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Review

Potential of Fruits and Vegetable By-Products as an Alternative Feed Source for Sustainable Ruminant Nutrition and Production: A Review

Hassan Jalal [1], Melania Giammarco [1,*], Lydia Lanzoni [1,*], Muhammad Zeeshan Akram [2], Ludovica M. E. Mammi [3], Giorgio Vignola [1], Matteo Chincarini [1], Andrea Formigoni [3] and Isa Fusaro [1]

[1] Department of Veterinary Medicine, Faculty of Veterinary Medicine, University of Teramo, 64100 Teramo, Italy
[2] Nutrition and Animal-Microbiota Ecosystems, Department of Biosystems, KU Leuven, 3001 Leuven, Belgium
[3] Department of Veterinary Medical Sciences, Alma Mater Studiorum—University of Bologna, 40064 Bologna, Italy
* Correspondence: mgiammarco@unite.it (M.G.); llanzoni@unite.it (L.L.)

Abstract: The agro-food industry produces tons of waste at different stages in the food production process, creating a massive ecological crisis. If implemented, the use of fruit and vegetable by-products (FVBPs) in animal nutrition has the potential to lessen the environmental footprint of the food production chain, lower animal feeding costs, and improve the quality and sustainability of animal products. Recent research on the inclusion of FVBPs, naturally enriched with polyphenols, in the diets of small and large ruminants has shown some promising outcomes, which we discuss in this review. The effects of FVBPs on digestion, rumen fermentation, methane emissions, rumen liquor fatty acid profile, and milk production are examined. Due to the chemical composition and the presence of certain bioactive compounds, FVBPs are capable of influencing the ruminal and intestinal ecosystem through improved kinetics of fermentation. Several in vivo studies have demonstrated that the dietary inclusion of FVBPs resulted in improved milk production and composition without any negative effect on animal performance. Using FVBPs as an alternative to conventional feedstuffs may promote sustainable animal production and nutrition. However, it must be stressed that the efficacy of these feed supplements is conditional on the source, kind, and quantity employed.

Keywords: methane; ruminants; milk production; bioactive compounds; sustainability; nutrition; animal production

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Citation: Jalal, H.; Giammarco, M.; Lanzoni, L.; Akram, M.Z.; Mammi, L.M.E.; Vignola, G.; Chincarini, M.; Formigoni, A.; Fusaro, I. Potential of Fruits and Vegetable By-Products as an Alternative Feed Source for Sustainable Ruminant Nutrition and Production: A Review. *Agriculture* **2023**, *13*, 286. https://doi.org/10.3390/agriculture13020286

Academic Editor: Federico Infascelli

Received: 13 December 2022
Revised: 10 January 2023
Accepted: 19 January 2023
Published: 25 January 2023

1. Introduction

Agro-industrial by-products consist of waste from agricultural crops or vegetable processing industries, and their disposal poses an environmental issue because they are potential pollutants [1]. The production of agro-industrial by-products in the European Union (EU) is projected to be 16 million tons, with Germany, the United Kingdom, Italy, France, and Spain being the main producers, creating 3 million tons, 2.6 million tons, 1.9 million tons, 1.8 million tons, and 1.6 million tons, respectively [2]. The increasing volume of agro-industrial by-products worldwide poses a significant environmental threat [2]. Landfilling, burning, and dumping are the most common methods used to dispose of these agro-industrial by-products, all of which result in environmental pollution [3]. The greenhouse gases produced from landfills, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), are released directly into the environment, contributing to global warming [4]. CH_4 production is a greater problem than CO_2 production since CH_4 traps 21 times more heat than CO_2 [5].

Recent reports have shown an increasing trend in the global demand for animal products [6]. Furthermore, the human population is estimated to surpass 10 billion by 2050, and food demand will be increased by 59–98% [7]. Correspondingly, livestock population will need to expand by 70% [8]. Since feed is a key factor in determining livestock production, efficient livestock feeding is crucial to achieving the desired production level [9]. However, global livestock production is constrained by an inadequate supply of feed owing to urbanization and industrialization [10,11]. An increased hike in the human population raises food-feed competition, posing yet another challenge for the animal production sector. This requires feeding animals with humaninedible ingredients and producing animal feed on arable land instead of human food [12]. The increasing costs of green fodders and grains are also impacting livestock production. In fact, forages are the base of ruminants' diet (such as corn silage, alfalfa, or grass hay), and concentrates provide additional protein and energy [13]. All these factors have driven animal producers to formulate livestock feed on cost-effective human-inedible ingredients that do not compete with human nutrition. Albeit, finding alternative feed ingredients for animal nutrition to support sustainable production has become challenging [14]. The use of fruit and vegetable by-products (FVBPs) from the winery, juice, and jam industries as a non-conventional feed source for ruminants could be a considerable option. FVBPs, which include pulps, skins, pomace, roots, and tubers, represent the most common waste products, accounting for 40–50% of all discarded material [15]. Grape and olive pomaces are derived from the wine and oil production industry, while apple pomace, citrus pulp and peel, and pomegranate pulp are derived from the juice, jelly, and jam industries [16]. Among vegetables, tomato pomace is a by-product of tomato paste and ketchup production [17]. Alongside serving as a feed source, FVBPs also contain a significant amount of bioactive substances, particularly polyphenols such as flavonoids and tannins [18]. These bioactive compounds modulate ruminal microbiota, fermentation, and digestion and help in the mitigation of greenhouse gas emissions [15]. However, global livestock sector contributes 14% of total anthropogenic greenhouse gas emissions and a large portion approximately 81% of the enteric CH_4 emissions come from ruminants [19,20]. Additionally, CH_4 accounts for 2–12% of energy loss in ruminants [21]. When added to ruminant diets, these polyphenol-rich FVBPs have been demonstrated to reduce CH_4 gas by inhibiting the growth and action of methanogens such as *Methanomicrobium* or *Methanobrevibacter*, which are accountable for CH_4 production [22]. Biologically active compounds, such as flavonoids derived from the by-products of the winery industry and citrus fruits, have gained attention for their ability to modulate ruminant immune systems [23], increase milk production, and have a positive effect on ruminant milk composition [24]. These resources could be used to produce environmentally sustainable ruminant nutrition and production. This strategy would provide financial and health benefits for the animal industry while also helping to alleviate the environmental problems associated with waste disposal [25]. The inclusion of these by-products in ruminant diets could lessen the environmental impact of their disposal [26] and promote the growth of a circular economy by recycling the biomass derived from crop production [1].

However, their usage in ruminant feeds is constrained by an inadequate understanding of the nutritional and economic benefits of FVBPs, as well as by their seasonal availability [2]. The current review discusses the nutritional values of FVBPs and investigates possibilities of using FVBPs as potential feed to improve the nutrition and productivity of ruminant animals sustainably.

2. Chemical Composition of FVBPs Used in Ruminant Feeding

The chemical compositions of FVBPs, including dry matter (DM), organic matter (OM), crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), ether extract (EE), and ash are indicated in Table 1. Moreover, FVBPs are usually rich in highly fermentable sugars [27]. Abarghuei et al. [28] observed grape pomace to have variable physical and chemical characteristics, with a low CP concentration (94 g/kg of DM), whereas Guerra-Rivas et al. [29] reported a high CP content (138 g/kg of DM). Correddu et al. [30] observed a high quantity of lipids in grape pomace (109 g/kg of DM).

Citrus by-products are a good source of energy for dairy ruminants, pigs, and other domesticated animals because they have low protein levels (50 g/kg of DM) and NDF levels (194–308 g/kg of DM) [1,31,32]

Pomegranate seeds and peels have demonstrated a greater NDF content (680 g/kg of DM) and a moderate CP level (154 g/kg of DM) [33]. However, García-Rodríguez et al. [1] reported the lipid contents of apple pomace as twice as reported in previous studies(60 g/kg of DM vs 18 and 37 g/kg of DM) 34,35]. The researcher believed that seeds in the residual debris increased lipid content [15]. Some studies have found that the chemical properties of vegetable pomace, such as tomato from ketchup and sauce manufacture, differ from those of fruit by-products [36,37]. Tomato pomace has greater CP (217 g/kg of DM) and NDF (554 g/kg of DM) levels than fruit by-products [38]. There has been a recent uptick in research on the feasibility of using agro-industrial by-products as livestock feed. However, their chemical compositions vary greatly due to various factors, including their horticultural or geological origin, cultivating and processing methods, and climatic conditions [39]. Several potential dietary components for ruminants exist to serve as alternates to conventional feeds. A high-energy by-product may replace grains in the diet, whereas a high-fiber by-product can take the place of roughage [40]. In addition to conventional protein sources, such as soybean meal, various by-products can serve as alternatives, such as tomato pomace [41–43]. There is a need to expand our knowledge about the exact chemical properties and nutritional value of co-products from horticulture, agriculture, and fruit farming to make proper recommendations for their inclusion in the diets of ruminants.

Table 1. Chemical compositions of FVBPs (g/kg of DM).

By-Products	DM	OM	CP	EE	NDF	ADF	Ash	References
Grape pomace	439	918	95	85	474	440	82	[44]
	950	-	119	73	376	317	89	[45]
	525	940	94	52	568	476	-	[28]
	-	811	138	32	243	193	-	[29]
Grape marc	910	938	113	89	558	465	-	[46]
	934	-	111	69	527	389	87	[36]
Grape seed	-	960	116	52	682	584	-	[1]
	974	-	93	109	539	-	27	[30]
Citrus pulp (orange)	904	831	77	49	194	128	168	[32]
	-	940	110	25	308	223	-	[1]
	937	-	50	26	230	162	90	[31]
Citrus pulp (lemon)	-	957	76	77	247	171	-	[1]
	872	-	66	32	209	164	51	[47]
	905	-	87	27	175	145	81	[48]
Citrus (clementine)	-	972	73	20	139	96	-	[1]
Tomato pomace	-	952	191	100	552	462	48	[37]
	851	966	194	-	500	340	-	[49]
	941	955	217	93	554	422	-	[38]
	926	-	157	62	616	507	44	[36]
Pomegranate pulp	912	-	69	26	314	228	36	[50]
		971	78		413			[51]
Pomegranate seed	951	-	154	6	680	490	24	[33]
	880		126	121	496	390	20	[52]
Pomegranate peel	875	943	35	18	-	-	56	[53]
	961	-	36	6	208	151	54	[33]
Apple pomace	973	982	77	18	306	244	-	[34]
	921	981	67	37	-	442	354	[35]
	-	984	51	60	672	460	-	[1]

DM: dry matter; OM: organic matter; CP: crude protein; EE: ether extract; NDF: neutral detergent fiber; ADF: acid detergent fiber.

3. Bioactive Compounds of FVBPs Used in Ruminant Feeding

Polyphenols are plant secondary metabolites that protect plants from infections, insects, grazing animals, and the harmful effects of solar radiation [54]. These compounds are characterized by aromatic rings with one or more hydroxyl groups. Polyphenols are further categorized based on their chemical structure into flavonoids, non-flavonoids, and tannins [2].

Flavonoids have two aromatic rings connected by three carbon atoms to form an oxygenated heterocycle. Flavonoids have gained prominence owing to a wide range of biological effects and antimicrobial properties. Flavones, flavonols, flavanones, isoflavones, and anthocyanidins are all types of flavonoids [55]. The most common examples of non-flavonoids are simple phenols (cresol, thymol, and resorcinol), phenolic acids (syringic, gallic, and vanillic acid), and stilbenes. Additionally, a wide variety of molecular weights and degrees of complexity may also be found in tannins. They are classified into two categories: hydrolyzable tannins (HT) and condensed tannins (CT). Tannins may have favorable or unfavorable effects depending on the animal's species, physiological condition, and diet composition [56]. These bioactive compounds have no direct nutritional value and may have negative effects on animal productivity as antinutritional substances [57]. However, several studies have declared these antinutritional substances to be effective natural feed additives. Their prudent and efficient usage as feed additives has been associated with improved rumen fermentation efficiency, including better protein metabolism [58], decreased CH_4 production [58], minimized nutritional stress such as bloating [30], and improved animal health and productivity [15]. The polyphenols, such as flavonoids, non-flavonoids, and tannins, in FVBPs have beneficial biological effects on the rumen ecology, such as modifying the rumen micro-biota, which affects the ciliated associated methanogen population [59] to reduce CH_4 emissions and protein degradation [26]. The phenolic compositions of FVBPs are shown in Table 2.

Table 2. Bioactive compounds (polyphenols) in FVBPs used in ruminant feeding.

Fruits and Vegetables	FVBPs	Bioactive Compounds	References
Grapes	Pomace	Flavanols, flavanols, anthocyanins, CT, catechin, epicatechin, gallic acids, and proanthocyanidin	[26,36,60,61]
	Seeds	Anthocyanins, proanthocyanins, ferulic acids, caffeic, gallic acids, CT, and catechin	[26,30,62,63]
	Stalk	CT, flavanols, hydroxycinnamates, and flavanols	[64]
Citrus fruits	Peel	Diosmin, narirutin, didymin, sinesetin, gallic acid, p-coumaric, hesperidin, catechins, ferulic acid epicatechins, quercetin, and proanthocyanidin	[23,65,66]
Tomato	Pomace	Naringenin, rutin, quercetin, and kaempferol	[36,37]
Pomegranate	Seed	Anthocyanins, HT, and flavonoids	[67]
	Peel	Flavonoids, punicalagin, gallic acid, HT, and CT	[68,69]
	Pulp	Tannins	[70]
Apple	Pomace (peels, core, seeds, stems)	Catechins, proanthocyanidins, hydroxycinnamates, flavonols, dihydrochalcones, anthocyanins, quercetin, and glycosides	[26,71]

4. Effect of Feeding FVBPs on Ruminant's Nutrition

4.1. Effects on Dry Matter Intake

DM intake (DMI) is dependent on the type of FVBPs used and on which ruminant species. Ruminants' DMI was reduced when FVBPs, particularly citrus and grape pomace over 150 g/kg DM, were offered to them [45,72]. Owing to the asperity that proanthocyanidins impose on feed by interacting with salivary proteins, the feed becomes less palatable and has a high fiber content, contributing to a reduced DMI [73]. The dried citrus pulp may substitute up to 20% of the concentrate in dairy cattle [74], and up to 30% in ewes, without lowering DMI [32]. However, recent research has demonstrated that citrus and winery by-product inclusion levels below 150 g/kg of DM in ruminants promote DMI because of their distinctive flavor, smell, and higher palatability at these lower inclusion levels [45,75–77]. The literature suggests that feeding ensiled apple pomace to lactating Holstein cows at rates of up to 30% had no detrimental effects on their performance. Meanwhile, a 15% inclusion of apple pomace was shown to be the optimal level for a better feed conversion ratio [78]. On the other hand, Fang et al. [79] suggested that the apple pomace content should not exceed 44 g/kg of DM, or 5%, in the overall mixed ration treatments. Tomato waste may be fed to animals either fresh or after storage by ensiling or sun drying. The high water content of tomato pomace prevents it from ensiling on its own. Therefore, to overcome this problem, it is frequently mixed in a 70:30 ratio with wheat, rice, or corn stovers. Multiparous dairy cows (producing 26 kg of milk per day) had their concentrate mixtures supplemented with up to 32.5% dried tomato pomace with no adverse effects on their DMI [80]. Moreover, tomato pomace can be supplemented as feed in sheep's diets, but the level should not exceed 40% [41]. Inconsistencies in results are present which suggest the need for further research to better understand the prudent exploitation and optimum inclusion level of each agro-industrial by-product in ruminants' diets.

4.2. Effects on Rumen Digestibility

The rumen digestibility of DM, OM, CP, and NDF tends to decrease as FVBPs levels in ruminant diets increase, as shown in Table 3. One possible explanation could be the complex interactions between polyphenols in these FVBPs and polymers, such as proteins and carbohydrates, to create complexes, reducing their digestibility in ruminants' digestive tracts [81]. A lower digestibility of FVBPs is typically associated with increased lignin and tannin contents, as well as the industrial process to which co-products are subjected [82]. FVBP phenolic groups, which include proanthocyanidins, eugenol, and limonene, interact with protein by forming hydrogen bonds at various sites. More specifically, proanthocyanidins interact with the hydrophobic sites of proteins and the aromatic ring structure of tannins to form complexes [83]. Moreover, the use of FVBPs decreases protein digestibility [28,84] because of the tannin's capacity to bind proteins. When FVBPs supplemented with other feeds, NDF digestibility is further hampered as their tannin contents create indigestible complexes with cell wall carbohydrates inside the rumen [28]. In industrial processes, the heat required to extract juices, wine, and jam increases the quantity of nitrogen or tannin compounds in the cell wall of the by-products, hence decreasing CP digestibility [85]. In this case, polyethene glycol can help in increasing the CP digestibility of by-products [28]. However, evidence from in vivo and in vitro studies shows that essential oils and polyphenols from citrus and winery by-products protect dietary polyunsaturated fatty acids from biohydrogenation in the rumen and limit the metabolism and proliferation of ruminal bacteria, which are responsible for biohydrogenation, especially those implicated in the final step, which transform vaccenic acid into stearic acid [86,87]. *Clostridium proteoclasticum* inhibition without affecting *Butyrivibrio fibrisolvens* to a great extent permits polyunsaturated fatty acids and their biohydrogenation products, such as rumenic acids and vaccenic acids, to bypass rumen biohydrogenation and be absorbed into animal tissues [88]. In conclusion, using FVBPs in high amounts might be detrimental to DMI and nutrient digestion.

Table 3. Effects of FVBPs on the nutrient digestibility of ruminants.

By-Products	Inclusion g/kg	Animals	DMD g/kg	OMD g/kg	CPD g/kg	NDFD g/kg	ADFD g/kg	References
Grape pomace	762	lambs	453	510	345	343	-	[28]
	20	steers	625	665	725	622	533	[89]
Citrus pulp	90	cows	741	-	759	574	-	[90]
	180	cows	754	-	765	576	-	[90]
	50	calves	667	-	698	546	476	[91]
	100	calves	654	-	696	541	462	[91]
	150	calves	653	-	691	531	459	[91]
	200	calves	652	-	690	525	451	[91]
	100	lambs	695	716	714	501	472	[92]
	200	lambs	691	713	706	495	470	[92]
	300	lambs	681	705	703	488	465	[92]
	400	lambs	678	704	692	471	461	[92]
Tomato pomace	72	cows	667	680	-	397	-	[93]
Pomegranate peel extract	10	cows	566	-	601	414	-	[94]
	20	cows	582	-	606	416	-	[94]
	40	cows	609	-	648	458	-	[94]
Pomegranate marc	80	lambs	732.4	754	705.6	501.8	424.9	[95]
	160	lambs	701.4	723.7	617.3	445.2	293.3	[95]
Pomegranate peel	10	lambs	671	668	717	-	-	[96]
	20	lambs	664	663	692	-	-	[96]
	40	lambs	653	661	683	-	-	[96]
Ensiled mixed apple and tomato pomace	150	cows	665	703.6	662.5	590	-	[97]
	300	cows	668	702.1	662.4	586	-	[97]
Apple pomace	50	cows	525	576	638	458	415	[98]
	100	cows	518	570	595	465	412	[98]
	200	cows	508	554	537	452	402	[98]
	50	wethers	631	580	746	422	401	[79]
	100	wethers	625	571	717	424	399	[79]
	200	wethers	618	566	698	437	409	[79]

DMD: Dry matter digestibility; OMD: organic matter digestibility; CPD: crude protein digestibility; NDFD: neutral detergent fiber digestibility; ADFD: acid detergent fiber digestibility.

4.3. Effects on Methane Production

One contributor to global warming is the CH_4 gas emitted during enteric fermentation by ruminants. Enteric CH_4 emissions account for around 90% of total CH_4 emissions and 47% of total greenhouse gas (GHG) emissions from the ruminant industry [99]. Strategic feeding of animals has the potential to minimize CH_4 and N_2O emissions during animal production [100]. Some of the phytochemicals in FVBPs, including tannins, saponins, and essential oils, might potentially alter microbial diversity and fermentation in the rumen, hence reducing ruminal methanogenesis [101]. Additionally, tannins and other phytochemicals containing phenolic groups may be more adept at binding with proteins, slowing their degradation by rumen microbes [102]. Likewise, the tannins' interaction with FVBPs and ruminal bacteria or their suppression of fiber digestion may be directly or indirectly responsible for the reduction in CH_4 production [103]. Reduced feed degradability as a result of interactions between FVBPs' naturally occurring substances, such as bioactive components and ruminal microorganisms, leads to lower concentrations of hydrogen ions, which in turn leads to lower levels of CH_4 production [104]. However, unfortunately, a decrease in the digestibility of OM often accompanies anti-methanogenic action [56]. Additionally, adding polyphenolic compounds from citrus by-products and grape pomace to dairy animal diets has been shown to lower CH_4 emissions by preventing the growth and activity of methanogens such *Methanomicrobium* and *Methanobrevibacter* [22,105]. The use of dried distiller grains soluble with 1–20% grape seed meal in vitro lowered CH_4 emission and the amount of *Methanobrevibacter* spp. [106]. In another study, feeding dairy cows with dried and ensiled grape pomace at a 5 kg DM/day inclusion rate in partial replacement for alfalfa hay reduced CH_4 emissions by 22.6%, with positive stimulation of rumen bacteria and archaeal populations [22]. Essential oils from these by-products, such as eugenol and limonene, have been found to directly inhibit methanogenic archaea or indirectly limit CH_4 emissions by directly reducing particular microbial metabolic pathways, leading to methanogenesis [107]. Additionally, essential oils may alter the structure of the archaeal community and/or the activity of the methanogenic pathway, reducing the abundance of methanogens and CH_4 production [108]. Some protozoa, which live in symbiosis with archaea and may contribute up to 37% to rumen CH_4 synthesis, may be suppressed by these compounds, reducing methanogenesis. CH_4 production in the rumen may be cut by as much as 94% through the use of essential oils, which have been shown to have this effect [108,109]. As a result, there is an opportunity to offer high feeding value while minimizing CH_4 production by supplementing feed items rich in phytochemical-nutrient complexes into ruminant diets.

4.4. Effect on Rumen Fermentation Parameters

The dietary effects of FVBPs enriched with polyphenols on ruminal fermentation parameters such as ammonia (NH_3) production and volatile fatty acids (VFA) have been diversely investigated. Polyphenols have shown the ability to reduce ruminants' born environment footprints through the mitigation of urea and CH_4 emissions. In Table 4, the main effects of the inclusion of different FVBPs on the ruminal parameters are presented. Reduced rumen VFA concentration is reported because of the presence of proanthocyanidins in these by-products, as they lower microbial activity and substrate degradation in the rumen [30]. Among other effects, polyphenols lower feed degradability, which results in reduced total VFA concentration, particularly acetate contents [56], which could be associated with decreased ruminal microbial activity. It may be due to the inhibition of cellulolytic bacteria by polyphenols, particularly tannins, that their main product, acetate, is produced. In a few cases, an increase in propionate was observed, which lead to a decrease in the acetate-to-propionate ratio. A negative correlation between propionate and CH_4 production exists because of hydrogen molecules required for assimilation, which is an important effect of polyphenols from an environmental point of view [2]. However, ruminal VFA production is substrate-dependent; increasing the amount of FVBPs (such as grape pomace and citrus by-products) in ruminants' diets by up to 150 g/kg of DM enhances the overall VFA profile [23]. Previous studies have also shown a decrease in ruminal NH_3 production, which is probably associated with a decrease in protein degradability [42]. It is widely established that polyphenols bind with dietary proteins and limit the degree to which they ferment in the rumen [110]. This last aspect remains paramount for a couple of reasons: first, it increases nitrogen use by animals from a nutritional viewpoint; second, it minimizes nitrogen excretion from an environmental standpoint. In addition, proanthocyanidins and essential oils from citrus by-products and grape pomace lessen the amount of NH_3 and nitrogen produced in the rumen owing to reduced protein degradation [111]. Furthermore, bioactive compounds from FVBPs likely affect ruminal NH_3 concentrations by lowering the number of protozoa, which are essential for the breakdown of the protein in feed [111,112]. Several studies have demonstrated that NH_3 nitrogen released by microbial protein degredation can be bound by polyphenols in a balanced chemical reaction regulated by NH_3 concentrtion to provide a continuous supply of sufficient NH_3 for rumen microbial growth. [109].

Table 4. The effects of feeding FVBPs on rumen fermentation parameters.

FVBPs	Species	Inclusion Level	Main Findings	References
Grape pomace	Sheep	762 g/kg	Reduced NH_3 concentration and pH values	[28]
	Steer	20 g/kg	Increased NH_3 concentration, increased total volatile and propionate, reduced acetate-to-propionate ratio	[89]
Grape seed	Sheep	300 g/day	Increased NH_3, increased rumenic acid and vaccenic acid, reduced linoleic and linolenic acids	[30]
Grape marc	Cows	5 kg/day or 247 g/kg	Reduced NH_3 concentration, increased acetic acid, reduced propionic acid, increased acetic-to-propionic ratio	[113]
Tomato silage	Goat	850 g/kg	Reduced acetate-to-propionate ratio	[114]
Tomato pomace	Lambs	50–150 g/kg	Reduced NH_3–nitrogen concentration, increased acetate, propionate, butyrate, iso-butyrate and valerate concentrations, and higher total VFA concentration	[115]
Ensiled mixed tomato and apple pomace	Cows	150–200 g/kg	Higher acetic and propionic concentrations, higher acetic-to-propionic ratio and total VFA concentration, lower ruminal pH	[97]
Citrus pulp	Ewe	390 g/kg	Reduced rumen NH_3 concentration, increased acetate-to-propionate ratio, reduced butyrate proportion	[116]
	Ewe	300 g/kg	Less in vitro NH_3 production, low pH, reduced acetate-to-propionate ratio, improved total VFA yield	[117]
Pomegranate peel extract	Cows	400 ml/cow/day	Decreased NH_3–nitrogen concentration, no effect on ruminal pH or the concentration of volatile fatty acids	[118]
	Cows	200 g/kg	Reduced NH_3 concentration and pH	[119]
Apple pulp	Cows	250–750 g/kg	No effect on NH_3–nitrogen concentration in the rumen or acetate-to-propionate ratio	[35]
Apple pomace	Cows	200 g/kg	Increased acetic acid, decreased propionic concentration, reduced NH_3	[79]
	Cows	200 g/kg	Reduced NH_3 concentration, and increased acetic acid	[98]

5. Effect of Feeding FVBPs on Milk Production and Composition

Table 5 details the effects of feeding FVBPs on the milk yield and quality of small and large ruminants. Milk production and quality were affected differently by including FVBPs in the diets of small ruminants. The grape marc supplementation at an inclusion level of 100 g/day/head in dairy sheep produced 200 g more milk per day than the control group, and their milk included 8.4 and 5.5 more grams of protein and fat per day, respectively [36]. The authors confirmed that the milk quality in terms of fatty acid profile and milk yield were not impacted when 47% of conventional ingredients in a concentrate for lactating goats was substituted with a mixture of tomato fruits and citrus pulp [120]. Additionally, Arco-Pérez et al. [114] found that supplementing lactating goats' diets with sunflower oil (20 g/kg of DM) and replacing oat hay with silage prepared from tomato or olive oil by-products resulted in higher milk quality without lowering animal efficiency. Tomato silage was fed to dairy goats for an extended period, and the animals gained weight consensually without having any adverse effects in terms of milk production or composition [114]. Another study showed that milk production and the ratios of saturated, monounsaturated, and polyunsaturated fatty acids were not affected by supplementation with winery industry waste [36,121,122]. However, the total solids and fat content of milk produced by sheep fed with grape residue were found to be higher [122]. The literature provides inconsistent findings when investigating how FVBPs influence the content of milk produced by small ruminants. Contradictory results were observed when grape by-products were included as dietary supplements in dairy sheep's diets [123]. Tomato by-products have been shown to decrease milk protein content, as reported by other authors [124]. Reducing dietary energy supply or the lower rumen degradability of the tomato by-product were both posited to have contributed to a drop in milk production [36]. There are few studies examining the effects of adding FVBPs to the diets of large ruminants on milk production or composition. Milk fat and protein levels were not affected when grape pomace was substituted for grain in dairy cow diets [125]. The milk yield and composition of jersey cows in terms of protein and fat content were not found to change when dried apple pomace was substituted for ground maize [35]. Santos et al. [90] also tested the effects of feeding citrus pulp pellets and maize grain to dairy cows, finding no detrimental impacts on milk quality or production. In addition, Abdel Gawad et al. [24] found that substituting wheat bran with tomato pomace, citrus, and beet pulp as a concentrate in animal diets improved milk fat in the buffalo species. Tomato pomace silage was substituted for clover as a forage in the diets of lactating Egyptian buffalos, which boosted milk production and fat content through better nutrient digestion [126]. An increase in milk production was observed in cows fed a diet of mixed ensiled tomato and apple pomace, which is thought to be attributable to the increased nutrient digestibility and palatability of the feed [97]. When 2% pomegranate peel was included in dairy cows' diets, milk production, total solids, solid non-fats, and protein levels were all significantly higher than with the control diet. However, adding 4% pomegranate peel to the feed drastically decreased milk production [53]. In contrast to this study, Jami et al. [94] found that feeding dairy cows a diet containing 4% pomegranate peel extract increased milk production. Accordingly, the increased daily milk protein output in cows given pomegranate peel extract may be due to the higher flow of microbial protein to the intestine, which benefits the cows by increasing the number of amino acids available for absorption [118].

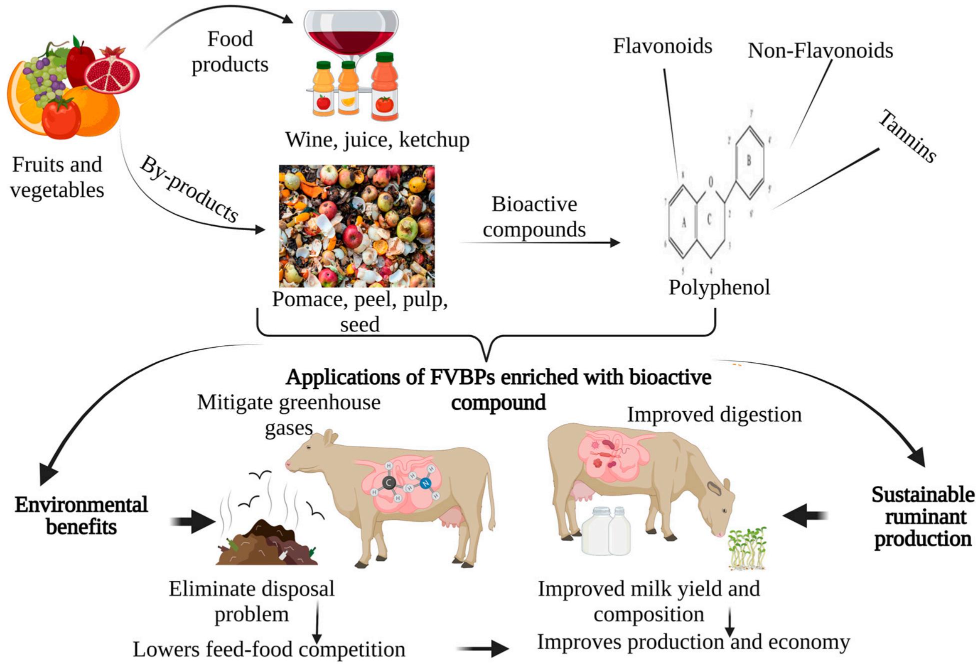
Table 5. Effects of FVBPs on milk production and composition in ruminants.

By-Products	Species	Inclusion Level of by-Products	Milk Yield	Fat	Protein	Lactose	Urea	References
Grape pomace	Sheep	100g/day	↑s	↓s	↓s	ns	ns	[36]
	Sheep	5g/100 g	ns	ns	ns	↓s	-	[121]
	Sheep	10g/100 g	ns	ns	ns	↓s	-	[121]
	Cows	150 g/kg	ns	ns	ns	↑s	-	[125]
	Sheep	10 g/kg	ns	ns	ns	ns	-	[46]
Grape residue flour	Sheep	20 g/kg	ns	↑s	ns	ns	ns	[36]
Grape seed	Sheep	300 g/day	ns	ns	ns	ns	ns	[123]
Citrus pulp	Cows	90 g/kg	ns	ns	ns	ns	ns	[90]
	Cows	180 g/kg	ns	ns	ns	ns	ns	[90]
Citrus pulp plus tomato pomace	Buffaloes	100 g/kg	↑s	ns	↑s	ns	-	[24]
Tomato pomace	Sheep	300 g/kg	ns	ns	ns	↑s	-	[37]
	Sheep	100 g/day	ns	↓s	↓s	ns	ns	[36]
	Goats	202 g/kg	ns	↑s	ns	ns	-	[114]
Mixed tomato and apple pomace	Cows	150 g/kg	↑s	ns	ns	-	-	[24]
	Cows	300 g/kg	ns	ns	ns	-	-	[24]
Pomegranate seed pulp	Goats	60 g/kg	ns	↑s	ns	ns	-	[127]
	Goats	120 g/kg	ns	↑s	ns	↑s	-	[127]
Pomegranate pulp	Sheep	648 g/kg	ns	ns	ns	ns	ns	[50]
Pomegranate peel extract	Cows	400 mL	ns	ns	ns	ns	-	[118]
	Cows	800 mL	↑s	ns	ns	ns	-	[118]
	Cows	1200 mL	ns	ns	ns	ns	-	[118]
Pomegranate peel	Cows	20 g/kg	↑s	↑s	↑s	↓s	-	[53]
	Cows	30 g/kg	ns	ns	ns	ns	-	[53]
	Cows	40 g/kg	↓s	ns	ns	ns	-	[53]
Pomegranate pulp silage	Cows	75 g/kg	ns	ns	ns	ns	-	[128]
	Cows	150 g/kg	ns	ns	ns	ns	-	[128]
Apple pomace	Cows	250	ns	ns	ns	↑s	-	[35]
	Cows	500	ns	ns	ns	↑s	-	[35]
	Cows	750	↓ns	ns	ns	↑s	-	[35]
	Cows	4 kg/day	↑s	↑s	↑s	-	-	[129]

ns = not significant; ↑s value = increased significant and ↓s value = decreased significant value (respectively); values were compared to the control ($p < 0.05$).

6. Merits and Demerits of Using FVBPs in Ruminant Feeding

FVBPs have the potential to be used as supplementary feed ingredients for ruminant production, particularly in low-to-middle-income countries [130]. This is because the increasing demand for animal products, driven by rising incomes and populations and urbanization, imposes a huge demand on feed resources [130]. Efficient utilization of locally available feed resources is key to sustainable ruminant production, including reducing waste through the use of FVBPs and expanding the feed resource base with non-human food sources. An overview of the use of FVBPs in ruminant feeding is presented in Figure 1. Using FVBPs in animal nutrition has the added benefit of providing bioactive compounds that can have positive environmental impacts, such as reducing methane and nitrogen excretion, and increasing the nutraceutical value of human food from animal sources [23]. FVBPs are rich in cellulose, minerals, vitamins, polyunsaturated fatty acids, and phytochemicals and have been linked to a variety of benefits with regard to animal health and milk production [61,131–133]. However, the use of by-products is severely restricted in the case of the production of long-ripening cheeses such as Parmigiano Reggiano for fear of negative influences on the cheese making process or of altering the sensory characteristics of the cheese [134,135]. FVBPs can be a financially beneficial addition to ruminant diets due to their ability to reduce feeding costs and feed shortages, and improve animal nutrition, leading to increased farm economy [23]. Since no study pursuing a cost-benefit analysis has been published, it is difficult to estimate the exact reduction in feeding costs that FVBPs may provide, but their low cost and good nutritional value make them a promising replacement for green fodders and concentrates in ruminant diets [120]. Romero-Huelva et al. [120] found that tomato and cucumber by-products, as well as a combination of the two, could be an effective and low-cost alternative to concentrate in ruminant diets. Colombino et al. [136] also suggested that fruit pomaces could be a new, low-cost fiber source in animal nutrition. Romero-Huelva et al. [120] further demonstrated that replacing 47% of conventional ingredients in a concentrate for lactating goats with a mixture of tomato fruits, citrus pulp, brewer's grain, and brewer's yeast reduced animal feeding costs and methane emissions. There are several challenges that prevent the widespread use of FVBPs as feed. One major issue is their high moisture content, which can often exceed 60–80%, making them difficult to handle, store, and potentially leading to spoilage [137,138]. This high moisture content can also lead to animals consuming less feed, as they are receiving more water, potentially resulting in a lack of enough DM intake, which negatively impacts productivity. The cost of transporting FVBPs with high water content is also higher. In addition, the limited storage time for FVBPs with more than 20% water content can impact feed production. The seasonal availability of fruits and vegetables and their by-products also impacts feed production; Bistanji et al. [139] found that citrus pulp from the juice industry is only available during fall, winter, and spring. Seasonality, bulkiness, and high moisture content accelerate microbial spoilage, the oxidation of organic macromolecules, and the degradation of bioactive compounds; hence, these by-products also require preservation prior to utilization as animal feed [140]. To ensure the long-term use of FVBPs as animal feed, it is important to employ simple, low-cost methods of preservation, such as dehydration and ensiling. These methods can help to conserve FVBPs for use during periods of feed scarcity or throughout the year [141]. Tomato pomace ensiled with dried molasses sugar beet pulp produces high quality silage with improved fermentation [142]. The combination of two or more by products often produces a positive impact on milk production, rumen environment, and nitrogen efficiency, as was the case for the use of a bakery's former foodstuff and a wheat distiller's grain [143]. These results are of great interest from an environmental point of view. Tomato and apple pomace ensiled in a 50:50 ratio also had good nutritive value for use in the diet of dairy cows [97]. Citrus pulp ensiled with wheat or rice straw in a 70:30 ratio has also been shown to produce high quality silage [77]. However, the presence of pesticides may limit the use of FVBPs in animal feed, so it is important to regularly monitor for contaminants before incorporating them into ruminant diets [130]. Further research is needed to ascertain the optimum inclusion levels of these by-products from a variety of cultivars grown in a range of conditions and extracted and processed using several methods. There should be a readily accessible facility or analytical technique for the complete measurement and categorization of micronutrients and phytochemicals from FVBPs. The bioactivity, bioavailability, toxicity, interactions, and mode(s) of action of these phytochemicals with other dietary components should be investigated in future research by a thorough evaluation of in vitro and in vivo experiments.



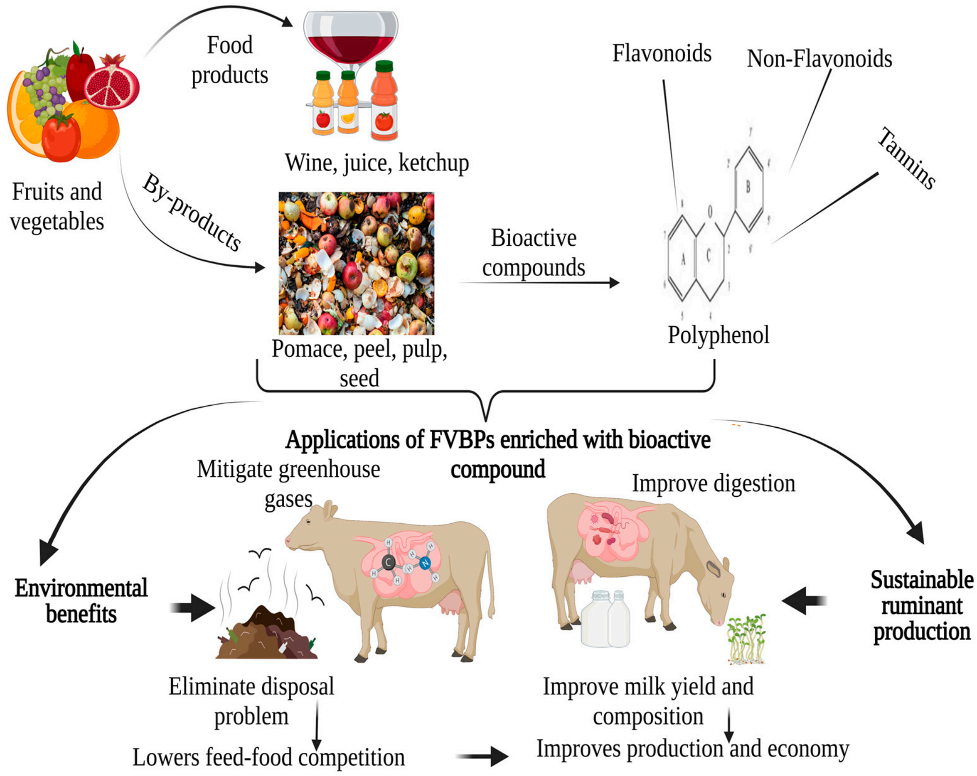


Figure 1. A summary of merits of using FVBPs in ruminant's diets.

7. Conclusions

FVBPs could be potential sources of non-edible human feed for animal production on a global scale. FVBPs have been shown to promote rumen fermentation efficiency (e.g., increased concentrations of total VFAs, propionate, and acetate-to-propionate ratio, and decreased concentration of NH_3-nitrogen etc.) and reduce rumen CH_4 emission when added to feed as non-conventional feedstuffs. Since FVBPs are rich in plant secondary compounds, supplementing feed containing bioactive substances has been demonstrated to reduce rumen methanogenesis and lower the animal's need for food. However, in vivo research revealed that FVBPs had no detrimental effects on animals' ability to produce. Animal feeding costs can be reduced, farmer revenue can be increased, and the competition between food and feed can be reduced by making efficient and effective use of fruit and vegetable waste products. Additionally, using these non-conventional feed sources will aid in waste management and lessen environmental pollution. To create feed innovations and policy intervention strategies that will promote the broad use of FVBPs for sustainable ruminant production, further study is required.

Author Contributions: Conceptualization, H.J., M.G., L.L. and I.F.; methodology, H.J., M.Z.A. and G.V., supervision L.M.E.M. and A.F.; writing original draft, H.J., M.G. and I.F.; control of the content and structure H.J., G.V., L.L., M.Z.A. and M.C.; supervision I.F., G.V. and A.F. All authors have read and agreed to the published version of the manuscript.

Funding: This publication was funded by the European Union – Next Generation EU. Project Code: ECS00000041; Project CUP: C43C22000380007; Project Title: Innovation, digitalization and sustainability for the diffused economy in Central Italy—VITALITY.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

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

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