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Citrus Co-Products in Ruminants Feeds: A Review

Review Article

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ABSTRACT

The generation of co-products continues at an accelerating pace, driven by population growth. Many of these co-products can be included in ruminant feed, which has the ability to transform them into good quality animal protein, and also help to reduce the disposal of undesirable residues to the environment. One of the co-products with potential use in animal feed, the citrus pulp, represents residues of the crushing of the fruit to remove the juice. In this review, these co-products are studied for their nutritional value, nutrient digestibility, and their influence on animal performance, in addition to ruminal characteristics. Due to its chemical composition, citrus pulp is widely used as an energetic component in the diet, replacing mainly maize, since these two have a similar energy value. In addition to increasing energy intake in the diet, citrus pulp has a greater capacity to assist in the maintenance of adequate ruminal performance compared to starchy cereals.

KEY WORDS alternative feeds, citrus pulp, ruminants.

INTRODUCTION

The large increase in world population has boosted the intake of a large diversity of products, either for food or to satisfy other necessities. The process of industrialization of these products has generated a series of co-products that when disposed of in an inadequate way, can cause serious damages to the environment. Most of these co-products of plant origin can be used in animal feed, mainly for ruminants, which have an intrinsic capacity to convert several of these agro-industrial co-products into valuable products such as meat and milk, allowing a residue to become a feeding resource. In livestock production, feed costs in most cases are the main expense incurred by farmers, generating concerns about high dependence on cereals and their highly volatile prices, and making the potential use of relatively inexpensive and locally available co-products as a substitute for cereals a highly attractive alternative (Gobindram *et al.* 2017). The citrus co-products are derived from the commercially produced citrus fruit, being a result of crushing the fruit in order to remove the juice. They present characteristics of highly digestible fiber due to the presence of pectin. Pectin is part of the cell wall components, acting as some kind of "cement" between cells. In high concentrate diets, in addition to replacing maize, it still presents improvements in ruminal metabolism due to the functionality of its fiber and because it is associated with a favorable fermentation type, with lower production of lactic acid, thus helping to maintain a favorable ruminal environment, which in many studies resulted in a performance equal to or higher than that with diets involving popular cereals.

Because they are cheaper than traditional foods, co-products are present in most confinement-based diets in Brazil. In a survey carried out by Oliveira and Millen (2014), it was shown that the principal co-products, which are widely used in the finishing diets, were the cotton seed, followed by the soybean bran and, finally, the citrus pulp. In most cases, the citrus pulp is used it its dehydrated form as pellets. However the drying process is expensive and often inconvenient. In fact, the use of the ensiled orange pulp is cheaper than the dry processing and can be easily done by the farmer (Paya *et al.* 2015). Thus, there are many studies that make use of this co-product fresh or in the form of silage, (Macías-Cruz *et al.* 2010; Gado *et al.* 2011; Williams *et al.* 2018). Due to its high fiber content, the long rumination of the citrus pulp produces large amounts of saliva which has a buffering effect on the pH of the rumen, being therefore considered to be a safer food for rumen health than the usual cereals. Moreover, among the different applications of citrus co-products, their use as a feed source is the cheapest and most realistic option for the food industry (Pacheco *et al.* 2019).

Citrus pulp is mainly used as an energy source in the diet, replacing maize, but it has also been used as a bulk substitute. Although co-products are considered to be of lower cost, their inclusion in the diet requires a feasibility study, since depending on the composition of the co-products, the price paid for the nutrient may make it unfeasible for traditional feeds. Therefore, the objective of this review was to gather relevant information about the nutritive value and the use of citrus pulp in the diet of ruminants, in order to elucidate scientific data to better understand the use of these co-products.

Nutritional quality of citrus co-products

What makes the citrus pulp an excellent co-product for use in animal feed is its high nutritional quality. Unlike most co-products, citrus pulp has a low neutral detergent fiber (NDF) content of 16% (Table 1). In addition, its NDF includes a highly digestible compound, pectin, which, although a structural carbohydrate, is rapidly degradable in the rumen, a characteristic that ensures the use of the citrus pulp as an energetically concentrated feed that has voluminous characteristics and is similar to some forage species (Cribbs *et al.* 2015).

Citrus pulp, as it is commonly called, may be obtained from various types of citrus fruit. Its dry matter (DM) values are close to 90%, as is the case in most concentrates, and the total carbohydrates (CHO) content exceeds 80% when compared to other common energy-efficient feeds. The pectin content, which differentiates this product from other types of feed, is greater than 30% of DM. Thus, the limiting nutritional factor of this co-product is its crude protein (CP) content. However, even here, the levels are close to those observed in traditional energy-efficient feeds such as maize and sorghum.

When comparing the gas production between the citrus pulp and the maize in two forms (steam flocculated and ground), the citrus pulp presented a lower latency time, lower asymptote and a higher rate of degradation (Table 2).

The rapid degradation of immature citrus pulp during incubation with ruminal fluid was documented by Hall *et al.* (1998) and appears to be associated with its high sugar and pectin content (Bampidis and Robinson, 2006), both of which are rapidly and extensively degraded in the rumen (Kim *et al.* 2007). The citrus pulp also takes more time for its fibers to be colonized by microorganisms in the rumen.

For the use of co-products, it is important to know their nutritional characteristics to the fullest, thus allowing a balanced diet to be formulated appropriately in order to promote maximum performance. Fractionation of carbohydrates, proteins and the digestibility of citrus co-products are presented in Table 3. For carbohydrates, fraction A corresponds to sugars that are rapidly degraded in the rumen, whereas fraction B1 is equivalent to starch and pectin. Although pectin is present in the soluble fraction, it is considered a structural carbohydrate, but is found in the same category with starch, because they have similar digestibility. Fractions B2 and C correspond to the available cell wall and non-available cell wall, respectively. Five fractions were considered in the fractionation of crude protein, and the citrus pulp has higher concentrations of fraction A, non-protein nitrogen and B2, which corresponds to the slowly degraded protein. The citrus pulp still presents low concentration of fraction C for both carbohydrate and proteins, showing that the carbohydrate content of the citrus co-products can be easily fermented in the rumen, which is evidenced by the digestibility results.

Compared with the usual energy-efficient types of feed used in animal nutrition in Brazil, the citrus pulp presents a higher fraction A content, which corresponds to sugars, a lower fraction B1 corresponding to the starch, and a higher fraction B2, corresponding to pectin. The degradation rate of the fraction B1 in the citrus pulp, corresponding to the starch, is equal to that of the soybean bran and to the cotton, since only the cotton presents a value similar to the degradation rate of the pectin. In relation to the NDF, the citrus pulp shows a higher degradation rate (Table 4).

The quality of ensiled citrus pulp was evaluated in several studies as well. Due to the high content of water, the ensiled citrus pulp can be associated with large losses, besides its difficult storage. In this respect, the addition of straw in the silage seeks to correct the adequate DM content to promote the good fermentation process. In relation to pH, the citrus pulp presents high pectin and soluble carbohydrate content, which results in the fermentation of the carbohydrates leading to the rapid decrease of the final pH.

Table 1 Chemical composition[1] of citrus co-products (g/kg DM)

Co-products	DM	CHO	Pectin	CP	Ash	EE	NDF	ADF
Grapefruit pulp	909.1	826.1	384.9	91.4	58.6	23.7	166.5	130.8
Lemon pulp	871.0	815.0	276.8	95.4	54.5	34.4	166.8	151.3
Lime pulp	905.1	809.7	312.7	81.6	81.2	27.4	174.9	145.3
Orange pulp	893.3	825.3	310.5	85.0	55.1	34.4	147.4	119.5
Average	894.6	819.0	321.2	88.3	62.3	30.0	163.9	136.7

DM: dry matter; CHO: carbohydrate; CP: crude protein; EE: ether extract; NDF: neutral detergent fiber and ADF: acid detergent fiber. Adapted from Lashkari and Taghizadeh (2015).

Table 2 Cumulative gas production kinetics of the energy sources included in the diets

Item	SFC	GC	CP
Asymptotic gas production, mL	491	501	439
Lag time, h	2.69	3.55	1.07
$T_{1/2}$, h[1]	13.6	19.1	10.2
Fractional degradation rate, h^{-1}	0.066	0.055	0.079

[1] $T_{1/2}$: time to achieve half asymptote. Adapted from Gouvêa *et al.* (2016).
SFC: steam-flaked corn; GC: ground corn and CP: citrus pulp.

Table 3 Fractionation of carbohydrates, proteins and digestibility of co-products[1]

Type of citrus co-products	Carbohydrate					
	CHO	NSC	A	B1	B2	C
Grapefruit pulp	82.6	83.1	35.3	47.8	14.3	2.5
lemon pulp	81.5	82.4	45.4	36.7	16.0	1.4
Lime pulp	80.9	80.7	38.8	40.8	17.0	2.1
Orange pulp	82.5	85.2	46.2	38.9	12.9	1.8
Tangerine pulp	85.1	89.3	59.1	30.1	9.7	0.9
Average	82.5	84.1	44.9	38.9	13.9	1.7

	Protein				
	A	B1	B2	B3	C
Grapefruit pulp	42.8	9.0	26.0	7.7	14.6
lemon pulp	33.8	6.8	34.7	23.9	0.8
Lime pulp	28.3	4.0	44.0	15.8	8.0
Orange pulp	24.1	11.5	34.5	19.8	10.1
Tangerine pulp	5.4	38.2	21.5	21.9	13.0
Average	26.9	13.9	32.1	17.8	9.3

	In vitro DM digestibility				
	ARD	TRD	IVDMD	DOM	ME
Grapefruit pulp	61.9	85.8	74.8	62.2	9.8
lemon pulp	76.2	88.3	64.9	71.3	11.2
Lime pulp	61.9	85.7	74.8	62.2	9.7
Orange pulp	70.4	89.0	75,0	62.4	9.8
Tangerine pulp	79.7	92.1	80.4	77.5	12.7
Average	70.0	88.2	73.9	67.1	10.6

[1] Three samples analyzed for each feed.
CHO: carbohydrate (% DM); NSC: non-structural carbohydrate (% CHO); A: sugars and soluble fraction (% CHO); B1: starch and pectin (% CHO); B2: fraction available cell wall (% CHO) and C: unavailable cell wall (% CHO).
A: non-protein nitrogen; B1: true soluble protein; B2: neutral detergent soluble protein; B3: neutral detergent insoluble protein but soluble in acid detergent and C: insoluble protein in acid detergent.
ARD: apparent rumen digestibility; TRD: true rumen digestibility; IVDMD: *in vitro* dry matter digestibility; DOM: digestible organic matter and ME: metabolizable energy. Adapted from Lashkari and Taghizadeh (2012).

Table 4 Carbohydrate fractions and their corresponding degradation rates

Items	Fractions (g/kg DM)					Degradation rates (h^{-1})			
	A	B1	B2	B3	C	A4	B1	B2	B3
Corn grain, cracked	15	748	8	79	5	0.40	0.10	0.20	0.03
Sorghum grain, ground coarse	24	564	24	205	34	0.40	0.05	0.20	0.03
Soy hulls	7	10	156	616	32	0.40	0.30	0.08	0.08
Citrus pulp, dry	269	12	344	188	56	0.40	0.30	0.30	0.09
Cottonseed, whole	23	2	25	350	310	0.40	0.30	0.30	0.06

A4: sugars; B1: starch; B2: soluble fiber; B3: available neutral detergent fiber (NDF) and C: unavailable NDF (lignin(sa)×2.4).
B: degradation rate for CA1 is $0h^{-1}$; C: degradation rate for CA2 is $0.07h^{-1}$ and D: degradation rate for CA3 is $0.05h^{-1}$. Adapted from, Lanzas *et al.* (2007).
CA1: volatile fatty acids (VFA); CA2: lactic acid and CA3: other organic acids.

The quality of the citrus pulp silage was studied by Gado *et al.* (2011). In this study, 200 g/kg of rice straw was used together with the citrus pulp. The quality parameters of the silage were all within ranges considered normal for these types of feed. The observed values were: pH -3.85, ammonia-N (mg/g of CP)= 58, acetic acid (g/kg DM)= 11.6, propionic acid (g/kg DM)= 0.50 and butyric acid (g/kg DM)= 0.30. With the inclusion of 5 g/kg of enzymes there was an increase of 35% and 54% for lactic acid and ethanol, respectively.

In the work developed by Lashkari *et al.* (2014), qualitative characteristics, microbial profile and nutritive value of high moisture orange pulp ensiled with poultry by-product meal (PBM) or urea as an additional source of nitrogen (N) were evaluated. The treatments consisted of: 1) 73% of orange pulp + 27% of straw (control), 2) 74% of orange pulp + 12% of straw + 14% of poultry byproduct (OSP) and 3) 63% of orange pulp + 25% of straw + 12% of urea solution (3%). The material was ensiled for 90 days. The use of PBM and urea aims to improve the CP content of the silage. The results showed that both silages supplemented with N had higher pH values, being 8.13 for silage with PBM and 4.29 for that treated with urea. The control treatment showed a pH of 4.14. According to the authors, the high pH in silage treated with urea may be due to the extensive conversion of urea to ammonia-N. The silage with the inclusion of PBM presented the lowest values of NH_3-N, with 16.41 g/kg of total N. The silage supplemented with urea showed higher acetate production and total bacterial count and lower lactic acid count. The authors concluded that both sources of nitrogen used in this study increased the nutritive value of orange pulp silage. The ensiling can be applied as a practical approach to long-term preservation of fresh orange pulp.

Similarly, Paya *et al.* (2015) evaluated the fermentation and nutritional value of orange pulp silage with the inclusion of inoculants and enzymes. Four treatments were used: water-treated orange pulp (control), pulp with inoculant (*Lactobacillus plantarum*), pulp with enzymes (multiple enzymes) and pulp with inoculants + enzymes before ensileing. 16% wheat straw was used as sorbent, and the material was ensiled for 90 days. The pH values varied from 3.4 in the silage with inoculant + enzyme, and 3.8 in the control silage, the four silages also presented high concentration of lactic acid and low concentration of acetic and butyric acid.

Silages with inoculant and inoculant + enzymes showed higher production of lactic acid, as well as lower NH_3-N levels. The lower pH is explained by the authors by the greater degradation of the NDF in these silages, besides the availability of sugars sufficient to stimulate the fermentation. However, NH_3-N levels are reduced when lactic acid-producing homofermentative bacteria dominate the ensiling process, resulting in deamination and repressed proteolysis (Heron *et al.* 1989). The mean protein content of the silages did not vary and had an average value of 69.35 g/kg of DM.

NDF content was lower in silage with enzymes, showing a value of 312.6 g/kg DM. This lower value shows that the enzymes contributed to the hydrolysis of the cell walls of the plant in the orange pulp silage. Therefore, the authors concluded that bacterial inoculants and the combination of enzymatic and bacterial inoculants clearly improved the fermentation characteristic of citrus pulp silage.

Effects of citrus co-products on DM intake and weight gain

Several studies have been developed to evaluate the use of citrus co-products on the intake and performance of ruminants. Gobindram *et al.* (2017) evaluated the potential for replacement of barley by dehydrated citrus pulp at two inclusion levels (24% and 35% of the diet, respectively) in a fattening diet for lambs. Twenty six lambs of the *Comisana* breed, aged 90 ± 10, were used. The performance of the lambs did not change with the inclusion of the citrus pulp (Table 5). Although fiber intake increased with the inclusion of citrus pulp in the diet, it did not influence feed efficiency, daily gain, or the final weight of the carcass.

Favaro *et al.* (2016) evaluated the use of the citrus pulp and maize in diets containing 10% or 15% of crude glycerin and its effects on the intake, performance and carcass characteristics of Nellore breed steers.

18-month old animals with initial live weight of 402 ± 31 kg were used in the experiment, and the treatments contained 10 and 15% of glycerin and 25 and 20% of citrus pulp, respectively, in a diet that was 70% concentrate. The performance parameters were not affected by the treatments (Table 5). The results of this study confirm the potential use of both glycerin and citrus pulp in the diets of feedlot animals. Still, according to the authors, diets with citrus pulp and crude glycerin can be used strategically to reduce feed costs.

As the citrus co-products were gradually replacing other ingredients of the diets, the performance showed a quadratic effect. Inclusion levels that promoted higher gains differed according to the studied animal species, bulk sources and the substituted ingredient. Lashkari *et al.* (2017) evaluated the performance of lambs fed with diets where maize was replaced with orange pulp at levels of 0, 33, 66 and 100%. The diet was 44.4% lucerne and 55.7% concentrated mixture. The animals included a total of 20 males (3-3.5 months of age), with an average weight of 27.3 ± 1.3. Different levels of citrus pulp inclusion had a quadratic effect on the average daily gain, with greater gain achieved with the replacement level of 40.3% (Table 5).

The authors explain a decrease in weight gain at higher levels of substitution by a decrease in the absorption of Ca, P and Mg, as well as the possibility of metabolic disturbances with prolonged use on these diets. Macías-Cruz *et al.* (2010) used fresh citrus pulp as a partial or total replacement of buffel hay (*Cenchrus ciliaria*) in fattening diets for lambs. The diet was 60% concentrate and 40% forage. Twenty lambs with a mean weight of 24.5 kg and 3 months of age were used in the experiment. A quadratic increase in daily weight gain and daily feed intake was observed as the citrus pulp content increased, reaching maximum values at the 75% replacement level. This maximum gain observed in the diet with 75% of citrus pulp is due to the higher intake of DM (Table 5). Gouvêa *et al.* (2016) evaluated feedlot Nellore fed diets that had maize substituted by citrus pulp during 103 days. For the experiment, they used 216 Nellore bulls (350±24 kg initial BW). Four levels of citrus pulp (0, 25, 50 and 75% of DM) were used. All diets contained 12% sugarcane bagasse and 88% concentrate (DM base). There was a quadratic effect for the weight gain, and the 50% level of citrus pulp inclusion (402 g/kg of citrus pulp in the DM of the diet) was where the highest average daily gain (ADG) was observed (Table 5).

Polizel *et al.* (2016) evaluated the partial replacement of maize by the CP on the performance and carcass characteristics of feedlot steers, with treatments having 50% of maize substituted by CP (% of DM) in a diet that consisted of 90% concentrate. The use of citrus pulp promoted an increase in DM intake, average daily gain, and better feed conversion (Table 5). The higher gain is associated with an increase in DM intake, caused by the higher capacity of maintaining pH stability in diets with citrus pulp.

Sharif *et al.* (2017) evaluated increasing levels (10, 20, 30 and 40%) of citrus pulp on nutrient intake and growth performance in lambs. In this experiment, 40 lambs with an average age of 4-5 months were used. The diet consisted of 70% concentrate. The DM intake was not influenced by the levels of citrus pulp in the diet (Table 5). In this research, the cost per kg of body weight decreased with the higher inclusion of citrus pulp.

In another study, Gado *et al.* (2011) evaluated the effects of the inclusion of orange slime pulp on the performance of lambs. A total of 24 animals were used in the experiment, weighing between 20.9 and 21.4 kg on average. Treatment 1 was the control group with 0% of ensiled orange pulp, while treatment 2 contained 150 g of ensiled orange pulp/kg of diet. For the ensiling of citrus pulp, 200 g/kg of chopped rice husk (3-5 cm) was used, in order to avoid losses due to the high moisture content of the orange. The inclusion of 150 g/kg of citrus pulp silage in the diet did not influence ingestion of DM. However, the increase in nutritional quality of the diet reflected in improvements in animal performance, with higher values shown for the treatment that included citrus pulp silage in the diet (Table 5), mainly due to the increase of ruminal fermentation activities and the digestion of nutrients. Cribbs *et al.* (2015) evaluated the performance of heifers during the first 56 days of feedlot life.

The animals received dehydrated citrus pulp that replaced maize in the diet. Three treatments were used: a control treatment without inclusion of citrus pulp, treatment with a 10% inclusion in relation to the DM base and treatment with a 20% inclusion of citrus pulp, replacing the flocculated maize in the diet. Heifers were fed a 63% concentrate diet from day 0 to 28, then with a 73% concentrate from day 28 to 42 and a diet with 83% of concentrate to complete the research (days 42-56). There was a decrease in feed intake and consequently heifer weight gain (Table 5). The author explains the lower intake as a consequence of the palatability of the citrus pulp. However, the authors clarify that the intensity of intake suppression saw some reduction over time as the animals adapted to diet.

Tadayon *et al.* (2017) evaluated the performance of 36 male lambs (with an initial BW of 28±2.2 kg), receiving diets with the inclusion levels of 0, 110 and 220 g/kg of dehydrated citrus pulp. The DM intake was higher in the diets with citrus pulp inclusion (Table 5), in the same way the weight gain was also maximized with inclusion of citrus pulp in the diet. Another study, carried out by Caetano *et al.* (2019), aimed to evaluate the effects of the inclusion levels of 0.70, 140, 210 g/kg of citrus pulp in the diet on the performance of 112 Nellore bulls (initial BW 378.3±21.28 kg).

Neither DM intake, nor ADG were influenced by the inclusion of citrus pulp in the diet.

Rodrigues *et al.* (2011) carried out carious studies that involved citrus pulp in different forms. They evaluated the effects of the dehydrated dried citrus pulp (DCP), wet low pectin citrus pulp (WLPCP) and wet low pectin citrus pulp silage (WLPCPS) on the performance of 64 lambs fed diets containing 95% concentrate and 5% bagasse of young sugar cane. The experiment lasted for 56 days. The control diet contained 69.5% of DCP and then 30% of DM was replaced by WLPCP or WLPCPS. There was no difference in the DM intake and in the average daily weight gain. Only the feed conversion of lambs fed with WLPCP showed some difference, being lower than that of animals fed with DCP (Table 5). The results of this work show that, regardless of the type of citrus pulp used, the latter does not have a negative effect on animal performance, when partially replacing components of the diet.

Oltramari *et al.* (2018) evaluated the intake and performance of calves fed with 4 L of milk substitute daily, and with three concentrate types: 1- 64% maize and 0% citrus pulp, 2- concentrate containing 32% maize and 32% citrus pulp; and 3- concentrate containing 0% maize and 64% citrus pulp. The composition of the concentrate did not influence the intake or weight gain (Table 5). In addition, according to the authors, the use of citrus pulp probably contributed to the better development of the proximal digestive tract of the animals.

Effects of citrus co-products on milk production and composition

Citrus pulp was also used in diets of dairy cows. Leite *et al.* (2017) evaluated the intake, production, and composition of milk in dairy cows fed diets containing silage and concentrates based on citrus pulp or ground maize. The diets used 50% of forage in the form of maize silage and two types of concentrate: one with citrus pulp and another with no citrus pulp. The DM intake was lower for diets containing citrus pulp, compared to the diet with ground maize (Table 6). In addition, animals fed with citrus pulp spent more time ingesting, chewing and masticating (total time) per kg of DM and NDF than cows fed maize. However, despite the lower intake, there were no differences for milk production and composition parameters among the different types of carbohydrates, which indicate that the nutritive value of the citrus pulp compensated for the lower intake. Another factor would be the maintenance of the ruminal pH, which provides better environment for microorganisms found in the rumen.

In a study by Williams *et al.* (2018), citrus pulp silage was used in diets for dairy cows replacing lucerne cubes. Thirty-two Holstein dairy cows were used. In all diets, the animals received 6.0 kg of DM in the form of maize, 2.0 kg of DM/d of cold-pressed canola and 0.2 kg of DM/d of a mineral mix. In the control diet, the animals received 14.5 kg DM of lucerne cubes, and in the diet with the citrus pulp, the cows received 11.5 kg of DM/d of lucerne cubes and 3.0 kg of DM/d of ensiled citrus pulp. The inclusion of citrus pulp silage promoted a lower intake of DM, but had no effect on milk production and on the concentrations of the main components of the milk (Table 6). According to the authors, issues related to the palatability of citrus pulp, due to its higher proportion of skins, may have caused a decrease in intake, besides the silage process that may also have influenced the obtained responses.

Steyn *et al.* (2017) studied the effects of the gradual replacement of maize by citrus pulp in a concentrated supplement on the production and composition of the Jersey cow milk (68 lactating cows) in Azevém pasture. The cows received 6 kg DM/d of concentrate, in which maize was replaced by citrus pulp at 0, 33, 66 and 100%, corresponding to 0, 250, 500, and 750 g/kg of the concentrate. The inclusion of citrus pulp in the feed, to the detriment of maize, resulted in a linear decrease in milk production. The fat content was not altered, and a quadratic effect on protein and lactose content was observed (Table 6). According to the authors, the decrease in milk production may be related to a lower intake of forage, limited by the higher content of NDF in the diet with inclusion of citrus pulp. According to the authors, an increase in milk fat content was expected due to the increase in NDF content originating from the citrus pulp. However, there was no subsequent increase in ruminal pH or degradability of DM and NDF. The treatment did not affect the acetate: propionate ratio, thus, no difference in milk fat content was observed.

Goat milk production was evaluated by Lopez *et al.* (2014). The authors formulated diets, where maize was replaced by dehydrated citrus pulp in the proportions of 0 and 605.2 g/kg. Twelve multiparous goats with a body weight of 41.7 ± 2.8 kg were used in the experiment. The intake of DM brought similar results (Table 6), having no effect on milk production. The increase in milk fat is due to the higher concentration of acetic acid in the diets that include citrus pulp: this is a common factor in diets with higher fiber content.

Santos Silva *et al.* (2016) evaluated the effect of cereals being replaced by citrus pulp in diets supplemented with 5% soybean oil, on the production and composition of sheep milk. In this experiment, four multiparous ewes were used in their second month of lactation, arranged in a 2 × 2 double Latin square design. The citrus pulp was included in in the proportions of 0 and 240 g/kg of the diet, while maize silage constituted 45% of the diet. Milk production was higher and DM consumption tended to be higher with the citrus diet, while milk composition was not influenced (Table 6). According to the authors, the results indicate that the citrus pulp can substitute cereals in diets of dairy sheep without negative effects on the production.

Carmo *et al.* (2015) evaluated the effects of starch levels in diets with maize replaced by citrus pulp on production and milk composition of lactating cows. Twenty eight multiparous Holstein cows were used. The inclusion levels of citrus pulp in the diets were 0, 70, 131 and 196 g/kg. The DM consumption decreased linearly with the inclusion of citrus pulp in the diet. Milk production showed a quadratic response to increased levels of citrus pulp. The fat content did not differ between treatments, while the protein content decreased linearly with increase in the inclusion of citrus pulp (Table 6). The authors associate the decline in consumption with the resistance to breaking during chewing, which may have decreased the rate of ingestion. Thus, the negative effect of citrus pulp on DM intake, observed in this study, may be a combination of the ruminal distension effect and lower ruminal pH.

Digestibility of DM and nutrients of citrus co-products

The digestibility of DM and nutrients is linked to the efficiency of feed use. The different published works showed that the citrus pulp offers high digestibility of DM and the main nutrients. These results demonstrate the great potential of this by-product. Lashkari *et al.* (2017) evaluated the digestibility of diets composed of 44% lucerne and 55.7% of the concentrate mixture containing citrus pulp (0, 223.7, 456.6 and 675.4 g/kg of DM) replacing maize. In this experiment, twenty lambs (3-3.5 months of age) were used, with an average weight of 27.3 ± 1.3 kg. The use of citrus pulp did not affect the digestibility of the DM, while organic matter and crude protein had a quadratic effect, with maximum values observed for levels 57 and 55.1%, respectively. Citrus pulp inclusion levels promoted linear increase in NDF digestibility, and had a quadratic effect for ADF (Table 7). According to the authors, the positive effect of replacing starch concentrates with foods rich in easily degradable cell walls, such as citrus pulp, has generally been associated with a more favorable ruminal environment for cellulolytic bacteria.

In another experiment with lambs, Sharif *et al.* (2017) evaluated the digestibility of diets containing 10, 20, 30 and 40% of citrus pulp in the concentrate. 40 lambs with an average age of 4-5 months were used. The diet was 70% concentrate. Nutrient digestibility was not influenced by citrus pulp levels in the diet, with the mean value being 68.64% (Table 7).

Tadayon *et al.* (2017) used citrus pulp to substitute barley and maize grains, with inclusion levels in the diet at 0, 110 and 220 g/kg. Thirty-six lambs (initial live weight of 28±2.2 kg) were used. It was observed that the inclusion of dehydrated citrus pulp increased the digestibility of DM, OM, CP and NDFap (Table 7). The higher digestibility observed with the use of the citrus pulp may be related to the greater digestibility of soluble CHOs of grains such as maize (Miron *et al*. 2002). Moreover, pectin can promote a greater colonization of the particles, favoring its degradation in the rumen (Fondevila *et al*. 2002).

Macías-Cruz *et al.* (2010) evaluated the effect of partial or total replacement of buffel grass hay (*Cenchrus ciliaris*) with fresh citrus pulp on apparent digestibility in diets for fattening lambs. The diet was composed of 60% concentrate and 40% forage. The substitution levels were 0, 25, 50, 75 and 100%, corresponding to 0, 100, 200, 300 and 400 g/kg of the total diet. Twenty lambs with average live weight of 24.5 kg and 3 months of age were used. The digestibility coefficients of DM, OM, CP, NDF and hemicellulose increased in a quadratic manner (Table 7) with an increase of citrus pulp intake. The digestibility of these nutrients was higher at the 75% replacement level. According to the authors, the improvement in the apparent digestibility is due to the better nutritional profile of the citrus pulp in relation to the buffel grass hay, in having, for example, readily fermentable fiber, and lower lignin content. Another characteristic of the citrus pulp responsible for improving the digestibility of the diet is the ability to maintain ruminal pH even with high inclusion levels, maintaining good cellulolytic activity. However, the decrease in digestibility when using substitution levels greater than 75%, shows that the effectiveness of the fibrous portion of the citrus pulp is relevant only up to this level of substitution.

Gilaverte *et al.* (2011) evaluated the effect of maize replacement by pelleted citrus pulp on apparent digestibility of dietary nutrients. In total, 48 female lambs were evaluated. The diets were characterized by the total substitution of maize by the pelleted citrus pulp (46.9% of total DM) and consisted of 72% concentrate and 28% bulk. The substitution of maize by the pelleted citrus pulp did not influence the digestibility of the nutrients of the diet (Table 7).

Likewise, López *et al.* (2014), did not observe any difference in digestibility when they evaluated the effect of the substitution of maize grain by dehydrated citrus pulp on the apparent digestibility in goats with a body weight of 41.7 ± 2.8 kg. The citrus pulp was included in the amount of 0 and 605.5 g/kg, the diet being composed of 86% concentrate.

Effect of citrus co-products on rumen fermentation characteristics

The citrus pulp is considered a source rich in pectin, which is often associated with an increase in the molar ratios of acetic acids and decrease in propionic acid (Bampidis and Robinson, 2006).

Table 5 Effect of citrus co-products on ruminant performance

Citrus co-products	Inclusion level g/kg	Animal	DM intake (g DM/d)	BW gain (g/d)	Feed conversion (kg DM intake/kg BW gain)	Reference
Dehydrated citrus pulp	0	Lambs	749.2	181.0	4.13	Gobindram *et al* .(2017)
	240		767,0	181.3	4.23	
	350		756.4	179.2	4.22	
Citrus pulp	200	Nellore bulls	98000	1300	8.00	Favaro *et al.* (2016)
	250		10400	1410	7.37	
Orange pulp	0	Lambs	1000	194.2	5.14	Lashkari *et al.* (2017)
	223.7		1100	241.2	5.60	
	456.6		1100	203.3	5.60	
	675.4		1100	169.8	6.40	
Citrus pulp	0	Goat kids	650	160.0	4.06	Polizel *et al.* (2016)
	321		800	210.0	3.80	
Citrus pulp	100	Lambs	1350	67.50	20.0	Sharif *et al.* (2017)
	200		1370	76.33	17.9	
	300		1390	71.67	19.4	
	400		1410	75.83	18.5	
Orange pulp silage	0	Lambs	780	130.0	6.00	Gado *et al.* (2011)
	150		790	200.0	3.95	
Fresh citrus pulp	100	Lambs	1250	210.0	5.95	Macías-Cruz *et al.* (2010)
	200		1340	240.0	5.58	
	300		1530	260.0	5.88	
	400		1220	220.0	5.54	
Dehydrated citrus pulp	0	Crossbred heifers	6700	1500	4.46	Cribbs *et al.* (2015)
	100		6130	1280	4.78	
	200		5960	1130	5.27	
Dehydrated citrus pulp	0	Lambs	1266	208.0	6.08	Tadayon *et al.* (2017)
	110		1407	227.0	6.19	
	220		1447	261.0	5.54	
Citrus pulp	0	Nellore bulls	8890	1600	5.55	Gouvêa *et al.* (2016)
	198		9840	1740	5.65	
	402		10200	1850	5.51	
	602		9160	1700	5.38	
Dehydrated citrus pulp	203	Lambs	960.0	226.1	4.24	Rodrigues *et al.* (2011)
Wet low pectin citrus pulp	203		827.5	216.3	3.82	
Wet low pectin citrus pulp silage	203		880.0	217.9	4.03	
Citrus pulp	0	Dairy calves	353.7	322.1	1.09	Oltramari *et al.* (2016)
	320		467.1	412.4	1.13	
	640		348.0	373.4	0.93	
Citrus pulp	0	Nellore bulls	9910	1800	5.5	Caetano *et al.* (2019)
	70		10600	1750	6.0	
	140		11200	1880	5.95	
	210		10900	1970	5.53	

DM: dry matter and BW: body weight.

Another factor is that pectin could improve ruminal fermentation by increasing the extent or rate of adhesion of ruminal microbes to the particles. These patterns were observed in several studies. Lashkari *et al.* (2017), evaluated the ruminal fermentation characteristics of lambs fed on diets where maize was replaced by orange pulp at levels of 0, 33, 66 and 100%, respectively.

The diet was composed of 44.4% lucerne and 55.7% concentrated mixture. The pH of the ruminal fluid increased linearly with greater inclusion of citrus pulp and acetate linearly decreased in the same proportions with the inclusion of citrus pulp in the diet (Table 8). Cereals in general are rich in starch, which, during the process of degradation leads to a higher production of lactate.

Table 6 Effect of citrus co-products on milk production and composition

Citrus co-products	Inclusion level g/kg	Animal	DM intake (g DM/d)	Milk yield (L/d)	Fat (g/kg)	CP (g/kg)	Lactose (g/kg)	Reference
Citrus pulp	0	Cows	15.6	23.7	32.7	29.6	47.5	Leite *et al.* (2017)
	500		14.7	26.6	34.6	27.8	45.7	
Citrus pulp	0	Goats	1.51	1.75	49.5	37.4	45.3	López *et al.* (2014)
	605.2		1.53	1.92	59.0	34.4	46.1	
Orange pulp silage	0	Cows	22.3	27.4	38.1	32.2	49.9	Williams *et al.* (2018)
	132		21.0	26.2	37.6	32.5	49.3	
Dehydrated citrus pulp	0	Cows	-	21.1	44.8	34.9	46.5	Steyn *et al.* (2017)
	250		-	19.0	44.9	35.8	47.0	
	500		-	18.9	44.5	35.6	47.0	
	750		-	17.9	45.6	34.4	45.6	
Dehydrated citrus pulp	0	Sheep	1.22	0.71	51.5	54.5	53.9	Santos Silva *et al.* (2016)
	240		1.43	0.80	65.0	52.1	53.2	
Citrus pulp	0	Cows	22.9	29.6	34.6	30.8	45.1	Carmo *et al.* (2014)
	70		22.5	31.1	34.4	30.6	44.8	
	131		21.4	29.2	34.1	30.2	44.7	
	196		20.0	27.9	34.1	29.7	44.6	

CP: crude protein.

Table 7 Digestibility of dry matter and nutrients of citrus co-products

Citrus co-products	Inclusion level g/kg	Animal	Nutrient digestibility (g/kg DM)[1]						Reference
			DM	OM	CP	EE	NDF	ADF	
Citrus pulp	0	Lambs	795.2	815.2	685.6	577.0	576.2	581.7	Lashkari *et al.* (2017)
	223.7		822.7	852.7	719.0	604.5	626.2	659.0	
	456.6		812.6	842.6	705.5	594.4	637.7	679.0	
	675.4		814.5	834.5	701.5	596.3	636.7	677.0	
Citrus pulp	100	Lambs	695.3	-	714.4	-	500.9	471.8	Sharif *et al.* (2017)
	200		691.3	-	706.3	-	495.2	469.9	
	300		681.3	-	703.0	-	488.1	464.7	
	400		677.9	-	692.2	-	471.4	461.0	
Citrus pulp	0	Lambs	648.0	687.0	648.0	-	496.0	-	Tadayon *et al.* (2017)
	110		645.0	688.0	658.0	-	509.0	-	
	220		664.0	736.0	708.0	-	546.0	-	
Fresh citrus pulp	0	Lambs	684.0	-	715.0	-	528.0	-	Macías-Cruz *et al.* (2010)
	100		743.0	-	745.0	-	609.0	-	
	200		786.0	-	793.0	-	687.0	-	
	300		849.0	-	845.0	-	797.0	-	
	400		810.0	-	770.0	-	778.0	-	
Citrus pulp	0	Lambs	758.0	778.0	823.0	-	646.1	-	Gilaverte *et al.* (2011)
	469		787.0	804.0	805.0	-	763.9	-	
Citrus pulp	0	Goat	774.0	799.0	746.0	707.0	598.0	498.0	López *et al.* (2014)
	605.2		776.0	708.0	708.0	699.0	654.0	734.0	

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

This does not occur in diets rich in pectin, which, according to the authors, is one of the factors responsible for the observed results.

In a study by Tadayon *et al.* (2017), the pH value was not altered. These authors evaluated the ruminal fermentation parameters of 36 male lambs.

The animals were fed diets containing 0, 110 and 220 g/kg of citrus pulp. The results obtained in this study showed that the inclusion of citrus pulp in the diets increased the total concentration of volatile fatty acids and the proportion of acetic acid, while decreasing the proportion of propionic acid in the rumen (Table 8).

Table 8 The effect of citrus co-products on rumen fermentation characteristics

Citrus co-products	Inclusion level g/kg	Animal	pH	VFA[1] (mmol/L)	Molar proportions				Reference
					Acetic acid	Propionic acid	Butyric acid	Valeric acid	
Citrus pulp	0	Steers	6.79	85.0	0.623	0.199	0.141	38.0	Lenehan *et al.* (2017)
	855		6.64	104.0	0.620	0.232	0.118	30.0	
Dehydrated citrus pulp	0	Lambs	6.80	75.5	0.630	0.251	0.117	0.08	Tadayon *et al.* (2017)
	110		6.70	76.7	0.641	0.239	0.118	0.08	
	220		6.90	78.6	0.694	0.185	0.119	0.07	
Citrus pulp	0	Nellore bulls	6.34	95.3	0.534	0.279	0.121	1.53	Gouvêa *et al.* (2016)
	198		6.11	102.2	0.535	0.261	0.149	1.74	
	402		6.11	103.8	0.530	0.274	0.146	1.76	
	602		6.12	105.8	0.541	0.255	0.151	2.04	
	803		6.37	95.7	0.536	0.243	0.158	2.17	
Citrus pulp	0	Lambs	6.29	-	0.522	0.312	0.184	0.90	Lashkari *et al.* (2017)
	223.7		6.45	-	0.606	0.254	0.204	1.00	
	456.6		6.50	-	0.634	0.255	0.180	1.20	
	675.4		6.43	-	0.621	0.269	0.193	1.60	
Citrus pulp	0	Lambs	6.14	71.08	0.579	0.254	0.111	-	Gilaverte *et al.* (2011)
	469		6.19	61.37	0.640	0.228	0.95	-	

VFA: volatile fatty acids.

Gilaverte *et al.* (2011) evaluated the effect of maize replacement by pelleted citrus pulp on the performance of 48 feedlot sheep. The diets were characterized by the total replacement of maize by pelleted citrus pulp (46.9% of total DM). The experimental diets were composed of 72% concentrate. The replacement of maize by citrus pulp did not influence ruminal pH or propionate molar concentration. The acetate increased, and the butyrate decreased, though (Table 8).

Lenehan *et al.* (2017) evaluated the effects of barley (rich in starch) substitution by citrus pulp (rich in digestible fiber) on the diet of young growing cattle. Forty castrated bulls were used. The animals received grass silage at will, as well as 2 kg of concentrated mixture per day, with the inclusion of citrus pulp in the concentrate being 0 and 855 g/kg, respectively. The animals receiving citrus pulp had lower ruminal pH (P<0.01) and acetate: propionate ratio, as well as higher concentrations of fatty acids after ruminal feeding in relation to the animals that received barley (Table 8). The molar ratio of acetic acid was not influenced by the diet, the proportion of propionic acid was higher and the proportions of butyric acid and valeric acid were lower in the animals fed with citrus pulp. According to the authors, the high concentrations of sugars and pectin present in the pulp were more efficient in lowering the pH than the highly fibrous diet that is normally associated with the increase in pH.

Gouvêa *et al.* (2016) evaluated the ruminal parameters in feedlot Nelore cattle, where the diet had maize replaced by citrus pulp. The finishing test lasted 103 days, and 216 Nellore bulls (with an initial BW of 350±24 kg) were used in the experiment.

The diets had four levels of citrus pulp (0, 25, 50 and 75% of DM). All diets contained 12% sugarcane bagasse and 88% concentrate (DM based). The replacement of ground maize by citrus pulp did not influence the ruminal pH, neither the total concentration of AGV, nor the molar ratios of acetate, propionate, and ruminal valerate.

Only the butyrate had a linear increase with the inclusion of citrus pulp in the diet (Table 8). The authors hypothesized that the combination of a food rich in pectin (citrus pulp) with a diet rich in grains would reduce the incidence of ruminal acidosis and improve the performance of animals in feedlot. The results showed that the replacement of maize by citrus pulp not only decreased the starch content of the diet, but also increased the NDF content from 22 to 28%.

The maintenance of ruminal pH values even when maize was 100% replaced by citrus pulp was unexpected by the authors, who expected an increase in the proportion of acetate in rumen and the acetate: propionate ratio. According to the authors, this was due to the simple fact that there were no changes in ruminal ammonia concentrations. There was no indication that the addition of citrus pulp had a positive effect on the use of ammonia for microbial protein synthesis in the rumen.

CONCLUSION

The citrus pulp has high energy value and contains highly digestible fiber, besides having a very small indigestible fraction. Palatability and NDF content may influence ingestion. When used in high concentrate diets to replace traditional energy feeds such as maize, the performance of the animals was equivalent or superior, both for milk production and for weight gain. When it was used instead of forage, or at higher levels of inclusion in the diet, the lack of fiber effectiveness may have led to a reduction in consumption and consequent performance. The nutritional characteristics of citrus pulp generally allow for the maintenance of desirable ruminal characteristics that warrant good animal performance.

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