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REVIEW

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A review on the use of agro-industrial CO-products in animals' diets

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ABSTRACT

The use of agro-industrial co-products in animal nutrition could represent an opportunity to reduce the environmental impact of the food production chain. Co-products can decrease the feeding cost and improve animal products in terms of quality and sustainability. To evaluate the use of co-products as animal feed, 57 studies published in the last 11 years on agro-industrial residues were considered. *In vitro* trials demonstrated that some co-products, such as ginseng meal, grape pomace and olive cake, in animal diets could affect fermentation parameters decreasing the gas production, particularly the methane emission. Indeed, thanks to their chemical composition and the presence of some bioactive compounds, such as tannins, these co-products seemed able to modify the ruminal and the intestinal environment and consequently fermentation kinetics and end-product. Furthermore, fruits, vegetables and oil extraction co-products could be valid sources of energy, fibre and protein, respectively. The remaining studies, conducted *in vivo* on different animal species, evidenced as some fruits and oil extraction co-products (e.g., prickly pears, olive, and hemp cake) could improve milk and/or meat fatty acid profile. Moreover, the antioxidant compounds of these co-products could have beneficial effects on gut microbiota and animal health *status*. The replacement of traditional feedstuffs with agricultural or industrial co-products could represent an interesting prospect for animal production. However, it is important to individuate the right dosage of supplementation in the animal diet, considering that all fruit and vegetable residues showed high variability in chemical composition.

HIGHLIGHTS

- Reduce animal production environmental impact
- Increase animal welfare
- Reduce nutritional costs

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Introduction

The increase in food waste is a relevant problem of these last decades. On a global level, 1.3 billion tons of food are lost or wasted each year (FAO 2011). Reducing the environmental impact of human activities is one of the most difficult challenges. In this scenario, in 2015, 193 member states of the United Nations (UN) signed the Agenda 2030 with 17 Sustainable Development Objectives (SDO) and 169 targets which reflect the necessity of world leaders to improve policies and plans to preserve the natural resources to guarantee environmental sustainability (Duque-Acevedo et al. 2020). In particular, objectives #2 and #9 focus on sustainability in agriculture and industry and provide a foundation for concerns surrounding waste disposal and food waste over the years (FAO 2019). For this purpose, the European Commission (EC) set the strategy "Farm to Fork Strategy—for a fair, healthy and environmentally-friendly food system" (European Union 2020) to reduce the losses along the food chain and guarantee the sustainability of food's production, processing and consumption. To achieve these goals, the huge quantities of non-human-edible biomass waste generated along the food chain can be valorised as co-products (Rakita et al. 2021). In this regard, to reduce the environmental impact of waste, agro-industrial co-products, or former foods could represent a valid element like feed ingredients in animal nutrition. The co-products are obtained from different agro-industrial processes such as the production of oil, sugar, fruit juice and canned or frozen vegetables, root and tuber (Pinotti

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et al. 2020). While former foods are foods no long suitable for human consumption despite their important nutritional characteristics (Luciano et al. 2020). In this regard, former food could be useful in animal nutrition (Pinotti et al. 2021).

The co-products are already included in the animals' diet several times thanks to their interesting nutritional characteristics. Some co-products such as beet pulp, corn gluten feed, soybean (hulls, meal, and molasses) and sunflower meal are largely used as animal feedstuff like sources of fibre, protein and sugar (Vastolo et al. 2019; Serrapica et al. 2019; Rakita et al. 2021). However, new agro-industrial crops such as cardoon (*Cynara cardunculus* L.) and hemp (*Cannabis sativa* L.) are emerging within the last few years (Serrapica et al. 2019; Bailoni et al. 2021). Moreover, the co-products derived from fruit and vegetable processes seem to have applications in animal nutrition because of their considerable amounts of bioactive components (i.e. polyphenol, flavonoids, and tannins) (Correddu et al. 2020; Branciari et al. 2021). Indeed, co-products can bestow several advantages when included in animal diet, such as reducing the feeding cost for farmers, conferring added value to animal products and improving animal health status (Correddu et al. 2020). Moreover, some co-products such as olive mill vegetation water could be used to extract bioactive compounds (phenol metabolites), which are able to improve the microbial quality of meat (Branciari et al. 2021) or to increase the presence of bioactive molecules with antioxidant effects in milk and dairy products (Branciari et al. 2020).

In addition, the inclusion of agro-industrial residues in the animals' diet represents a major opportunity for the development of a circular economy, improving economic and environmental sustainability. Indeed, the traditional production models are based on a linear economy, where the natural resources are converted to useful products and unusable waste. Murray et al. (2017) represents a growing disposal problem. Today, the attention to limit the impacts of wastes is increased, so it is necessary to develop new production systems. The new economy, based on a circular model, aims to develop a more efficient system that ensures a reduction in natural resource use and wastes products as well, effectively reducing the wastes to be processed and designing their utilisation in systems such as valuable co-products (Toop et al. 2017).

Otherwise, co-products show some limits, such as the high variability in nutrients' composition due to the different processing methods to which they are submitted. Moreover, the co-products require preservation treatments that are essential for product stabilisation and attenuation of seasonal availability, and increase the shelf-life, particularly for the co-products which show high moisture and lipids values (Halmemies-Beauchet-Filleau et al. 2018; Salami et al. 2019).

Industrial processes are the main cause of residues development whose fruit and vegetable represented the most abundant waste, such as pulps, skins, pomace, roots and tubers, with a percentage of the residues around 40–50% of the total discards. In this regard, grape and olive pomace are derived from wine and oil production, whereas other fruit co-products (i.e. apples, pears, peaches, citrus fruits) are derived from juice, jelly and jam industries as well as all waste from the processing of vegetables such as potatoes, tomatoes, fennels, artichoke and carrots (Dilucia et al. 2020).

The review aims to emphasise the importance of introducing the co-products derived from agro-industrial processing as ingredients in animal diets.

Methodology

Duque-Acevedo et al. (2020) reported that nearly 60% (1888 on 3148) of articles about agriculture waste were published between 2009 and 2018. Moreover, the articles, which tested either former foods or extract obtained by co-products were excluded. The main database Scopus has been used to perform this review. Overall, 1637 articles were found and analysed for this study to guarantee the criteria of inclusion and exclusion. A total of 57 *in vitro* and *in vivo* studies on co-products derived from agriculture and industrial processing were selected and described. Figure 1 shows the different stages of research and selection of the articles described in the following manuscript.

Co-products characteristics and chemical composition

Among the 57 selected manuscripts, 37 (65% of all described articles) reported the chemical composition of tested co-products. The studies that reported only a few values of the main nutrient parameters (i.e. crude protein, structural carbohydrates; ether extract) were excluded from the chemical composition tables. The main part of described co-products is derived from fruit juice, jam and wine production (*citrus* spp., apple, pomegranate, prickly pears) (Table 1). Several authors (Paya et al. 2012; Brambillasca et al. 2013; Lashkari and

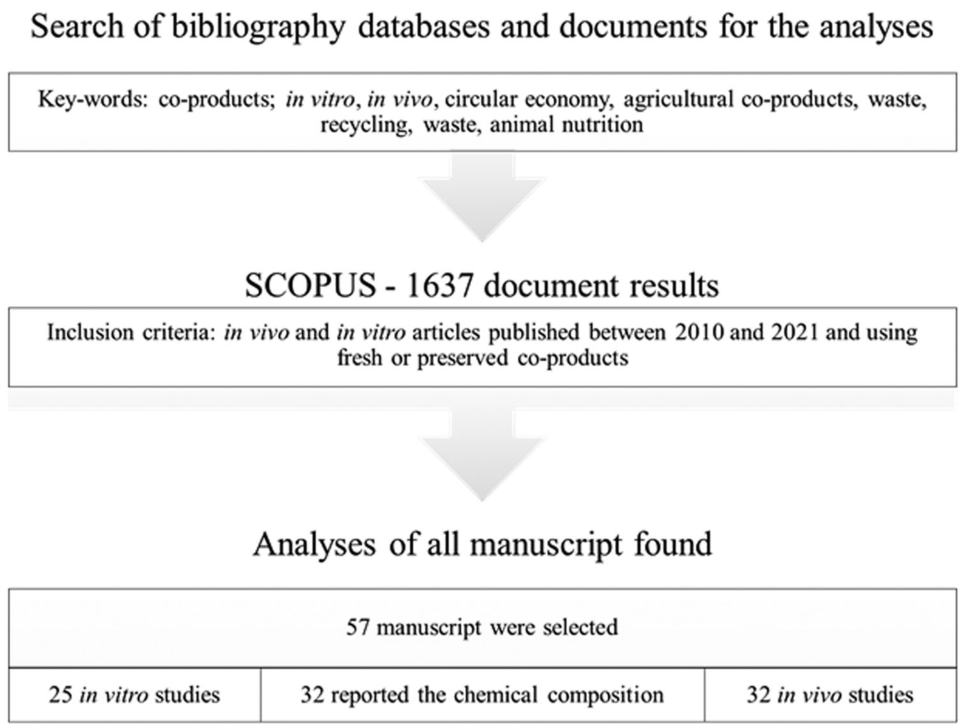

Figure 1. Stages of the bibliography research analysis process.

Taghizadeh 2013; Santos et al. 2014; Olivo et al. 2017; De Blas et al. 2018; Garcìa-Rodrìguez et al. 2019 ; Abdel Gawad et al. 2020) reported the chemical composition of citrus pulp obtained by different citrus fruits (orange, lemon, tangerine citrus). Indeed, all these co-products showed low levels of protein, a moderate amount of fibre (varying from 11 to 47% DM) and a high percentage of NSC (from 50 to 68% DM). The chemical composition of these co-products seemed to be affected more by the production method and by the process carried to increase the co-product self-life (drying, pelleting or addition of salt) than fruit species.

In any case, citrus pulp seemed to be a useful source of energy for ruminates, swine and companion animals.

The residues of grape, apple and prickly pear process could be considered sources of structural carbohydrates, with a high amount of NDF only partially lignified (Chedea et al. 2017; Steyn et al. 2018 ; Amer et al. 2019; Marcos et al. 2019; Atalay, 2020; Sato et al. 2020; Todaro et al. 2020) . Furthermore, Cilev et al. (2016) and Olivo et al. (2017) evidenced high amount (from 10 to 21% DM) of ether extract in grape residues. Similarly, Garcìa-Rodrìguez et al. (2019) reported a level of lipids about double apple pomace compared to the data reported by other authors (Abdollahzadeh et al. 2010; Paya et al. 2012; Brambillasca et al. 2013). In both cases, the authors considered that the higher content of lipids could be related to the higher incidence of seeds into the residual matter.

Mirzaei-aghsaghali et al. (2011) reported the chemical composition of pomegranate seed and peel. The seed co-product showed a high value of fibre (68.0% DM) and a moderate level of crude protein (15.4% DM). Otherwise, the peel had a high percentage of no-structural carbohydrates (NSC: 69.6% DM). Also, Serrapica et al. (2019) reported similar values for pomegranate seed cake (71.6% of NDF and 14.9% of crude proteins).

Furthermore, the refusals of vegetable (tomato, pepper, broccoli, artichoke, Jerusalem artichoke) transformation were studied by several authors (Abdollahzadeh et al. 2010; Aghajanzad et al. 2009; Cilev et al. 2016; Ersahince and Kara 2017; Panwar et al. 2017; Garcìa-Rodriguez et al. 2019; Abdel Gawad et al. 2020; Meneses et al. 2020) and the results of chemical composition are reported in Table 2. The chemical composition of this co-product varied considerably in function of the species and the portion of vegetable used, particularly in terms of carbohydrates fractions, crude protein and lipids contents. Artichoke and pepper skin showed a high percentage of NDF (>20 and 70% DM, respectively). Whileresidues of broccoli and pepper are sources of protein. Compared with the fruit co-products, the vegetable ones are richer in crude protein and NDF, but in some cases (e.g. artichoke, Jerusalem artichoke) the ADL content

Table 1. Fruit co-products chemical composition (% DM).

Co-products	CP	NDF	ADF	ADL	EE	Ash	NSC	References
***Citrus* spp pulp**								
dried orange[a]	7.95	12.3	10.4	–	3.04	5.22	–	Lashkari and Taghizadeh 2013
dried lemon[a]	8.65	17.7	15.1	–	2.87	5.90	–	Lashkari and Taghizadeh 2013
dried grapefruit	9.14	16.7	13.1	–	2.38	5.87	–	Lashkari and Taghizadeh 2013
dried lime	8.75	17.5	14.5	–	2.74	8.12	–	Lashkari and Taghizadeh 2013
dried tangerine	6.64	11.4	8.48	–	2.64	5.57	–	Lashkari and Taghizadeh 2013
dried orange	7.90	22.4	15.3	–	1.80	4.7	–	Paya et al. 2012
dried lemon	6.60	20.9	16.4	–	3.2	5.1	–	Paya et al. 2012
dried lemon	7.60	24.7	17.1	0.30	7.70	–	55.8	García-Rodríguez et al. 2019
dried orange[a]	9.50	26.5	17.9	0.80	2.55	–	56.8	García-Rodríguez et al. 2019
dried clementine	7.30	13.9	9.60	0.20	2.00	–	74.0	García-Rodríguez et al. 2019
dried citrus	7.12	22.6	13.9	1.21	3.50	4.90	–	De Blas et al. 2018
dried citrus	6.00	19.1	14.6	0.80	1.90	–	67.7	Santos et al. 2014
dried citrus	13.3	47.3	30.8	6.53	3.89	14.8	54.2	Brambillasca et al. 2013
fresh citrus	6.10	22.0	16.3	–	–	3.52	–	Olivo et al. 2017
pellet citrus	1.47	19.10	14.59	6.84	–		68.25	Styen et al. 2018
Apple								
dried pomace	5.10	67.2	46.0	15.0	6.00	–	20.1	García-Rodríguez et al. 2019
dried pomace	6.74	44.2	35.4	13.4	3.71	–	43.5	Steyn et al. 2018
dried pomace	2.65	34.0	23.8	–	–	1.75	–	Brambillasca et al. 2013
fresh pomace	5.60	45.3	38.0	–	4.70	–	–	Abdollahzadeh et al. 2010
fresh pomace	7.20	43.3	32.3	–	2.90	3.00	–	Paya et al. 2012
Grape								
fresh residues	12.7	–	–	–	10.6	4.36	–	Cilev et al. 2016
Residues	9.18	65.2	55.5	13.0	21.5	2.98	–	Olivo et al. 2017
dried pomace[a]	9.93	46.7	41.1	–	5.71	6.69	–	Atalay 2020
dried pomace	12.8	–	50.2	–	5.50	6.89	–	Chedea et al. 2017
dried pomace	12.4	38.8	37.5	–	4.02	11.8	–	Ianni et al. 2019
dried pomace	9.40	28.4	25.0	–	–	–	–	Kolláthová et al. 2020
fresh wine-less	9.30	20.9	9.60	–	0.40	32.2	37.3	Sato et al. 2020
Pomegranate								
Seed	15.4	68.0	49.0	–	0.60	2.40	13.5	Mirzaei-aghsaghali et al. 2011
Peel	3.6	28.0	15.1	–	0.60	5.40	69.6	Mirzaei-aghsaghali et al. 2011
peel	8.4	–	–	–	0.40	4.30	55.4	Kara, 2016
Pomace	9.2	35.3	30.6	12.3	6.3	3.20	49.9	Kara et al. 2018
seed cake	14.9	71.6	50.5	10.9	0.95	4.10	–	Serrapica et al. 2019
Prickly pear								
Fruit	7.60	24.70	13.70	11.20	3.50	9.45	–	Amer et al. 2019
Peel	7.20	22.10	13.80	8.90	1.90	9.61	–	Amer et al. 2019

[a]Data reported as mean value. DM: dry matter; CP: crude protein; CF: crude fibre; NDF: neutral detergent fibre; ADF: acid detergent fibre; ADL: acid detergent lignin; EE: ether extract; NSC: Non-structural carbohydrate.

Table 2. Vegetables refusal chemical composition (% DM).

Co-products	CP	NDF	ADF	ADL	EE	Ash	NSC	References
Jerusalem artichoke (*Helianthus tuberosus* L.)								
Vegetative	16.36	28.79	27.37	5.65	0.94	13.64	40.25	Ersahince and Kara, 2017
early flowering	7.37	39.03	31.70	6.78	1.70	11.7	40.15	Ersahince and Kara, 2017
full flowering	7.14	40.63	33.36	7.39	1.77	11.2	39.28	Ersahince and Kara, 2017
early seeding	6.59	44.74	36.69	8.82	2.19	8.90	37.56	Ersahince and Kara, 2017
Cynara spp								
raw	11.5	43.1	31.1	10.5	2.1	0.57	–	Meneses et al. 2020
Hay	17.7	67.8	46.7	7.6	4.1	5.2	5.1	García-Rodríguez et al. 2019
Cardoon cake	21.1	46.8	36.0	6.43	7.72	5.57	–	Serrapica et al. 2019
Broccoli								
boiled	31.1	20.4	13.1	1.8	3.1	0.632	–	Meneses et al. 2020
fresh chaffed	27.20	24.3	21.9	3.30	5.12	5.78	–	Panwar et al. 2017
stalk hay	15.5	55.6	34.9	5.4	6.6	12.2	–	García-Rodríguez et al. 2019
Pepper								
Core	19.2	31.1	22.2	5.50	6.70	–	32.3	García-Rodríguez et al. 2019
Skin	9.90	75.3	64.1	38.3	3.30	5.10	6.40	García-Rodríguez et al. 2019
fresh residue	18.8	–	–	–	8.18	–	–	Cilev et al. 2016
Tomato								
dried pulp	19.0	55.7	42.7	26.0	5.10	–	16.7	García-Rodríguez et al. 2019
dried pomace	13.7	–	–	–	0.90	11.1	55.2	Kara et al. 2018
dried pomace	22.2	49.2	32.6	–	15.0	–	6.63	Aghajanzad et al. 2009
dried pomace	18.9	45.2	13.4	5.30	4.14	7.56	41.6	Abdel Gawad et al. 2020
fresh residues	21.1	–	–	–	13.2	3.38	–	Klir et al. 2017
fresh pomace	21.7	57.4	50.7	–	13.4	–	–	Abdollahzadeh et al. 2010

. DM: dry matter; CP: crude protein; CF: crude fibre; NDF: neutral detergent fibre; ADF: acid detergent fibre; ADL: acid detergent lignin; EE: ether extract; NSC: Non-structural carbohydrate.

Table 3. Oil, sugar, beer, and flour production refusal and novel co-product chemical composition (% DM).

Co-products	CP	NDF	ADF	ADL	EE	Ash	NSC	References
Olive								
trees leave	9.8	52.9	34.5	23.1	4.7	–	16.8	García-Rodríguez et al. 2019
dried pomace	7.65	58.3	–	–	15.2	–	–	Castellani et al. 2017
cake	8.63	49.4	39.4	23.2	30.3	4.09	–	Chiofalo et al. 2020
cake	7.86	41.3	32.5	15.6	27.7	4.25	–	Liotta et al. 2019
cake	1.58	56.1	39.9	29.5	10.91	–	–	Marcos et al. 2019
cake	1.96	64.7	45.9	22.9	1.80	–	–	Marcos et al. 2019
cake	1.73	44.7	31.5	15.6	15.1	–	–	Marcos et al. 2019
Pumpkin								
seed cake	52.9	–	–	–	16.3	8.51	–	Klir et al. 2017
Sunflower								
cake	19.9	41.1	32.6	10.7	14.0	6.57	–	Serrapica et al. 2019
Canola								
meal	36.5	22.82	16.3	–	9.7	7.12	–	Woyengo et al. 2016
Soybean								
meal	50.7	13.9	39.6	5.82	13.5	5.03	16.2	Olivo et al. 2017
hulls	2.28	63.1	8.20	0.80	2.20	–	26.6	Santos et al. 2014
Brewer's grain								
dried	19.8	55.1	25.2	NA	8.0	–	13.1	Aghajanzad et al. 2009
fresh	19.5	21.9	12.9	–	7.8	4.9	–	Paya et al. 2012
Beet								
dried pulp	9.65	41.73	27.91	0.91	2.57	3.74	66.4	Abdel Gawad et al. 2020
pulp	27.4	13.5	4.00	1.50	11.1	5.20	43.2	Kröger et al. 2017
Hemp								
extracted flower	24.5	30.9	18.1	–	3.2	25.7	4.7	Kleinhenz et al. 2020
leaves	13.0	44.7	20.8	–	8.9	21.2	5.9	Kleinhenz et al. 2020
chaff	21.2	27.9	18.0	–	4.6	24.9	6.3	Kleinhenz et al. 2020
seed cake	33.4	43.6	36.2	–	11.7	–	–	Mierliţă, 2018
seed cake	34.4	39.3	32.1	–	12.4	6.7	–	Karlsson et al. 2010
seed cake	30.0	51.9	39.5	6.31	10.2	7.7	–	Serrapica et al. 2019
Coffee hulls	0.78	36.9	31.9	10.4	14.4	6.2	41.9	Olivo et al. 2017
Cassava								
Foliage	2.13	57.2	48.4	14.4	7.88	6.65	21.4	Olivo et al. 2017
Red ginseng								
meal	15.03	38.62	31.64	–	1.22	3.11	42.02	Hamid et al. 2020
Tobacco								
cake	37.0	46.7	34.7	10.9	12.0	5.65	–	Serrapica et al. 2019

. DM: dry matter; CP: crude protein; CF: crude fibre; NDF: neutral detergent fibre; ADF: acid detergent fibre; ADL: acid detergent lignin; EE: ether extract; NSC: Non-structural carbohydrate.

is quite high. This last characteristic could negatively affect their digestibility.

In Table 3, the chemical composition of different refusal of oil, beer, and flour production was reported. The examined data confirmed that the co-products often utilised as ingredients in animal diets, such as soybean meal, beet pulp, are sources of protein and fibre (Paya et al. 2012; Santos et al. 2014; Abdel Gawad et al. 2020). In additionally, olive cake showed lipid and lignin content higher than 10% DM (Castellani et al. 2017; Liotta et al. 2019; Chiofalo et al. 2020).

Recently, new co-products have been evaluated, such as hemp seed cake, red ginseng and canola meal, cassava foliage and coffee hulls (Mierliţă et al. 2018, Hamid et al. 2020; Woyengo et al. 2016; Olivo et al. 2017). Hemp seed cake and canola meal had a high content of protein, whereas cassava foliage and coffee hulls showed a high percentage of NDF (>50% DM). Kleinhenz et al. (2020) reported the chemical composition of extracted flower, leaves and chaff of hemp. The authors observed that all samples had high percentage of protein, fibre and ash. Hamid et al. (2020) reported that red ginseng meal showed a moderate amount of protein (>15% DM) and NDF (>38% DM).

Serrapica et al. (2019) evaluated the nutritional characteristics of sunflower and tobacco, suggesting that these co-products could be sources of protein. Indeed, all tested co-products reach the 20% DM of protein, except for the pomegranate seed cake that had less than 15% DM of crude protein.

The results demonstrate that the co-products could be useful sources of different nutrients. Furthermore, different parts of the co-product can provide different elements. For instance, as in the case of hemp, plant areal part residues are sources of structural carbohydrates, whereas the residues from the seeds could be sources of protein.

In vitro studies

Totally 25 *in vitro* papers described the *in vitro* fermentation parameters of co-products that have potential

Table 4. *In vitro* studies with ruminal liquor of large ruminants.

Co-products	Method	Species	Authors
pomegranate pomace apple pomace	(Menke and Steingass 1988)	Dairy cows	(Kara et al. 2018)
Pomegranate	(Menke and Steingass 1988)	Steers	(Mirzaei-Aghsaghali et al. 2011)
Jerusalem artichoke	(Menke and Steingass 1988)	Beef cattle	(Ersahince and Kara 2017)
hemp co-products	(Goeser et al. 2009)	Ruminant	(Kleinhenz et al. 2020)
red ginseng co-product	(Theodorou et al. 1994)	Cattle	(Hamid et al. 2020)
coffee hulls pelleted citrus pulp grape residue soybean hulls Cottonseed cassava foliage	(Tilley and Terry 1963)	Dairy cow	(Olivo et al. 2017)
wine lees	(Tilley and Terry 1963)	Beef cattle	(Sato et al. 2020)
pomegranate cake tobacco cake cardoon cake hemp cake	(Robinson et al. 1999)	Bulls	(Serrapica et al. 2019)

Table 5. *In vitro* studies with small ruminant liquor.

Co-products	Method	Species	Authors
citrus pulps	(Holden 1999)	Sheep	(Lashkari and Taghizadeh 2013)
citrus co-products	(Fedorah and Hrudey 1983)	Sheep	(Lashkari and Taghizadeh 2015)
brewers' grain, apple pomace, orange pulp, lemon pulp	(Orskov and Mcdonald 1979; Fedorah and Hrudey 1983)	Sheep	(Paya et al. 2012)
olive cake	(Goering and Van Soest 1975)	Sheep	(Marcos et al. 2019)
olive cake	(Pell and Schofield 1993)	Sheep	(Pallara et al. 2014)
artichoke Broccoli	(Goering and Van Soest 1975)	Goat	(Meneses et al. 2020)
grape pomace	(Menke et al. 1979)	Sheep	(Atalay 2020)
tomato pomace brewers grain	(Menke et al. 1979)	Rams	(Aghajanzad et al. 2009)
sugar beet Grape olive tree almond broccoli lettuce asparagus green bean artichoke peas broad beans tomato pepper apple pomace citrus pomace	(Goering and Van Soest 1975)	Sheep	(García-Rodríguez et al. 2019)
tomato Cucumber	(Tilley and Terry 1963).	Goat	(Romero-Huelva et al. 2013)

use in large and small ruminant, and monogastric animal nutrition (Tables 4–6, respectively).

Regarding the *in vitro* research performed using ruminal liquor of large ruminant (Table 4), mainly the two-stage system for digestibility (Tilley and Terry 1963) and the syringe method (Menke and Steingass 1988) for gas production have been used. In general, total gas production and volatile fatty acids (VFA) were reported and, sometimes, methane production has been evaluated.

In particular, Mirzaei-aghsaghali et al. (2011) studied *in vitro* parameters (organic matter digestibility, total gas production and volatile fatty acids) and estimated the nutritive value of pomegranate (*Punica granatum* L.) seeds and peel. The latter showed higher nutritive value and total gas production when compared with seeds. Similarly, Kara et al. (2018) incubated a total mix ratio (TMR: maize silage, wheat straw, alfalfa hay and concentrate) supplemented with 10 and 20% of pomegranate and apple pomaces silage (PPS and APS) and their mix (PAPS, 50 and 50%, respectively) to evaluate silage quality and *in vitro* parameters. Regarding the silage quality, PPS was significantly lower than APS for dry matter losses (19.78 vs. 27.37% DM, respectively), while the lactic acid concentration and pH value in APS and PAPS were significantly

Table 6. *In vitro* studies with monogastric feacal *inoculum*.

Co-products	Method	Species	Authors
citrus pulp	(Ramos et al. 1992)	Rabbit	(De Blas et al. 2018)
tomato pomace maize bran rice bran lentil bran pomegranate peel	(Menke et al. 1979)	Rabbit	(Kara 2016)
citrus pulp apple pomace	(Theodorou et al. 1994).	Dog	(Brambillasca et al. 2013)
canola co-products	(Menke and Steingass 1988)	Pig	(Woyengo et al. 2016)
Jerusalem artichoke	(Menke and Steingass 1988)	Horse	(Ersahince and Kara 2017)
Beet pulp Sugar cane fibre	(Theodorou et al. 1994)	Dog	(Calabrò et al. 2013)
Potato fibre	(Bourquin et al. 1993)	Dog	(Panasevich et al. 2013)

higher than PPS. Concerning *in vitro* parameters, both concentrations (10 vs. 20%) of PPS in the total mix ratio caused a reduction of total gas production, while it did not affect methane production. Substitution of APS or PAPS in dairy cow TMR instead of other forages did not negatively affect *in vitro* digestibility. In this regard, the results obtained by both studies demonstrate as pomegranate co-products fresh or ensiled could be good resources for ruminant nutrition.

Ersahince and Kara (2017) studied the nutrient composition and *in vitro* digestion parameters of Jerusalem artichoke (*Helianthus tuberosus* L.) herbage at different maturity stages (vegetative, early flowering, full flowering and early seeding) to evaluate its potential use as forage. In this regard, a significant difference between the vegetative and the early seed stages in terms of gas production was observed. The *in vitro* ruminal methane production at 24 h was significantly higher for the most precocious stages (vegetative: 39.82 vs. early flowering:30.31, ml g^{-1} DM). Moreover, *in vitro* dry matter disappearance, *in vitro* organic matter disappearance, and metabolisable energy values significantly decreased with plant maturation. The *in vitro* microbial crude proteins produced at 24 h in early and full flowering stages were higher than those of vegetative and early seeding stages (122 and 116 vs. 72 and 95 mg g^{-1} DM, respectively). The amount of acetate, propionate, butyrate and total VFA decreased with plant maturation. The authors concluded that artichoke co-products, especially at the vegetative stage (stem length $<$100 cm; no buds or flowers; green leaves), are suitable for alternative forage in terms of high nutrient composition and satisfactory digestion values in ruminants.

Kleinhenz et al. (2020) characterised the nutrient concentration, digestibility and cannabinoid concentration of hemp (*Cannabis sativa* containing $<$0.2% THC) plant and co-products (stalks remaining after seed harvesting, unprocessed female flowers intended for cannabinoid extraction, whole seed heads for seed production, leaves obtained from the drying process, chaff obtained after seed harvesting and cleaning, and processed female flowers after cannabinoid extraction). The results emerged as the nutrient concentration and fibre digestibility which varied in function of the tested plant portion. Regarding the NDF digestibility and *in vitro* rumen undigestible NDF at 240 h (uNDF), whole plant and plant parts are relatively indigestible, whereas the seed heads, chaff and leaves had the lowest uNDF. Besides, these last showed higher digestibility amounts are comparable to corn stalks, oat or barley straw. The authors concluded that the hemp plant, despite the great fat concentration, could be an interesting source of fibre for the ruminant.

Hamid et al. (2020) proposed red ginseng (*Panax ginseng* C.A. Meyer) co-products as protein resource in ruminants and studied *in vitro* effects at 48 h on rumen fermentation characteristics, microflora population, CO_2 and CH_4 production. Indeed, after the soluble substances have been extracted with water or alcoholic solution (70–75%), a residue, known as ginseng meal, is formed. The authors compared the red ginseng meal with three conventional co-products (corn gluten feed, wheat gluten and corn germ meal). The results obtained evidenced as red ginseng residue can be used as alternative protein source in ruminants' diets. However, this co-product showed the lowest *in vitro* crude protein digestibility compared to other co-products (83.72 vs. 94.55, 93.57, 90.20% CP, respectively). Additionally, ginseng co-product resulted in the lowest NH_3-N production (15.54 vs. 36.05, 34.09 and 22.58 mg/100 ml, respectively). Also interesting is its ability in decreasing CH_4 emissions without affecting the rumen fermentation characteristics thanks to its bioactive phenolic compounds (i.e. saponins, phenols, peptides, polysaccharides, alkaloids, lignans and polyacetylenes) that are able to modulate microbial behaviour. In this regard, Serrapica et al. (2019) characterised oilseed cakes from cardoon, hemp, tobacco and pomegranate by chemical composition and *in vitro* digestibility of dry matter, neutral detergent fibre and crude protein. The authors observed that the cakes residual after oil extraction from cardoon, hemp and tobacco seeds may be potentially used as protein feeds for ruminants. Concerning the *in vitro* digestibility, the highest value of rumen undegradable protein has been observed for pomegranate and hemp. Moreover, hempseed cake showed the highest value of intestinal digested protein. The rumen degradability of dry matter and especially of NDF of samples was quite low, particularly for pomegranate cake. The highest value of *in vitro* neutral detergent fibre (NDF) degradability was detected for the tobacco cake samples. In the same way, the study proposed by Olivo et al. (2017) determined the chemical composition, *in vitro* digestibility of dry matter, crude protein, and NDF, and gas production of eight different types of agro-industrial co-products and conventional feed (coffee hulls, pelleted citrus pulp, grape residue, soybean hulls, cottonseed, cassava foliage, corn silage and ground corn concentrate).

Pelleted citrus pulp and ground corn grain presented the highest levels of *in vitro* dry matter digestibility (DIVDM) 95.33 and 94.76% DM, respectively. These values were higher than the soybean hulls and the coffee hulls (83.44 and 80.73% DM, respectively), followed by corn silage (72.67% DM). The lowest values of DIVDM were found for samples of cassava foliage and grape residue (53.17 and 51.24% DM, respectively). Corn silage produced a larger volume of gas from the fast degradation fraction compared to the co-products and corn concentrate. The chemical composition, mainly lipid, pectin, and NDF content affected *in vitro* characteristics. The authors concluded that compared to common feeds, it is possible to use these co-products as a substitute for feed as a source of energy in the ruminants' diets.

Sato et al. (2020) investigated the usability of wine lees as feed for ruminants in fattening conditions by *in vitro* trials. Four treatments were prepared: 100% DM rolled barley as a control (WL0) and replaced 7.5, 15.0, and 22.5% DM of wine lees as three treatments (WL7.5, WL15, WL22.5, respectively). A linear decrease in gas production was observed at 48 h of incubation with an increase in the percentage of wine lees in the substrate. The dry matter and crude protein digestibility were linearly decreased with WL inclusion, while NDF expressed exclusive of residual ash (NDFom) digestibility was linearly increased. The polyphenolic contents and 1,1-diphenyl-2-picrylhydrazyl (DPPH) radical scavenging ability of fermented residue were linearly increased with WL inclusion. Furthermore, the proportion of α-linolenic acid and total polyunsaturated fatty acids (PUFA) in the residues after incubation was linearly increased with wine lees inclusion. The authors observed as the wine lees substituted for the fattening ration up to 20% DM had no adverse effects on apparent digestibility and ruminal fermentation. Although the gas production, dry matter, and crude protein digestibility were decreased, wine lees inclusion protected PUFA from ruminal biohydrogenation during ruminal fermentation. Thus, WL has the potential to be an important alternative as a partial substitute for antioxidant supplements.

Table 5 showed a selection of *in vitro* studies carried out with ruminal liquor of small ruminants. Lashkari and Taghizadeh (2013) measured the proportion of protein and carbohydrate fractionations, ruminal, post-ruminal and total tract protein disappearance rates, *in vitro* dry matter digestibility, apparent and true rumen digestibility, metabolisable energy and digestible organic matter of citrus co-products (pulps from fresh orange, lime, lemon, grapefruit, sweet lemon, bitter lemon, bergamot orange, and tangerine) using a modified three-step method (Holden 1999). Protein fractions and acid detergent insoluble nitrogen were the highest in grapefruit pulp; ruminal crude protein disappearance was the highest in orange pulp (71.89% CP); the level of post-ruminal crude protein disappearance was the highest for lemon pulp (45.95% CP). The highest *in vitro* dry matter digestibility was found for tangerine pulp followed by that estimated for bergamot pulp (80.44 and 78.38% OM, respectively). The estimated metabolisable energy (MJ/kg DM) varied from 9.77 for lime pulp to 12.91 for bergamot pulp. This study showed that the crude protein content of citrus co-products is potentially highly digestible. Additionally, it can be concluded that citrus co-products can be introduced as non-forage fibre sources that can release high metabolisable energy and high digestible organic matter. The same authors (Lashkari and Taghizadeh 2015) determined digestibility and fermentation characteristics of whole, NDF and ADF fractions of four citrus co-products using *in vitro* gas production. Pulps from orange, lime, lemon and grapefruit presented a potential appropriate source of degradable carbohydrate fractions which may be appropriate as the energy source for ruminant nutrition. Similarly, Paya et al. (2012) compared fresh brewers' grain and apple pomace and dried orange and lemon pulps co-product using *in vitro* e *in situ* technique. Potential gas production and rates of gas production differed among feedstuffs. Compared to the other feeds, apple pomace showed the highest potential gas production (364 ml g^{-1} DM), whereas lemon pulp had the lowest (220 ml g^{-1} DM), while orange pulp had a higher fermentation rate. The metabolisable energy (ME) values ranged from 7.66 to 10.83 MJ kg^{-1} DM in lemon pulp and apple pomace. Regarding *in situ* technique, orange pulp had higher soluble dry matter, while lemon pulp had higher insoluble potentially degradable dry matter (89.8% DM), and orange pulp presented a higher degradation rate than other feeds (36.9%). The authors concluded that all tested co-product can be economically employed as potential fibrous and energy sources in ruminant nutrition, even if apple pomace seemed to be the best one.

Atalay (2020) evaluated the chemical composition and anti-methanogenic potential of eight different samples of grape pomace deriving from wine production around the world, which differ in the function of grape type, production method and ratios of pomace components. The results showed that there is a considerable amount of variation among the grape pomace samples in terms of chemical composition, *in vitro* gas production, CH_4 production, ME and organic matter digestibility. However, many samples had CH_4 mitigation potential possibly associated with the EE, condensed tannins, lignin and tartaric acid contents and could be included in ruminant diets to mitigate the environmental impact.

Aghajanzad et al. (2009) compared brewers grain and tomato pomace (*Lycopersicon esculentum* Mill.) by *in vitro* technique at 24 h: tomato pomace showed higher values of the estimated organic matter digestibility (64.4 vs. 52.7% OM, respectively), VFA (0.86 vs. 0.69 mmol, respectively), ME (11.8 vs. 9.05 MJ kg^{-1}DM) than brewers grain. Overall, the authors did not exclude the use of both co-products as fibrous and protein sources, respectively, in animal diets. On this subject, Romero-Huelva et al. (2013) evaluated the *in vitro* inclusion of two agricultural co-products typical of the Mediterranean area, tomato and cucumber, in a ruminant diet. The results obtained by the authors showed that both co-products and their mix could represent an interesting low-cost strategy to replace concentrate in the diet. Moreover, it was observed that tomato and cucumber could have the potential to reduce some methanogen activities, unaffecting VFA production.

Regarding, co-products of oil extraction, Marcos et al. (2019) determined the variability in the chemical composition and *in vitro* ruminal fermentation deriving from oil production. Forty-two olive cake samples with different storage times (1–14 months) and processing (crude, exhausted, Aand cyclone) were evaluated. The exhausted ones had the greatest average gas production rate, whereas the greatest fermented organic matter was obtained for exhausted and cyclone. In this regard, Pallara et al. (2014) evidenced as supplementation of diets with stone olive pomace alters the rumen bacterial community, modifying the fatty acids profile of the rumen liquor. Hence, it was suggested that the use of olive co-products aimed to produce meat or dairy products enriched in functional lipids can be hypothesised.

Concerning vegetable co-products, Meneses et al. (2020) evaluated chemical composition, nutritive characteristics, *in vitro* rumen degradability, *in vivo* digestibility and phytosanitary residue contents of raw artichoke (*Cynara scolymus* L.), which correspond to whole outside bracts and stems leftover in the first stage of industrial process, and boiled broccoli (*Brassica oleracea*, var. *Italica*) that do not pass the quality control after washing and scalding at 90 °C for 20 min. The authors evidenced that both ensiled wastes of processed artichoke and broccoli were adequate for feeding ruminant animals thanks to their nutritive value. The *in vitro* rumen dry matter disappearance at 72 h was high although it was higher in the broccoli silage. The authors concluded that silage could be a suitable method to preserve both co-products.

García-Rodríguez et al. (2019) determined the chemical composition, *in vitro* digestibility, and fermentation kinetics of a wide range of agro-industrial co-products as an indicator of their potential use as feedstuffs for ruminants: dehydrated or ensiled sugar beet pulp, sugar beet tops (including leaves), beetroot leftovers (including rootlets, hairs, root tips, and beet tails), grape seeds, olive tree leaves, almond hulls, broccoli stalk (hay), lettuce leaves, asparagus rinds, green bean haulms, artichoke co-products, peas haulms, broad beans haulms, dried tomato pulp, pepper cores and skin, apple pomace, citrus pulps (lemon, clementine, and orange). As expected, chemical composition, *in vitro* digestibility, and fermentation kinetics varied largely among the co-products. Olive tree leaves, pepper skins and grape seeds were less degradable, whereas sugar beet, orange, lemon and clementine pulps were more degradable. Considering the large variability among co-products, most of them can be regarded as potential ingredients in ruminant diets. Depending on the characteristic nutritive value of each co-product, these feedstuffs can provide alternative sources of energy (e.g. citrus pulps), protein (e.g. asparagus rinds), soluble fibre (e.g. sugar beet pulp) or less digestible roughage (e.g. grape seeds or pepper skin).

Table 6 shows the *in vitro* studies on co-products that referred to monogastric species. De Blas et al. (2018) evaluated the use of citrus co-products in diets for rabbits as a source of energy. The authors analysed 33 samples of citrus pulp obtained from commercial industries using different manufacturing procedures for chemical composition (including dietary fibre), *in vitro* dry matter, and crude protein digestibility by two-step method (Ramos et al. 1992). Overall, citrus pulps can be considered a good source of energy and soluble fibre for rabbits due to their low supply of indigestible fibre and crude protein and the high level of calcium ($Ca(OH)_2$). Moreover, Kara (2016) studied both common (sugar beet pulp, wheat bran, lucerne meal) and uncommon (tomato pomace, maize bran, rice bran, lentil bran, and pomegranate peel) feed comparing nutrients, condensed tannins, fibre, and *in vitro* fermentation parameters using rabbit faecal *inoculum*. The author observed that tomato pomace, maize bran and rice bran could be recommended for use as alternative dietary fibre sources for post-weaning, young and breeding rabbits. Although tomato pomace showed excessive fermentation capacity, its dietary fibre content was low. On the other hand, pomegranate pomace and lentil bran can be recommended for the growing rabbit due to their high fibre content and low fermentation capacity.

Regarding the use of co-products in companion animal diets, Brambillasca et al. (2013) studied *in vitro* fermentation characteristics kinetics, and *in vivo* nutrient digestion, faecal characteristics and bacterial populations of dogs food mixed with citrus pulp and apple pomace. In the trial, a pre-digested dog food supplemented with both fibre source in four different inclusion levels (0, 30, 50 and 70 g/kg on DM basis) were tested. As result, citrus pulp and apple pomace included in a dog diet enhanced the fermentation activity in the hindgut. Apple pomace showed the highest maximal fermentation rate of gas production (R_{max}:14.08 ml/h) that reached in the shortest time ($T_{1/2}$: 5.46 h). Furthermore, gas production improved linearly and quadratically as fibre levels increased. The results evidenced as citrus pulp and apple pomace included in a dog diet could enhance the fermentation activity in the hindgut. Calabrò et al. (2013) tested *in vitro* several samples including some co-products (sugar-cane fibre, beet pulp, wheat bran, and pea hulls) to evaluate their inclusion in dogs' diets. The samples were incubated with the dog's faecal *inoculum* for 48 h at 39 °C under anaerobic conditions testing the gas production and fermentation kinetics (Theodorou et al. 1994). Moreover, VFA have been determined at the end of *in vitro* trial. Considering the tested co-products, the results showed as pea hull and beet pulps weremoderatly fermentable (low organic matter disappearance and VFA). While wheat bran had a rapid fermentation and produced a high proportion of butyrate. Otherwise, the sugar cane fibre produced a low quantity of gas and VFA. The authors observed that the tested co-products could be included in dogs' diets as sources of soluble and insoluble dietary fibre. On this basis, Panasevich et al. (2013) indicated potato fibre, which is a co-product of potato starch manufacture, as a high-quality fibre source in dog foods. The authors evaluated this co-product for chemical composition, *in vitro* digestion and fermentation characteristics and *in vivo* responses. For the *in vitro* digestion, the substrates were first subjected to hydrolytic-enzymatic digestion to determine organic matter disappearance and subsequently fermented using dog faecal inoculum, measuring the fermentation after 0, 3, 6, 9 and 12 h. When tested *in vitro*, the potato fibre resulted in high fermentability with a favourable proportion of insoluble to soluble fibre. In particular, acetate, propionate, butyrate and total VFA concentrations increased over time.

As sources of amino-acids and energy, Woyengo et al. (2016) determined the *in vitro* fermentation characteristics of the canola (*Brassica juncea* and *napus*) co-products (solvent-extracted meal, expeller-pressed meal, cold-pressed cake) in comparison with soybean meal in pig feeds. The authors observed as canola co-products can replace the soybean meal as a source of protein in pigs' diet. However, differences in fermentability among *B. napus* co-products indicate that fat may limit their fermentability in the hindgut of pigs. Hence, fermentation characteristics can vary depending on the efficiency of oil extraction.

Ersahince and Kara (2017), as previously illustrated for beef cattle, demonstrated that also in horses, Jerusalem artichoke (*Helianthus tuberosus* L.) herbage, especially at the vegetative stage, could be useful as forage with high/moderate nutrient characteristics and satisfactory digestion values.

All presented *in vitro* studies demonstrate as laboratory techniques highlight the main nutritional characteristics of numerous co-products. Suggesting that these last could be I used as fibrous, protein, or lipids sources in animal nutrition. Moreover, some studies

Table 7. *In vivo* studies on large ruminant.

Co-products	Species	Authors
grape pomace	Dairy cow	(Chedea et al. 2017)
apple pomace	Dairy cow	(Steyn et al. 2018)
olive pomace	Dairy cow	(Castellani et al. 2017)
citrus pulp	Dairy cow	(Santos et al. 2014)
tomato and apple	Dairy cow	(Abdollahzadeh et al. 2010)
hemp seed cake	Dairy cow	(Karlsson et al. 2010)
grape pomace	Beef cattle	(Ianni et al. 2019)
olive cake	Beef cattle	(Chiofalo et al. 2020)
tomato pomace	Buffaloes	(Abdel Gawad et al. 2020)
citrus pulp		
beet pulp		
tomato pomace	Buffaloes	(Ebeid et al. 2014)

evidenced that the co-products can improve the fermentative characteristics such as dry matter digestibility and can reduce methane emission. Moreover, *in vitro* experiments are cost-effective and short time-consuming methods that allow to verify the characteristics of new co-products or test the quality of conservation methods on nutritional characteristics.

In vivo *studies*

For this review, a total of 32 *in vivo* studies were selected so as to evaluate the potential use of some agricultural and industrial co-products; most of them evaluated the effect on animal health and the quality of animal products.

Table 7 reports the studies about large ruminant species. Much of the research concerns the integration of co-products into the diet of dairy cows. Chedea et al. (2017) evaluated the effect of grape pomace supplementation (3 kg head^{-1} day^{-1}) on general health status and the milk quality of dairy cows. The authors observed as dietary replacement of cereal with grape pomace did not affect dairy cows' plasma biochemistry parameters, except for urea concentration, which increased significantly with grape pomace (7.00 vs. 8.20 mg dl^{-1}, respectively). However, the inclusion of grape pomace did not affect milk fat and protein levels. Moreover, the significantly higher values of β-lactoglobulin and lactose give the milk properties of a functional food, particularly with respect to the biological activities of β-lactoglobulin. Similarly, Steyn et al. (2018) studied the effect of replacing ground maize with dried apple pomace on milk yield and rumen health of Jersey cows, evaluating four levels of inclusion (0, 25, 50, and 75%). As in the previous study, the authors did not observe any changes in milk composition in terms of protein and fat. On the contrary, as demonstrated by Castellani et al. (2017), the utilisation of dried olive pomace in the diet of lactating dairy cows may modify the quality of dairy products. Indeed, olive co-products could increase unsaturated fatty acid (oleic acid, vaccenic acid, and conjugated linoleic acid CLA) and decrease saturated fatty acid (short- and medium-chain fatty acids until palmitic acid) suggesting a positive role of dried olive pomace to improve the nutritional and nutraceutical properties of milk and corresponding cheese. Additionally, Santos et al. (2014) evaluated the substitution of corn grain with pelleted citrus pulp in mixed ratio for dairy cows' . The authors did not evidenced negative effects on diet nutritional value , milk yield, and quality. Furthermore, , the addition of pelleted citrus pulp (9 and 18%) to standard diets increased the total polyphenol and flavonoid concentration, and ferric reduction antioxidant power in cow milk. .

Abdollahzadeh et al. (2010) have used an ensiled mix of tomato and apple pomace (in ratio of 50:50) replacing alfalfa hay to evaluate Holstein dairy cows' performance. Three diets with different levels of replacement (0, 15 and 30% DM) were used. The results showed significant differences between diets in terms of milk yield (19.9, 21.9, 20.4 kg/d, for 0, 15 and 30%, respectively), dry matter intake (21.3, 23.7, 24.5 kg/d, respectively); feed efficiency (0.93, 0.92, 0.82, respectively). In this regard, the nutritional value of tomato and apple pomace improved when the co-products were used together; moreover, a mix of tomato and apple pomace silage can be substituted efficiently up to 30% of the diet without any adverse effect on dairy cows' performance.

Karlsson et al. (2010) studied the use of hemp seed cake as protein supplement in dairy cow diets, evaluating the effects on milk yield and composition. Four experimental diets formulated with different inclusion of hemp seed cake (HC0: 0, HC14: 143, HC23: 233, or HC32: 318 g/kg of DM) were tested. No effects in dry matter intake but significant linear increases in crude protein, fat, and NDF intakes were observed with the increase of the proportion of hemp seed cake in the diets. Milk yield and energy-corrected milk were affected by the proportion of dietary levels, with the highest value for the lowest inclusion (28.7 kg/d and 1.13, respectively, with 143 g/kg of DM of hemp seed cake). Moreover, with the increasing of hemp seed cake level, the milk protein (H0: 3.63, H14: 3.61, H23: 3.49, H32: 3.40%) and fat (H0: 4.31, H14: 4.21, H23: 4.07, H32: 3.89%) linearly decreased. Furthermore, due to the increase of crude protein intake, a significant linear increase in milk urea concentrations (H0: 2.7, H14: 3.7, H23: 4.4, H32: 5.1%) occurs with the enhancement of hemp seed cake. In conclusion, the optimal and maximum level of hemp seed cake inclusion suggested in this experiment was 143 g/kg DM.

Table 8. *In vivo* studies on small ruminant.

Co-products	Species	Authors
pumpkin seed cake	Lamb	(Antunović et al. 1970)
pumpkin seed cake	Goat	(Klir et al. 2017)
artichoke and broccoli	Goat	(Meneses et al. 2020)
Broccoli	Goat	(Panwar et al. 2017)
grape seed	Ewes	(Nudda et al. 2015)
wine lees	Wethers	(Sato et al. 2020)
tomato pomace grape marc exhausted myrtle berries	Dairy ewes	(Buffa et al. 2020)
tomato fruits citrus pulp brewer's grain	Goat	(Romero-Huelva et al. 2013)
Tomato Olive	Goat	(Arco-Pérez et al. 2017)
hemp seed cake	Sheep	(Mierliţă 2018)

Regarding buffalo's species, Abdel Gawad et al. (2020) observed that the use of tomato pomace, citrus, and beet pulp to replace wheat bran as a concentrate in animal diet had a positive effect on animal performance and fat milk. Moreover, tomato pomace silage in lactating Egyptian buffalos' diet could be substitute clover as forage having a positive effect on nutrients digestibility; besides, milk production and its fat percentage increased (Ebeid et al. 2014).

Only two studies that evaluated the effect of co-products on calves' performance and meat quality were found. In particular, Ianni et al. (2019) demonstrated that grape pomace inclusion in calves diet resulted in a significant increase of linoleic acid concentration in meat, a condition predisposing to a positive increase in the polyunsaturated and saturated fatty acids ratio (PUFA/SFA). Furthermore, an interesting improvement in the oxidative stability of meat samples was evidenced.

Chiofalo et al. (2020) evaluated the inclusion of olive cake in partial substitution of cereals in the beef cattle diet. The levels of 7 and 15% dry matter basis increased the body weight, average daily gain, slaughter traits, and intramuscular fat content probably due to lipids, amount, and quality, coming from the olive cake.

Regarding *in vivo* studies on small ruminants (Table 8), Antunović et al. (1970) and Klir et al. (2017) evaluated the use of pumpkin seed cake in lamb and goat, respectively. In both studies, the authors aimed to replace soybean meal with pumpkin seed cake. Antunović et al. (1970) observed an improvment of carcase characteristics and haemato-chemical parameters in Merinolandschaf lambs , ' . Klir et al. (2017) did not observed decrease in milk yield or sharp changes in fatty acid profile substituting soybean meal with pumpkin seed cake for dairy Alpine goats . Meneses et al. (2020), in the same study above mentioned as *in vitro* trial, evidenced *in vivo* that ensiled raw artichoke (*Cynara scolymus* L.) and boiled broccoli (*Brassica oleracea*, var. *Italica*) co-products were suitable for ruminant diet. No differences were observed *in vivo* for DM digestibility in both silages. However, crude protein digestibility was higher in the boiled broccoli silage than raw artichoke (83.00 vs. 55.11% DM, respectively). A similar result was observed for NDF digestibility (88.25 and 78.82% DM, for broccoli and artichoke, respectively). Furthermore, broccoli crop residue can successfully sustain the growth of small ruminants, especially goats without supplementing concentrate mix and in general can replace some of the soybean and corn in the ratio of animal diets (Panwar et al. 2017).

Nudda et al. (2015) and Sato et al. (2020) tested the use of grape co-products in ewes, and wethers, respectively. In both studies, the authors concluded that grape co-products can be included in the animals' diet without affecting production or nutrient apparent digestibility, ruminal fermentation, and nitrogen balance. Buffa et al. (2020) evaluated the use of small quantities of dried co-products (e.g. tomato pomace, grape marc, and exhausted myrtle berries) on rumen fermentation parameters, and microbiota in dairy ewes. Definitively, the use of these co-products at low dosage did not evidence any negative effects on rumen bacteria or animal performance.

The use of a mixture of different co-products in the goat diet could be also useful for environmental sustainability, as demonstrated by Romero-Huelva et al. (2013). Indeed, the authors verified as the replacement of 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. Furthermore, the quality of milk in terms of fatty acids profile improved, whereas ruminal fermentation, nutrient digestibility, and milk yield were not compromised. Besides, Arco-Pérez et al. (2017) noted as replacing oats hay in the diet of lactating goats with silages made of tomatoes or olive oil co-products together with sunflower oil supplementation (20 g/kg of DM) improved milk quality without affecting animal efficiency. Additionally, the long-term use of tomato silage in dairy goats fostered voluntary intake, which resulted in higher body weight gain, without compromising the milk production and composition.

Mierliţă (2018) studied the effect of dietary intake of hemp seeds or cake on milk production, fatty acid profile, and milk oxidative stability. In particular, the author carried out an experiment using 30 Turcana dairy sheep divided into three groups consisting of a

Table 9. *In vivo* studies on monogastric animals.

Co-products	Species	Authors
prickly pears	Rabbit	(Amer et al. 2019)
tomato pomace	Rabbit	(Peiretti et al. 2013)
olive cake	Pig	(Liotta et al. 2019)
citrus pulp	Pig	(Cerisuelo et al. 2010)
tomatoes, peppers Grapes	Piglet	(Cilev et al. 2016)
apple pomace blackcurrant pomace strawberry pomace	Poultry	(Colombino et al. 2020)
grape pomace	Horses	(Kolláthová et al. 2020)
citrus pulp apple pomace	Dog	(Brambillasca et al. 2013)
potato fibre	Dog	(Panasevich et al. 2013)
beet pulp	Dog	(Kröger et al. 2017)

control diet based on hay and mixed concentrates and two experimental diets designed to provide the same amount of fat using hemp seed (180 g/d) or cake (480 g/d). Both hemp co-products compared to the control diet increased milk yield and ewes' milk fat content, and decreased milk lactose; moreover, the PUFA content (especially n-3 fatty acids) increased, and the n-6/n-3 ratio improved. Total CLA content doubled in the milk of the ewes that received hemp seed and increased over 2.4 times with the hemp cake inclusion. The alpha-tocopherol and antioxidant activity increased using hemp seed in the diets, reducing the risk of lipid oxidation in raw milk.

Concerning the *in vivo* studies using co-products in monogastric species (Table 9), Amer et al. (2019) tested prickly pears (*Opuntia ficus-Indica* L. Mill.) co-products in rabbits 'diets. In particular, the study was carried out to evaluate the effects of different levels (25 and 50% of DM) of dietary substitution of barley by prickly pear fruits and peel as alternative feed resources and antioxidants on growth performance, carcase traits, and antioxidant status of weaned male New Zealand White rabbits. As result, the inclusion of both co-products in the two concentrations had positive effects on rabbits' performance. Prickly pear fruits and peel are excellent sources of dietary antioxidants components that may have beneficial effects on rabbits' health.

Peiretti et al. (2013) observed as rabbits' diet integrated with 6% of tomato pomace could positively influence the quality of meat. Indeed, the authors divided 144 weaned crossbred rabbits into three groups. The first group was fed a basal diet without tomato pomace, while the other two groups were fed the basal diet after replacing 3 or 6% of DM with tomato pomace, respectively. They observed a significant difference between the experimental groups in terms of live and carcase weights. The meat of rabbits fed a 6% DM tomato pomace diet exhibited higher yellowness and chroma values when compared to others. Moreover, the saturated fatty acids (SFA) content in the *Longissimus dorsi* muscle and perirenal fat decreased significantly with increasing tomato inclusion, while PUFA increased.

Similarly in swine, Liotta et al. (2019) studied the inclusion of olive cake to evaluate the meat quality. Seventy-two Pietrain pigs, during the growing-finishing period, were fed with three dietary treatments: 0 (as control), 5, and 10% of the olive cake. The results showed as the inclusion of the lowest level of olive cake in the diet improved significantly (112.20, 117.19, and 113.08 kg, for 0, 5, and 10% of olive cake inclusion) body weight, while the highest level of inclusion increased feed conversation ratio (3.70, 3.28, and 4.13 $kg^{*}kg^{-1}$ of weight gain, for 0, 5, and 10% respectively). The inclusion of olive cake in both concentration reduced significantly backfat thickness and intramuscular fat. Morevoerthe authors observed significant improvemnt of meat fatty acid profile in term of increaseing PUFA level . Otherwise 10% of inclusion increased monounsaturated fatty acids (MUFA) amount.

Cerisuelo et al. (2010) supplemented ensiled citrus pulp in diets for growing pigs to evaluate the effect on growth performance, gut microbiology, and meat quality. Three dietary treatments were formulated to contain 0, 50, and 100 g of ensiled citrus pulp per kg on DM basis. The inclusion of citrus pulp significantly reduced *Enterobacteriaceae* in faeces and did not affect the *Lactobacillus* population. Moreover, no differences were found in backfat thickness at *Glutaeus medius* and meat colour, but carcase yield tended to decrease, and oleic acid percentage in subcutaneous fat increased. This study evidenced that growing pigs can use the citrus pulp as a source of high-fermentable carbohydrates without detrimental effects on growth performance and meat quality, and potential benefits on gut microbiology.

On the same species, Cilev et al. (2016) examined the possibilities of the maize's substitution as an energetic nutrient with co-products obtained by manufacturing tomatoes, peppers, and grapes in the nutrition of weaned piglets. The piglets from the control group were fed with a mixture without a share from the examined co-products, whereas the experimental groups were fed a diet with the substitution of maize with different qualities of the above-mentioned co-products. No significant differences were observed between the groups. Maize's partial substitution with a co-product (3% DM) has any negative effects on a weaned piglet performance.

Colombino et al. (2020) studied whether apple, blackcurrant, or strawberry pomaces could be suitable ingredients in broiler diets and their effect on gut health. A total of 480 male broilers were randomly allotted to 8 dietary treatments with lower or higher level of dietary fibre (3 and 6%, respectively). The results of the study suggest that fruit pomaces could be a new, low-cost fibre source in poultry nutrition. Indeed, they did not impair growth performance or gut morphometry/histopathology, they improved the production of volatile fatty acids (VFA), and they reduce the production of putrefactive short-chain fatty acid (PSCFAs) both in the small intestine and in the caeca. However, they showed a potential negative modulation of gut microbiota with a decrease of *Lactobacillus* spp. and an increase of *Enterobacteriaceae* and *Enterococcaceae*.

Kolláthová et al. (2020) aimed to investigate the effects of dietary inclusion of dried grape pomace on biochemical blood serum indicators and digestibility of nutrients in horses. Animals were divided into three groups: control group, experimental group 1 (feed rations + 200 g of dried grape pomace), and experimental group 2 (feed rations + 400 g of dried grape pomace). The concentrations of potassium increased in experimental group 2 compared to control and experimental group 1 and alanine aminotransferase decreased in experimental group 2 in comparison with experimental group 1 and control. No statistical differences emerged between the experimental groups compared to control one for digestibility coefficients (dry matter, organic matter, and crude protein). Nevertheless, in experimental group 2, lower digestibility of all the studied nutrients was found in comparison with the control group and experimental group 1. These results suggest that dried grape pomace could be used in horse diets up to 200 g without negative effect on their health and for a possible digestibility improvement of some nutrients.

According to *in vitro* study, as discussed previously, Brambillasca et al. (2013) conducted an *in vivo* trial to evaluate the digestibility of nutrients, stool characteristics, and faecal microbial populations of dogs fed two fibre sources (citrus pulp and apple pomace) added at different levels in pre-digested dog food. The inclusion of fibre sources in the diets resulted in higher faecal output and defaecation frequency, and lower faecal pH and digestibility values. Faecal consistencies and microbial populations did not differ among treatments. Citrus pulp and apple pomace included in a dog diet led to well-formed faeces with small reductions in nutrient digestion. Similarly, Panasevich et al (2013) performed *in vitro* and *in vivo* trials to evaluate the inclusion of potato fibre in dogs' diets as a carbohydrates source. Regarding the *in vivo* experiment, the authors provided different concentrations (0, 1.5, 3, 4.5, or 6%) of potato fibre to 10 female mixed-breed dogs by 5×5 Latin square design. The results showed that the physiological outcomes measured (faecal branched-chain fatty acids, ammonia, phenol, and indole concentrations) were mostly unaffected by dietary potato fibre concentrations. Additionally, spermidine, which is considered a beneficial biogenic amine, and its concentration were increased with graded concentrations of that co-products. Moreover, an excellent stool consistency, without negative effects on nutrient digestibility, has been observed. The authors indicated that potato fibre has the potential to compare favourably with most dietary fibres found in commercial foods. Kröger et al. (2017) compared the effect of lignocellulose (LC) and sugar beet pulp (SBP) on apparent nutrient digestibility, microbial composition, metabolites, and faecal parameters. The authors tested three diets: high SBP (12% SBP and 3.1% crude fibre), low SBP (2.7% SBP and 0.96% crude fibre), and lignocellulose (2.7% LC and 2.4% crude fibre) on eight Beagles divided into two groups. The diets were formulated with the same concentration of fibre sources or a similar percentage of crude fibre. The authors observed as the daily faeces amount was lower and the faecal dry matter was higher when dogs were fed the LC diet and the low SBP diet compared with the high SBP diet. Moreover, apparent digestibility of crude protein, Na, and K was highest with the low SBP diet. Considering the bacterial cell counts of *Lactobacillus* spp., *Bifidobacterium* spp., and the *Clostridium leptum* cluster were lower when dogs received LC diet compared to faeces obtained with diets high SBP and low SBP. The bacterial cell count of the *Clostridium coccoides* cluster was lower in LC and low SBP compared with high SBP. The faeces of dogs fed LC and low SBP had lower concentrations of acetate, propionate, *n*-butyrate, total fatty acids, and l-lactate compared with dogs fed high SBP. The administration of LC diet was higher with LC diet compared to high and low sugar beet pulp diets. The lignocellulose and sugar beet pulp affected differently the faecal microbiota and the apparent digestibility of nutrients. However, both fibre sources could be used in dog feed.

In vivo studies evidenced as the inclusion of agro-industrial co-products in animal diets could improve the performance and sometimes animal health, increasing technological and nutritional characteristics of meat and milk. In the case of the inclusion of co-products in horses and companion animal diets, the residues improved nutrient digestibility and did not negatively affect the animal health status. Furthermore, these studies allow us to understand the right level of inclusion of co-products into the diets to avoid negative effects.

Conclusion

In conclusion, all studies proposed proved that co-products could be a useful source of several nutrients in animal diets. In this regard, *in vitro* trials demonstrated like the supplementation of co-products can influence the fermentative parameters. Indeed, most of the tested co-products showed high digestibility and degradability comparable to the conventional feed. Moreover, these studies demonstrated that the co-products could decrease the gas production (i.e. pomegranate peel) or additionally could decrease the methane emission like in the case of red ginseng meal, whereas *in vivo* studies showed that the co-products do not negatively affect the production of livestock animals. Still, in some cases, they could improve the nutritional characteristics and microbiological quality of milk, cheese, and meat. Moreover, in such cases, particularly for horses could improve the health status of the animals. Regarding the companion animals, several studies described as the co-products could be useful sources of fibre in alternative to conventional feed. Indeed, the inclusion of agro-industrial residues into the diet seem do notinfluence nutrient digestibility.

Furthermore, some authors tested the co-products with ensilage storage technique, testifying as this approach could be a valid method to guarantee the presence of fresh co-products during the year and reduce the seasonality. Nevertheless, fruit and vegetable processing co-products still showed high variability in chemical composition, which might influence their digestibility either in the rumen or in the intestine. Commercial application of fruit and vegetable industry co-products as functional feed ingredients provides challenges and opportunities. Indeed, investing in the development of these co-products could guarantee the implementation of the circular economy, towards greater sustainability, with a reduction of waste along the production chain.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article.

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