedo and albedo, respectively (Rafiq et al., 2018). Flavedo has been shown to be an important source of ascorbic acid, polymethoxyflavones, and carotenoids, while albedo contains phenolics, flavanones, and antioxidant activity (Escobedo-Avellaneda et al., 2014). Bioactive substances in citrus pomaces include essential oil (mainly monoterpenes and triterpenoids), phenols (coumaric, caffeic, and ferulic acids), and flavonoids, mainly flavanones glycosides (hesperidin, naringin, and narirestin), flavones (hesperetin, naringenin), flavones aglycon (luteolin), and polymethoxylated flavones (tangeretin) (Fermoso et al., 2018). However, the concentration of flavonoids found within the citrus peels was reported to be higher than in juice and seeds (Tao et al., 2014). The nutrient composition and antioxidant capacity of citrus pomace are presented in Tables 2 and 3

2.5. Grape (Vitis vinifera) pomace

Grape is one of the fruits that have been reported to contain high polyphenols, especially in its skin. Grape pomace is the main derived product of the wine industry and mainly consists of skin, seeds, stems, and the remaining pulp (Fermoso et al., 2018; Gowman et al., 2019; Erinle et al., 2021). FAOSTAT (2021) surmised that about 111,374 hectograms per hectare of grapes are produced annually and globally. The dietary fibre and phenolics in grape pomace are largely dependent on its varieties and technology employed in the wine-making process. The most abundant polyphenols in grape pomace include phenolic acids (caffeic acid, gallic acid, protocatechuic, 4-hydroxybenzoic, and syringic acid), phenolic alcohols (hydroxytyrosol), flavonoids (catechin, epicatechin, quercetin-3-O-rhamnoside, and luteolin), stilbenes (resveratrol), and proanthocyanidins (Teixeira et al., 2014; Erinle et al., 2021). The ability of grape pomace to significantly improve the synthesis of vitamin E in the liver of poultry birds has been reported (Goñi et al., 2007). Increased vitamin E concentration in the body suggests a reinforced antioxidant capacity. In addition, the antioxidant potential of grape pomace has been implicated in increased levels of glutathione peroxidase and superoxide dismutase enzyme activities in the gastrointestinal tract (Kithama et al., 2021). Besides the bioactivities of grape pomace, reports have shown that it contains some nutrients including protein, fibre, soluble sugar, etc. The nutrient content, TPC, and antioxidant capacity of grape are reported in Tables 2 and 3.

2.6. Apple (Malus domestica) pomace

Among the most important pomaces that have been sought in livestock feeding is the apple pomace. According to FAOSTAT (2021), the global production of apples is estimated at 184,925 hectograms per hectare. Interestingly, apple pomace contains dietary fibre, phenolic compounds, vitamins, and organic acids which are essentially of health significance. Important phenolic compounds found within the pomace include quercetin glycosides, kaempferol, catechin, procyanidins, and especially dihydrochalcone phlorizin (Fermoso et al., 2018; Mourtzinos and Goula, 2019). Bioactive substances in apple pomace have shown antimicrobial, anticancer, and cardio–protective activities.

2.7. Pineapple (Ananas comosus) pomace

Pineapple pomace is a significant by-product of the juice industry using pineapple in their production process. During and after the juice extraction, there is a large amount of recoverable by-products including peel and pomace accounting for 25%–50% of the fruit weight (Larrauri et al., 1997; Ugwuanyi, 2016). The fibre component of pineapple pomace is approximately 76% out of which 99.2% and 0.8% represent the insoluble and soluble fibre fractions, respectively (Martínez et al., 2012). However, their phytochemical profile shows the pomace contain 7.61 mg/100 g gallic acid, 11.09 mg/100 g caffeic acid 0.63 mg/100 g syringic acid, 0.12 mg/100 g ferulic acid (Saikia and Mahanta, 2015).

2.8. Cranberry (Vaccinium macrocarpon) pomace

Cranberry pomace is one of the fruit pomaces that has come into the limelight as possible feedstuff in livestock production. Alongside blueberry, cranberry remains an economically important crop, especially in Canada. The amount of derivable pomace per weight of fresh cranberry fruit is reported in Table 1. Ross et al. (2017) reported that organic cranberry pomace contains total phenolics (12.99 mg GAE per gram), tartaric esters (2.77 mg caffeic acid equivalent per gram), flavonols (3.08 mg quercetin equivalent per gram), and anthocyanins (4.46 mg cyanidin-3-glucoside equivalent per gram). Other polyphenols in cranberry pomace include catechin, caffeic acid, quercetin, and cyanidin-3-glucoside (Harrison et al., 2013). The antioxidant, antimicrobial, anti-inflammatory, and vasodilatory activities of these phenolic compounds have been reported in vitro (Biswas et al., 2012; Harrison et al., 2013) and meat studies (Das et al., 2017).

3. Potential of some fruit pomaces in poultry nutrition

3.1. Growth performance

Fruit pomaces have been reported to majorly maintain growth performance in poultry species, mostly chickens. This could be partly due to their dietary fibre constituents and polyphenolic profile, which may influence their inclusion levels in poultry diets. For example, the xyloglucans present in the cell wall of olive pomace have been thought to be an antinutritional factor that might affect the metabolism of the ingesting animals. Reis et al. (2002) confirmed that the xylose-to-glucose ratio in olive pomace is 7:1; this suggests that the antinutritional factor is considerably high. However, Sayehban et al. (2016) demonstrated that the xyloglucans concentration in both processed and unprocessed olive pomace would not reduce the performance of broiler chickens when included at 100 g/kg of diet. There are reports suggesting that the addition of olive pomace up to 150 g/kg could be used in broiler chicken diets without adverse effects on growth (El Hachemi et al., 2007). Conversely, there was a significant deterioration of growth performance in local hen fed 12% olive pulp meals; however, at 8% dietary inclusion, feed intake (FI), body weight (BW), weight gain (WG), and feed conversion ratio (FCR) were significantly improved (El-Galil, 2017). In duckling, a decrease in FI, BW, WG, and FCR was reported as inclusion levels of olive cake meal increased from 10% to 30% (Hassan, 2020). However, at lower inclusion (up to 4%), olive cake meal was shown to enhance growth parameters of broiler chickens, particularly when supplemented with *Bacillus licheniformis* (Saleh et al., 2020). Supplementation of 750 mg/kg olive pomace extract (containing 2% polyphenols and 10% triterpenes) was found to improve the average daily gain (ADG) and FCR of broiler chickens during the grower-finisher period (Herrero-Encinas et al., 2020). Most studies using olive pomace reported a neutral effect on the hen-day production of birds. Rezar et al. (2015) and Zangeneh and Torki (2011) found that the addition of olive pomace at 100 and 4.5 g/kg did not increase egg production compared to the control treatment in Isa Brown and Lohmann birds, respectively. According to Pavlovski et al. (2009), the success of the modern poultry enterprise could be reliably measured using their production efficiency index (PEI) compared to the performance. The PEI is calculable using the following equation: PEI = [(Average birds' weight × Livability)/Market age × FCR] × 100. When processed olive pomace was fed to broiler chickens, Sayehban et al. (2016) observed an improvement in the PEI. Although, olive pomace contains antioxidant polyphenols, it may suffer oxidative rancidity due to its high oil and moisture contents. However, an approriate optimization technique might suffice prior to the application of olive pomace in poultry production. Like every other pomaces inclusion levels of olive by-products are critical for its better utilization among poultry species. Unfortunately, application of additives, including enzymes, citric acid, etc., seems not to present the desired utilization efficiency in poultry. However, from most recent studies, inclusion level of ≤10% could be considered optimum for olive by-products and would probably present a cost-friendly advantage in poultry feeding without negatively affecting performance (Table 4).

The dietary fibre of apple pomace contributes to the improvement in the digestion and metabolism of livestock. With their prebiotic mode of action, apple pomace promotes the population of beneficial gut microflora (Beermann et al., 2021; Kithama et al., 2021). Soluble dietary fibre increases viscosity and retention time of digesta within the gut of livestock. Apple pomace contains malic acid which acts as a functional compound that modulates the peristaltic movement of food in the gastrointestinal tract (Sato et al., 2010). Like other fruit pomaces, there are inconsistencies in literature reports on the impact of apple pomace on the growth performance of poultry birds. In addition to these inconsistencies, various authors proposed a varying inclusion level which they perceived to be optimum. In the study conducted by Ayhan et al. (2009) and Bhat et al. (2000), 10% level of apple pomace was reported to be optimum to maintain BW of broiler chicken study while inclusion at 15% resulted in reduced BW and increased FCR. Akhlaghi et al. (2014) reported that inclusion of dried apple pomace up to 25% did not affect BW of breeder roosters, however, fertility, hatchability of set eggs, hatchability of fertile eggs, and embryonic mortality were significantly reduced. In layer chickens, Yildiz et al. (1998) demonstrated that egg production and feed efficiency were positively improved when a 5% dried apple pomace diet was supplemented with multi-enzyme containing hemicellulose, pentosanase, β-glucanase, pectinase, protease, and amylase. The major cause of these inconsistencies could be due to varying nutrient and polyphenol profiles in fruits and their cultivars. In addition, fruits by-products like apple pomace contain an excellent amount of pectin and/or methoxyl, which could adversely impact nutrient absorption by increasing goblet cells in the small intestine.

There is paucity of information on the dietary application of citrus pomace to promote growth of poultry birds. However, report has shown that supplementation of sweet orange pomace as high as 30% would cause a significant depression in FI, final live weight, WG, and increased FCR of broiler chickens with or without fermentation (Oluremi et al., 2010). In a 21-day feeding trial conducted by Yang et al. (2015), dietary citrus pomace at 8% was reported to significantly reduce feed efficiency in Sischuan white geese but significantly improve serum lipoprotein content. However, inclusion level as low as 6% citrus pomace was better utilized in the same study.

Islam et al. (2020) reported 2.24, 2.30, and 2.07 kg average carcass weight of broiler chickens fed 0%, 1%, and 2% inclusion level of cranberry pomace in a wheat–organic peas–barley diet. The authors further reported slightly better FCR and mortality among a group of birds consuming cranberry pomace. The fibre fraction in cranberry pomace is made up of more coarse fibre to fine fibre, which implies a more mechanical degradation activity at the gizzard level. Mateos et al. (2012) reported that the higher coarse-to-fine fibre ratio in cranberry pomace caused the improvement in FI, WG, and performance parameters of chickens. Jiménez-Moreno et al. (2010) submitted that a higher fraction of coarse fibre could also participate in the development of the digestive tract by stimulating gizzard mechanical function and thus, increasing its content and size.

The adoption of grape pomace as nutraceutical and alternative ingredient in poultry production has been gaining momentum in the last 2 decades. The capacity of grape by-products to improve growth performance is mainly dependent on the form of the by-product and the amount incorporated into the diet (Erinle et al., 2021). The study conducted by Kumanda et al. (2019) was the only study that reported that the addition of 7.5% grape pomace improves the growth performance of broiler chickens. Viveros et al. (2011) demonstrated that feeding 6% grape pomace improved the growth of birds like avoparcin antibiotics did. Goñi et al. (2007) and Sáyago-Ayerdi et al. (2009) submitted that dietary grape pomace could be added up to 6% in broiler chicken diets without impairing growth performance. Contrarily to the reports of Kumanda et al. (2019), Goñi et al. (2007), Brenes et al. (2008), Sáyago-Ayerdi et al. (2009), Chamorro et al. (2015), and Ebrahimzadeh et al. (2018) reported that dietary supplementation of dietary grape pomace in the range of 5% to 10% did not affect growth performance of broiler chickens. However, a lower dosage of raw or fermented supplemental grape pomace of less than 3% has been demonstrated to improve growth performance in broiler chickens (Pop et al., 2015; Aditya et al., 2018; Erinle et al., 2021; Gungor et al., 2021; Altop and Erener, 2021). Increasing the inclusion level of grape pomace from 1% to 2% resulted in the improvement of BW and FCR in broiler chickens (Pop et al., 2015). However, incorporation of grape pomace at 2.5% was also observed to improve FI and FCR in the same magnitude of bacitracin methylene disalicylate antibiotics (Erinle et al., 2021).

There is inadequate information on the impact of wild blueberry pomace on poultry production. A similar dressed carcass weight was observed when dietary wild blueberry pomace was included in broiler chicken diets at 1% and 2% compared control treatment (Islam et al., 2019); however, birds were raised on free-range. Polyphenol-protein matrix in wild berry pomace was reported to hinder gluconeogenesis by inhibiting phosphoenol pyruvate carboxykinase (Jiang et al., 2011; Welch et al., 2018; Hoskin et al., 2019). This suggest that the adoption of wild blueberry pomace in poultry feeding might technically improve their performance by inhibiting the depletion of non-carbohydrate body nutrient reserve for glucose formation. In addition, to the best of our knowledge, in vivo studies using pineapple pomace particularly in poultry are very limited despite the tremendous in vitro dietary demonstrations (Martínez et al., 2012; Saikia and Mahanta, 2015; Selani et al., 2014; Henning et al., 2016).

There are a lot of variations when it comes to the significance of fruit pomaces on FI, BW, and other growth parameters of poultry birds. As earlier mentioned, the variations in most reports are due to the variation in the inclusion levels and antinutritional factors present in each fruit pomace. With possible technological optimization techniques, fruit pomace might be efficiently utilized when fed to poultry birds. From a critical perspective, fruit pomaces might improve growth performance; however, their capacity to reduce abdominal fat is noteworthy and could partially occlude the increase in performance, particularly BW.

Table 4
Growth performance and health of poultry birds fed fruit pomaces as reported in recent literature.

Fruit pomaces	Inclusion levels, %	Poultry species	Effects	References
Apple pomace				
Dried apple pomace (DAP)	4, 8, and 12 8, 12, and 16 12, 16, and 20	Broiler chickens	i. Incremental DAP at 4% and 8% improved daily FI and DWG of birds DAP at starter and grower phases, respectively, better than those fed 12% and 16% DAP. ii. Improved gut morphology parameters. iii. Increased antibody titre against Newcastle disease virus (NDV) and sheep red blood cell iv. Increased IgG and IgM titre and total antioxidant capacity.	Aghili et al. (2019)
Apple pomace (AP)	10, 15, and 20	Broiler chickens	A significant depression of weight gain (WG) when 15% and 20% DAP. However, WG was significantly improved following enzyme supplementation.	Matoo et al. (2001)
AP	3 and 6	Broiler chickens	i. No effect was observed for growth performance, gut histomorphometry, and histopathology. ii. Significant increase in the intestinal Short-chain fatty acid concentrations among birds fed fruit pomace diets. iii. In AP-fed birds, beta-diversity was significantly increased while alpha-diversity was unaffected. AP reduced the population of genus Lactobacillus, while the Streptococcaceae family was increased compared to the control treatment.	Colombino et al. (2020)
AP	10 and 20	Broiler chickens	Dietary 20% AP significantly reduced WG and FE. However, at 10%, birds' performance was not affected.	Bhat et al. (2000)
AP ± molasses	15	Broiler chickens	With 10% molasses supplementation into dietary AP, BW, FI, FCR, and survivability of birds were not affected.	Bhat (2004)
AP	5, 10, and 15	Broiler chickens	Increased FI and FCR.	Ayhan et al. (2009)
AP	5	Turkey	On the overall, AP maintained growth performance and carcass characteristics of turkey.	Juskiewicz et al. (2015)
AP	5	Turkey Poult	i. Maintained BW of birds. ii. Increased small intestine weight. iii. Increased maltase and sucrase activities in the small intestine. iv. Improved bacterial enzymes in the caecal digesta. v. Increased butyric, valeric and total putrefactive SCFA in the caecum.	Juskiewicz et al. (2016)
Olive pomace/by-products				
Olive pulp ± xylanase (enzyme)	9	Laying hens	i. Feed intake and EM were similar across the treatments. ii. Improved FCR among birds fed olive pulp treated with xylanase. No report on gut health.	Zarei et al. (2011)
Olive pulp ± yeasture (probiotic)	16	Laying hens	i. Dietary olive pulp at the inclusion level yielded a similar FI, % HDP, and EM, and a significantly increased FCR. ii. Probiotic supplementations into all the dietary treatments significantly reduce haugh unit and %HDP. iii. No significant interaction between olive pulp and probiotic supplementation. No report on gut health.	Afsari et al. (2013)
Olive pomace	10	Laying hens	i. Feed intake and FCR were maintained. ii. Reduced egg cholesterol content by downregulating five genes responsible for cholesterol biosynthesis. No report on gut health.	Iannaccone et al. (2019)
Olive pulp ± hemicell (enzyme)	4.5 and 9	Laying hens	i. Non-significant improvement in the overall egg mass and FCR fed 4.5% olive pulp with or without enzyme supplementation. ii. A significant interaction effect of olive pulp and enzyme which increases egg weight when β-mannanase was included in the 9% olive pulp diet. iii. Diet containing 4.5% olive pulp increases antibody response against NDV.	Zangeneh and Torki (2011)

Table 4 (*continued*)

Fruit pomaces	Inclusion levels, %	Poultry species	Effects	References
			iv. Blood Serum hormones and metabolites were not affected by dietary olive pulp. No report on gut health	
Olive pulp	2.5 and 5 5 and 8	Male broiler chickens	i. Regardless of the inclusion level of olive pulp, FI, BW gain, and FCR of birds were not affected during the grower and finisher phase. ii. In addition, the proportion of total PUFA was not affected.	Papadomichelakis et al. (2019)
Olive pulp	2.5 and 5 5 and 8	Broiler chickens	i. Overall FI and BW gain were not affected; however, FCR was significantly reduced among birds fed 8% olive pulp. ii. Mortality was reportedly similar across the treatment; however, it was zero when 5 and 8% olive pulp was fed. iii. No difference in the plasma SOD, CAT, GST, and GPx. No report on gut health.	Pappas et al. (2019)
Olive pomace	2.5, 5, and 7.5	Broiler chickens	Increased growth rate and reduced FCR were achieved when birds were fed 5% and 7.5%. No report on gut health.	Nasopoulou et al. (2018)
Olive cake ± yeast	5 and 10	Broiler chickens	i. Similar FI, FCR, and EPEI were reported regardless of dietary olive cake and/or yeast supplementation inclusion levels. ii. Relative weight of spleen and bursa was similar across the treatments. iii. Olive cake diet at 5% and 10% without yeast supplementation reduces total plasma lipid, increases plasma TAG and cholesterol, HDL:LDL, and VLDL. No report on gut health.	Al-Harthi (2016)
Olive cake	5, 10, and 20	Broiler chickens	i. The best BW and FCR were achieved at 5% and 10% olive cake supplementation. ii. Decreased abdominal fat among birds fed olive cake. iii. Significant reduction in total plasma cholesterol in all birds fed olive cake. iv. Significant increase in breast muscle vitamin E and reduction in liver MDA in birds fed olive cake. No report on gut health.	Saleh and Alzawqari (2021)
Olive pulp ± multi-enzyme ± processing (destoning)	5 and 10	Broiler chickens	i. No difference in FI, WG, FE among birds fed 5% and 10% olive pulp. Enzyme supplementation also makes no difference in the growth performance parameters. ii. In addition, the destoning processing method yielded a significantly reduced WG and increased feed efficiency. iii. Feed cost was significantly lower in the 5% olive pulp diet compared to 10%. Processing and enzyme supplementation did not affect feed cost; however, they produced a significant interaction effect.	Sayehban et al. (2016)
Olive cake ± citric acid	10 and 20	Broiler chickens	i. Feed intake and BW of birds fed 10% Olive cake or control with no citric acid, respectively, were better compared to the FI and BW obtained at 20% olive cake with or without citric acid. ii. RBC was significantly reduced in birds fed 20% Olive cake which increased following citric acid supplementation. However, in the 10% Olive cake treatment, RBC, PCV, haemoglobin, MCV, and MCH were favourably compared to control with or with citric acid. iii. Liver ratio was significantly reduced compared to the 20% olive cake and control treatments.	Al-Harthi and Attia (2016)
Olive pulp ± multi-enzyme ± processing (destoning)	5 and 10	Broiler chickens	Despite the processing method and enzyme supplementation, carcass and offal traits of broiler chickens were not affected by olive pulp supplementation.	Sayehban et al. (2020)
Olive pulp	5, 10, and 15	Broiler chickens	i. Significantly reduced BW and FCR among birds fed 10% and 15% olive pulp. However,	Elbaz et al. (2020)

(*continued on next page*)

Table 4 (*continued*)

Fruit pomaces	Inclusion levels, %	Poultry species	Effects	References
			the reduction might be due to the significantly reduced abdominal fat in birds fed 10% and 15% olive pulp. ii. A significant linear increase in the percentage of gizzard as olive pulp inclusion increases. iii. Unlike other immune organs, the percentage of the thymus was significantly increased with increasing inclusion levels of olive pulp.	
Olive pulp ± irradiation	5 and 10	Quail	i. Live BW was significantly increased in all the olive pulp treatments with or without irradiation. However, WG was non-significantly improved in all olive pulp treatments. ii. Dietary olive pulp significantly increased WBC, Hb, MCH, MCHC, and AST.	El-Hady et al. (2018)
olive pulp ± irradiation	3 and 6	Quail	i. Egg production, EW, FE, fertility, embryonic mortality, hatching percentage, and weight of chicks at hatch were significantly improved at both 3% and 6% irradiated olive pulp (IOP); however, it was highest at the latter. ii. Significant improvement in RBC and PCV in all diets containing olive pulp regardless of processing. However, WBC and Hb were significantly higher in the IOP treatments. iii. Intestinal length was also highest in the IOP treatments.	Ibrahim et al. (2019)
Grape pomace				
Red grape pomace (RGP)	2.5	Broiler chickens	i. Birds' FI was higher when 2.5% RGP was fed and was compared favourably to antibiotic-treated birds. Reduced BW was observed in RGP-birds during the grower phase; however, overall FCR was similar compared to antibiotics. ii. Significant improvement in gut histomorphometric on the RGP-fed birds and was better compared to antibiotic treatments. iii. Significantly decreases Firmicute to Bacteroidetes ratio and improves the population of beneficial microbes, including *Lactobacillus* spp.	Erinle et al. (2021)
RGP	1.5, 3, 4.5, and 6	Cockerels (chickens)	i. The increasing dietary RGP did not affect the overall FI, body WG, FCR and slaughtered weight of cockerels. ii. MCH and GLB increase significantly with increasing inclusion levels of RGP.	Jonathan et al. (2021)
Grape pomace (GP)	450, 350, and 250 mg/kg	Broiler chickens	i. Similar BW was reported across the dietary treatments. ii. There was a significant reduction in LDL of birds at 450 mg/kg inclusion of GP. iii. Increased SOD at the highest dose of GP while GPx was not affected.	Dupak et al. (2021)
GP ± fermentation	1.5	Broiler chickens	i. Fermented GP (FGP) improves final BW in the same capacity as the synthetic antioxidant treatment; however, it was better when compared to raw GP. ii. Raw GP at 1.5% significantly increased serum GPx and SOD, while CAT was increased when 1.5% FGP was fed. iii. FGP significantly decimates *Clostridium perfringens* population compared to other treatments; however, other bacterial species, including *Lactobacillus* were not affected. iv. Regardless of fermentation, the GP treatments significantly reduce VH and VH:CD.	Gungor et al. (2021)
GP	7.5 and 15	Broiler chickens	i. Dietary GP significantly lower FI and FCR and higher BW and was compared favourably to birds fed vitamin C and E, respectively.	Mankola et al. (2021)

Table 4 (*continued*)

Fruit pomaces	Inclusion levels, %	Poultry species	Effects	References
			ii. Dietary GP significantly lower AST, ALT, and TAG and higher TP, GLB, HDL; however, it was similar to the vitamin C, and E-fed birds. Additionally, 15% GP reduces TC and LDL compared to other treatments. iii. Dietary GP significantly increases IgG, IgM, IgA, and SOD, and lower MDA and were comparable to vitamins C and E.	
GP ± enzyme complex ± tannase	5 and 10	Broiler chickens	i. Dietary 5% GP significantly increases protein and total polyphenol digestibilities. However, supplementation of enzyme complex or tannase or a combination of both reduces the 2 digestibilities. ii. Significant increase in the plasma α-tocopherol and antioxidant capacity of birds fed 5% GP and vitamin E, respectively.	Chamorro et al. (2017)
RGP	2.5, 4.5, 5.5, and 7.5	Broiler chickens	i. Average weekly FI and FCR significantly reduced when 7.5% RGP was fed compared to other RGP levels and control. However, overall WG was not affected. ii. Blood parameters and carcass characteristics were not affected.	Kumanda et al. (2019)
GP	5, 7.5, and 10	Broiler chickens	i. No difference in the performance of birds by the increasing inclusion levels of GP. ii. Blood antioxidants, SOD and GPx, were significantly higher while MDA was reduced among 5 and 7.5% GP-fed birds. iii. All inclusion levels of GP reduced serum TAG and LDL while HDL was increased. iv. Significantly increased antibody titre against NDV among birds fed 5% and 10% GP.	Ebrahimzadeh et al. (2018)
RGP	5, 10, and 20	Broiler chickens	i. Increasing levels of GP increase FI particularly at the starter and grower phase; however, BW gain and FCR were not affected. ii. Increasing levels of GP reduce abdominal fat in heat-stressed birds. iii. Increasing levels of GP reduce plasma cholesterol, LDL, AST, MDA, and TAG while HDL, TP, GPx, and SOD were increased. iv. GP increases weights of immune organs, bursa and thymus.	Hosseini-Vashan et al. (2020)
RGP and white grape pomace (WGP)	20 RGP and 20 WGP	Broiler chickens	i. Dietary WGP did not affect BW, daily WG, FI and FCR, while RGP increased overall FCR. ii. Dietary WGP increases the antioxidant capacity of breast and leg meat compared to the RGP and control treatments.	Reyes et al. (2020)
GP	1, 2, 3, and 4	Laying hens	i. Dietary GP at 3% and 4% improved FCR, %EP, EM, SOD, and GPx compared to control treatment. ii. The %EP, EN, and EM were significantly higher among 4% GP-fed birds compared to those fed Vitamin E.	Alm El-Dein et al. (2017)
RGP	1.5, 3.5, and 5.5	Quail	i. Overall, FI was significantly improved at 3.5% RGP compared to other treatments. However, overall BW gain, FCE, and final BW were not influenced by the varying inclusion level of RGP. ii. Similarly, the serum biochemical parameters of the birds were not affected.	Mnisi et al. (2021)
Strawberry pomace				
Strawberry pomace (SP) and/or Seedless strawberry pomace	5	Turkey	i. On overall, SP, seedless SP, and a combination of both maintained turkey's growth performance and carcass characteristics.	Juskiewicz et al. (2015)
SP	3 and 6%	Broiler chickens	i. No effect was observed for growth performance, gut histomorphometry, histopathology. ii. Significant increase in the intestinal SCFA concentrations among birds fed fruit pomace diets including SP. iii. In SP-fed birds, beta-diversity was significantly increased while alpha-diversity was	Colombino et al. (2020)

(*continued on next page*)

Table 4 (*continued*)

Fruit pomaces	Inclusion levels, %	Poultry species	Effects	References
			unaffected. SP reduced the population of genus Lactobacillus compared to the non-fruit pomace treatment.	
SP	5	Turkey Poult	i. Maintained BW of birds. ii. Decreased small intestine weight. iii. Reduced maltase and sucrase activities in the small intestine. iv. Improved bacterial enzymes in the caecal digesta. v. Increased butyric acid in the caecum.	Juskiewicz et al. (2016)
Seedless strawberry pomace (SSP)	5	Turkey Poult	i. Maintained BW of birds. ii. Decreased small intestine weight and increased digesta viscosity. iii. Reduced maltase and sucrase activities in the small intestine. iv. Improved bacterial enzymes in the caecal digesta. v. Increased butyric and propionic acids in the caecum	Juskiewicz et al. (2016)
SSP	5	Turkey	i. TBARS concentration in raw and frozen breast muscle of turkey fed 5% SSP was drastically reduced compared to some other fruit pomaces. ii. Similarly, vitamin E levels were highest in raw breast meat of Turkey.	Juskiewicz et al. (2017)
Blueberry pomace				
Blueberry extract (BE)	0.5, 1, and 2	Broiler chickens	i. Significantly increased BW gain and reduced FI and FCR as BE inclusion levels increases. ii. Significantly increased slaughter weight and dressing and gizzard percentage among BE-fed birds compared to control.	Ölmez et al. (2021)
Blueberry pomace	1 and 2	Broiler chickens	i. Decreased TAG and ALT. ii. Reduced prevalence of necrotic enteritis when 1% blueberry pomace was fed.	Das et al. (2020)
Cranberry pomace				
Cranberry pomace	1 and 2	Broiler chickens	i. Increased serum IgG among birds bed 2% cranberry pomace. ii. Both levels of cranberry pomace resulted in improved innate immune and suppressed proinflammatory cytokine.	Das et al. (2021)
cranberry pomace extract	0.1, 0.2, and 0.4	Broiler chickens	i. Improved immunity caused by increased IgM concentration. ii. Antibody titres against infectious bursa disease virus increase as the cranberry pomace extract increases.	Islam et al. (2017)
cranberry pomace	1 and 2	Broiler chickens	i. Decreased TAG and ALT. ii. Increased the relative abundance of Lactobacillaceae in the caecal of birds fed 2% cranberry pomace. iii. Upregulation of adaptive immune related genes. iv. Similar to antibiotic effect, 1% cranberry pomace reduced prevalence of necrotic enteritis v. Improved BW in the same capacity of Bacitracin-fed birds.	Das et al. (2020)
cranberry pomace	1 and 2	Broiler chickens	i. Improved blood serum iron while cholesterol was reduced. ii. Selective modulation of gut microbe by improving beneficial, SCFA-producing gut bacteria while reducing the pathogenic ones.	Islam et al. (2020)

± = with or without; ALT = alanine transaminase; AST = aspartate transaminase; BW = body weight; CAT = catalase; DWG = daily weight gain; EM = egg mass; EW = egg weight; EN = egg number; %EP = percentage egg production; EPEI = European production efficiency index; FCR = feed conversion ratio; FCE = feed conversion efficiency; FE = feed efficiency; FI = feed intake; GLB = globulin; GST = glutathione transferase; GPx = glutathione peroxidase; HDL = high density lipoprotein; %HDP = percentage hen-day production; IgM = immunoglobin M; IgG = immunoglobin G; IgA = immunoglobin A; LDL = low density lipoprotein; MCHC = mean corpuscular hemoglobin concentration; MCV = mean corpuscular volume; MCH = mean corpuscular haemoglobin; MDA = malondialdehyde; PCV = packed cell volume; PUFA = polyunsaturated fatty acids; RBC = red blood cell; SOD = superoxide dismutase; TAG = triglycerides; TBARS = thiobarbituric acid reactive substances; TC = total cholesterol; TP = total protein; VLDL = very low density lipoprotein; WG = weight gain.

3.2. The use of fruit pomaces to improve gut morphology

The gut performs an indispensable role when it comes to digestion and absorption of nutrients, as well as plays a selective barrier function by regulating the passage of metabolites and strengthening its structural integrity against pathogens. There is a constant cross-interaction between gastrointestinal epithelial tissue and its environment. In the presence of certain conditions, including a low-quality diet, the crucial gut functions may be compromised.

Bioactive substances present in fruit pomaces have the capacity to improve broiler feed efficiency by increasing nutrient digestibility, motility of the gastrointestinal tract, and bile acid function. In gut-related poultry studies, villus height and crypt depth in small intestinal segments are often considered indicators for nutrient absorption and a slower rate of enterocyte epithelial cell renewal. In the study demonstrated by Colombino et al. (2020), dietary apple, blackcurrant, and strawberry pomaces did not cause histopathological alteration of birds; however, were able to maintain growth performance compared to birds fed corn–soya–wheat diet. Reports on the impacts of the different fruit pomaces on gut health have been inconsistent depending on their inclusion levels in the poultry diets. Supplementation of grape pomace at 6% and 2.5% inclusion levels have been reported to improve villus height-to-crypt depth ratio (VH:CD) in broiler chickens (Viveros et al., 2011; Erinle et al., 2021). Villus height and VH:CD were reported to decrease when 7.5% and 10% grape pomace was fed to broiler chickens; however, at 5% inclusion level, there was a significant improvement in the VH:CD at the duodenum and jejunum (Ebrahimzadeh et al., 2018).

In the small intestine, dietary fruit pomaces were found to reduce digesta viscosity and increase the concentration of short-chain fatty acids particularly acetic and butyric acid compared to control-fed birds (Colombino et al., 2020). Butyric acid provides the suitable form of energy necessary for stimulation of growth of intestinal epithelial cells and mucin production and thus, maintaining the tight junction integrity at the intestinal level (Jung et al., 2015; Peng et al., 2009).

3.3. *The use of fruit pomaces to modulate gut microbiota*

The gut microbiome plays a significant role in the health and metabolism of poultry species (Lin et al., 2016). In a healthy poultry gut, Firmicutes, Bacteroidetes, and Proteobacteria are the 3 most abundant bacteria phyla; however, phyla Bacteroidetes and Firmicutes are considered the relative most abundant (Qin et al., 2010; Almeida et al., 2019; Forster et al., 2019). The novel application of probiotics, prebiotics, exogenous enzymes, and phytogenic compounds have been shown to modulate the gut microbiome of poultry (Dibner and Richards, 2005; Oakley et al., 2014). Interestingly, dietary fibre has also been reported to induce a beneficial effect on gut health, including serving as a prebiotic to selectively enrich beneficial gut bacteria (Gong and Yang, 2012). This suggests that the phenolic compounds and dietary fibre component of fruit pomaces could be adopted to modulate the gut microbial population. Islam et al. (2019) and Erinle et al. (2021) found a significant decrease in the relative abundance of phylum Firmicutes and an increase in the relative abundance of phylum Bacteroidetes at the ileum and caeca of broiler chickens fed 1% dietary wild blueberry pomace and 2.5% dietary grape pomace, respectively. Higher Firmicutes-to-Bacteroidetes ratios have been associated with the incidence of obesity in humans and animals (Ley et al., 2006; Magne et al., 2020).

The fraction of fermentable digestible fibre in fruit pomaces was reported to modify gut microbiota by its stimulatory roles on the growth of beneficial bacterial genera including *Ruminococcus* and *Oscillospira* in chickens and rabbits (Aura et al., 2015; Dabbou et al., 2019; Islam et al., 2020). Sarica and Urkmez (2016) demonstrated that oleuropein and hydroxytyrosol—bioactive compounds in olive pomace regulate the composition of gut microbiota and reinforce gut structural integrity. Beneficial bacteria belonging to the family of Lactobacillaceae can maintain the intestinal barrier functions by modulating the expression of heat shock proteins, tight junction proteins, and restricting pathogens adherence (Liu et al., 2015). The inclusion of 750 mg/kg olive pomace extract did not alter the relative abundance of main bacteria families; however, increased bacteria belong to the family of Lactobacillaceae and suppressed Clostridiciaceae in broiler chickens (Herrero-Encinas et al., 2020). With regards to the bacteria genera in the chicken gut microbiota, *Clostridium, Ruminococcus, Lactobacillus*, and *Bacteroides* are the most abundant. Comparing the impact of a control diet with dietary fruit pomaces, Colombino et al. (2020) demonstrated that there was no change in the α-diversity of gut microbiota of poultry birds. However, when comparing within pomaces, there was an increase in α-diversity among birds fed 6% strawberry pomace compared to other pomaces. The population of *Weissella* and *Lactobacillus* in the excreta microbiota was reported to increase and decrease, respectively upon feeding the birds with 6% dietary fruit pomaces and also an increase in the concentration of *Erwinia* among strawberry and blackcurrant pomaces fed birds (Colombino et al., 2020).

Phenolic compounds in fruit pomaces play a significant role in reinforcing the immune and protective functions in epithelial cells by stimulating the growth of *Bifidobacterial* species. Puupponen-Pimiä et al. (2005), Wu et al. (2008), and Diarra et al. (2020) found that polyphenolics and non-phenolic compounds in cranberry, blueberry, and strawberry could destabilize the structural integrity of the outer cell membrane of Gram-negative bacteria, consequently decreasing their viability. Grape, wild blueberry, and cranberry pomaces were reported to increase the *Bifidobacteria* counts in chickens and rats (Chacar et al., 2018; Islam et al., 2019, 2020). Viveros et al. (2011) and Islam et al. (2019) also reported a decrease in the abundance of *Enterococcus* bacteria in grape pomace and wild blueberry-fed birds, respectively, compared to the control group. Unfortunately, *Enterococcus* species have been implicated in the incidence of colorectal cancer and damaged eukaryotic cellular DNA in the colon epithelial cell by stimulating the secretion of superoxides and hydroperoxides (Huycke et al., 2002; Balamurugan et al., 2008; Jones et al., 2008). While the gut of chickens houses communities of microbes, *Lactobacillus, Clostridium, Enterococcus,* and *Escherichia coli* are recognized, normal residents. However, supplementation of wild blueberry pomace was also demonstrated to reduce the population of *Clostridium perfringens* and increase *Lactobacillus* (Islam et al., 2019). The relative abundance of genera *Bacteroides, Bifidobacterium,* and *Faecalibacterium* were reported to be increased following dietary incorporation of wild blueberry and grape pomaces in broiler chicken's diets (Islam et al., 2019; Erinle et al., 2021). *Bacteroides* were suspected to contribute to the degradation of indigestible carbohydrates found in its host. Louis et al. (2010) reported that *Faecalibacterium,* a member of the Ruminococcaceae, contributes to the production of butyrate, which could act as an anti-inflammatory in the host cell. However, *Bifidobacterium* and *Bacteroides* also contribute to mucin degradation (Hooper et al., 2002; Ruas-Madiedo et al., 2008). The synergistic effect resulting from the combination of different fruit powders has also been reported. An in vitro study by Vattem et al. (2005) showed that combined supplementation of blueberry, grape seed, and oregano extract enhanced the antioxidant and anti-*Helicobacter pylori* activity of cranberry powder.

While fruit pomaces tend to have modulatory effects on the gut microbiota of poultry, their inclusion at higher levels could potentially antagonize the beneficial modulatory effects. In grape pomace trials, Chamorro et al. (2017) reported that grape pomace-fed at 5% and 10% did not influence the population of ileal *Lactobacillus*. Inclusion of grape pomace at 10% was shown to upturn the antimicrobial effect of grape pomace against *C. perfringens* (Chamorro et al., 2017). Viveros et al. (2011) also demonstrated that 6% dietary grape pomace significantly increase the concentration of

E. coli, Lactobacillus, Enterococcus, and *Clostridium*. A similar result was reported when 0.72% grape seed extract was fed to the birds. At a lower inclusion level, 1% to 4% grape pomace was reported to significantly increase in the relative abundance of *Bacteroides* and *Lactobacillus* bacteria species (Hafsa and Ibrahim, 2018; Erinle et al., 2021) and a significantly reduced relative abundance of genera *Escherichia-Shigella* and *Clostridia_unclassified* (Erinle et al., 2021). A reduction in the abundance of *Bacteroides* has been associated with inflammatory bowel disease, Crohn's disease, and ulcerative colitis disease conditions (Zhou and Zhi, 2016). Another mechanism of action of *Lactobacillus* is to secrete antimicrobial peptides known as bacteriocins, and lactic acid which lowers the pH of their immediate environment thereby inhibiting the proliferation of pathogenic bacteria including *E.coli*, *Campylobacter jejuni*, and *C. perfringens* (Murry et al., 2004; Neal-McKinney et al., 2012).

3.4. *The use of fruit pomaces to prevent oxidative stress*

The inverse relationship between pro-oxidants and antioxidants in a body system determines the incidence of oxidative stress (Mosele et al., 2015). Oxidative reactions that generate free radicals are inevitable as they occur during normal bodily metabolism. However, the harmful effects of oxidants could be potentiated in the presence of stressors and in fast-growing animals like broiler chickens (Panda and Cherian, 2013).

Polyphenolic compounds are recognized as natural, exogenous antioxidants that could act in similar capacities of some vitamins including α-tocopherol, ascorbic acids, etc (Akbarian et al., 2016). In some studies, involving higher dietary levels of polyphenols, stimulation of the activity of plasma superoxide dismutase and glutathione peroxidase was reported in broiler chickens (Vossen et al., 2011) and an increased concentration of vitamin E in the blood of heat-stressed quail (Sahin et al., 2010). Fruit flavone glycosides including naringin, hesperidin, and diosmin, have been reported to alleviate oxidative stress either by modulating NF-κB-dependent signaling pathways or enhancing the antioxidant status in the plasma, liver, and kidneys (Srinivasan et al., 2019). The beneficial antioxidant activity of strawberry pomace was demonstrated particularly against reactive oxygen species and hydroxyl radical species (Šaponjac et al., 2015). The antioxidant property is conferred when fruit pomaces are incorporated into poultry diets. Juskiewicz et al. (2017) demonstrated the inclusion of strawberry, apple, and blackcurrant pomaces into poultry diets improves their total antioxidant capacity with strawberry pomace having their highest antioxidant influence (Juskiewicz et al., 2017). Thiobarbituric acid reactive substances are a product of oxidation of lipids, particularly those localized in the cell membrane, and thus, act as an indicator of oxidative stress. In kidneys and serum of rabbits treated with blackcurrant pomace extract, suppression of thiobarbituric acid reactive substances (TBARS) concentration was reported following attenuation of hyperlipidemia caused by high dietary fat (Jurgonski et al., 2014). Even in non-poultry study, it was reported that water extract of citrus pomace scavenges DPPH, alkyl, hydroxyl radicals, and reactive oxygen species, and consequently improve cell viability both in in vitro (Vero Cells) and in vivo (Zebrafish) (Wang et al., 2018).

Olive pomace contributes to the high concentration of polyunsaturated fatty acids (PUFA) to the diet to which they are added. The serum malondialdehyde (MDA) increases with increasing dietary PUFA (Zhang et al., 2019). In contrast, the high concentration of PUFA in olive pulp diet does not translate to the formation of MDA in the plasma of chickens (Rezar et al., 2015). Although the storage condition was not specified, Rezar et al. (2015) demonstrated that dietary inclusion of olive pulp at 10 g/kg marginally decreased MDA concentration in egg yolk up to 40 days' storage period compared to dietary inclusion of vitamin E for layers. This is not unexpected as hydroxytyrosol formed following the degradation of oleuropein glycoside exhibit profound antioxidant and anti-inflammatory bioactivities.

Lipoxidation reactions have been implicated as one of the leading causes of quality deterioration in lipid-containing substances, including meat and derived meat products in poultry. The possibility of improving the quality and shelf life of meat has been correlated with the enhanced antioxidant capacity in the muscle (Tavárez et al., 2011). Like other fruit pomaces, consumption of dietary grape pomace with or without enzyme was reported to reduce oxidation in chicken meat by reducing MDA concentration upon storage in the same equivalent as dietary α-tocopheryl acetate (Chamorro et al., 2015). Supplementation of α-tannase into 10% grape pomace diet was found to achieve a similar protective effect without impairing the growth of birds. Furthermore, the success of grape by-products as anti-lipoxidation in beef patties, pork, turkey and chicken meats, and fish have been extensively reported (Lau and King, 2003; Pazos et al., 2005; Mielnik et al., 2006; Bañón et al., 2007; Carpenter et al., 2007).

In an in vitro study, polyphenols of blueberry pomace were shown to reduce nitric oxide and reactive oxygen species production in lipopolysaccharide-activated cells (Hoskin et al., 2019). This was correlated to the high concentration of TPC and antioxidant capacity of blueberry pomace (Reis et al., 2002). Polyphenols in apple pomace have been reported to have about 10 to 30 times the superoxide anion radical-scavenging activity of vitamins C and E (Lu and Yeap Foo, 2000). Surprisingly, fruit pomaces could indirectly influence the survivability of growing chick in the shell and even upon hatching due to their direct effect on the reproductive system. In the male reproductive system, supplementation of dried apple pomace improved seminal TBARS and seminal total antioxidant capacity and, consequently, increased seminal forward motility of broiler breeder roosters (Akhlaghi et al., 2014). Aghili et al. (2019) demonstrated a significant increase in the plasma total antioxidant capacity following incremental feeding of 12%, 16%, and 20% dried apple pomace to broiler chickens at the starter, grower, and finisher phase, respectively. Oxidative stress could be considered as the primary underlying mechanism that weakens immune systems.

Similarly, proanthocyanidins—one of the most reliable antioxidants of plant origin—is reported to possess about 20 times and 50 times higher antioxidant bioactivity compared to vitamins E and C, respectively (Shi et al., 2003). Grape pomace is particularly a rich source of these compounds. A chicken study conducted by Goñi et al. (2007) revealed that supplementation of grape pomace at 0.5%, 1.5%, and 3% inclusion levels significantly increases vitamin E concentrations in the liver and antioxidant capacity of the chicken meat especially at the highest inclusion level of the pomace. This suggests that grape pomace could be used as an alternative not only to antibiotics but also synthetic vitamin E in the poultry diet and thus, may reduce costs related to the purchase of the vitamin additives.

4. Optimizing the use of fruit pomaces for poultry feeding

4.1. *Exogenous enzyme supplementation*

Dietary fibre act as a buffer in the digesta medium and binds substances including cholesterol, gastric juice, and hydrochloric acid, increases intestinal peristalsis and faecal bulkiness, and provides a suitable substrate for healthy intestinal flora (Jiménez-Escrig and Sánchez-Muniz, 2000; Nawirska and Kwaśniewska, 2005). Unfortunately, poultry birds do not secret essential enzymes necessary for the degradation of non-starch polysaccharides component of dietary fibre. Thus, tapping the potentials of crop residues including fruit pomaces might be limited in poultry due to their high fibre content.

In a monomer analysis conducted by Juskiewicz et al. (2015), cellulose was reported to be the leading non-starch polysaccharide in fruit pomaces. In fact, olive stone—a component of olive pomace was reported to contain about 22 to 28 g/100 g DM hemicellulose, 30 to 34 g/100 g DM cellulose, and 21 to 25 g/100 g DM lignin as its principal component (Niaounakis and Halvadakis, 2006; Rodríguez-Gutiérrez et al., 2012). In addition, report has shown that sweet lemon, blue grapes, pineapple, and orange pomaces had 57.76, 50.29, 48.45, and 73.90 mg DM of phytic acid, respectively (Nagarajaiah and Prakash, 2016). Although the range of phytate concentration, 48.45 to 73.90 mg DM, was much lower compared to the 223–1,419 mg DM reported in most grains by Ma et al. (2005) and may not interfere with mineral metabolism. However, it might be quintessential to incorporate exogenous enzyme complex-containing amylase, cellulose complex, protease, and phytase into fruit pomace diets to facilitate the digestion of the fibre components and thus, maximize their potential in poultry nutrition. While there is no consensus on the accurate mode of actions for exogenous enzymes, their roles in improving animal performance by degrading the deleterious factors present in feedstuff, reducing animal maintenance requirements, maintaining intestinal architecture, and modifying gut microbial populations have all been reported (Wu et al., 2004; Cowieson et al., 2009; Bedford and Cowieson, 2012; Ojha et al., 2018). The use of exogenous enzymes would permit flexibility in least-cost feed formulation by allowing a wide range of ingredients, including fruit pomaces.

In the poultry industry, for instance, enzyme supplementation has been reported to improve bird performance at a reduced cost by increasing the available energy content in wheat- and barley-based diets and by degrading anti-nutritional factors, like β-glucans, β-mannose, protease inhibitors, and lectins in corn-soybean diets (Abu, 2019; Yang et al., 2010). Unfortunately, enzyme supplementation in dietary fruit pomaces is one technique that is yet to be fully experimented given the scanty and controversial research information. According to a demonstration by Matoo et al. (2001), replacing maize in broiler chicken diet with 5%, 10%, 15%, and 20% apple pomace without enzyme supplementation resulted in depressed feed consumption and BW gain of birds. However, there was a significant improvement in feed consumption, WG, and consequently, feed conversion efficiency of birds following enzyme supplementation (Matoo et al., 2001). In layer chickens, multi-enzyme supplementation in the apple pomace diet was also reported to improve egg production and feed utilization efficiency (Yildiz et al., 1998). In another study involving fruit pomace, the addition of enzyme was reported to non-significantly increase daily FI and WG of broiler chickens at 28 and 42 days of age (Aghili et al., 2019). The measurable improvement in growth and feed efficiency of poultry birds have been attributed as signs of enzyme supplementation in their feed (Hesselman and Åman, 1986; Pettersson and Åman, 1989; Campbell et al., 1989; Choct et al., 1996). Chamorro et al. (2015) and Chamorro et al. (2017) reported that supplementation of enzyme complex and tannase reduced digestibility of total polyphenols and protein and as a result had no significant influence on the growth performance of broiler chickens. In most recent layer chickens study, the reports of some authors showed that supplementation of enzyme in olive pomace diets did not increase laying performance in hens (Zangeneh and Torki 2011; Zarei et al., 2011; Afsari et al., 2013). This could be due to the single enzyme used in the study. In recent grape pomace studies conducted by Gungor et al. (2021) and Altop and Erener (2021), it is convincing that enzyme supplementation might be a worthy consideration for full-scale adoption of fruit pomaces.

Although enzyme supplementation may not convincingly improve the growth or laying performance of poultry birds, however, it would maintain it and afford birds to efficiently utilize more dietary fibre than they can ordinarily handle without exogenous enzymes. While enzyme supplementation does not provide an avenue for indiscriminate inclusion of fibre into poultry diets, the onus lies on poultry nutritionists and experts to identify the optimum amount of enzyme-treated fruit pomaces that would yield desirable outcomes.

Besides the growth performance improvement, exogenous enzymes contribute positively to environmental sustainability by reducing animal-related pollution.

4.2. Pre-treatment methods

In addition to the above, the biodegradability of fruit pomaces could be enhanced when subjected to pre-treatments before incorporation into poultry diets. Pre-treatment methods that could be employed include but are not limited to steam explosion, amination, and fermentation.

4.2.1. Steam explosion and amination

Given the fibre component of fruit pomaces including lignocellulose, improving their nutritive value may also be achieved through amination and steam explosion. Amination method is one of the commonly used pre-treatment methods which could increase the digestibility of structural cell wall, particularly the lignocellulose material and improve available nitrogen content (Dryden and Kempton, 1983; Cann et al., 1993; Goto and Yokoe, 1996; Shen et al., 1998) and soluble sugar content (Chen et al., 2005). A steam explosion has been reported to breakdown lignin fraction linked to cellulose and hemicellulose in high fibre feedstuff (Xie et al., 2011; Estevez et al., 2012; Frigon et al., 2012; Monlau et al., 2012; Sambusiti et al., 2013; Iram et al., 2019). Although, these techniques are mostly used on ruminants feedstuff and biofuel production, however, reports have shown that bio-utilization of lignocellulose materials in crop residues by intestinal microbes was improved following steam explosion treatment (Dekker, 1991; Sciaraffia and Marzetti, 1991; Mokomele et al., 2018; Iram et al., 2019). The steam explosion techniques will not undermine the phenolic component in fruit pomaces. The concentration of soluble organic matter and phenolic compounds were reported to double and triple, respectively following a steam explosion at 220 °C for 5 min (Cubero-Cardoso et al., 2020). The use of steam explosion pre-treatment is one method that has also not been fully exploited in the feeding of fruit pomaces in poultry production. The superiority of steam explosion over some other methods of fibre modification includes its cost-effectiveness, no or less use of hazardous processing chemicals, and lower energy expenditure during the modification process.

4.2.2. Fermentation

Several fermentation techniques have been used in both human and animal nutrition to improve the nutritive value of food and feed, respectively. This is because fermentation increases the amount of polyphenols, polysaccharides, and/or mannoproteins from substrates (Vergara Salinas, 2014). In the in vitro demonstration by Espinosa-Pardo et al. (2017), fermentation of orange pomace significantly increases total phenolic yield, TPC, and antioxidant activity, particularly the DPPH and oxygen radical absorbance capacity values and crude protein content compared to the unfermented orange pomace. Furthermore, neutral detergent fibre (NDF) and acid detergent fibre (ADF) were reported to be appreciably reduced following fermentation of wheat bran and consequently improved the FCR and gut microbiota of broiler chickens when fed the diet (Teng et al., 2017).

However, Wanzenböck et al. (2020) demonstrated that both 15% fermented and unfermented wheat bran did not negatively affect FCR, egg production, and relative abundances and α-diversity of microbiota in the gut of layer chickens. Squire (2005) reported that 15% fermented corn condensed distillers' soluble did not have any influence on the final BW, ADG, and feed efficiency of pig. In layer chickens, 24% fermented cassava pulp had a similar effect on FI and egg weight; however, FCR, and protein efficiency ratio were reported to be significantly increased as fermented cassava pulp inclusion increased from 16% to 32% (Okrathok et al., 2018). In quail, incorporation of fermented palm kernel cake at 15%–25% was reported to have no effect on FI, BW gain, protein consumption, and protein efficiency (Nurhayati (2019)). Application of fermentation in less-fibrous feedstuff including, soybean meal and soy-milk waste, was reported to improve the growth performance of turkeys and broiler chickens, respectively (Chachaj et al., 2019; Ciptaan et al., 2021). Based on the reports above, fermented less-fibrous feed ingredients are better utilized than fibrous ones. This is attributable to the higher inclusion levels of fermented fibre ingredients rather than the fermentation methods and inocula used.

In poultry, there is a dearth of information on the impact of fermentation of fruit pomaces on growth performance and intestinal health. However, dietary supplementation of fermented grape pomace was reported to foster the proliferation of gut-friendly microbes (Viveros et al., 2011). Nardoia et al. (2020) demonstrated that growth performance was maintained when 3% fermented grape skin was fed to broiler chickens. However, a similar feat was not achieved when 6% fermented grape skin was fed. Similarly, the work of Gungor et al. (2021) indicated a significant improvement in overall BW and feed conversion, reduction in the population of *C. perfringens* when fermented 1.5% grape pomace was fed to broiler chickens. The efficacy of fermentation method, particularly in the optimization of fruit pomaces in poultry feeding is dependent mainly on the amount of the fermented fruit pomaces incorporated into their diets.

5. Threats to the optimization techniques of fruit pomace for use in poultry production

High inclusion levels of fruit pomaces in poultry diets may frustrate the capacities of the above-described optimization techniques and thus, impede the adoption of fruit pomaces as partial substitutes to some conventional feedstuff like maize and wheat. Nevertheless, the adoption of enzyme supplementation and fermentation method in fruit pomace for use poultry production would be more rewarding when optimal inclusion level is used. Thus, the importance of optimization methods is dependent on fibre inclusion levels and should not be particularly used as an alternative route to be using high inclusion of fruit pomaces in poultry feeding.

6. Conclusion

There is no doubt that fruit pomaces can act as a dual-capacity alternative to antibiotics and some conventional feedstuff. However, the major bone of contention limiting their utilization in poultry nutrition is identifying the appropriate inclusion levels with or without optimization. More extensive studies are still needed to identify the most suitable optimization approach that would afford the maximization of the fruit pomaces in poultry production. Cost-benefit analysis on the use of fruit pomaces in poultry production is essential. This would furnish commercial poultry farmers and feed millers with convincing information about whether its adoption is economically worthwhile.

Declaration of competing interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, and there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the content of this paper.

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