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Review

Citrus by-products as ruminant feeds: A review

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Abstract

Increased disposal costs in many parts of the world have increased interest in utilization of citrus by-product feedstuffs (BPF) as alternative feeds for ruminants. The main citrus BPF fed to ruminants are fresh citrus pulp, citrus silage, dried citrus pulp, citrus meal and fines, citrus molasses, citrus peel liquor, and citrus activated sludge. Other minor BPF from citrus include cull or excess fruit. This review evaluates citrus BPF in regard to their physical characteristics, nutrient composition, nutrient digestion, and ruminal fermentation, and their impact on animal performance. Citrus BPF can be used as a high energy feed in ruminant rations to support growth and lactation, with fewer negative effects on rumen fermentation than starch rich feeds. However, when very high levels of some citrus BPF are fed, rumen parakeratosis may occur, particularly when the level of dietary forage is low.

Keywords: Citrus by-products; Nutritional value; Ruminants; Performance

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Abbreviations: ADF, acid detergent fibre; ASH, ammoniated stargrass hay; BPF, by-product feedstuff; BUN, blood urea N; BW, body weight; CCMS, citrus condensed molasses solubles; CMDS, citrus molasses distillers solubles; CP, crude protein; CSC, cracked shelled corn; CW, cell wall; DCP, dried citrus pulp; DE, digestible energy; DLP, dried lemon pulp; DM, dry matter; DOP, dried orange pulp; HMEC, high-moisture ear corn; FCR, feed conversion ratio; GE, gross energy; ME, metabolizable energy; MUN, milk urea N; ND, neutral detergent; NDF, neutral detergent fibre; NDS, neutral detergent solubles; NDSC, neutral detergent soluble carbohydrates; NDSF, neutral detergent soluble fibre; NE, net energy; OM, organic matter; SBM, soybean meal; SNF, solids not-fat; TMR, total mixed ration; VFA, volatile fatty acids

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1. Introduction

Feeding by-products of the crop and food processing industries to livestock is a practice as old as the domestication of animals by humans. It has two important advantages (Grasser et al., 1995), these being to diminish dependence of livestock on grains that can be consumed by humans (which was almost certainly the primary original reason), and to eliminate the need for costly waste management programs (which has become very important in recent years as the world human population has increased and the amount of crop and food by-product has increased, particularly in developed countries). Ruminant feeding systems based on locally available by-product feedstuffs (BPF) are often a practical alternative because the rumen microbial ecosysten can utilize BPF, which often contain high levels of structural fibre, to meet their nutrient requirements for maintenance, growth, reproduction and production. The term ‘citrus by-product’ includes numerous BPF, which vary according to the originating crop and method of production, that are an important component of ruminant feeding systems in many areas of the world.

Total world citrus production averaged 69.4 million tonnes/year from 2000 through 2003, inclusive (USDA/FAS, 2003). The genus *Citrus* includes several important fruits (Kale and Adsule, 1995), with the most important on a worldwide basis being sweet orange (*C. sinensis*: 67.8% of world citrus production; USDA/FAS, 2003), tangerine (*C. reticulata*: 17.9%), lemon (*C. limon*: 6.3%) and grapefruit (*C. paradisi*: 5.0%). Minor citrus genuses that comprise the bulk of the remaining 3.0% include sour orange (*C. quarantium*), shaddock (*C.

grandis), citron (*C. medica*) and lime (*C. aurantifolia*). About 24% of world production of citrus is in the Mediterranean countries of Spain, Italy, Greece, Egypt, Turkey and Morocco, with Brazil (24%) and the USA (21%) being major individual citrus producing countries.

The objective of this review is to discuss production methods and physical characteristics of citrus BPF, summarize available data on nutrient composition and examine available data on their nutritive value to ruminants.

2. Production of citrus by-products

Citrus fruits are principally consumed by humans as fresh fruit or processed juice, either fresh chilled or concentrated. After juice is extracted from the fruit, there remains a residue (Table 1) comprised of peel (flavedo and albedo), pulp (juice sac residue), rag (membranes and cores) and seeds. These components, either individually or in various combinations, are the source materials from which citrus BPF are produced (Sinclair, 1984; Ensminger et al., 1990). The main citrus BPF from citrus processing (Fig. 1) are fresh citrus pulp which is the whole residue after extraction of juice, representing between 492 and 692 g/kg of fresh citrus fruit with 600–650 g dry matter (DM)/kg peel, 300–350 g/kg pulp and 0–100 g/kg seeds (Martínez-Pascual and Fernández-Carmona, 1980a), and dried citrus pulp (DCP) which is formed by shedding, liming, pressing and drying the peel, pulp and seed residues to about 80 g/kg moisture, and citrus meal and fines which is formed and separated during the drying process. A typical processing plant produces these BPF in a ratio of about 850 g/kg DCP, 140 g/kg citrus meal and 10 g/kg citrus fines. Other citrus BPF include citrus

Table 1
Products and by-products from various tissues of citrus fruits (Sinclair, 1984)

Whole peel or rind (pericarp)	Consists of flavedo (exterior yellow peel, epicarp) and albedo (interior whity spongy peel, mesocarp). Albedo is rich in pectin. The whole peel combined with the pulp residue (rag) and/or molasses can becomes a feed for animals. It is also used for production of human foods and food supplements
Pulp (principal edible portion, endocarp)	Used mainly to produce raw juice for human nutrition, after mechanical extraction and screening. The material screened from the raw juice is also called pulp and is usually combined with other residues to produce by-products used in animal nutrition
Pulp residue (called rag in the industry)	Consists of the fraction screened from the pulp, being cores, segment walls or membranes, juice vesicles and seeds. The pulp residue is usually combined with peel residue to manufacture by-products feeds. From the lime-treated mass peel and pulp residues, citrus processors produce such by-products as press liquor, citrus molasses, citrus pulp, citrus meal and feed yeast. It is also used for production of human foods and food supplements
Seeds	Sometimes separated from the rag to produce seed oils, seed meals and dried seed pressed cake
Waste waters (aqueous effluent emulsions from processing plants)	Have potential uses for production of such products as activated sludge and yeasts. It is also used for production of human foods and food supplements

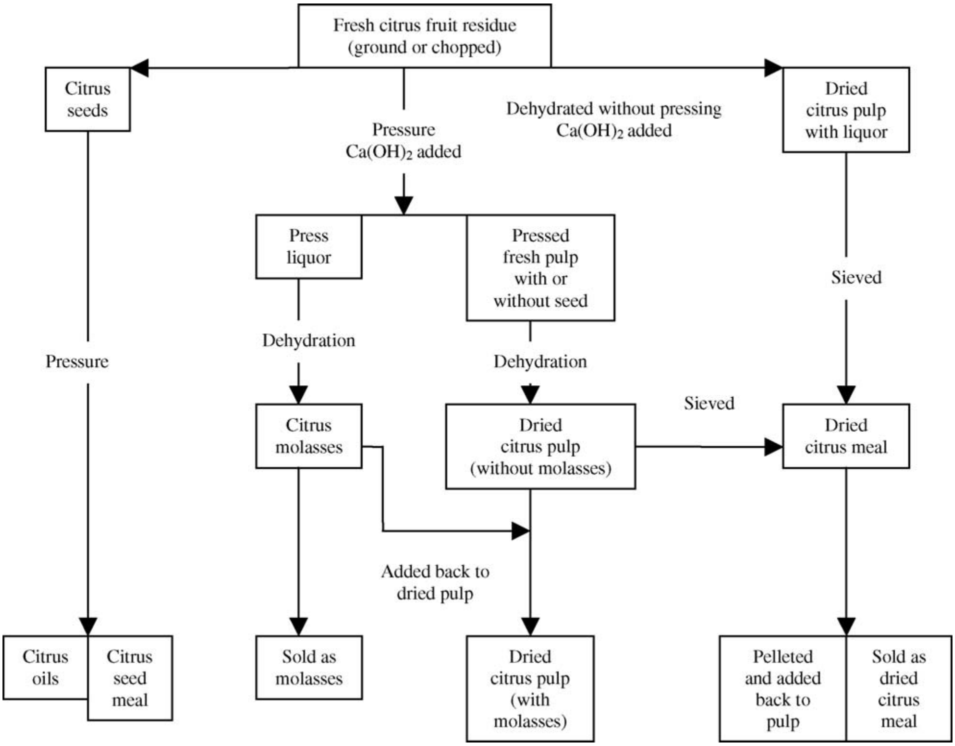

Fig. 1. Schematic presentation of citrus by-product production (adapted from Sinclair (1984)).

molasses, made by concentrating the press liquor from the citrus peel residue, which has a bitter taste and contains about 100–150 g/kg solubles of which 500–700 g/kg consists of sugar (Ensminger et al., 1990), citrus peel liquor, which is similar to citrus molasses, but not as concentrated, and citrus activated sludge which is produced from liquid wastes from citrus processing plants. Other minor BPF from citrus include cull or excess fruit (Madrid et al., 1996).

3. Physical characteristics of citrus by-products

The physical decription of the feed, such as a seed or meal, characterizes the dimension, or size, of the seed or particle as measured by screening or other processes (Kammel, 1991), as well as bulk density and hydration rate. Bulk density measures a feed's weight per unit volume space occupied, and generally varies with particle size. Hydration can affect bulk density by causing swelling of the feed matrix, due to absorption of water, and so hydration rate is important in determining the effective bulk density in the rumen. As bulk density before feeding, hydration rate and effective bulk density are potentially important factors impacting feed intake of total mixed rations (TMR) due to rumen fill, it is perhaps surprising that there is little published information on physical characteristics of citrus BPF.

Citrus pulp bulk density was estimated to be 324 kg/m^3 by Kammel (1991) and 303 kg/m^3 by Ammerman et al. (1966; reported by Arthington et al. (2002)). Pelleting reduces the volume of DCP and increases density by about 1.7 (Wing, 1975). Giger-Reverdin (2000) reported immediate hydration, and effective bulk density, of 0.715 in citrus pulp by measuring the mass of sample occupying 100 ml before mixing for 15 s in a graduated cylinder as a proportion of the mass of water occupying a volume equal to that occupied by the sample after gentle agitation. Giger-Reverdin (2000) also reported that water holding capacity was 4.33 l/kg DM, and the osmotic pressure was 79.0 mOsm/kg H_2O. The initial pH of citrus pulp, determined as the pH after 2 h of mixing 10 g of it in 200 ml of distilled water, was 5.77, indicating a moderate buffering capacity, compared with 23 other feedstuffs, which Giger-Reverdin et al. (2002) suggested to be associated with a low risk of ruminal acidosis.

Migwi et al. (2001) reported that fresh citrus pulp had a titratable acidity of 20 mmol/100 g DM, and a pH of 4.16. Wadhwa et al. (2001) developed an *in vitro* technique to evaluate production and neutralization of acid as feeds ferment in the rumen. With this technique, the acidogenicity value of citrus pulp and 27 other feed ingredients was determined as the dissolution of Ca from $CaCO_3$ powder added to the media (1 g DM feed sample in 30 ml buffered rumen liquor) at the end of a 24 h *in vitro* incubation. High protein feeds had low acidogenicity value, forages intermediate and starchy feeds had the highest acidogenicity value. The acidogenicity value of citrus pulp, 16.3 mg Ca/g DM, was relatively high, although Ca in citrus pulp contributed to the acidogenicity value.

4. Nutrient composition of citrus by-products

The composition of citrus fruit is affected by factors such as growing conditions, maturity, rootstock, variety and climate (Kale and Adsule, 1995). Citrus fruits contain N (1–2 g/kg on a wet basis), lipids (oleic, linoleic, linolenic, palmitic, stearic acids, glycerol, and a phytosterol), sugars (glucose, fructose, sucrose), acids (primarily citric and malic, but also tartaric, benzoic, oxalic, and succinic), insoluble carbohydrates (cellulose, pectin), enzymes (pectinesterase, phosphatase, peroxidase), flavonoids (hesperidin, naringin), bitter principles (limonin, isolimonin), peel oil (*d*-limonene), volatile constituents (alcohols, aldehydes, ketones, esters, hydrocarbons, acids), pigments (carotenes, xanthophylls), vitamins (ascorbic acid, Vitamin B complex, carotenoids), and minerals (primarily calcium and potassium).

The nutrient content of citrus BPF is influenced by factors that include the source of the fruit and type of processing (Ammerman and Henry, 1991). Most citrus BPF have been assigned a unique international feed number (Table 2), and the chemical composition of various citrus BPF from several sources is summarized in Tables 3–9.

5. Use of citrus by-products in ruminant nutrition

5.1. General

A large number of the citrus BPF are suitable for inclusion in ruminant diets because of the ability of ruminants to ferment high fibre feeds in the rumen (Grasser et al., 1995). An

Table 2
International feed numbers of some citrus by-products (Ensminger and Olentine, 1978; NRC, 1982, 1988, 2001)

International feed number	Description
3-01-234	Citrus pulp silage
4-01	Orange fresh (whole)
4-01-235	Citrus pulp fines (dried citrus meal)
4-01-237	Dried citrus pulp without fines
4-01-238	Citrus pulp (ammoniated, dried)
4-01-241	Citrus molasses
4-01-244	Grapefruit pulp (dried without fines)
4-01-247	Lemon pulp (dried without fines)
4-01-254	Orange pulp (dried without fines)
4-01-255	Orange pulp (ammoniated, dried)
4-08-376	Citrus pulp (wet)
5-01-239	Citrus seeds meal (mech extd)
5-01-240	Citrus molasses (ammoniated)

important benefit of citrus BPF feeding is often its relatively low cost. In fiscally successful ruminant production systems, reduction of feed costs, while maintaining high productivity, is a primary strategy. However, without the feed market as an outlet for citrus BPF, citrus processors in some parts of the world would be unable to remain competitive due to relatively high costs of BPF disposal, primarily by land filling and as soil amendments.

Citrus pulp is usually fed dehydrated and should be introduced gradually into a ration to allow the animals time to become accustomed to its dinstictive smell and taste (Bath et al., 1980). However, citrus pulp can also be fed fresh or as silage. Both are generally very rapidly accepted by ruminants, but pulp and peels from lemons are somewhat more acceptable than those from oranges and grapefruit (Bath et al., 1980).

Fresh citrus is readily consumed by dairy cattle, but has transportation, storage and handling issues (Lundquist, 1995). Indeed, fresh citrus pulp is generally only transported short distances because of its high moisture content and resulting high transportation costs (Grasser et al., 1995), it must be utilized rapidly as high levels of residual sugars often support secondary fermentation and/or mold growth as well as attracting flies, and its wet and sticky nature makes it difficult to store in sheds, bunkers or silos.

Fresh citrus can meet part of the water requirements of ruminants, which can be important in some areas of the world. The nutritionally unbalanced Ca:P ratio of citrus BPF can result in higher incidences of milk fever in cattle at, or soon after, parturition (Bath et al., 1980). Some reports (Cullen et al., 1986) have indicated that high feeding levels of citrus pulp can increase the risk of lactic acidosis in dairy cattle. This is counter to the general expectation of high pectin feeds, such as citrus BPF, as pectin does not ferment to lactic acid. Indeed, feeding citrus pulp does not appear to increase the incidence of acidosis at the levels at which it is commonly fed (*i.e.*, 100–150 g/kg of ration DM). During processing, calcium oxide or calcium hydroxide is often added to aid dehydration. The amount of calcium left in the pulp varies depending upon the process, but it inflates calcium levels as well as appearing to influence feed intake.

Generally, citrus BPF does not seem to affect intake of the diets in which it is included for ruminants. For example, partial or total substitution of corn or barley grain by dried

Table 3

Chemical composition of citrus by-products (NRC, 1982, 1988, 2001)

Citrus by-product	Citrus pulp silage (NRC, 1988)	Orange fresh (whole) (NRC, 1988)	Dried citrus meal (NRC, 1982)	Dried citrus pulp (NRC, 2001)	Dried citrus pulp (NRC, 1982, 1988)	Citrus molasses (NRC, 1982, 1988)	Dried orange pulp (NRC, 1988)
DM[a] (g/kg)	210	130	910	858	910	680	880
OM (g/kg DM)	945	956	931	928	934	921	962
CP (g/kg DM)	73	75	71	69	67	82	85
Crude fat (g/kg DM)	97	19	36	49	37	3	17
NDF (g/kg DM)	–	–	–	242	230	–	210
ADF (g/kg DM)	–	140	–	222	220	–	160
Lignin(sa) (g/kg DM)	–	–	–	9	30	–	–
NE_l (MJ/kg DM)	7.49	7.49	7.70	7.36	7.41	7.20	7.49
NE_g (MJ/kg DM)	5.19	5.19	5.19	5.23	5.10	4.85	5.19
NE_m (MJ/kg DM)	7.86	7.86	7.86	7.91	7.78	7.49	7.86
Calcium (g/kg DM)	20.4	–	21.7	19.2	18.4	17.2	7.1
Phosphorus (g/kg DM)	1.5	–	1.2	1.2	1.2	1.3	1.1
Magnesium (g/kg DM)	1.6	–	1.8	1.2	1.7	2.1	1.6
Potassium (g/kg DM)	6.2	–	6.8	11.0	7.9	1.4	6.2
Sodium (g/kg DM)	0.9	–	1.1	0.6	0.9	4.1	0.9
Chlorine (g/kg DM)	–	–	–	0.8	–	1.1	–
Sulfur (g/kg DM)	0.2	–	–	1.0	0.8	2.3	0.2
Cobalt (mg/kg DM)	0.16	–	–	–	0.16	0.16	0.16
Copper (mg/kg DM)	6	–	7	8	6	108	6
Iron (mg/kg DM)	160	–	180	151	378	508	160
Manganese (mg/kg DM)	7	–	8	9	7	38	7
Molybdenum (mg/kg DM)	–	–	–	0.9	–	–	–
Zinc (mg/kg DM)	16	–	16	11	15	137	16
Arginine (g/kg DM)	–	–	3.1	2.34	2.7	–	–
Cystine (g/kg DM)	–	–	1.2	0.95	1.2	–	–
Histidine (g/kg DM)	–	–	–	1.30	–	–	–
Isoleucine (g/kg DM)	–	–	–	1.93	–	–	–
Leucine (g/kg DM)	–	–	–	3.46	–	–	–
Lysine (g/kg DM)	–	–	2.2	1.77	2.2	–	–
Methionine (g/kg DM)	–	–	0.9	0.71	1.0	–	–
Phenylalanine (g/kg DM)	–	–	–	2.50	–	–	–
Threonine (g/kg DM)	–	–	–	2.01	–	–	–
Tryptophan (g/kg DM)	–	–	0.7	0.52	0.7	–	–
Valine (g/kg DM)	–	–	–	2.61	–	–	–
Choline (mg/kg DM)	–	–	–	–	867	–	–
Niacin (mg/kg DM)	–	–	23	–	24	40	–
Pantothenic acid (mg/kg DM)	–	–	14.3	–	15.4	18.8	–
Riboflavin (mg/kg DM)	–	–	2.7	–	2.5	9.2	–
Thiamine (mg/kg DM)	–	–	1.4	–	1.6	–	–

[a] ADF, acid detergent fibre; CP, crude protein; DM, dry matter; NDF, neutral detergent fibre; NE, net energy; OM, organic matter.

Table 4
Chemical composition of dried citrus pulp summarized from several sources[a]

	n	Mean	S.E.M.
DM[b] (g/kg)	20	897	5.0
OM (g/kg DM)	26	937	3.1
CP (g/kg DM)	33	69	1.4
NDFCP (g/kg DM)	5	4.4	1.5
ADFCP (g/kg DM)	3	3.3	0.5
Crude fat (g/kg DM)	24	23	2.0
NDF (g/kg DM)	24	220	10.6
ADF (g/kg DM)	21	197	10.4
Lignin(sa) (g/kg DM)	15	21	4.9
Sugar (g/kg DM)	3	241	14.8
Organic acids (g/kg DM)	1	90	
Soluble fibre (g/kg DM)	1	329	
Water soluble carbohydrate (g/kg DM)	2	246	17.0
ND soluble fibre (g/kg DM)	1	345	
Ethanol insoluble OM (g/kg DM)	1	589	
Ethanol insoluble CP (g/kg DM)	1	51	
Pectin (g/kg DM)	1	223	
Starch (g/kg DM)	7	23	11.4
GE (MJ/kg DM)	4	17.87	0.44
ME (MJ/kg DM)	1	12.47	
Calcium (g/kg DM)	13	16.0	1.6
Phosphorus (g/kg DM)	13	1.1	0.1
Magnesium (g/kg DM)	9	1.2	0.1
Potassium (g/kg DM)	9	8.2	0.7
Sodium (g/kg DM)	8	5.8	2.0
Sulfur (g/kg DM)	2	0.8	0.2
Cobalt (mg/kg DM)	1	0.1	
Copper (mg/kg DM)	5	3.0	0.8
Iron (mg/kg DM)	5	85.7	16.9
Manganese (mg/kg DM)	6	9.5	2.6
Zinc (mg/kg DM)	6	34.1	7.3

[a] Welch and Smith (1971), Bhattacharya and Harb (1973), Durand et al. (1988), Ammerman and Henry (1991), Brown and Johnson (1991), Deaville et al. (1994), de Marichal and Bayardo (1994), Arosemena et al. (1995), Lundquist (1995), Sunvold et al. (1995), Belibasakis and Tsirgogianni (1996), DePeters et al. (1997), de Castro and Zanetti (1998), Hall et al. (1998), Henrique et al. (1998), de Martins et al. (1999), O'Mara et al. (1999), Zeoula et al. (1999), Giger-Reverdin (2000), Fonseca et al. (2001), Schalch et al. (2001), Wadhwa et al. (2001), Broderick et al. (2002), Bueno et al. (2002), Cone et al. (2002b) and Hall (2003).

[b] ADF, acid detergent fibre; CP, crude protein; DM, dry matter; GE, gross energy; ME, metabolizable energy; ND, neutral detergent; NDF, neutral detergent fibre; OM, organic matter.

orange pulp (DOP) or dried lemon pulp (DLP) in the concentrates fed to Friesian dairy cattle had no effects on intake of the ration (Lanza, 1984). The intake of a ration fed to Awasi lambs containing DCP was reported to be the same as that containing corn grain at up to 400 g DCP/kg DM, but declined at higher levels (Bhattacharya and Harb, 1973), while ammoniation of 450 g DCP/kg DM, either with urea or ammonium hydroxide, to increase N content, did not alter palatability for sheep (Rihani et al., 1993b). Additionally, Volanis et al. (2004) reported that ensiled sliced oranges at 309 g/kg DM of the TMR was palatable to

Table 5
Chemical composition (mean ± S.E.M.) of several orange by-products summarized from several sources[a]

Citrus by-product	Orange peel (fresh)	Orange peel silage	Orange pulp silage	Orange pulp (fresh)	Dried orange pulp
n	2	1	1	7	5
DM[b] (g/kg)	233 ± 16.6	193	154	192 ± 3.5	902 ± 10.1
OM (g/kg DM)	975	954	–	965 ± 1.4	909 ± 3.0
CP (g/kg DM)	58 ± 7.3	81	109	64 ± 4.6	72 ± 2.1
Crude fat (g/kg DM)	–	–	–	40 ± 5.7	30 ± 9.6
NDF (g/kg DM)	200 ± 71.1	228	–	–	193 ± 13.4
ADF (g/kg DM)	129	170	–	150 ± 14.7	169 ± 24.3
Lignin(sa) (g/kg DM)	–	–	–	13 ± 1.1	5 ± 2.0
pH	3.64	3.10	3.50	3.70	–
Lactic acid (g/kg DM)	23.0	83.6	21.9	1.1	–
Acetic acid (g/kg DM)	20.0	64.3	29.8	3.3	–
Proponic acid (g/kg DM)	0.3	3.3	2.9	1.1	–
Isobutyric acid (g/kg DM)	0.6	3.6	–	–	–
Butyric acid (g/kg DM)	–	1.3	0.5	0.2	–
Carbohydrate (g/kg DM)	–	–	–	–	790
Arabinose (g/kg DM)	–	–	–	–	68.0
Fructose (g/kg DM)	–	–	–	–	102
Galactose (g/kg DM)	–	–	–	–	65.7
Glucose (g/kg DM)	–	–	–	–	290
Mannose (g/kg DM)	–	–	–	–	26.2
Uronic acid (g/kg DM)	–	–	–	–	215
Xylose (g/kg DM)	–	–	–	–	21.4
GE (MJ/kg DM)	–	–	–	–	16.23
DE (sheep, MJ/kg DM)	–	–	–	–	15.35
ME (sheep, MJ/kg DM)	–	–	–	–	12.80
NE_l (sheep, MJ/kg DM)	–	–	–	–	8.37
NE_g (sheep, MJ/kg DM)	–	–	–	–	8.87
NE_m (sheep, MJ/kg DM)	–	–	–	–	10.00
Calcium (g/kg DM)	7.3	–	–	–	35.4 ± 17.3
Phosphorus (g/kg DM)	1.7	–	–	–	3.4 ± 0.7
Magnesium (g/kg DM)	–	–	–	–	1.5 ± 0.3
Potassium (g/kg DM)	–	–	–	–	7.0 ± 0.1
Sodium (g/kg DM)	–	–	–	–	0.3 ± 0.1
Sulfur (g/kg DM)	–	–	–	–	1.2 ± 0.1
Cobalt (mg/kg DM)	–	–	–	–	0.6 ± 0.0
Copper (mg/kg DM)	–	–	–	–	11.3 ± 3.2
Iron (mg/kg DM)	–	–	–	–	159.3 ± 7.1
Manganese (mg/kg DM)	–	–	–	–	10.2 ± 2.7
Zinc (mg/kg DM)	–	–	–	–	20.9 ± 13.0
Alanine (g/kg DM)	–	–	–	–	2.2 ± 0.1
Arginine (g/kg DM)	–	–	–	–	2.3 ± 0.7
Aspartic acid (g/kg DM)	–	–	–	–	5.6 ± 0.3
Cystine (g/kg DM)	–	–	–	–	0.6 ± 0.1
Glutamic acid (g/kg DM)	–	–	–	–	5.9 ± 1.0
Glycine (g/kg DM)	–	–	–	–	2.4 ± 0.1
Histidine (g/kg DM)	–	–	–	–	1.0 ± 0.0
Isoleucine (g/kg DM)	–	–	–	–	1.9 ± 0.1
Leucine (g/kg DM)	–	–	–	–	3.2 ± 0.3
Lysine (g/kg DM)	–	–	–	–	1.4 ± 0.3

Table 5 (*Continued*)

Citrus by-product	Orange peel (fresh)	Orange peel silage	Orange pulp silage	Orange pulp (fresh)	Dried orange pulp
Methionine (g/kg DM)	–	–	–	–	0.3 ± 0.1
Phenylalanine (g/kg DM)	–	–	–	–	2.0 ± 0.1
Proline (g/kg DM)	–	–	–	–	3.3 ± 1.0
Serine (g/kg DM)	–	–	–	–	1.8 ± 0.0
Threonine (g/kg DM)	–	–	–	–	1.6 ± 0.0
Tryptophan (g/kg DM)	–	–	–	–	0.2 ± 0.1
Tyrosine (g/kg DM)	–	–	–	–	0.7 ± 0.1
Valine (g/kg DM)	–	–	–	–	2.4 ± 0.1

[a] Martínez-Pascual and Fernández-Carmona (1980a), Lanza (1984), Cervera et al. (1985), Megías et al. (1993), Silva et al. (1997), Scerra et al. (1994), Fegeros et al. (1995) and Miron et al. (2001).

[b] ADF, acid detergent fibre; CP, crude protein; DE, digestible energy; DM, dry matter; GE, gross energy; ME, metabolizable energy; NDF, neutral detergent fibre; NE, net energy; OM, organic matter.

Table 6

Chemical composition (mean ± S.E.M.) of lemon by-products summarized from several sources[a]

Citrus by-product	Lemon pulp fresh	Lemon peel fresh whole	Lemon dried whole	Dried lemon pulp
n	2	3	1	1
DM[b] (g/kg)	181 ± 16.5	202 ± 18.0	920	903
OM (g/kg DM)	962	967	895	948
CP (g/kg DM)	72 ± 1.0	66 ± 8.1	81	90
Crude fat (g/kg DM)	40 ± 17.0	16	39	36
NDF (g/kg DM)	–	330 ± 33.6	365	–
ADF (g/kg DM)	168	–	257	–
Lignin(sa) (g/kg DM)	18	–	26	–
Sugar (g/kg DM)	–	191	–	–
GE (MJ/kg DM)	–	–	20.08	–
Calcium (g/kg DM)	–	7.8 ± 0.3	–	–
Phosphorus (g/kg DM)	–	1.5 ± 0.4	–	–
Magnesium (g/kg DM)	–	0.8	–	–
Potassium (g/kg DM)	–	8.7	–	–
Sodium (g/kg DM)	–	0.04	–	–
Sulfur (g/kg DM)	–	0.06	–	–
Iron (mg/kg DM)	–	44.6	–	–
Biotin (mg/kg DM)	–	0.135	–	–
Choline (mg/kg DM)	–	598.5	–	–
Folic acid (mg/kg DM)	–	0.269	–	–
Inositol (mg/kg DM)	–	11752	–	–
Niacin (mg/kg DM)	–	19.4	–	–
Pantothenic acid (mg/kg DM)	–	17.4	–	–
Pyridoxine (mg/kg DM)	–	9.4	–	–
Riboflavin (mg/kg DM)	–	4.3	–	–
Thiamine (mg/kg DM)	–	3.2	–	–

[a] Martínez-Pascual and Fernández-Carmona (1980a), Lanza (1984), Sinclair (1984), Madrid et al. (1996) and Silva et al. (1997).

[b] ADF, acid detergent fibre; CP, crude protein; DM, dry matter; GE, gross energy; NDF, neutral detergent fibre; OM, organic matter.

Table 7
Chemical composition of some miscellaneous citrus by-products summarized from several sources[a]

Citrus by-product	Bergamot peel	Grapefruit pulp fresh	Mandarin pulp fresh	Citrus condensed molasses solubles	Citrus molasses distillers solubles
n	1	1	1	1	1
DM[b] (g/kg)	163	197	197	450	520
OM (g/kg DM)	957	962	960	–	–
CP (g/kg DM)	–	71	80	106	73
Crude fat (g/kg DM)	13	63	61	2	–
NDF (g/kg DM)	101	–	–	–	–
ADF (g/kg DM)	73	168	174	–	–
Lignin(sa) (g/kg DM)	27	19	21	–	–
Sugar (g/kg DM)	–	–	–	–	43
GE (MJ/kg DM)	15.94	–	–	–	–
NE_l (MJ/kg DM)	–	–	–	–	8.28
Calcium (g/kg DM)	–	–	–	24.8	9.0
Phosphorus (g/kg DM)	–	–	–	1.8	1.9

[a] Martínez-Pascual and Fernández-Carmona (1980a), Chen et al. (1981), Wing et al. (1988) and Scerra et al. (1999).

[b] ADF, acid detergent fibre; CP, crude protein; DM, dry matter; GE, gross energy; NDF, neutral detergent fibre; NE, net energy; OM, organic matter.

lactating dairy sheep, possibly due to its pleasant odour, while Migwi et al. (2001) suggested that the level of citrus pulp, ensiled with wheat straw and poultry litter, in the ration of sheep should be maintained between 150 and 200 g/kg DM to avoid depressed intake that may arise with higher citrus pulp levels, presumably due to low palatability. Finally, orange has been used as a food flavour in sheep (Ralphs et al., 1995).

Large amounts of citrus molasses are used for production of beverage alcohol. Remaining sugars, primarily pentoses and residual yeast from fermentation comprise citrus molasses distillers solubles (CMDS), which is a potential source of feed energy for cattle (Wing et al., 1988), while citrus condensed molasses solubles (CCMS) is the condensed residue from the fermentation of citrus molasses to alcohol (Chen et al., 1981).

Another citrus BPF, citrus sludge, which is a decomposition product from plant materials discarded during citrus processing, possesses a desirable amino acid composition and has been proposed as a feedstuff (Coleman and Shaw, 1977).

5.2. *Fibrous characteristics of citrus pulp*

The difference between plant ‘cell wall’ (CW), or total fibre, in an agronomic context and ‘neutral detergent fibre’ (NDF), or structural fibre, in an animal feeding context is important with most citrus BPF because of their high contect of pectin, which is a part of CW but not part of NDF. Thus, throughout this review, the terms CW and NDF will not be used interchangeably, but in the context of ‘fibre’ either inclusive (*i.e.*, CW) or exclusive (*i.e.*, NDF) of pectin.

The NDF level of citrus pulp is intermediate between that of most concentrates and forages. Welch and Smith (1971) studied effects of citrus pulp on rumination activity, and found that rumination time for DCP fed rams was lower *versus* those fed a chopped mixed hay

Table 8

Chemical composition of some citrus by-products (Ensminger and Olentine, 1978)

Citrus by-product	Citrus pulp silage	Dried citrus pulp	Dried citrus pulp ammoniated	Citrus molasses	Dried grape-fruit pulp	Dried lemon pulp	Dried orange pulp	Dried orange pulp ammoniated	Wet citrus pulp	Citrus seed meal, mechanical extract	Citrus molasses ammoniated
DM[a] (g/kg)	220	900	870	680	900	930	880	890	180	880	610
OM (g/kg DM)	945	935	947	926	940	943	958	937	923	932	923
CP (g/kg DM)	73	69	138	71	77	70	85	165	66	354	352
Crude fat (g/kg DM)	97	40	64	3	35	15	19	37	33	116	35
NE_l (MJ/kg DM)	8.49	8.03	8.37	7.07	7.70	7.53	8.66	6.69	7.95	8.20	7.32
NE_g (MJ/kg DM)	6.02	5.56	5.90	4.52	5.23	5.02	6.19	5.81	5.48	5.73	4.81
NE_m (MJ/kg DM)	8.83	8.28	8.70	7.11	7.86	7.61	9.04	8.79	8.16	8.49	7.40
Calcium (g/kg DM)	–	20.7	19.0	16.1	14.8	–	7.1	–	–	12.5	16.8
Phosphorus (g/kg DM)	–	1.3	1.4	1.4	1.8	–	1.1	–	–	7.5	2.6
Magnesium (g/kg DM)	–	1.6	0.8	2.1	4.3	–	–	–	–	6.8	1.3
Potassium (g/kg DM)	–	7.7	–	1.3	–	–	–	–	–	14.9	–
Sodium (g/kg DM)	–	1.0	–	4.0	–	–	–	–	–	–	–
Chlorine (g/kg DM)	–	–	–	1.0	–	–	–	–	–	–	–
Sulfur (g/kg DM)	–	0.7	–	–	–	–	–	–	–	–	–
Cobalt (mg/kg DM)	–	0.155	–	0.159	–	–	–	–	–	–	–
Copper (mg/kg DM)	–	6.3	–	108	–	–	–	–	–	7.5	–
Iron (mg/kg DM)	–	170	–	500	–	–	–	–	–	330	–
Manganese (mg/kg DM)	–	7.2	–	38.5	–	–	–	–	–	8.5	–
Zinc (mg/kg DM)	–	14.4	–	137	–	–	–	–	–	8.0	–
Arginine (g/kg DM)	–	2.5	–	–	–	–	–	–	–	–	–
Cystine (g/kg DM)	–	1.2	–	–	–	–	–	–	–	–	–
Lysine (g/kg DM)	–	2.2	–	–	–	–	–	–	–	–	–
Methionine (g/kg DM)	–	1.0	–	–	–	–	–	–	–	–	–
Tryptophan (g/kg DM)	–	0.7	–	–	–	–	–	–	–	–	–
Vitamin A (IU/kg DM)	–	400	–	–	–	–	–	–	–	–	–
Choline (mg/kg DM)	–	884	–	–	–	–	–	–	–	–	–
Niacin (mg/kg DM)	–	24	–	39	–	–	–	–	–	–	–
Pantothenic acid (mg/kg DM)	–	15.1	–	18.6	–	–	–	–	–	–	–
Riboflavin (mg/kg DM)	–	2.5	–	9.1	–	–	–	–	–	–	–
Thiamine (mg/kg DM)	–	1.6	–	–	–	–	–	–	–	–	–

[a] CP, crude protein; DM, dry matter; NE, net energy; OM, organic matter.

Table 9
Chemical composition of citrus by-products (Bath et al., 1980)

Citrus by-product	Citrus pulp	Citrus pulp dried	Citrus pulp silage	Citrus mol-asses	Grape-fruit pulp	Grape-fruit pulp dried	Lemon pulp dried	Lime pulp dried	Orange	Orange pulp wet	Orange by-product dried	Orange pulp dried	Orange pulp ammoniated dried	Orange pulp silage	Tangerine pulp dried
DM[a] (g/kg)	183	900	200	650	140	910	930	850	128	250	906	880	890	113	870
OM (g/kg DM)	923	930	943	934	963	940	943	–	956	962	964	962	962	947	950
CP (g/kg DM)	66	69	73	109	81	67	69	91	75	89	83	85	165	88	81
Crude fat (g/kg DM)	33	38	104	3	44	15	15	34	19	18	30	17	37	22	57
ADF (g/kg DM)	160	230	200	0	130	170	200	220	140	160	180	160	170	220	140
NE_l (MJ/kg DM)	7.91	7.36	8.03	7.36	8.20	7.66	7.36	6.65	7.49	7.36	6.74	7.49	7.03	6.19	7.66
NE_g (MJ/kg DM)	6.65	4.89	5.44	4.89	5.73	5.27	4.89	4.06	4.89	4.69	3.89	4.98	4.22	3.22	5.06
NE_m (MJ/kg DM)	8.28	7.36	8.20	7.36	8.58	7.82	7.49	6.65	7.74	7.66	6.74	7.49	7.11	6.11	8.03
Calcium (g/kg DM)	–	20.7	20.4	20	5.1	14.8	–	–	5.7	2.1	7.1	7.1	7.1	–	15.7
Phosphorus (g/kg DM)	–	1.3	1.5	1.4	1.5	1.8	–	–	1.3	2.8	1.1	1.1	1.1	–	1.4
Magnesium (g/kg DM)	–	1.6	1.6	2.2	–	–	–	–	–	–	–	–	–	–	–
Potassium (g/kg DM)	–	6.2	6.2	1.4	–	–	–	–	–	10.5	–	–	–	–	–

[a] ADF, acid detergent fibre; CP, crude protein; DM, dry matter; NE, net energy; OM, organic matter.

(0.16 min/g *versus* 0.34 min/g DM consumption), but similar relative to CW constituents, at 0.56 min/g *versus* 0.50 min/g CW consumption. Similarly, rumination time for DCP fed cattle was lower *versus* those fed a long mixed hay (0.041 min/g *versus* 0.072 min/g DM consumption), but similar with regard to CW (0.154 min/g *versus* 0.109 min/g CW consumption).

In a similar study, Sudweeks et al. (1975) studied effects of wheat silage, corn silage, sorghum silage and bermudagrass hay, as well as DCP, corn grain and soybean mill feed, at concentrate levels of 100, 400, and 700 g/kg DM, on chewing time (*i.e.*, eating plus ruminating) of steers. Diets containing DCP were eaten more slowly than diets containing corn, but equal to diets containing soybean mill feed, although ruminating time was not affected by concentrate type. Both eating and ruminating times decreased with each increase in concentrate level. Eating and ruminating times for DCP pooled from the four forages were 220, and 308 min/d, respectively. Bermudagrass hay increased eating time, and wheat silage and bermudagrass hay increased ruminating time. The determined ‘fibrosity index’ for DCP was 30.9 min of chewing time/kg DM.

Sudweeks (1977a) studied effects of the DCP, corn grain and soybean mill feed at concentrate levels of 100, 400, and 700 g/kg DM on chewing time and rumen volatile fatty acid (VFA) levels of steers. Chewing time was not affected by concentrate type, but it was reduced with each increase in concentrate level (713, 490, and 387 min/d, respectively). For the three concentrate levels of DCP, Sudweeks calculated that the synthesis rates of acetate, propionate, and butyrate were 42, 13, and 18 mmol/l rumen fluid/h, respectively.

5.3. *Effects of processing*

Martínez-Pascual and Fernández-Carmona (1980a) reported that drying of citrus pulp causes little variation in the nutrient composition, if temperatures range between 80 and 130 °C. However, above 130 °C, the acid detergent fibre (ADF), acid detergent lignin and DM losses increase 2–2.5% for each additional 10 °C, while crude protein (CP) losses seem to be low at temperatures below 200 °C; it is well known that heating proteins can reduce their nutritive value due to Maillard polymerization (Martínez-Pascual and Fernández-Carmona, 1980a).

5.4. *Improving the nutritional value of citrus by-products*

Although most citrus BPF have a low N content, low NDF and moderate nutrient density, processing can raise their nutritive value. Taiwo et al. (1995) reported that unfermented citrus pulp (910 g/kg DM) had relatively high levels of glucose and low levels of other nutrients. However, fermentation of citrus pulp without or with 100 g/kg molasses for 61 days resulted in production of primarily lactic and acetic acid (Taiwo et al., 1995), which enhanced citrus pulp ammonia holding capacity from 0.1 g NH_3 N/kg DM in unfermented citrus pulp to 10.6 and 16.4 g NH_3 N/kg DM in fermented citrus pulp without and with molasses, respectively. This suggests that the N content of citrus pulp can be enhanced by trapping excess ammonia generated from, for example, urea treated barley straw (Taiwo et al., 1995). In addition, citrus pulp buffering capacity was 7.81 mequiv./kg in unfermented citrus pulp, and 408.4 and 658.5 mequiv./kg in fermented citrus pulp without or with 100 g/kg molasses, respectively, at 61 days of fermentation (Taiwo et al., 1995). The pH of citrus pulp declined from 6.3 (unfermented) to 4.2, and 3.9 (fermented without or with molasses, respectively).

DCP contains relatively large amounts of pectins and soluble carbohydrates and very limited amounts of available N. In an attempt to improve efficiency of non-protein N utilization and animal performance by synchronizing ruminal NH_3 N and energy availability, Rihani et al. (1993a) studied effects of level and method of urea supplementation on N utilization and characteristics of digestion of an N deficient (*i.e.*, 8.5 g N/kg DM) high DCP (450 g DCP/kg DM) diet by sheep. Neither organic matter (OM) digestion, or microbial net synthesis or efficiency, was enhanced by high levels of ruminal ammonia or by continuous N release in the rumen. Additionally, when steers were fed rolled barley grain and DCP in proportions 477:0 and 173:300 g/kg DM, microbial efficiency did not differ between treatments (22.4 g *versus* 19.3 g of microbial N/kg of OM digested in the rumen in the DCP *versus* control treatment (Taniguchi et al., 1999)).

Rihani et al. (1993b) examined effects of source of supplemental N on digestion and feeding value of a DCP based diet for sheep. Four treatments, being four sources of supplemental N (*i.e.*, ammoniation of DCP with urea, ammoniation with ammonium hydroxide, supplementation with urea, and supplementation with the α-amino N source faba bean), were used. Diets were isonitrogenous (18 g N/kg DM) and contained DCP 450 g/kg of DM. The feeding value of the diet supplemented with faba bean was superior to diets supplemented with non-protein N. Ammoniation of DCP, either with urea or ammonium hydroxide, resulted in an increased N content (33 and 29 g/kg of DM, respectively, *versus* 10 g/kg in untreated DCP). While the source of supplemental non-protein N did not influence OM digestion, the net microbial N synthesis, absorption, retention and microbial efficiency were higher for the diet that contained DCP ammoniated with urea *versus* the diets supplemented with urea or DCP ammoniated with ammonium hydroxide.

5.5. Degradation rate and effective degradability of citrus by-product nutrients

Degradation rate and effective degradability of citrus BPF nutrients was evaluated by use of a ruminal *in situ* technique in ruminally fistulated sheep (Barrios-Urdaneta et al., 2003). The degradation rate of OM was higher in fresh citrus pulp *versus* DCP (Table 10), and the rate of ruminal *in situ* DM and NDF degradation increased when DCP was incorporated into the diet of ewes (Barrios-Urdaneta et al., 2003). The effective ruminal degradability of DCP ranged between 0.550 and 0.750 for OM and 0.591 and 0.704 for CP, at outflow rates of 0.02–0.08 h^{-1} (Table 11).

Silva et al. (1997) reported that the degradation rates (k_d) of the slowly ruminally degradable fraction of DM did not differ among fresh lemon, orange peels and orange peel silage, averaging 0.029 h^{-1}. Effective ruminal degradability was also similar for these three citrus BPF, ranging from 0.510 to 0.630 at a ruminal outflow rate of 0.05 h^{-1}. Silva et al. (1997) found that the potentially ruminal degradable DM of citrus peels in all forms was close to unity, suggesting a high nutritive value for cattle, similar to that of processed cereal grains. Ruminal outflow rate of solids, and the acetate clearance rate, were unaffected by DCP supplementation to lamb diets at up to 400 g/kg DM, while the ruminal outflow rate of liquids tended to increase (Fonseca et al., 2001). It is known that increasing ruminal outflow rate

Table 10
Degradation rate (h^{-1}) of citrus by-products (BPF)

Feedstuff	Animal	Citrus BPF level[a]	Degradation rate (h^{-1})					Reference
			DM	OM	CP	NDF	Non-N OM	
DCP[a]	Wethers		–	0.045	0.054	–	0.047	de Marichal and Bayardo (1994)
Citrus pulp	Cows		–	0.082	–	0.091	–	DePeters et al. (1997)
DCP	Cows		0.035	–	0.013	–	–	de Martins et al. (1999)
Citrus pulp	Cows		–	0.102	0.062	–	–	Cone et al. (2002a,b)
DOP concentrate (g/kg)	Ewes	0	0.041	–	–	0.045	–	Barrios-Urdaneta et al. (2003)
		268	0.052	–	–	0.058	–	
		542	0.047	–	–	0.054	–	
		823	0.049	–	–	0.065	–	

[a] CP, crude protein; DCP, dried citrus pulp; DM, dry matter; DOP, dried orange pulp; NDF, neutral detergent fibre; OM, organic matter.

Table 11
Effective degradability of citrus by-products

Feedstuff	Animal	Outflow rate (h^{-1})	Effective degradability				Reference
			DM	OM	CP	Non-N OM	
DCP[a]	Wethers	0.050	–	0.550	0.160	0.560	de Marichal and Bayardo (1994)
Citrus pulp	Cows	0.065	–	0.750	–	–	Tagari et al. (1995)
DCP	Cows	0.020	0.798	–	0.704	–	de Martins et al. (1999)
		0.050	0.675	–	0.621	–	
		0.080	0.617	–	0.591	–	

[a] CP, crude protein; DCP, dried citrus pulp; DM, dry matter; OM, organic matter.

can positively influence the supply of microbial protein to the duodenum (Fonseca et al., 2001). Additionaly, Cone et al. (2002a,b) found that the proportional rumen escape CP of citrus pulp was 330, and the fermentable OM was 748 g/kg. The same authors found that solubility of citrus pulp CP was 867 g/kg after 24 h of *in vitro* incubation with a *S. griseus* protease enzyme, and that total *in vitro* gas production was 360 ml/g OM, when 400 mg of OM was incubated for 72 h in 60 ml of buffered rumen fluid.

5.6. Fermentation of citrus by-products

5.6.1. Fermentation of citrus by-products during ensiling

Megías et al. (1993) studied chemical changes during ensiling of orange peel and concluded that the initial high content of water, which is the result of processing to obtain the BPF, affects the quality of the ensiled forage and makes a preparatory treatment of drying or moisture reduction necessary. Fermentive changes in organic acids and pH suggest that ensiling of orange peel causes a lactic acid fermentation (Megías et al., 1993), which is not apparent during ensiling of orange pulp (Cervera et al., 1985).

Citrus pulp may be ensiled alone or in combination with high DM cereal crop residues, such as wheat straw and poultry litter (Migwi et al., 2001), to produce silage with a relatively high fermentation quality. Therefore, silage produced by ensiling citrus pulp (in proportions 0, 150, 300, and 450 g/kg DM of silage) with wheat straw and poultry litter was suggested to be safe and of high fermentation quality (Migwi et al., 2001). This silage has a medium to high feeding value for sheep, provided that the level of citrus pulp in the ration is maintained between 150 and 200 g/kg DM to avoid depressed intake that may arise with higher citrus pulp levels. Increasing the level of citrus pulp in the silage resulted in a linear decrease in pH and a linear increase in titratable acidity of the silage after 60 days of fermentation. Silages made from mango fruit, lemon (at inclusion levels up to 200 g/kg), corn stover and molasses, with or without addition of urea, can also be utilized for feeding ruminants, with CP and NDF content with or without addition of urea (20 g/kg), being 214 and 553, and 65 and 644 g/kg, respectively, with an optimum fermentation time of 30 days (Aguilera et al., 1997).

Scerra et al. (1999) found that colonization of bergamot fruit peel with 10 strains of *Penicillium* spp. improved its nutritional value by increasing levels of CP, crude fat and structural carbohydrates *versus* untreated bergamot fruit peel.

5.6.2. Fermentation of citrus by-products in the rumen and in vitro

The nonstructural carbohydrate fraction includes sugars, starches, fructans, galactans, pectins, and β-glucans (Van Soest et al., 1991). Citrus pulp contains both pectin and cellulose, with pectin comprising approximately 450 g/kg of CW (Sunvold et al., 1995). Pectins are degraded very rapidly and extensively in the rumen but, unlike starch, yield little lactate, causing less decline of rumen pH (Strobel and Russell, 1986; Barrios-Urdaneta et al., 2003). Ruminococci and *Bacteroides ruminicola* degrade xylan and pectin and produce no lactate, but *Butyrivibrio fibrisolvens* and *Lachnospira multiparus* can produce lactate from xylan and pectin or pectin, respectively (Strobel and Russell, 1986). In mixed diets, substitution of starchy feeds by others rich in easily fermentable CW, such as citrus pulp, avoids, at least in part, the negative effect on forage digestibility caused by high dietary starch levels (Barrios-Urdaneta et al., 2003).

In non-lactating Angus cows fed TMR that contained ground fescue hay (750 g/kg DM) and a concentrate (250 g/kg DM) consisting of soyhulls, corn grain, corn gluten feed or DCP, microbial OM flow to the abomasum was higher in DCP supplemented TMR *versus* all other treatments (1765 *versus* 1252 g/d), and the efficiency of microbial protein synthesis was also higher *versus* all other treatments (14.8 g *versus* 11.8 g of bacterial N/100 g of OM digested), probably due to the highly, and rapidly, fermented carbohydrate of citrus pulp in the presence of the readily available N in highly soluble soy protein (Highfill et al., 1987). Similarly, Taniguchi et al. (1999) showed in steers that microbial efficiency was higher in the DCP *versus* control treatment (22.4 g *versus* 19.3 g of microbial N/kg of OM digested).

Citrus pulp has a higher potential to produce lactic acid during *in vitro* fermentation than sugar beet pulp, corn grain or sorghum grain (Cullen et al., 1986). Sunvold et al. (1995) evaluated *in vitro* fermentability of citrus pulp and citrus pectin by ruminal microflora from cattle. OM disappearance was 730 and 903 g/kg for citrus pulp, and citrus pectin, respectively, at 48 h of fermentation. Brown and Johnson (1991) also found *in vitro* at 96 h that, for citrus pulp, *in vitro* OM digestibility was 0.872, NDF digestion 0.758, ADF digestion 0.821, and that NDF had a relatively very high digestion rate of $0.114\,h^{-1}$. In Holstein cows fed TMR containing DCP at 236 g/kg DM and corn hominy at 37 g/kg DM, or corn hominy at 253 g/kg DM and DCP at 22 g/kg DM, the *in vitro* OM digestibility of the TMR was slightly higher for the corn hominy diet *versus* the DCP diet (Leiva et al., 2000).

When Durand et al. (1988) used a semi-continuous culture system, adapted from the rumen stimulation technique (RUSITEC; Czerkawski and Breckenridge, 1977), to evaluate microbial digestion of citrus pulp, they found that digestibility coefficient of OM, hemicellulose, and cellulose for citrus pulp was 0.902, 0.780, and 0.787 (DM), respectively. Total VFA production of citrus pulp in semi-continuous culture was 93.7 mmol/d, acetate molar proportion was 0.625, propionate was 0.261, and butyrate was 0.068. Ariza et al. (2001) measured differences in fermentation patterns in continuous culture fermenters between starch and neutral detergent (ND) soluble fibre (NDSF) as components of the ND soluble carbohydrate (NDSC) fraction using hominy feed and DCP as starch and NDSF sources, respectively. Two diets were tested, with the DCP diet containing 236 g/kg DM of DCP and hominy feed at 37 g/kg DM, and the hominy feed diet contained 22 g/kg DM of DCP and hominy feed at 253 g/kg DM. In the DCP *versus* hominy feed diets, the true digestibility coefficients of OM, NDF, ADF, starch, NDSF and NDSC were 0.552 *versus* 0.560, 0.504 *versus* 0.528, 0.681 *versus* 0.675, 0.951 *versus* 0.943, 0.391 *versus* 0.196, and 0.548 *versus* 0.547 (DM), respectively. In addition, total VFA production of DCP *versus* hominy feed diets in continuous culture was 104.2 mmol/d *versus* 101.2 mmol/d, and the acetate molar proportion increased (0.689 *versus* 0.626), propionate decreased (0.167 *versus* 0.227), resulting in an increased acetate/propionate ratio (4.1 *versus* 2.8). Butyrate was not affected, but the branched-chain VFA were lower for the DCP diet (0.030 *versus* 0.037), and NH_3 N concentrations were 93 mg/l *versus* 142 mg/l, and CP degradation was 560 *versus* 619 g/kg. In contrast, total N, nonammonia N, microbial N, and dietary N flows were not affected by treatments, but efficiency of microbial protein synthesis was higher for the DCP diet *versus* the hominy feed diet (30.6 g *versus* 27.8 g of bacterial N/kg of OM truly digested). These results suggest that NDSF from DCP provides similar amounts energy, *versus* starch from hominy feed, relative to its ability to support ruminal microbial growth.

Madrid et al. (1999) compared five *in vitro* techniques to predict OM digestibility of whole dried lemon fruit. The *in vitro* OM digestibility of DCP was 0.838 upon digestion with a rumen fluid-pepsin technique, 0.765 with a pepsin-cellulase enzymatic solubility technique, 0.889 with an NDF/cellulase solubility technique, 0.943 with an amylase/NDF/cellulase solubility technique, and 0.964 with a rumen liquid/NDF digestibility technique. All *in vitro* techniques had a high correlation with *in vivo* OM digestibility of dried lemon in goats. Deaville et al. (1994) determined *in vitro* OM digestibility in DCP using a rumen fluid/pepsin technique and an ND amylase/cellulase technique. The *in vitro* OM digestibility for imported and UK domestic DCP samples was 0.814, and 0.857 (DM), respectively, with the rumen fluid/pepsin technique, and 0.906, and 0.921 (DM), respectively, with the ND amylase/cellulase technique. The digestible energy (DE) and metabolizable energy (ME) of the two DCP samples were 15.2 and 15.8, and 12.6 and 13.2 MJ/kg DM, respectively.

5.7. Nutrient digestibility of citrus by-products

Deaville et al. (1994) determined the nutritive value and chemical composition of DCP for ruminants with four Suffolk cross-bred wethers receiving grass hay and one of two DCP (imported and domestic UK produced) in proportions 260:740 and 240:760 g/kg DM, respectively. The DM intake was 33.3, and 28.7 g/kg body weight $(BW)^{0.73}$/d, respectively. Apparent digestibility coefficient of OM, CP, crude fat, NDF, and gross energy (GE) calculated by difference for the above DCP samples are shown in Table 12. Moreover, Bhattacharya and Harb (1973) calculated the apparent digestibility coefficient of DCP nutrients by difference, when DCP was incorporated, as a replacement for corn grain, at 200, 400, and 600 g/kg in the ration of Awasi lambs (Table 12). Fegeros et al. (1995) studied the nutritive value of DCP with six Karagouniko wethers fed ryegrass hay (800 g/wether/d) and six proportions of DCP (75, 150, 225, 300, 375, and 450 g/wether/d). The apparent digestibility coefficients of the DM, OM, CP and crude fat for DCP are shown in Table 12. The net energy (NE) content of DCP was estimated to be 6.95 MJ of NE_l/kg of DCP DM. Scerra et al. (1994), using four rams fed DOP (916.4 g/kg DM) and soybean meal (SBM; 83.6 g/kg DM) ad libitum, determined the digestibility coefficients of DM, OM, CP, crude fat, NDF, ADF (Table 12), cellulose (0.927) and hemicellulose (0.551).

Table 12
Nutrient and energy digestibility of citrus by-products (BPF) calculated by difference summarized from several sources

Feedstuff	Citrus BPF level	Animal	Digestibility calculated by difference							Reference
			DM	OM	CP	Crude fat	NDF	ADF	Energy	
DCP[a] (g/kg)	200	Yearling lambs	0.724	–	0.699	0.655	–	–	0.743	Bhattacharya and Harb (1973)
	400		0.770	–	0.757	–	–	–	0.733	
	600		0.719	–	0.619	0.831	–	–	0.696	
DCP (g/kg DM)	740	Wethers	0.890	–	0.560	0.850	0.890	–	0.870	Deaville et al. (1994)
	760		0.880	–	0.570	0.370	0.900	–	0.850	
DOP (g/kg DM)	916	Rams	0.876	0.905	0.734	0.654	0.840	0.871	0.945	Scerra et al. (1994)
DCP (g/kg)	300	Wethers	0.786	0.872	0.527	0.820	–	–	–	Fegeros et al. (1995)
Dried lemon (g/kg DM)		Castrated male goats	0.729	0.781	0.453	–	0.665	0.685	0.751	Madrid et al. (1996)
Citrus pulp (g/kg DM)		Wethers	–	0.844	0.505	–	0.710	–	–	O'Mara et al. (1999)
		Steers	–	0.826	0.422	–	0.690	–	–	

[a] ADF, acid detergent fibre; CP, crude protein; DCP, dried citrus pulp; DM, dry matter; DOP, dried orange pulp; NDF, neutral detergent fibre; OM, organic matter.

Madrid et al. (1996, 1997) calculated, by difference, the apparent digestibility of whole dried lemon fruit nutrients and its DE and ME in goats, when it was fed with alfalfa hay in a DM proportion of 50:50. The apparent digestibilities for DM, OM, CP, NDF, and ADF are shown in Table 12, while those for cellulose and hemicellulose were 0.768 and 0.606, respectively, and the estimated DE was 15.1 MJ/kg, and ME was 12.7 MJ/kg, of lemon DM. High digestibility of NDF and cellulose indicates that dried lemon is a good source of rapidly digestible NDF.

O'Mara et al. (1999) compared the *in vivo* digestibility of citrus pulp between sheep and cattle. Four wether sheep, 7–9 months of age, were fed 0.8 kg/d of a diet consisting of citrus pulp (777 g/kg), hay (160 g/kg) and SBM (63 g/kg), and four steers, 1.5 years old, were fed 6.25 kg/d of a diet consisting of citrus pulp (736 g/kg), hay (160 g/kg) and SBM (104 g/kg). The digestibility coefficients of citrus pulp OM, CP and NDF were similar between sheep and cattle (Table 12).

McCullough and Sisk (1972) studied digestibility of concentrates containing DCP at two proportions (150 and 250 g/kg DM) fed with either corn or wheat silage. Concentrates and silages were fed to wethers in proportions of 450 and 550 g/kg DM of the TMR. In the 250 DCP *versus* 150 DCP TMR, pooled between silages, the apparent digestibility coefficient of CP was lower, and the apparent digestibility coefficients of cellulose and crude fat were higher (Table 13). The level of digestible DM (729 g/kg DM) and OM (745 g/kg DM), and NE_l (7.74 MJ/kg DM) were similar among TMR. In another study, Sudweeks (1977b) determined the digestibility of concentrates containing DCP, or corn grain, or soybean mill feed at proportions of 40, 161, and 474 g/kg of ration DM fed to wethers to one of corn silage, sorghum silage or bermudagrass hay. The DM and crude fat digestibility coefficients were similar among concentrates, but DCP- and corn-based concentrates had a higher digestibility of CP *versus* the soybean mill feed concentrate (Table 13).

Martínez-Pascual and Fernández-Carmona (1980b) evaluated the nutritive value of DCP in diets for wethers and fattening lambs. With diets containing 100 g/kg alfalfa hay and 900 g/kg of a concentrate mixture with 0, 150, 300, 450 and 600 g/kg DM DCP, and fed at 46.6 g/kg $BW^{0.75}$/d to wethers in metabolism cages, digestibility of ADF increased but that of DM, crude fat and CP tended to decrease with increasing levels of DCP (Table 13). In another digestibility trial with lambs, digestibility of ADF increased, crude fat decreased, and DM, OM, and CP were unaffected with increasing levels of DCP up to 600 g/kg DM (Table 13; Martínez-Pascual and Fernández-Carmona, 1980b). Bhattacharya and Harb (1973) studied DCP as a replacement for corn grain in Awasi lambs. Corn and DCP were fed to lambs in proportions of 600:0, 400:200, 200:400 and 0:600 g/kg. The DM digestibility was similar among treatments, but CP digestibility was lower at the highest DCP level, while crude fat digestibility was higher and energy digestibility lower for the 400 and 600 g/kg DCP inclusion level (Table 13). The digestible nutrients of DCP, at the 200, 400, and 600 g/kg level of incorporation in the ration, were 771, 844 and 783 g/kg DM, respectively. The GE content was similar among treatments, but DE for the highest DCP level and ME for the 400 and 600 g/kg DCP inclusion level were lower *versus* other treatments. The N intake for the highest DCP level was lower than the control treatment. Fecal N excretion was similar among treatments, but urine N excretion for the highest DCP level was lower than the other treatments, and N retention was similar among treatments (Table 13). Additionally, Ben-Ghedalia et al. (1989) studied effects of a pectin-rich (DCP based) diet on quantitative

Table 13
Nutrient and energy digestibility, and N retention of citrus by-products (BPF) summarized from several sources

Feedstuff	Citrus BPF level	Animal	Nutrient digestibility						Energy digestibility	N retention (g/day)	Reference
			DM	OM	CP	Crude fat	NDF	ADF			
DCP concentrate[a] (g/kg DM)	150[b]	Wethers	–	–	0.722	0.730	–	–	–	–	McCullough and Sisk (1972)
	250[b]		–	–	0.695	0.801	–	–	–	–	
Corn-DCP concentrate (g/kg)	600-0	Yearling	0.813	–	0.773	0.473	–	–	0.813	3.7	Bhattacharya and Harb (1973)
	400-200	Lambs	0.796	–	0.758	0.468	–	–	0.799	3.2	
	200-400		0.792	–	0.768	0.779	–	–	0.781	3.6	
	0-600		0.753	–	0.680	0.688	–	–	0.743	2.6	
Corn silage-DCP TMR (g/kg)	820-0	Steers	0.639	–	0.691	–	–	–	0.624	–	Schaibly and Wing (1974)
	550-270		0.696	–	0.691	–	–	–	0.691	–	
	270-550		0.750	–	0.698	–	–	–	0.751	–	
	0-820		0.737	–	0.624	–	–	–	0.749	–	
Corn-DCP TMR (g/kg)	327-0	Steers	0.655	–	0.605	–	–	–	0.595	–	Wing (1975)
	218-108		0.630	–	0.600	–	–	–	0.619	–	
	110-217		0.645	–	0.573	–	–	–	0.580	–	
	0-327		0.640	–	0.590	–	–	–	0.626	–	
	0-392		0.630	–	0.580	–	–	–	0.595	–	
DCP concentrate	–[c]	Wethers	0.700	–	0.690	0.760	–	–	–	–	Sudweeks (1977b)
DCP concentrate (g/kg DM)	0	Wethers	0.832	0.856	0.858	0.793	–	0.414	–	5.3	Martínez-Pascual and Fernández-Carmona (1980b)
	150		0.817	0.853	0.843	0.833	–	0.600	–	7.3	
	300		0.812	0.846	0.833	0.787	–	0.693	–	6.0	
	450		0.802	0.858	0.826	0.732	–	0.751	–	4.0	
	600		0.787	0.860	0.830	0.726	–	0.763	–	4.3	

DCP concentrate (g/kg DM)	0	Lambs	0.760	0.781	0.728	0.755	–	0.341	–	10.9	Martínez-Pascual and Fernández-Carmona (1980b)
	300		0.752	0.785	0.707	0.739	–	0.621	–	8.3	
	600		0.726	0.766	0.706	0.675	–	0.693	–	7.7	
DCP concentrate (g/kg DM)	0	Lambs	0.800	0.793	0.762	0.786	–	0.390	–	11.0	Martínez-Pascual and Fernández-Carmona (1980b)
	300		0.781	0.802	0.730	0.719	–	0.672	–	9.1	
	600		0.765	0.796	0.726	0.643	–	0.771	–	6.7	
CCMS diet (g/kg DM)	0	Lambs	0.666	0.677	0.543	0.789	–	–	–	2.8	Chen et al. (1981)
	100		0.658	0.665	0.499	0.815	–	–	–	2.8	
	200		0.651	0.661	0.474	0.848	–	–	–	2.1	
CMDS TMR (g/kg DM)	0	Cows	0.644	0.660	0.537	–	–	0.454	–	–	Wing et al. (1988)
	60		0.690	0.704	0.520	–	–	0.435	–	–	
	120		0.624	0.637	0.504	–	–	0.436	–	–	
	180		0.553	0.570	0.494	–	–	0.412	–	–	
Barley-DCP-SBM (g/kg DM)	765-204-0	Rams	–	0.821	0.746	–	0.636	–	–	–	Ben-Ghedalia et al. (1989)
	0-844-125		–	0.818	0.652	–	0.794	–	–	–	
ASH + DCP (g/kg DM)	1000-0	Steers	–	0.585	–	–	0.659	0.619	–	–	Brown and Johnson (1991)
	800-200		–	0.617	–	–	0.625	0.583	–	–	
Barley-DCP TMR (g/kg DM)	477-0	Steers	–	–	0.681	–	0.601	–	–	–	Taniguchi et al. (1999)
	173-300		–	–	0.647	–	0.590	–	–	–	
Corn-DCP (g/kg)	695-0	Kids	0.724	0.742	0.733	0.885	0.539	0.511	–	–	Bueno et al. (2002)
	460-230		0.746	0.763	0.710	0.847	0.597	0.627	–	–	
	220-460		0.740	0.753	0.719	0.784	0.637	0.667	–	–	
	0-665		0.719	0.744	0.703	0.673	0.670	0.700	–	–	

Table 13 (*Continued*)

Feedstuff	Citrus BPF level	Animal	Nutrient digestibility						Energy digestibility	N retention (g/day)	Reference
			DM	OM	CP	Crude fat	NDF	ADF			
Corn-DCP TMR (g/kg DM)	204-96	Cows	0.621	–	0.588	–	0.493	–	–	–	Miron et al. (2002)
	93-207		0.654	–	0.613	–	0.538	–	–	–	
Barley-DOP concentrate (g/kg)	833-0	Ewes	0.682	0.708	–	–	0.647	–	–	–	Barrios-Urdaneta et al. (2003)
	564-268		0.693	0.720	–	–	0.674	–	–	–	
	286-542		0.689	0.722	–	–	0.684	–	–	–	
	0-823		0.693	0.726	–	–	0.693	–	–	–	

[a] ADF, acid detergent fibre; ASH, ammoniated stargrass hay; CCMS, citrus condensed molasses solubles; CMDS, citrus molasses distillers solubles; CP, crude protein; DCP, dried citrus pulp; DM, dry matter; DOP, dried orange pulp; NDF, neutral detergent fibre; OM, organic matter; SBM, soybean meal; TMR, total mixed ration.

[b] Pooled data from two different forages.

[c] Pooled data from three DCP proportions in the concentrate fed with three different forages.

aspects of digestion in sheep in comparison to a starch-rich (barley grain based plus a small proportion of DCP) diet. Four Merino rams received alfalfa hay (0.180 kg DM/ram/d) and one of two concentrates, being DCP based (0.71 kg DM/ram/d) or barley based (0.70 kg DM/ram/d). The DCP concentrate consisted of DCP (844 g/kg DM) and SBM (125 g/kg DM), and the other of barley (765 g/kg DM) and DCP (204 g/kg DM). OM was equally digestible in both diets, but CP was more digestible in the starch-rich diet, and NDF was more digestible in the pectin-rich diet (Table 13). Digestibility coefficients of pectic uronic acid, fructose and glucose residues were high in both diets (Table 14), their digestion being essentially complete in the forestomachs. Ben-Ghedalia et al. (1989) concluded that DCP, even at a high dietary proportion, creates favourable conditions for cellulolysis in the rumen and has a positive effect on N supply to the intestine.

Barrios-Urdaneta et al. (2003) examined effects of supplementation with various proportions of barley grain or DOP on digestion of ammonia-treated straw by sheep. Four dry ewes were fed one of four diets in a 4 × 4 Latin square design. The ewes received ammonia-treated barley straw (0.4 kg/ewe/d) and one of four concentrates at 0.4 kg/ewe/d. Barley grain and DOP were incorporated into the concentrates at proportions of 833:0 g/kg in the first concentrate, 564:268 g/kg in the second, 286:542 g/kg in the third, and 0:823 g/kg in the fourth. Rates of DM and NDF degradation, and DM and OM digestibility coefficients were unchanged as the DOP proportion in the diet increased (Table 13). In contrast, digestibility of NDF increased linearly with the increase in DOP proportion. Urinary excretion of purine derivatives decreased linearly as the proportion of DOP in the diet increased, which is consistent with a decrease in the total concentration of rumen bacteria.

Bueno et al. (2002) evaluated effects of replacing corn grain with DCP on apparent digestibility, N balance and energy level of diets of 16 growing Saanen kid goats in metabolic cages. Kids received chopped grass hay ad libitum and a concentrate mixture restricted to 20 g/kg BW/d with four levels of replacement of corn grain by DCP. The concentrate to forage ratio was 72:28. Ground corn and DCP were incorporated into the concentrates at proportions of 695 and 0 g/kg in the first concentrate, 460 and 230 g/kg in the second, 220 and 460 g/kg in the third, and 0 and 665 g/kg in the fourth. The N balance and apparent digestibility of OM and CP did not differ among diets (Table 13). With increasing levels of DCP, apparent digestibility of DM had a quadratic effect (with a maximum values at intermediate inclusion levels), while apparent digestibility of NDF and ADF increased linearly, and the apparent digestibility of crude fat decreased linearly. With increasing levels of DCP, the apparent digestibility of Ca and P decreased sharply at the high DCP level, suggesting reduced proportional absorption of these minerals, while the apparent digestibility of Mg decreased linearly overall.

Schaibly and Wing (1974) studied effects of forage to concentrate ratio on digestibility of corn silage/DCP TMR. Corn silage and DCP were fed to steers in proportions of 820:0, 550:270, 270:550, and 0:820 g/kg, while SBM was fed at 180 g/kg of DM in all treatments. The DM and energy digestibilities increased for DCP treatments, CP digestibility decreased with the higher DCP treatment (Table 13), and cellulose digestibility was unaffected. Wing (1975) also studied effects of DCP as a replacement for corn grain on nutrient digestibility. Corn and DCP were fed to steers in proportions of 327:0, 218:108, 110:217, 0:327, and 0:392 g/kg TMR. The apparent digestibility coefficients of the DM, CP and energy for rations containing the above DCP proportions are shown in Table 13.

Table 14
Carbohydrate digestibility of citrus by-products (BPF) summarized from several sources

Feedstuff	Citrus BPF level	Animal	Digestibility								Reference
			Glucose	Xylose	Arabinose	Galactose	Mannose	Uronic acids	Fructose	Total carbohydrate	
Barley-DCP-SBM[a] (g/kg DM)	765-204-0	Rams	0.929	0.484	0.813	0.815	0.911	0.966	0.982	–	Ben-Ghedalia et al. (1989)
	0-844-125		0.906	0.719	0.974	0.962	0.963	0.987	0.990	–	
DOP		*In vitro*	0.897	0.688	0.954	0.937	0.890	0.977	–	0.923	Miron et al. (2001)
Corn-DCP TMR (g/kg DM)	204-96	Cows	0.731	0.536	0.761	0.818	0.847	0.775	0.890	0.725	Miron et al. (2002)
	93-207		0.768	0.511	0.830	0.852	0.838	0.839	0.908	0.771	

[a] DCP, dried citrus pulp; DM, dry matter; DOP, dried orange pulp; SBM, soybean meal; TMR, total mixed ration.

Brown and Johnson (1991) evaluated DCP supplementation of ammoniated stargrass hay (ASH) in rations of six Brahman crossbred steers individually fed ASH alone (4.2 kg OM/d) or ASH plus DCP (4.3 kg OM/d) in a proportion 80:20 or ASH plus cane molasses (4.3 kg OM/d) in a proportion 80:20. Supplementation with DCP or molasses improved OM digestibility, but reduced NDF and ADF digestibility coefficients (Table 13). However, OM, NDF, and ADF digestibility coefficients were similar between the diets supplemented with DCP or molasses. Taniguchi et al. (1999) studied the digestion site and extent of carbohydrate fraction digestion in steers fed one of four TMR. The first TMR consisted of Italian ryegrass (400 g/kg DM), rolled barley grain (477 g/kg DM) and SBM (93 g/kg DM), the second TMR of Italian ryegrass (372 g/kg DM), rolled barley (173 g/kg DM), DCP (300 g/kg DM) and SBM (125 g/kg DM), the third TMR of Italian ryegrass (266 g/kg DM), rolled barley (313 g/kg DM), beet pulp (300 g/kg DM) and SBM (91 g/kg DM), and the fourth TMR of Italian ryegrass (135 g/kg DM), rolled barley (502 g/kg DM), soybean hulls (300 g/kg DM), and SBM (33 g/kg DM). In DCP supplemented TMR, total carbohydrate and CP digestibility in the whole tract was lower than in other treatments (0.729 g/kg *versus* 0.770 g/kg DM, and 0.647 *versus* 0.690 (DM), respectively), but the DE intake was similar to the other treatments (*i.e.*, 74.3 MJ/d). The whole tract digestibility of NDF in the DCP treatment was similar to the control treatment (Table 13), but lower than the other two treatments, while non-fibre carbohydrate digestibility in the whole tract was similar to the beet pulp treatment, but lower than the other two treatments, and non-fibre non-starch polysaccharides and starch digestibility in the whole tract were similar to the other treatments.

Highfill et al. (1987) examined effects of energy supplements of varying fibre content on *in vivo* digestibility coefficients of low quality fescue hay using four non-lactating Angus cows fed TMR containing ground fescue hay at 750 g/kg DM and concentrate at 250 g/kg DM. The first concentrate consisted of soyhulls (250 g/kg DM), the second of corn grain (238 g/kg DM) and SBM (12 g/kg DM), the third of corn gluten feed (250 g/kg DM), and the fourth of DCP (218 g/kg DM) and SBM (32 g/kg DM). Apparent DM, NDF and ADF digestibility coefficients for the DCP supplemented TMR (0.554, 0.504 and 0.482, respectively) were similar to the other treatments. Miron et al. (2002) studied effects of non-structural carbohydrate source in TMR using a high starch (corn grain) or high pectin (DCP) diet with 10 lactating Holstein cows that received one of two TMR being either high starch (22.0 kg DM/cow/d), which contained corn grain (204 g/kg DM) and DCP (96 g/kg DM), or high pectin (20.8 kg DM/cow/d), which contained corn grain (93 g/kg DM) and DCP (207 g/kg DM). The DM, CP and total carbohydrate digestibility coefficients were higher with the high pectin TMR (Table 13). Moreover, digestibility coefficients of the NDF monosaccharide components galactose, mannose and uronic acids were higher in the high pectin TMR, and digestibility coefficients of the ND soluble monosaccharide components glucose, arabinose and uronic acids were also higher in the high pectin TMR (Table 14). Similarly, the high pectin TMR had a higher overall digestibility of NDF (0.538 *versus* 0.493 (DM)), and total ND soluble carbohydrate digestibility (0.868 *versus* 0.803 (DM)). In contrast, total NDF monosaccharide digestibility did not differ between TMR (mean = 0.582 (DM)). *In vitro* digestibility of glucose, xylose, arabinose, galactose, mannose, uronic acids, total carbohydrate, and DM of DOP are shown in Table 14 (Miron et al., 2001). The authors concluded that partial replacement of dietary corn by DCP in TMR of high producing dairy cows creates favourable conditions for cellulolysis in the rumen and improves feed efficiency.

The nutritive value of urea-, or urea plus sodium hydroxide-treated, barley straw was enhanced by dried lemon supplementation at four levels and fed to goats at up to 300 g DM/d. The DM and OM digestibility coefficients of the diets, and DE and ME in the diets, increased linearly as the level of dried lemon increased, resulting in increased digestible OM and ME intake (Madrid et al., 1996, 1997, 1998, 1999).

Chen et al. (1981) evaluated CCMS as an energy source for lambs in a balance study where CCMS was added to diets at 0, 100 and 200 g/kg DM to replace corn grain and SBM. The DM and OM digestibility coefficients were similar among treatments, but the high CCMS diet had a lower CP digestibility (but no difference in N retention), and a higher digestibility of crude fat *versus* the control treatment (Table 13). Wing et al. (1988) evaluated CMDS as a dietary energy source in an experiment with four dry Holstein cows in which CMDS was added to the diet in proportions of 0, 60, 120 and 180 g/kg of DM in replacement for corn grain. The DM and OM digestibility coefficients increased with the 60 g/kg DM CMDS level, *versus* the control, but decreased with higher CMDS levels, while CP digestibility decreased linearly with increasing levels of CMDS, and ADF digestibility was not affected (Table 13).

Overall, results suggest similar citrus BPF digestibility among ruminant species. Supplementation of forages with citrus BPF that are rich in pectin or highly degradable NDF usually has a less negative effect on the rumen environment, and thus on cellulolytic activity, than supplementation with starch- or sugar-rich feeds. Citrus BPF contain a variety of energy substrates for ruminal microbes, including soluble carbohydrates and readily digestible NDF. When citrus BPF substituted for starchy feeds, DM and OM digestibility coefficients tend to remain unaffected, while CP digestibility decreases, and NDF and ADF digestibility coefficients increase. Lanza (1984) reported that decreased digestibility of CP in some DCP diets may be due to high temperatures of dehydration (*i.e.*, >140 °C). Citrus BPF improve utilization of dietary fibrous fractions, possibly due to positive effects on rumen microflora. Moreover, when straw is used as the basal feed for ruminants, the diet is improved by offering citrus BPF to correct nutrient deficiencies of the straw and to increase the digestion of its nutrients.

5.8. *Effect of citrus by-products on rumen fermentation characteristics*

Ben-Ghedalia et al. (1989) studied effects of a pectin-rich (844 g DCP/kg DM of the concentrate) diet on rumen fermentation characteristics in rams in comparison to a starch-rich (765 g barley grain/kg DM and 204 g DCP/kg DM of the concentrate) diet. In the pectin-rich *versus* starch-rich diets, rumen pH, ammonia concentration, and total VFA concentration are shown in Table 15. In another study, Barrios-Urdaneta et al. (2003) studied effects of supplementation with various proportions of barley grain or DOP on rumen fermentation of ammonia-treated straw by ewes. Barley grain and DOP, incorporated in the concentrates at levels up to 833 g/kg, resulted in similar rumen pH, rumen ammonia concentration, total VFA concentration, and molar proportions of acetic acid, propionic acid, butyric acid, isovaleric acid and valeric acid among treatments (Table 15). Inclusion of DOP in the diet linearly reduced isobutyric acid concentration. In lambs fed corn and DCP in proportions of 600:0,

Table 15
The effect of citrus by-products (BPF) on fermentation characteristics summarized from several sources

Feedstuff	Citrus BPF level	Animal	pH	VFA (mmol/l)	Molar proportions						NH_3 N (mg/l)	Reference
					Acetic acid	Propionic acid	Butyric acid	*i*-Butyric acid	Valeric acid	*i*-Valeric acid		
Corn-DCP TMR[a] (g/kg)	600-0	Steers	6.84	82.6	0.679	0.197	0.124	–	–	–	925	Pinzon and Wing (1976)
	390-190		6.64	100.4	0.699	0.176	0.124	–	–	–	1065	
	180-380		6.62	107.9	0.703	0.173	0.124	–	–	–	923	
	0-550		6.61	108.9	0.692	0.172	0.135	–	–	–	911	
Corn-DCP TMR (g/kg)	710-0	Steers	–	114.5	0.451	0.362	0.136	–	0.018	0.032	–	Vijchulata et al. (1980)
	85-600		–	94.4	0.583	0.195	0.178	–	0.027	0.016	–	
CCMS diet (g/kg DM)	0	Lambs	–	80.1	0.666	0.183	0.131	–	0.007	0.013	–	Chen et al. (1981)
	100		–	78.3	0.617	0.241	0.128	–	0.012	0.007	–	
	200		–	85.0	0.589	0.262	0.123	–	0.015	0.007	–	
CMDS TMR (g/kg DM)	0	Cows	5.95	–	0.575	0.258	0.167	–	–	–	218	Wing et al. (1988)
	60		5.83	–	0.580	0.259	0.161	–	–	–	208	
	120		6.05	–	0.602	0.227	0.170	–	–	–	181	
	180		6.19	–	0.615	0.191	0.193	–	–	–	192	
Barley-DCP-SBM (g/kg DM)	765-204-0	Rams	6.18	82.4	0.650	0.176	0.143	0.007	0.014	0.012	240	Ben-Ghedalia et al. (1989)
	0-844-125		6.42	74.4	0.691	0.144	0.142	0.005	0.010	0.009	171	
Barley-DCP TMR (g/kg DM)	477-0	Steers	6.40	131.0	0.641	0.137	0.153	0.015	0.015	0.023	135	Taniguchi et al. (1999)
	173-300		6.30	157.0	0.732	0.127	0.121	0.006	0.012	0.006	109	
Corn hominy-DCP TMR (g/kg DM)	22-253	Cows	6.24	106.1	0.674	0.214	0.112	–	–	–	–	Leiva et al. (2000)
	236-37		6.19	116.4	0.677	0.208	0.115	–	–	–	–	
HMEC-DCP TMR (g/kg DM)	384-0	Cows	6.10	103.3	0.627	0.208	0.114	0.013	0.020	0.018	128	Broderick et al. (2002)
	191-191		6.12	107.4	0.637	0.187	0.130	0.012	0.018	0.016	152	
Barley-DOP concentrate (g/kg)	833-0	Ewes	6.20	95.0	0.679	0.157	0.136	0.008	0.011	0.008	112	Barrios-Urdaneta et al. (2003)
	564-268		6.30	95.0	0.685	0.158	0.132	0.007	0.009	0.009	124	
	286-542		6.30	100.0	0.697	0.159	0.122	0.006	0.008	0.007	110	
	0-823		6.30	97.0	0.681	0.166	0.129	0.006	0.010	0.007	97	

[a] CCMS, citrus condensed molasses solubles; CMDS, citrus molasses distillers solubles; DCP, dried citrus pulp; DM, dry matter; DOP, dried orange pulp; HMEC, high-moisture ear corn; SBM, soybean meal; TMR, total mixed ration; VFA, volatile fatty acids.

400:200, 200:400, and 0:600 g/kg, blood glucose (706.5 mg/l), blood VFA (3.25 mequiv./l), and rumen pH (6.65) did not differ among treatments (Bhattacharya and Harb, 1973).

McCullough and Sisk (1972) studied rumen fermentation characteristics of steers fed concentrates containing DCP at 150 and 250 g/kg DM along with either corn or wheat silage. Concentrates and silages were fed to steers in proportions of 450 and 550 g/kg DM of the TMR. Ruminal pH, as well as acetic, propionic and butyric acid molar proportions, and the acetate/propionate ratio, was similar for the 150 DCP and 250 DCP TMR pooled between forages. In contrast, Schaibly and Wing (1974) found that ruminal pH declined with increasing DCP at levels up to 820 g/kg DM, and the acetate/propionate ratio was higher at the higher DCP level. Pinzon and Wing (1976) also studied effects of DCP, as a replacement for corn grain in high urea rations for steers, on ruminal fermentation. Corn and DCP were fed to steers in proportions of 600:0, 390:190, 180:380, and 0:550 g/kg. Increasing DCP reduced rumen pH values to 6.61 (Table 15). Rumen ammonia N was not affected by treatments (mean = 956 mg/l), but blood urea N (BUN) was lower (606 mg/l) for steers fed the 180:380 and 0:550 g/kg proportions *versus* the other groups (673 mg/l), suggesting increased N utilization. Decreased molar proportion of propionate (0.174 *versus* 0.197) in the three DCP treatments resulted in an increased acetate/propionate ratio (4.02 *versus* 3.43). However, when corn grain and DCP were fed to steers in proportions of 327:0, 218:108, 110:217, 0:327 and 0:392 g/kg TMR, VFA molar proportions did not differ among treatments (Wing, 1975). Additionally, Vijchulata et al. (1980) studied effects of DCP, as a replacement for corn grain, on ruminal fermentation of steers using diets with corn and DCP fed in proportions of 710:0 or 85:600 g/kg of the TMR. Ruminal total VFA concentrations were affected by the energy source. On the DCP *versus* corn diets, the molar proportions of acetic, propionic, butyric, isovaleric and valeric acids shown in Table 15 resulted in an increased acetate/propionate ratio (3.15 *versus* 1.36). Moreover, Taniguchi et al. (1999) used the detergent fibre system to study the digestion site, and extent of digestion, of carbohydrate fractions in steers offered BPF based diets. Four Holstein steers were assigned to one of four diets fed as TMR based on barley grain, DCP, beet pulp and soybean hulls, respectively. With the DCP supplemented TMR, rumen pH (6.3) was similar in all treatments (Table 15), rumen ammonia N concentration (109 mg/l) was similar to the control and beet pulp treatments but lower than the soybean hulls treatment (160 mg/l), and total VFA concentration (157 mmol/l) was similar to all other treatments, with acetate (115 mmol/l) higher than the control treatment (84 mmol/l) but similar to the other two BPF treatments, and the ruminal acetate/propionate ratio was 5.75 *versus* 4.67 (control).

Highfill et al. (1987) determined effects of energy supplements with various fibre contents on fermentation characteristics of low quality fescue hay using four non-lactating Angus cows fed a TMR containing ground fescue hay (750 g/kg DM) and concentrate (250 g/kg DM). The first concentrate consisted of soyhulls (250 g/kg DM), the second of corn grain (238 g/kg DM) and SBM (12 g/kg DM), the third of corn gluten feed (250 g/kg DM), and the fourth of DCP (218 g/kg DM) and SBM (32 g/kg DM). Ruminal pH and ammonia N concentrations for DCP supplemented TMR were similar to the other treatments. Leiva et al. (2000) evaluated rumen fermentation characteristics of dairy cattle fed DCP or corn products as sources of ND soluble carbohydrates. Diets were compared within 11 Holstein cows, using reversal experiments with two periods, individually fed TMR containing DCP (236 g/kg DM) and corn hominy (37 g/kg DM) or corn hominy (253 g/kg DM) and DCP

(22 g/kg DM). Ruminal pH values, total VFA concentration in the rumen fluid, and the acetate/propionate ratio were similar between treatments (Table 15).

Broderick et al. (2002) studied the effectiveness of several TMR carbohydrate sources, being high-moisture ear corn (HMEC; 384 g/kg DM), cracked shelled corn (CSC; 387 g/kg DM), and a mixture of HMEC (191 g/kg DM) plus DCP (191 g/kg DM) on rumen fermentation in dairy cows. In the DCP *versus* CSC TMR, the rumen pH was 6.12 *versus* 6.17, while the rumen ammonia N concentration was 152 *versus* 185 mg/l. In DCP *versus* HMEC and CSC TMR, the total VFA concentration was 107.4 mmol/l *versus* 103.3 and 101.5 mmol/l, with a rumen acetate/propionate ratio of 3.42 *versus* 3.03 and 3.25 (Table 15). Blood glucose was also lower with the DCP TMR, but not consistently. There were no differences among TMR in milk urea N (MUN) and BUN. Broderick et al. (2002) concluded that, compared to HMEC and CSC, feeding pectin-rich DCP positively altered ruminal fermentation in dairy cows.

Feeding CCMS to lambs, at levels of 0, 100 and 200 g/kg of DM, to replace corn grain or SBM, decreased ruminal molar proportions of acetic and isovaleric acids, and increased molar proportions of propionic and valeric acids (Table 15), which resulted in a lower acetate/propionate ratio (2.43 *versus* 3.71; Chen et al., 1981). Total VFA production was not treatment affected. Wing et al. (1988) evaluated CMDS as an energy source on ruminal parameters, using four ruminally fistulated dry Holstein cows, where CMDS was added to the diet in proportions of 0, 60, 120 and 180 g/kg of DM in replacement for corn grain. Acetic acid molar proportion increased linearly with increasing level of CMDS, from 0.575 to 0.615, and propionic acid molar proportion decreased linearly from 0.258 to 0.191 (Table 15), resulting in a linear increase in the acetate/propionate ratio (from 2.44 to 3.28). Butyric acid molar proportion increased only at the 180 g/kg DM CMDS level *versus* the control (0.193 *versus* 0.167, respectively). Ruminal pH was lower with the 60 g/kg DM CMDS level (5.83), but higher at the 120 and 180 g/kg DM CMDS level (6.05 and 6.19, respectively), *versus* the control (5.95), and the rumen ammonia N concentration was similar among treatments (200 mg/l), but tended to decrease with increasing CMDS level.

Overall results suggest that citrus BPF, as high pectin energy sources, cause little or no decline of rumen pH, increase the molar proportion of acetic acid and decrease the molar proportion of propionic acid, resulting in an increased acetate/propionate ratio.

5.9. *Effects of citrus by-products on production*

5.9.1. *Effects of citrus by-products on production of growing ruminants*

Martínez-Pascual and Fernández-Carmona (1980b) determined the nutritive value of DCP in diets of fattening lambs. In three growth studies, diets with DCP with up to 600 g/kg DM of a concentrate mixture were fed to 108 lambs. The BW gain, feed conversion ratio (FCR) and dressing proportion were not affected up to 300 g/kg DM of DCP in the diet, but the animal response was poorer with higher DCP feeding levels (Table 16). A high degree of rumen keratosis developed in two lambs fed the diet containing 300 g/kg DM DCP, without hay.

Scerra et al. (2001) studied effects of orange pulp silage on growth and carcass characteristics of lambs. To limit ensiling losses due to the high moisture content of the citrus pulp, it was ensiled with chopped wheat straw in a ratio 80:20 (DM). Twenty lambs received one of

Table 16
The effect of citrus by-products (BPF) on performance of growing ruminants summarized from several sources

Feedstuff	Citrus BPF level	Animal	DM intake (g DM/d)	BW gain (g/d)	Feed conversion (kg DM intake/kg BW gain)	Carcass yield (kg/100 kg of BW)	Reference
Barley-DCP concentrate[a] (g/kg)	820-0	Male calves	6900	1090	6.3	57.9	Hadjipanayiotou and Louka (1976)
	200-600		7000	1070	6.5	56.5	
DCP concentrate (g/kg)	0	Male lambs	999	312	3.2	49.2	Martínez-Pascual and Fernández-Carmona (1980b)
	300		913	272	3.4	48.8	
	600		928	234	3.9	48.8	
DCP concentrate (g/kg)	0	Male lambs	929	259	3.6	55.8	Martínez-Pascual and Fernández-Carmona (1980b)
	150		942	272	3.5	53.3	
	300		955	256	3.6	54.7	
	450		778	127	5.5	53.9	
DCP concentrate (g/kg)	0	Female lambs	824	188	4.5	56.5	Martínez-Pascual and Fernández-Carmona (1980b)
	150		845	199	4.3	56.7	
	300		820	171	4.9	54.3	
	450		821	143	5.7	56.6	
Corn-DCP TMR (g/kg)	710-0	Steers	9130	1170	7.81	58.1	Vijchulata et al. (1980)
	355-400		8280	1060	7.83	57.5	
Corn-DCP TMR (g/kg)	710-0	Steers	10760	1020	10.5	–	Vijchulata et al. (1980)
	85-600		10660	990	10.7	–	

CCMS TMR (g/kg DM)	0	Steers	8760	1180	7.4	61.6	Chen et al. (1981)
	31.5		9330	1080	8.7	60.7	
	63.0		8940	1030	8.7	60.1	
	94.5		9390	1110	8.6	61.2	
CCMS diet (g/kg DM)	0	Lambs	961	142	–	–	Chen et al. (1981)
	100		959	139	–	–	
	200		942	97	–	–	
DOP concentrate (g/kg)	0	Bullocks	6510	1211	5.4	53.2	Lanza (1984)
	250		7200	1120	6.4	55.2	
	500		7180	1098	6.5	54.3	
ASH + DCP (g/kg DM)	1000-0	Cull cows	13400	490	–	48.5	Brown and Johnson (1991)
	800-200		13600	680	–	50.4	
Corn-DCP concentrate (g/kg DM)	650-0	Young bulls	7020	1413	5.0	52.4	Henrique et al. (1998)
	0-650		4490	746	6.0	51.4	
Oat hay or orange pulp-wheat straw silage	Hay	Male lambs	285	261	–	56.7	Scerra et al. (2001)
	Silage		372	256	–	57.1	
Oat hay or orange pulp-wheat straw silage	Hay	Female lambs	271	220	–	57.7	
	Silage		344	188	–	57.1	
DCP concentrate (g/kg)	0	Calves	526	453	–	–	Schalch et al. (2001)
	150		458	424	–	–	
	300		605	489	–	–	
	450		434	437	–	–	
Corn-DCP concentrate (g/kg)	695-0	Kids	–	86	7.5	–	Bueno et al. (2002)
	460-230		–	107	6.8	–	
	220-460		–	94	7.1	–	
	0-665		–	85	7.6	–	

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[a] ASH, ammoniated stargrass hay; BW, body weight; CCMS, citrus condensed molasses solubles; DCP, dried citrus pulp; DM, dry matter; DOP, dried orange pulp; TMR, total mixed ration.

two diets, a diet of oat hay plus concentrate and a diet of citrus pulp silage plus concentrate. The authors concluded that use of citrus pulp silage was economically advantageous to produce lambs with acceptable carcass and meat quality characteristics (Table 16).

Bueno et al. (2002) evaluated effects of replacing corn grain with DCP on performance of 32 Saanen kids (16 males and 16 females) fed chopped grass hay ad libitum and a concentrate mixture restricted to 20 g/kg BW/d, with four levels of replacement of corn grain by DCP, for 2 months. The concentrate to forage ratio was 58:42, and ground corn and DCP were incorporated into the concentrates at the proportions 695 and 0 g/kg in the first concentrate, 460 and 230 g/kg in the second, 220 and 460 g/kg in the third, and 0 and 665 g/kg in the fourth. The BW was not affected by DCP incorporation into the concentrates, but BW gain, and DM intake increased (Table 16), while FCR had a quadratic effect (with a minimum values at intermediate DCP levels). The authors concluded that replacing about 400 g/kg DM of corn grain by DCP resulted in the best performance of growing kids.

Hadjipanayiotou and Louka (1976) studied the nutritional value of DCP as a barley grain replacement in calf fattening diets. Forty-four British Friesian male calves (120 day of age) were fed one of two experimental diets for 48 weeks that contained barley straw (1.0 kg/d) and ad libitum concentrate. The first concentrate consisted of barley grain (820 g/kg) and SBM (150 g/kg), and the second of barley (200 g/kg), DCP (600 g/kg) and SBM (180 g/kg). The BW gain, feed intake, FCR and dressing proportion were similar among diets (Table 16). The authors concluded that replacement of barley grain with DCP had no depressing effect on growth, and that the nutritive value of DCP approached that of barley grain. In addition, Schalch et al. (2001) partially, or totally, replaced ground corn and wheat grain with DCP in the starter concentrate of 28 Holstein calves fed one of four treatments with each having a different level of DCP in the concentrate (*i.e.*, 0, 150, 300 and 450 g/kg). The concentrate was fed ad libitum from the fourth day of life with 4 l of whole milk in the first month and 3 l in the second month. The BW gain, DM intake and FCR were similar among treatments (Table 16). The authors concluded that DCP can successfully substitute for cereals in the starter diet of calves. DCP can also be used in starter diets of calves as a substitute for an NDF rich feed, such as bermuda grass hay, and have similar BW gain, DM intake and FCR (de Castro and Zanetti, 1998).

Vijchulata et al. (1980) studied effects of DCP, as a replacement for corn grain, on performance and carcass characteristics of steers. In two feeding experiments, corn grain and DCP were fed to steers in proportions of 710:0 or 355:400 g/kg in the first experiment, and 710:0 or 85:600 g/kg in the second. In both experiments, BW gain, FCR and dressing proportion were not affected by energy source, but in the first experiment, daily feed intake was 9.3% lower with the diet containing DCP (Table 16). Results suggest that DCP, when properly fed, is a similar energy source to corn grain for cattle. Henrique et al. (1998) also studied effects of replacing corn grain with DCP in diets containing various concentrate levels on performance and carcass characteristics of 28 young bulls assigned to one of four corn silage-based diets with concentrate fed at levels of 200 or 800 kg/tonnes DM in the TMR. In the low concentrate TMR, corn grain or DCP was incorporated at 70 g/kg DM of the concentrate, and in diets with a high concentrate level, corn or DCP was incorporated at 650 g/kg DM. No differences occurred between treatments in BW gain, DM intake or FCR, but performance of bulls fed corn, in the high concentrate treatment, was better from that of bulls fed DCP (Table 16), and *versus* both treatments with the low concentrate level. Performance of bulls fed DCP, in the high concentrate treatment, was lower than that of bulls fed the low concentrate level. Carcass dressing proportion was similar among treatments.

Lanza (1984) reported that half substitution of corn grain by DOP in concentrates fed to Friesian heifers, from age 6 to 18 month, did not negatively effect BW, age at first calving or conception rate. In contrast, inclusion of 250 and 500 g/kg DOP in concentrate diets for bullocks, substituting for corn grain, resulted in lower final BW, by 3.2 and 5.1%, respectively, and BW gain by 7.5 and 9.3%, respectively, and higher daily feed intake, by 10.6 and 10.3%, respectively, FCR, by 19.5 and 21.6%, respectively, and dressing proportion, by 3.9 and 2.1%, respectively (Table 16). Brown and Johnson (1991) evaluated DCP supplementation of ASH in rations of 56 Brahman crossbred cull cows fed ASH alone (13.4 kg DM/d), or ASH (11.4 kg DM/d) plus DCP (2.2 kg DM/d), or ASH (12.1 kg DM/d) plus cane molasses (2.2 kg DM/d). The BW gain and carcass characteristics were better in animals fed DCP or molasses supplemented diets *versus* those fed hay alone (Table 16).

Chen et al. (1981) evaluated CCMS as an energy source for ruminants. In two feeding studies with steers, CCMS was added to the DCP and corn grain based diets in the first study at 0, 70, 140, and 210 g/kg to replace corn or DCP and, in the second, at 0, 25, 50, and 100 g/kg to replace sugarcane molasses. The BW gain, FCR and carcass characteristics did not differ among treatments (Table 16). In another study with lambs, CCMS was added to the diets at 0, 100 and 200 g/kg DM to replace corn grain or SBM, and BW gain was lower for the high CCMS diet, but DM intake was similar among treatments (Table 16).

Overall, results suggest that substitution of corn and wheat grains with citrus BPF results in equal growth of ruminants.

5.9.2. *Effects of citrus by-products on production of lactating ruminants*

Fegeros et al. (1995) studied the nutritive value of DCP, and its effect on milk yield and composition of 26 Karagouniko lactating ewes fed alfalfa hay (700 g/d), wheat straw (300 g/d) and one of two concentrates. The DCP concentrate was DCP (300 g/kg) in partial replacement for corn grain, barley grain, wheat middlings and SBM. The NE_l, DM, CP and crude fat intakes, and milk yield and milk fat, protein and lactose contents were unaffected by diet (Table 17). In contrast, milk fatty acid composition was affected to some degree.

Lanza (1984) reported that partial or total substitution of corn or barley grain by DOP or DLP in the concentrates fed to Friesian dairy cattle had no negative effects on milk production or the fat content or flavour of milk. Moreover, DCP in high NDF concentrates at inclusion levels of 175 and 200 g DCP/kg concentrate for lactating cows resulted in similar production *versus iso*-NE_l substitution of starchy concentrates (Sutton et al., 1987).

Van Horn et al. (1975) studied effects of high corn grain (80 g/kg DCP) and high DCP (431 g/kg DCP) TMR on lactating dairy cow performance and milk composition. Feed intake, milk yield and milk protein content were similar among treatments (Table 17), but BW was higher in cows fed the high corn diet at the end of the 84 day experiment. In high DCP *versus* high corn TMR, milk fat content was 42.2 g/kg *versus* 35.4 g/kg, and milk solids not-fat (SNF) content was 90.3 g/kg *versus* 88.4 g/kg. Wing (1975) also studied DCP as a replacement for corn grain on lactating dairy cow performance and milk composition. Lactating Guernsey cows were fed one of four TMR that differed in DCP physical form (*i.e.*, ground and pellets) and the forage source (*i.e.*, pangola hay and sugarcane bagasse).

Table 17
The effect of citrus by-products (BPF) on performance of lactating ruminants summarized from several sources

Feedstuff	Citrus BPF level	Animal	DM intake (g DM/d)	Milk yield (g/d)	Fat (g/kg)	CP (g/kg)	Lactose (g/kg)	SNF (g/kg)	Reference
DCP TMR[a] (g/kg)	80	Cows	18700	18200	35.4	34.8	–	88.4	Van Horn et al. (1975)
	431		18700	17900	42.2	34.6	–	90.3	
CMDS + corn silage TMR (g/kg DM)	0	Cows	23300	20200	33.5	29.6	–	–	Wing et al. (1988)
	30		22300	19600	32.1	29.0	–	–	
	60		27000	21900	32.4	28.1	–	–	
	90		26500	21600	34.0	28.6	–	–	
DCP concentrate (g/kg)	0	Ewes	1413	824	70.4	53.6	46.8	–	Fegeros et al. (1995)
	300		1441	784	72.7	53.2	46.4	–	
DCP TMR (g/kg DM)	0	Cows	18600	23100	41.2	32.2	50.5	89.7	Belibasakis and Tsirgogianni (1996)
	200		18700	23600	44.8	32.5	50.3	89.8	
Corn-DCP TMR (g/kg DM)	204-96	Cows	22000	38300	33.3	28.7	46.0	–	Solomon et al. (2000)
	93-207		20800	38200	33.0	28.2	46.6	–	
Corn hominy-DCP TMR (g/kg DM)	22-253	Cows	21400	32800	34.3	28.3	–	–	Leiva et al. (2000)
	236-37		20900	31300	35.4	27.1	–	–	
Cornmeal-DCP TMR (g/kg DM)	195-96	Cows	–	31800	32.7	30.8	–	–	Leiva et al. (2000)
	92-205		–	27900	34.5	31.3	–	–	
HMEC-DCP TMR (g/kg DM)	384-0	Cows	20000	34500	34.6	29.2	47.9	84.7	Broderick et al. (2002)
	191-191		19200	29900	34.0	28.4	46.1	81.4	
Orange silage TMR (g/kg DM)	0	Ewes	1620	769	65.7	44.9	54.4	108.0	Volanis et al. (2004)
	309		1620	680	78.4	43.7	58.3	111.0	

[a] CMDS, citrus molasses distillers solubles; CP, crude protein; DCP, dried citrus pulp; DM, dry matter; HMEC, high-moisture ear corn; SNF, solids not-fat; TMR, total mixed ration.

DCP, regardless of physical form, was 350 g/kg of the TMR. No differences due to physical form of the DCP occurred on milk yield, or milk fat, protein or SNF contents.

Belibasakis and Tsirgogianni (1996) evaluated effects of dietary inclusion of DCP on performance and blood serum metabolites and electrolytes with 20 cows fed to one of two TMR, containing either DCP at 200 g/kg DM and concentrate at 300 g/kg DM, or dried beet pulp 150 g/kg DM, ground corn grain 80 g/kg DM and concentrate 270 g/kg DM, plus corn silage at 500 g/kg DM. The TMR had similar concentrations of CP, NDF, ADF and ME. The DM, ME and CP intakes, as well as milk yield, milk protein content and yield, milk lactose, total solids and SNF contents were not diet affected (Table 17). In contrast, DCP supplementation increased milk fat content (44.8 g/kg *versus* 41.2 g/kg) and milk fat yield (1.06 kg/d *versus* 0.95 kg/d). There were no differences in blood serum concentrations of glucose, total protein, albumin, globulin, urea, triglycerides, phospholipids, Na, K, Ca, P, Mg and Cl. Additionally, serum concentrations of cholesterol were higher (2350 mg/l *versus* 2230 mg/l) when cows were fed the diet containing DCP. Solomon et al. (2000) also studied effects of the TMR non-structural carbohydrate source, being high starch (corn grain) or high pectin (DCP), on lactating dairy cow performance and milk composition. Ten lactating Holstein cows were fed one of two TMR, a high starch TMR (22.0 kg DM/cow/d), which contained corn grain (204 g/kg DM) and DCP (96 g/kg DM), and a high pectin TMR (20.8 kg DM/cow/d), which contained corn grain (93 g/kg DM) and DCP (207 g/kg DM). Milk yield and fat content was not affected by non-structural carbohydrate source (Table 17), but milk fatty acid profile was affected. In contrast, milk protein content was higher in the high starch TMR. Leiva et al. (2000) evaluated the performance of dairy cattle fed DCP or corn products as sources of NDSC. In experiment 1, 11 Holstein cows were individually fed TMR containing DCP (236 g/kg DM) and corn hominy (37 g/kg DM) or corn hominy (253 g/kg DM) and DCP (22 g/kg DM). DM, CP and NDF intakes, as well as milk yield, milk fat content and yield, and milk protein yield were not affected by diet (Table 17). In contrast, NDSF and sugar intakes were higher with the DCP diet, and starch intake and milk protein content were higher with the corn hominy diet. In experiment 2, 184 cows fed as two groups received TMR containing DCP (205 g/kg DM) and ground corn grain (92 g/kg DM) or ground corn (195 g/kg DM) and DCP (96 g/kg DM). Milk yield, milk fat and protein yield were lower, while milk fat content and MUN were higher with the DCP diet (Table 17). The higher MUN with a lower yield of milk and protein on DCP diet in experiment 2, combined with a reduced conversion of feed N to milk N in experiment 1, suggest less efficient use of dietary protein for milk production with diets containing more NDSF. Broderick et al. (2002) studied the effectiveness of TMR carbohydrate sources, being HMEC (384 g/kg DM), CSC (387 g/kg DM) and a mixture of HMEC (191 g/kg DM) plus DCP (191 g/kg DM) on lactating dairy cow performance and milk composition. DM intake and yields of milk, fat, protein, lactose, and SNF were lower with diets containing DCP *versus* HMEC and CSC (Table 17). Broderick et al. (2002) concluded that, compared to HMEC and CSC, feeding the pectin-rich DCP carbohydrate source lowered feed intake and milk production in lactating cows.

Wing et al. (1988) evaluated CMDS as an energy source on lactational performance in an experiment with 32 lactating Holstein cows. The CMDS was added to corn silage or cottonseed hull diets in proportions of 0, 30, 60 and 90 g/kg of DM to replace corn grain. Milk yield and DM intake tended to increase with increasing level of CMDS (Table 17), but no differences occurred in milk composition or BW change. The authors concluded that CMDS, at up to 60 g/kg DM of the TMR, was nutritionally superior to corn grain.

Volanis et al. (2004) evaluated effects of feeding ensiled sliced oranges to lactating dairy sheep. Ninety-six lactating ewes of the Sfakian dairy sheep breed, divided into two equal groups, were used. Three kilograms (79.5%) of sliced orange silage mixture were offered daily to the animals in replacement for part of the maize grain/soybean meal/oat hay ration fed to the control group. Milk yield was 12% higher for controls and ewes fed orange silage had a 16% higher fat content in milk (Table 17).

Overall, results suggest that substitution of corn grain, as well as several other high starch feeds with citrus BPF results in equal milk yield and composition in lactating ruminants.

5.10. *Citrus toxicosis*

When high levels of DCP were fed, along with low level of dietary forage, rumen parakeratosis occured in lambs. Loggins et al. (1968) reported that 18 of 20 growing lambs fed a diet of 240 g/kg cottonseed meal and 745 g/kg DCP had moderate to severe parakeratosis and, with addition of 100 g/kg chopped bermudagrass hay, only 14 of 20 growing lambs had moderate rumen parakeratosis with none considered to be severe.

The pruritis pyrexia haemorrhagic syndrome affected 8 of 175 commercial cows fed 3–4 kg DCP/cow/d (Griffiths and Done, 1991). The presence of visible moulds, high fungal counts and detection of citrinin confirmed the poor quality of this feed, as citrinin, a mycotoxin, was identified in the DCP at between 30 and 40 ppb (DM). Six cows died of the syndrome and five calves were born with superior prognathism at birth from cows that were 2 to 3 months in calf at the time of the outbreak. When DCP was withdrawn from the ration, the syndrome resolved (Griffiths and Done, 1991).

The death of 13 lactating cows, in a commercial herd of 650, was attributed to citrus pulp consumption (60 kg/tonnes of TMR) due to type IV hypersensitivity, which was resolved by eliminating citrus pulp from the diet (Saunders et al., 2000).

6. Conclusions

The nutrient content of citrus BPF is influenced by several factors including source of fruit and type of processing. Citrus BPF are important components of ruminant feeding systems in many areas of the world, and are commonly used as sources of dietary energy. The main citrus BPF fed to ruminants are fresh citrus pulp, citrus silage, dried citrus pulp, citrus meal and fines, citrus molasses, citrus peel liquor, and citrus activated sludge. Other minor BPF include cull or excess fruit. Citrus silage and pulp are generally very rapidly accepted by most classes of ruminants.

Citrus BPF have similar digestibility among ruminant species. Supplementation of forages with citrus BPF that are rich in pectin or highly degradable NDF usually has a less negative effect on the rumen ecosystem, and thus on cellulolysis, than supplementation with starch- or sugar-rich feeds. Citrus BPF contain a variety of energy substrates for ruminal microbes, including both soluble carbohydrates and rapidly digested NDF. When citrus BPF substituted for starchy feeds, DM and OM digestibility coefficients tend to remain unaffected, CP digestibility decreases, and NDF and ADF digestibility coefficients increase. Citrus BPF improve the utilization of other dietary NDF, possibly due to positive effects on rumen microflora. Moreover, when straw is used as the basal feed for ruminants, their diet is improved by feeding citrus BPF to correct nutrient deficiencies of the straw and to increase digestibility of its nutrients.

Citrus pulp contains both pectin and cellulose, with pectin comprising approximately 450 g/kg of CW. Pectins are degraded very rapidly and extensively in the rumen but, unlike starch, yield little lactate, causing less decline in rumen pH. Citrus BPF, as high pectin energy sources, when included in diets for ruminants, tends to increase the molar proportion of acetic acid and decrease the molar proportion of propionic acid, resulting in an increased acetate/propionate ratio. In mixed diets, substitution of starchy feeds by citrus pulp rich in rapidly fermentable CW avoids, at least in part, the negative effect on forage digestibility caused by high dietary starch levels.

Citrus BPF can be used as a high energy feed in rations that support growth and lactation in ruminants. However, when very high levels of DCP are fed, rumen parakeratosis may occur, particularly when the level of dietary forage is low, while poor preservation of citrus BPF can lead to development of mycotoxins that may have detrimental effects on ruminants.

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