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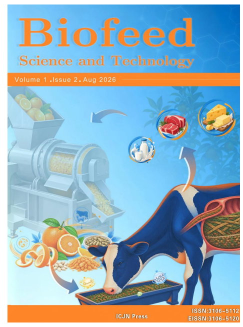

REVIEW

Citrus Processing By-Products and Their Phytochemicals in Ruminant Nutrition: From Rumen Modulation to Animal Performance, Product Quality, and Environmental Sustainability

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Abstract

Citrus processing generates substantial quantities of peel, pulp, membranes, seeds, and extraction residues that present both a waste-management challenge and a potential resource for ruminant production. These by-products are characterized by a fermentable nutritional matrix rich in pectin and soluble sugars, together with diverse phytochemicals, including flavanone glycosides, polymethoxylated flavones, essential oils, phenolic acids, carotenoids, and limonoids. This review critically examines how interactions between these nutrients and phytochemicals affect rumen fermentation, microbial ecology, animal performance, metabolic health, product quality, and environmental sustainability. Citrus pulp can partially replace cereal-based concentrates and provide rapidly fermentable energy with relatively low lactate production. However, responses depend on inclusion level, basal diet, processing method, by-product composition, animal species, and production potential. Citrus flavonoids and essential oils may modulate rumen microorganisms, methanogenesis, nitrogen metabolism, oxidative balance, and inflammatory regulation, although evidence from high-dose *in vitro* studies cannot be directly extrapolated to whole by-products or commercial production. Citrus-derived interventions may also modify milk and meat fatty-acid profiles, antioxidant capacity, oxidative stability, sensory properties, and shelf life, but results remain heterogeneous. From a circular bioeconomy perspective, feeding citrus residues can divert organic material from disposal and reduce reliance on human-edible feeds. Nevertheless, drying, extraction, transportation, reduced animal productivity, and alternative residue uses may offset these benefits. Overall, citrus by-products should be considered integrated nutrient-phytochemical matrices rather than uniform feed ingredients. Standardized chemical characterization, long-term dose-response studies, mechanistic multi-omics research, and combined life-cycle and techno-economic assessments are required to support their safe, effective, and environmentally credible use in ruminant production systems.

Keywords

Citrus phytochemicals; Rumen microbiome; Animal performance; Milk and meat quality; Environmental sustainability; Circular bioeconomy

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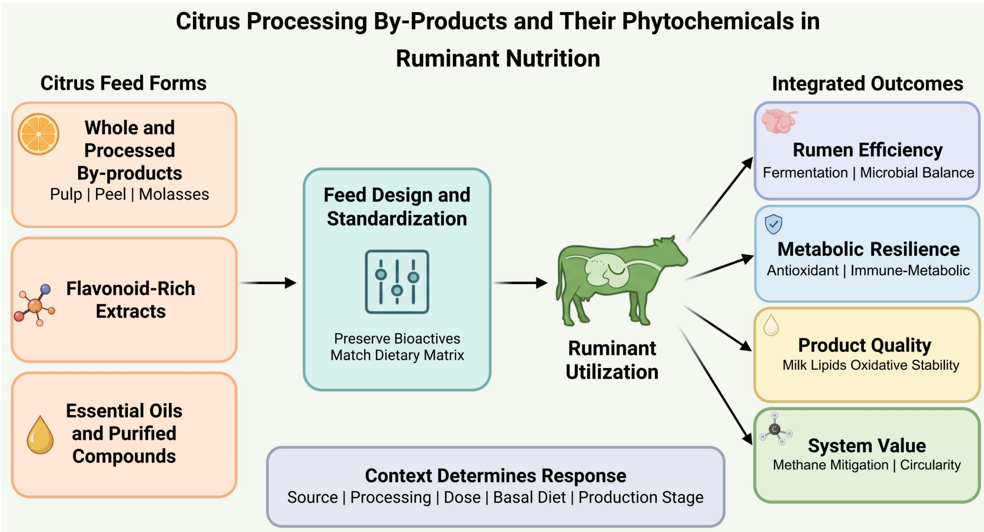
Graphical Abstract



Highlights

- Citrus by-products provide fermentable nutrients and diverse bioactive phytochemicals.
- Processing methods reshape nutrient availability, phytochemical stability, and feed value.
- Citrus-based feeds modulate rumen fermentation, microbial ecology, and host metabolism.
- Dietary inclusion can enhance product quality and support methane emission mitigation.
- Standardized processing, dose-response, safety, and life-cycle studies remain priorities.

1. Introduction

Ruminant production must contribute to food and nutrition security while reducing competition for human-edible feeds and greenhouse-gas emissions. Within circular food systems, ruminants can convert low-opportunity-cost biomass into milk and meat, thereby recovering nutrients that would otherwise be lost[1,2]. This role aligns with the european union farm to fork strategy and circular economy agenda, as well as Chinese legislation and planning that promote the utilization of crop residues and agricultural-processing by-products[3-5].

Global citrus production exceeds 160 million tonnes annually, and industrial processing commonly leaves 40%–60% of the fruit mass as peel, pulp, segment membranes, seeds, and residual soluble solids[6,7]. These wet, seasonal materials deteriorate rapidly and may generate odor, leachate, high organic loading, and greenhouse-gas emissions if they are not stabilized. Their conversion into feed is therefore relevant to both waste management and resource-efficient livestock production[7,8].

Fresh, ensiled, dried, and pelleted citrus pulp provides soluble sugars and rapidly fermentable pectin but little starch. It can partially replace cereal concentrates while posing less risk of ruminal lactate accumulation than highly fermentable starch[9]. However, feeding value varies with citrus species, anatomical fraction, essential-oil or pectin recovery, preservation, and drying. Meta-analyses indicate a dose-dependent response: inclusion up to 10% of dietary dry matter can support milk production, whereas greater substitution may reduce intake and milk yield, particularly in high-producing cows[10,11]. A recent trial in tropical dairy cows similarly showed that replacing 60% of corn meal reduced digestibility, microbial nitrogen capture, and milk production[12].

Citrus by-products are also phytochemical matrices containing flavanone glycosides, polymethoxylated flavones, D-limonene-rich essential oils, phenolic acids, carotenoids, and limonoids[13]. Concentrated citrus flavonoids have altered the rumen microbiome and metabolome and improved lactational responses[14], while flavanone combinations inhibited methanogenesis and ammoniagenesis *in vitro*[15]. Orange essential oil reduced methane emissions by 12% at 0.50% of dietary dry matter in heifers[16]. By contrast, complete replacement of corn with dried citrus pulp increased methane from 24.70 g/d to 34.80 g/d in goats[17]. These opposing outcomes show why whole by-products and purified phytochemicals cannot be treated as equivalent interventions.

Previous reviews have described citrus composition, feed value, or waste valorization, but they have rarely integrated processing-dependent phytochemical changes with rumen microbial mechanisms, host signaling, product quality, safety, and whole-chain environmental trade-offs. This review addresses that gap by treating citrus by-products as interacting nutrient-phytochemical matrices. It critically compares whole materials with extracts, evaluates dose and processing as sources of heterogeneity, and identifies evidence needed for safe and environmentally credible application in cattle, sheep, and goats.

2. Generation, Classification, and Processing of Citrus By-Products

2.1. Industrial Origins and Classification

Industrial processing of oranges, mandarins, lemons, limes, grapefruits, and pomelos into juices, concentrates, essential oils, pectin, and other products generates heterogeneous residual streams that may account for approximately 50%–60% of the original fruit mass[18-20]. Once collected and managed as feed resources, these materials are more appropriately termed by-products rather than waste. Anatomically, they comprise the flavedo, albedo, segment membranes, juice vesicles, pulp residues, and seeds, whereas industrial classification additionally includes citrus molasses, peel liquor, meal and fines, essential-oil extraction residues, pectin-depleted residues, and rejected or culled fruits[9,13]. Wet citrus pulp, the predominant feed stream, is therefore not equivalent to fruit pulp alone but is a variable mixture of peel, internal tissues, seeds, and residual juice. Its composition depends on citrus species and cultivar, maturity, tissue proportions, juice-extraction efficiency, and subsequent recovery of essential oils or pectin[19,21]. A biologically meaningful classification should consequently specify the botanical source, anatomical fraction, processing history, and physical form rather than using the generic term "citrus pulp". As summarized in the **Figure. 1**, citrus processing generates peel, pulp, membranes, seeds, culled fruits, molasses, and extraction residues, which can be used fresh or stabilized through drying, pelleting, ensiling, or fermentation before their conversion by ruminants into milk and meat. This pathway can simultaneously substitute conventional feed resources, avoid waste disposal, and facilitate the recycling of manure nutrients to citrus production.

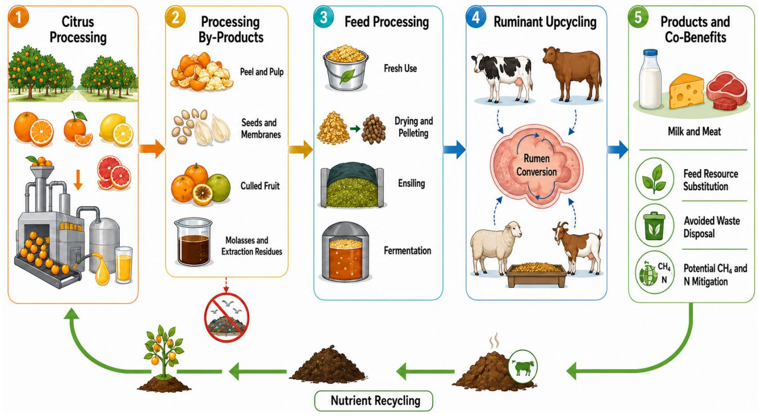


Figure. 1 Generation, processing, and circular utilization pathways of citrus processing by-products in ruminant production systems. Citrus processing generates peel and pulp, seeds and membranes, culled fruits, molasses, and extraction residues. These materials can be used fresh or stabilized through drying and pelleting, ensiling, or fermentation before being incorporated into cattle, sheep, and goat diets. Rumen microorganisms convert their fermentable nutrients into milk and meat, while replacing part of conventional feed resources and diverting organic residues from disposal. Depending on by-product composition, processing method, dietary inclusion level, and basal diet, citrus-derived feeds and phytochemicals may also contribute to mitigating methane and nitrogen losses. Manure nutrients can be returned to citrus orchards, closing nutrient cycles and linking citrus processing with ruminant production within a circular bioeconomy. Solid arrows represent material flows, whereas dashed arrows indicate biological conversion within the ruminant system. **NOTE:** CH_4: methane; N: nitrogen. Copyright: Created with BioRender.

2.2. Processing and Preservation for Feed Use

Fresh citrus pulp and culled fruits can be fed close to processing plants, avoiding dehydration energy, but their high moisture and sugar contents increase transport cost and spoilage risk[9,22]. Commercial dried citrus pulp is commonly produced by liming, pressing, thermal drying, grinding, molasses reincorporation, and pelleting. Drying improves storage and handling but changes the matrix according to time-temperature exposure. Hot-air, vacuum, and freeze-drying cause different losses of phenolics, flavonoids, pigments, and antioxidant capacity[23]. More severe heating promotes sugar-amino reactions and formation of Maillard-derived brown polymers; these reactions can reduce the availability of reducing sugars and reactive amino groups while increasing apparent antioxidant activity through melanoidin formation[24]. Heating and aeration also accelerate the loss or oxidation of D-limonene and other volatiles. Therefore, drying temperature, residence time, lime addition, and molasses reincorporation should be reported rather than treating all dried citrus pulp as one ingredient.

2.3. Processing-Dependent Modification of Phytochemicals

Processing determines both shelf life and phytochemical exposure. Mechanical separation changes the proportions of flavonoid-rich peel, pectin-rich albedo, oil-rich flavedo, and limonoid-containing seeds, whereas cold pressing or hydrodistillation selectively removes volatile terpenes. Sequential fractionation can recover essential oils, flavonoids, and pectin from one processing stream, leaving a residue unlike untreated pulp[21]. Industrial pectin extraction may nevertheless leave measurable hesperidin, naringin, and diosmin, while polymethoxylated flavones are generally more abundant in less-depleted residues[25]. These changes affect palatability, antimicrobial pressure, fermentable substrate supply, and the release kinetics of phytochemicals in the rumen.

Biological upgrading is enzyme-specific and organism-specific. *Aspergillus niger (A. niger)* produces pectinases, cellulases, xylanases, α-L-rhamnosidase, and β-glucosidase; these enzymes can depolymerize cell walls and hydrolyze rutinoside or neohesperidoside moieties, increasing aglycones such as hesperetin and naringenin[26,27]. Mixed solid-state fermentation with *Trichoderma reesei* and *A. niger* released pectin-bound or fiber-bound ferulic and p-coumaric acids, and the release was associated with cellulase, xylanase, and β-glucosidase activities and disruption of the insoluble fiber structure[28]. Enzymatic saccharification can increase soluble carbohydrate availability, whereas microbial growth may consume sugars, enrich microbial protein, or introduce mycotoxin and process-contamination risks. Thus, future feed studies should identify the microbial strain or enzyme preparation, activity units, inoculum, moisture, pH, temperature, duration, aeration, and post-treatment stabilization, and should test whether the processed residue — not only the recovered extract — improves rumen function and animal performance.

Representative sources, processing methods, and nutrient composition are summarized in **Table 1**. Because process-derived differences in phytochemical concentration are analytically important, major compound classes and their measurement methods are summarized separately in **Table 2**.

Table 1. Sources, processing methods, and representative nutritional composition of citrus processing by-products used in ruminant diets

By-Product / Botanical Source	Anatomical Source and Generation	Processing and Feed Form	Representative Nutritional Composition	Key References
Fresh or Wet Mixed Citrus Pulp	Mixed residues after juice extraction: peel (flavedo and albedo), rag/segment membranes, residual pulp, and variable seeds; often dominated by sweet orange	Screw-pressing or decanting; direct fresh feeding near processing plants; short-term chilled storage where feasible	DM 13%–23%; CP 5.80%–7.50%; EE 1.90%–4%; NDF ~20%–24%; ADF ~13%–17%. Rich in rapidly fermentable sugars and soluble fibre; low starch and P, but relatively high Ca	[6,29,30]
Ensiled Citrus Pulp or Peel	Wet pulp or peel alone, or co-ensiled with dry roughages/concentrates to absorb effluent and improve fermentation	Chopping/mixing, compaction and anaerobic ensiling; sometimes pressed before ensiling or combined with straw, hay, beet pulp, or cereal residues	DM commonly 15%–25%; CP 7%–11%; NDF 20%–30%; ADF 15%–22%; composition depends strongly on co-ensiled material; Soluble sugars support lactic fermentation; silage preserves much of the pectin-rich matrix.	[9,11,31]
Dried Citrus Pulp (DCP; Mixed Citrus)	Pressed juice residues, frequently with lime added during dewatering; the commercial product may contain peel, pulp, membranes, and seeds	Pressing, optional $Ca(OH)_2$ addition, thermal drying, grinding and pelleting	DM ~89.70%; OM 93.70%; CP 6.90%; EE 2.30%; NDF 22%; ADF 19.70%; lignin 2.10%; sugars 24.10%; soluble fibre 32.90%; pectin 22.30%; starch 2.30%; Ca 1.60%, P 0.11%	[9-11]
Orange Peel and Pulp (Citrus Sinensis)	Peel, albedo, rag and pulp remaining after sweet-orange juice or concentrate production	Fresh feeding, pressing, drying/pelleting, ensiling; peel may also undergo EO or pectin extraction before the residual solids are used	Fresh peel: DM 23.30%, CP 5.80%, NDF 20%, ADF 12.90%. Fresh pulp: DM 19.20%, CP 6.40%, EE 4%, ADF 15%; Dried orange pulp: DM 90.20%, CP 7.20%, EE 3%, NDF 19.30%, ADF 16.90%	[9,29,31,32]
Lemon Peel and Pulp (Citrus Limon)	Peel, membranes and pressed pulp after lemon juice, concentrate, or EO manufacture	Fresh feeding, pressing, drying, ensiling; cold pressing or distillation may first remove EO; acid/enzymatic processing may remove pectin	Fresh pulp: DM 18.10%, CP 7.20%, EE 4%, ADF 16.80%. Fresh whole peel: DM 20.20%, CP 6.60%, EE 1.60%, NDF 33%, sugars 19.10%; Dried whole lemon: DM 92%, CP 8.10%, EE 3.90%, NDF 36.50%, ADF 25.70%	[9,13,32,33]
Grapefruit Peel and Pulp (Citrus × Paradisi)	Peel, rag and residual pulp from grapefruit juice processing	Fresh or pressed feeding, drying/pelleting, ensiling; EO/flavonoid extraction may precede feed use	Fresh pulp: DM 19.70%; OM 96.20%; CP 7.10%; EE 6.30%; ADF 16.80%; lignin 1.90%. Fibre and fat values vary with peel and seed inclusion.	[9,13,31,32]
Mandarin/Tangerine Peel and Pulp (Citrus Reticulata and Hybrids)	Peel, membranes and residual pulp after juice, segment, or canned-fruit manufacture	Fresh feeding, pressing, drying, ensiling; solvent or hydrothermal extraction may recover flavonoids before use of solids	Fresh pulp: DM 19.70%; OM 96%; CP 8%; EE 6.10%; ADF 17.40%; lignin 2.10%. Peel proportion governs fibre, EO, and pigment content	[9,13,31,32]
Bergamot Peel and Pulp (Citrus Bergamia)	Peel and juice residues from bergamot EO and juice processing	Fresh or dried feeding; pressing/centrifugation and EO recovery are common; polyphenol extraction yields a more depleted solid residue	Fresh peel: DM 16.30%; OM 95.70%; EE 1.30%; NDF 10.10%; ADF 7.30%; lignin 2.70%. Values are highly process-specific because EO and juice streams are often separated	[9,13,32]

Table 1. Sources, processing methods, and representative nutritional composition of citrus processing by-products used in ruminant diets (continued)

By-Product / Botanical Source	Anatomical Source and Generation	Processing and Feed Form	Representative Nutritional Composition	Key References
Citrus Molasses and Condensed/Distillers Solubles	Soluble stream produced by evaporating press liquor; distillers solubles arise after fermentation and alcohol recovery	Clarification and vacuum evaporation; may be liquid-fed, blended into complete feeds, or sprayed onto DCP before pelleting	Citrus molasses: DM ~68%, CP 8.20%, EE 0.30%; predominantly soluble carbohydrate. Condensed molasses solubles: DM ~45%, CP 10.60%, EE 0.20%, Ca 2.48%, P 0.18%. Distillers solubles: DM ~52%, CP 7.30%; residual sugars ~4.30%	[9,31,34]
Citrus Seed Meal or Press Cake	Seeds separated from juice residues; nutrient-dense fraction distinct from pectin-rich peel/pulp	Cleaning and drying, mechanical cold pressing or solvent oil extraction, grinding; sometimes included within commercial DCP rather than marketed separately	Mechanical-extracted seed meal: DM 88%; OM 93.20%; CP 35.40%; EE 11.60%; Ca 1.25%, P 0.75%. Residual lipid and protein vary with de-oiling efficiency and seed species.	[9,13,31]
Citrus Essential Oil (Functional Feed Additive)	Volatile flavedo oil from peel oil sacs; composition differs among orange, lemon, grapefruit, mandarin and bergamot	Cold pressing, hydrodistillation or steam distillation; filtration/fractionation; supplied neat, adsorbed, emulsified, or microencapsulated	Not a conventional nutrient ingredient; inclusion is normally expressed as mg/kg diet or g/animal/day; The carrier and encapsulation matrix, rather than EO itself, determines proximate composition.	[16,32,33]
Citrus Flavonoid-Rich Extract (Functional Feed Additive)	Concentrated peel or whole-by-product phytochemical fraction; may be standardized to total flavonoids or selected marker compounds	Water/ethanol or other solvent extraction; enzyme-, ultrasound-, microwave-, or pressurized-liquid assistance; filtration, concentration, drying and optional encapsulation	Not compositionally equivalent to bulk citrus pulp. Nutrient contribution is generally negligible at additive doses; extract yield, carrier content, and purity must be reported for dose	[13-15,31]

NOTE: 1. DM is expressed as a percentage of the as-fed material; all other proximate, fibre, carbohydrate and mineral values are percentages of DM unless otherwise stated. Values are representative literature means, ranges or individual-source values and should not be treated as commercial specifications; **2.** Composition varies with citrus species and cultivar, anatomical fractions retained, fruit maturity, seed inclusion, juice-extraction efficiency, lime addition, drying temperature, ensiling conditions, prior recovery of essential oil or pectin, storage, and analytical method. Batch-specific laboratory analysis is therefore required before ration formulation; **3.** Pectin and other neutral-detergent-soluble fibre fractions are not quantitatively recovered by conventional NDF analysis; pectin values should not be interpreted as an additive fraction of NDF. The relatively high Ca and low P of many pulp products should also be considered when balancing minerals; **4.** Essential oils and flavonoid-rich extracts are functional additives, not bulk feed ingredients. Their dose should be reported together with marker-compound concentration, extraction/standardization procedure, carrier or encapsulation system, and analytical method; values for extracts are not directly comparable with those for intact peel or pulp; **5.** Abbreviations: ADF: acid detergent fibre; Ca: calcium; CP: crude protein; DM: dry matter; DCP: dried citrus pulp; EE: ether extract; EO: essential oil; NDF: neutral detergent fibre; OM: organic matter; P: phosphorus.

3. Nutritional Matrix and Phytochemical Profile

3.1. The Fermentable Carbohydrate-Fiber Matrix

Citrus processing by-products differ from cereal grains because their carbohydrate matrix is dominated by pectin, soluble sugars, and digestible fiber rather than starch. Representative citrus pulp contains approximately 20%–40% pectin, 15%–25% soluble sugars, about 9% cellulose, and 10% hemicellulose on a dry-matter basis[9,11,35]. Acid-detergent lignin is generally low: commercial dried citrus pulp and fresh grapefruit or mandarin pulp contain about 1.90%–2.10% of dry matter, although peel-rich bergamot residues can approach 2.70%[9,36]. This low-lignin, pectin-rich matrix explains why dried citrus pulp is positioned between conventional concentrates and fibrous by-products. Crude protein and ether extract are usually 6%–8% and 2%–3% of dry matter, respectively, and starch is commonly near 2% unless cereal material is introduced during processing[9-11]. Citrus pulp therefore supplies energy rather than protein and requires complementary rumen-degradable and metabolizable protein.

Mineral composition is also process- and tissue-dependent. Commercial dried citrus pulp typically contains 1%–2% calcium and approximately 0.10% phosphorus on a dry-matter basis; a representative product contained 1.60% Ca and 0.11% P, whereas condensed citrus-molasses solubles contained 2.48% Ca and 0.18% P[9,36]. Potassium is commonly close to 1% of dry matter, but cultivar-level measurements show broad variation in Ca, K, Mg, Na, Fe, Zn, and Mn between pulp and peel[37,38]. Lime added during pressing can further increase Ca and widen the dietary Ca:P ratio. Citrus molasses is enriched in soluble sugars and minerals; peel and albedo contain more pectin and structural fiber, and seeds contain more lipid and protein. Batch-specific mineral analysis is therefore necessary when citrus ingredients are used at high inclusion rates.

3.2. Diversity and Tissue Distribution of Citrus Phytochemicals

Citrus by-products contain flavonoids, phenolic acids, terpenes, limonoids, carotenoids, and vitamins that distinguish them from conventional energy feeds[13,31,39]. **Table 2** summarizes the tissue distribution, representative concentrations, chemical characteristics, and analytical methods of the major phytochemical classes; **Figure. 2** provides a complementary visual overview. Flavanone glycosides are usually the predominant phenolics. Hesperidin and narirutin are abundant in sweet-orange and mandarin residues, whereas naringin and neohesperidin characterize grapefruit and bitter-orange materials. Lemon and lime by-products contain eriocitrin together with hesperidin and hydroxycinnamic acids[40,41]. Their aglycones — hesperetin, naringenin, and eriodictyol — generally occur at lower concentrations but can increase after enzymatic or microbial hydrolysis. Peel, especially the flavedo, also contains nobiletin, tangeretin, sinensetin, and other polymethoxylated flavones that are uncommon in conventional feeds[42,43].

Table 2. Major phytochemicals in citrus processing by-products: sources, representative characteristics, and analytical methods

Phytochemical Class	Principal Compounds	Major Matrix / Tissue	Representative Content or Characteristic	Common Analytical Methods	Key References
Flavanone Glycosides	Hesperidin, narirutin, naringin, eriocitrin, neohesperidin	Peel, albedo, membranes, extraction residues	Usually the dominant phenolics; reported dry-extract values include hesperidin 41.30–43 mg/g, naringin 52 mg/g, and eriocitrin 27.70 mg/g	HPLC-DAD; UHPLC-MS/MS; LC-HRMS	[13,31,40-42]
Polymethoxylated Flavones	Nobiletin, tangeretin, sinensetin	Flavedo and peel-rich residues	Lipophilic and peel-selective; reported dry-extract values include nobiletin 16.90 mg/g and tangeretin 3.87 mg/g	HPLC-DAD; LC-MS/MS	[42,43]
Essential-Oil Terpenes	D-limonene, γ-terpinene, β-pinene, myrcene, citral, linalool	Flavedo oil glands; residual peel oil	D-limonene commonly represents 68%–98% of sweet-orange oil, 45%–76% of lemon oil, and 32%–45% of bergamot oil	GC-MS; GC-FID; headspace GC	[21,32,33]
Phenolic Acids	Ferulic, p-coumaric, caffeic, sinapic, chlorogenic acids	Free and cell-wall/pectin-bound fractions of peel and residues	Both soluble and bound forms occur; conventional solvent extraction underestimates the bound pool	HPLC-DAD; LC-MS/MS after free, esterified, and bound-fraction extraction	[28,34,41,44]
Carotenoids	β-Cryptoxanthin, β-carotene, lutein, zeaxanthin, violaxanthin	Pigmented flavedo and pulp	Strongly cultivar- and tissue-dependent; sensitive to oxygen, light, and thermal processing	HPLC-DAD; LC-MS; spectrophotometry for screening only	[31,39,40]
Limonoids	Limonin, nomilin, and glucosides	Seeds, membranes, peel	Nonvolatile oxygenated triterpenoids; may contribute bitterness	LC-MS/MS; HPLC-DAD	[13,31,39]

NOTE: 1. Concentrations are representative values from individual extracts and must not be interpreted as specifications for intact peel, pulp, or commercial feed. Expression basis, solvent, extraction yield, cultivar, tissue, maturity, and processing should be reported; **2.** Compound-specific chromatography is preferred to colorimetric total-phenolic or total-flavonoid assays. DAD: diode-array detection; FID: flame-ionization detection; GC: gas chromatography; HPLC: high-performance liquid chromatography; HRMS: high-resolution mass spectrometry; LC: liquid chromatography; MS: mass spectrometry; UHPLC: ultra-high-performance liquid chromatography.

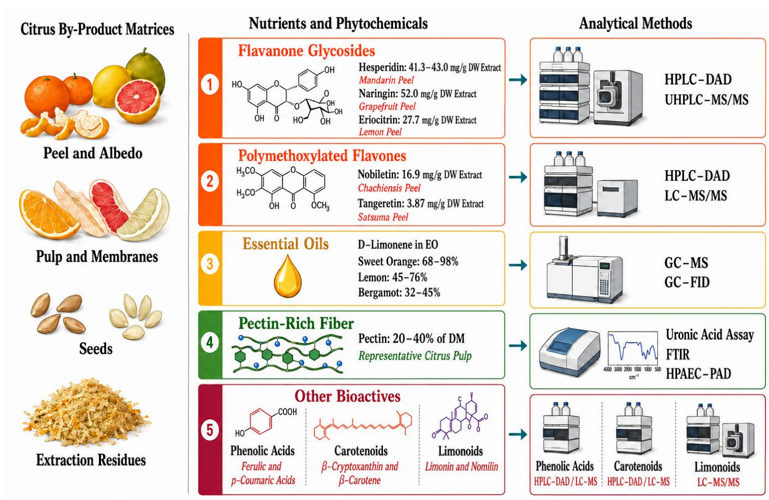


Figure. 2 Major nutrient and phytochemical classes in citrus processing by-product matrices and their corresponding analytical methods. Peel, albedo, pulp, membranes, seeds, and extraction residues contain variable proportions of flavanone glycosides, polymethoxylated flavones, essential oils, pectin-rich fiber, phenolic acids, carotenoids, and limonoids. Representative quantitative values are provided for selected compounds, including hesperidin, naringin, eriocitrin, nobiletin, tangeretin, D-limonene, and pectin. Flavonoids, phenolic acids, carotenoids, and limonoids are commonly separated and quantified using liquid chromatographic techniques coupled with diode-array or mass-spectrometric detection; essential-oil constituents are analyzed by gas chromatography; and pectin is characterized using uronic acid assays, spectroscopic analysis, or monosaccharide profiling. Reported concentrations are illustrative and should not be compared directly across matrices because they vary with citrus species, cultivar, tissue, maturity, processing, extraction procedure, expression basis, and analytical method. Chemical structures are schematic. **NOTE:** DM: dry matter; DW: dry weight; EO: essential oil; FTIR: Fourier-transform infrared spectroscopy; GC–FID: gas chromatography-flame ionization detection; GC–MS: gas chromatography-mass spectrometry; HPAEC–PAD: high-performance anion-exchange chromatography with pulsed amperometric detection; HPLC–DAD: high-performance liquid chromatography with diode-array detection; LC–MS/MS: liquid chromatography-tandem mass spectrometry; UHPLC–MS/MS: ultra-high-performance liquid chromatography-andem mass spectrometry. Copyright: Created with BioRender.

Phenolic acids include caffeic, ferulic, p-coumaric, sinapic, and chlorogenic acids, occurring in both soluble and cell-wall-associated forms. Analyses of orange juice by-product powder showed that conventional solvent extraction does not recover the entire phenolic pool because a relevant fraction remains bound to the insoluble matrix; these bound compounds may also contribute disproportionately to antioxidant capacity[44]. The volatile fraction is dominated by monoterpenes, particularly D-limonene, accompanied by β-pinene, γ-terpinene, myrcene, linalool, and citral. Their relative abundance is highly species-dependent and tissue-dependent and is lower when essential oils have already been recovered industrially[21,39]. Limonoids, principally limonin and nomilin, are nonvolatile oxygenated triterpenoids concentrated in seeds, membranes, and peel tissues; although biologically active, they can contribute to bitterness and reduced palatability.

Citrus carotenoids include β-carotene, α-carotene, lutein, zeaxanthin, β-cryptoxanthin, violaxanthin, and citrus-specific apocarotenoids. Their profiles differ among yellow-pigmented, orange-pigmented, and red-pigmented cultivars and between flavedo and internal pulp[39,40]. Ascorbic acid and tocopherols provide additional antioxidant potential, although their concentrations are more sensitive than those of many flavonoid glycosides to oxygen, heat, and prolonged storage[19].

3.3. Matrix Interactions, Compositional Variability, and Analytical Standardization

The biological value of citrus by-products cannot be predicted solely from the concentration of individual phytochemicals. Pectin, cellulose, hemicellulose, and residual proteins can entrap or bind phenolic compounds, thereby regulating their solubility, ruminal release, microbial transformation, and post-ruminal availability. The coexistence of free and bound phenolics also means that assays based only on aqueous or hydroalcoholic extraction may underestimate the total phytochemical pool[37]. Conversely, mechanical disruption, drying, ensiling, fermentation, or pectin extraction may release bound compounds or convert flavonoid glycosides into more accessible derivatives. Notably, substantial amounts of hesperidin, naringin, and diosmin may remain in pectin-extracted orange residues, whereas polymethoxylated flavones tend to be better preserved in less extensively processed materials[27]. Thus, whole citrus pulp, deoiled peel, pectin-depleted residues, flavonoid-rich extracts, and purified compounds should not be considered biologically equivalent.

Compositional variation arises from genotype, cultivar, maturity, climate, anatomical fraction, processing sequence, drying temperature, fermentation, and storage. Feed characterization should therefore extend beyond proximate composition to include pectin, soluble sugars, starch, fiber fractions, major flavanone glycosides, polymethoxylated flavones, total free and bound phenolics, D-limonene, limonoids, and representative carotenoids. Because citrus peels may also retain agricultural contaminants, pesticide residues, heavy metals, mycotoxins, and microbial quality should be monitored when these materials are intended for repeated or high-level feeding[33]. Such multidimensional standardization is essential for linking the chemical identity of a citrus by-product to its effects on rumen fermentation, animal metabolism, and product quality.

4. Nutrient-Phytochemical Interactions in Rumen Fermentation and the Rumen Microbiome

4.1. Fermentable Carbohydrate Matrix and Ruminal Nutrient Partitioning

The effects of citrus processing by-products on rumen fermentation arise from their distinctive combination of rapidly fermentable carbohydrates and secondary metabolites. Citrus pulp contains abundant pectin and soluble sugars but relatively little starch and lignin. Consequently, replacing cereal grains with citrus pulp shifts carbohydrate fermentation from amylolytic toward pectinolytic pathways. Unlike starch, pectin is rapidly fermented without necessarily promoting substantial lactate accumulation, thereby supporting a comparatively stable ruminal pH when sufficient physically effective fiber is supplied[6]. Pectinolytic microorganisms degrade galacturonic acid-rich polymers into intermediates that are predominantly converted to acetate and, to a lesser extent, butyrate. This explains why citrus pulp generally exhibits a more lipogenic fermentation profile than cereal grain.

Early dairy-cow studies showed that citrus pulp could replace corn-derived neutral detergent-soluble carbohydrates while ruminal pH and total-tract fiber digestion remained unchanged[45]. Similarly, complete replacement of extruded maize constituting 20% of a dairy-sheep diet with dried citrus pulp increased diet degradability in rumen simulation fermenters while producing only limited changes in bacterial diversity and microbial growth[46]. However, the fermentation response is dependent on the extent of substitution. A recent meta-analysis found that citrus-pulp inclusion increased the molar proportions of acetate and butyrate by 0.64 mol/100 mol and 1.09 mol/100 mol total volatile fatty acids, respectively, while decreasing propionate by 1.18 mol/100 mol; increasing inclusion was also associated with reduced dry matter intake and milk yield, particularly in high-producing cows[11]. Consistently, replacing 60% of dietary corn meal with citrus pulp under tropical conditions reduced nutrient intake, apparent digestibility and milk production, although feed efficiency was maintained[12]. Thus, citrus pulp should not be considered nutritionally equivalent to starch: moderate inclusion can supply fermentable energy while maintaining rumen conditions, whereas extensive substitution may restrict glucogenic propionate supply or reduce dietary energy density.

These responses also demonstrate why the nutrient and phytochemical fractions cannot be evaluated independently. The pectin-sugar matrix determines microbial growth and fermentation rate, whereas flavonoids, essential oils and phenolic acids influence which microbial groups utilize these substrates. Conversely, adsorption of phytochemicals to the fiber matrix, their release during fermentation and the residence time of the by-product in the rumen determine the effective exposure of microorganisms to these compounds.

4.2. Microbial Biotransformation and Community Modulation by Citrus Phytochemicals

Hesperidin, naringin, and eriocitrin occur mainly as glycosides and are poorly absorbed in their native forms. Microbial α-L-rhamnosidase first removes terminal rhamnose, and β-glucosidase then cleaves glucose, yielding hesperetin, naringenin, and eriodictyol; ring fission and dehydroxylation subsequently generate smaller phenolic acids. The appearance of hesperetin, naringenin, and hippuric acid in rumen fluid after citrus-flavonoid supplementation confirms that the rumen microbiome controls the chemical exposure presented to the host[14]. This biotransformation also releases linked sugars for fermentation. The microbiome is therefore both a target and a metabolic gatekeeper: membrane-active aglycones or terpenes may inhibit susceptible organisms, while pectinolytic or phenolic-transforming taxa can gain substrate or detoxification advantages.

In lactating dairy cows, supplementation with 50–150 g/d of citrus flavonoid extract increased total ruminal volatile fatty acids, acetate, propionate, butyrate and microbial crude protein without altering ruminal pH[11]. At 150 g/d, the extract enriched cellulolytic genera, including *Ruminococcus, Clostridium and Butyrivibrio*, together with carbohydrate-active functions, while reducing *Prevotella brevis, Methanobacterium and Methanosarcina.* The ruminal concentrations of hesperetin, naringenin and hippuric acid also increased, linking microbial flavonoid metabolism with changes in fermentation. Nevertheless, this experiment involved only eight cows in a Latin-square design and used a concentrated extract; extrapolation to heterogeneous whole citrus by-products therefore requires caution.

Citrus flavonoids may be particularly useful in high-concentrate diets, in which rapid starch fermentation and lipopolysaccharide release challenge the rumen epithelium. Supplementation with Citrus *aurantium* flavonoids improved concentrate-use efficiency and reduced macroscopic indicators of ruminal inflammation in Holstein bulls[40]. Subsequent work suggested that these effects were accompanied by changes in epithelial genes related to barrier integrity and inflammatory signaling[41]. In dairy cows, citrus flavonoid extract also reduced ruminal lipopolysaccharide concentrations, supporting a link between microbial remodeling and epithelial protection[11].

Evidence obtained with whole peel further supports a matrix-dependent response. Feeding processed or unprocessed orange peel at 11% of the diet for 84 days stabilized *Prevotella* populations and attenuated the increase in *Proteobacteria* observed in control dairy ewes; processed peel reduced *Methanobacteria* abundance by 19.30%[42]. Importantly, methanogens were detected differently by full-length bacterial and prokaryotic primers, emphasizing that apparent microbiome responses may depend on primer selection and sequencing strategy.

Essential oils, particularly D-limonene, provide an additional antimicrobial component. Their hydrophobicity enables interaction with microbial membranes, potentially disrupting ion gradients and enzyme activity. However, the response is strongly dose-dependent. Orange essential oil containing 78.84% D-limonene reduced daily methane production by 12% at 0.50% of dietary dry matter in beef heifers, but also decreased dry matter digestibility; 0.25% produced no significant *in vivo* methane reduction[13]. Volatilization, adsorption to feed particles and microbial adaptation may therefore explain discrepancies between strong batch-culture effects and more modest animal responses.

Current omics evidence supports plausible networks but not yet causal mechanisms. Most ruminant studies combine 16S rRNA relative abundance with untargeted metabolomics in small Latin-square or short feeding experiments[14,47-49]. Relative-abundance shifts can reflect changes in another taxon; functional genes are often inferred rather than measured, and bacterial primers incompletely capture archaea, protozoa, fungi, and phages. Stronger designs should combine absolute microbial quantification, shotgun metagenomics and metatranscriptomics, targeted enzyme assays, and isotope-labeled hesperidin, naringin, or limonene to connect microbial transformation with metabolite flux. Parallel rumen-epithelial transcriptomics, *ex vivo* barrier assays, and temporal sampling before and after adaptation would distinguish direct phytochemical signaling from secondary responses to volatile fatty acids or lower endotoxin exposure.

4.3. Integrated Effects on Methanogenesis, Nitrogen Metabolism and Biohydrogenation

Cross-study comparison reveals that methane responses depend on whether the intervention is a fermentable matrix or a concentrated antimicrobial. Complete replacement of corn with dried citrus pulp increased methane from 24.70 g/d to 34.80 g/d in dairy goats, consistent with more acetate-producing fermentation and hydrogen availability[17]. By contrast, orange essential oil at 0.50% of dietary dry matter reduced methane from 139.60 g/d to 122.70 g/d (12%) in heifers, but apparent dry-matter digestibility declined from 653 g/kg to 613 g/kg[16]. *in vitro* combinations of naringin and hesperidin suppressed methane and ammonia more strongly than either compound alone and reduced *Methanobrevibacter, Isotricha, and Entodinium*[15]. These comparisons indicate that a lower methane value is beneficial only when digestibility, volatile-fatty-acid supply, microbial protein, and animal output are maintained.

Effects on nitrogen utilization are similarly context-dependent. Citrus flavonoids can suppress protozoal proteolysis and ammoniagenesis, while fermentable pectin and sugars provide energy for microbial protein synthesis. Nevertheless, citrus pulp is protein-poor, and its benefits depend on synchronization with rumen-degradable nitrogen. Finally, flavonoids and essential oils may alter Butyrivibrio and other organisms involved in lipid biohydrogenation. Diets combining dried citrus pulp with soybean oil changed milk C_{18} fatty-acid profiles without impairing fermentation or production[50], but direct microbial evidence remains limited. Overall, citrus by-products function as integrated nutrient-phytochemical matrices whose effects depend on inclusion rate, processing, basal-diet composition and phytochemical release, rather than as uniform antimicrobial feed additives.

5. Animal Performance, Metabolic Health, and Biological Resilience

Citrus processing by-products influence animal performance through two overlapping pathways. Whole materials, particularly dried or ensiled pulp, substitute pectin and sugars for cereal starch at percentage-level inclusion, whereas standardized extracts and purified flavonoids act at gram- or milligram-level doses through ruminal, intestinal, and systemic signaling. Responses to whole pulp are therefore governed mainly by substitution rate and diet formulation; responses to extracts additionally depend on marker-compound concentration, bioavailability, and physiological state. **Table 3** compares controlled studies and quantitative syntheses while separating whole by-products from flavonoid-rich extracts, purified compounds, and essential oils.

Table 3. Effects of citrus processing by-products and their phytochemicals on rumen fermentation, nutrient utilization, animal performance, and metabolic health

Citrus Material/ Active Fraction	Animal or Experimental Model	Dietary Treatment / Dose	Rumen Fermentation and Microbiota	Nutrient Intake and Utilization	Animal Performance	Metabolic Health / Resilience	Ref.
A. Evidence Syntheses							
Citrus Pulp (CP; Mainly Dried or Pelleted)	Meta-analysis of lactating dairy-cow studies; dose-stratified database	0%, > 0%–10%, > 10%–20%, and > 20% of diet DM; CP generally replaced cereal grain	Descriptive evidence: ruminal pH mostly NS; NH_3-N often ↓; acetate and butyrate commonly ↑ and propionate/branched-chain VFA ↓ as starch was displaced by pectin + sugars	Digestibility was not pooled; dietary starch ↓ and pectin + sugars ↑; DMI was maintained at ≤ 10% CP but tended to decline above 10%	≤ 10% CP: milk, fat and protein yields ↑; > 10%: DMI and milk yield ↓, but higher milk fat maintained energy-corrected milk output	NR; the authors highlighted the lack of systemic and mechanistic measurements	[7]

Table 3. Effects of citrus processing by-products and their phytochemicals on rumen fermentation, nutrient utilization, animal performance, and metabolic health (continued)

Citrus Material/ Active Fraction	Animal or Experimental Model	Dietary Treatment / Dose	Rumen Fermentation and Microbiota	Nutrient Intake and Utilization	Animal Performance	Metabolic Health / Resilience	Ref.
A. Evidence Syntheses							
Citrus Pulp	Meta-analysis/meta-regression of dairy-cow trials	Study-specific inclusion; inclusion level and diet composition evaluated as moderators	Acetate + 0.64 mol/100 mol and butyrate + 1.09 mol/100 mol total VFA; propionate -1.18 mol/100 mol	DM apparent total-tract digestibility: NS; DMI -0.62 kg/d; negative intake response intensified with higher inclusion and production level	Milk yield -0.71 kg/d; milk protein -0.08 g/100 g and lactose -0.09 g/100 g; adverse effects were greater in high-yielding cows	NR; outcomes indicate a dose- and context-dependent energetic trade-off rather than a uniform response	[8]
B. Whole and Processed Citrus By-Products							
Citrus Pulp as Principal Energy Source	18 high-producing lactating dairy cows; 2 × 21-d crossover; tropical system	Isocaloric, isonitrogenous rations with corn meal (control) or CP as the main energy source	NR in the principal outcome set	DMI 19.90 kg/d → 19.50 kg/d; digestible OM 12.30 kg/d → 11.70 kg/d; Apparent digestibility of DM, OM, CP, NDF and ADF ↓; microbial N supply/capture also ↓	Milk yield 23.70 kg/d → 22.70 kg/d; milk/DMI NS	No demonstrated metabolic-health advantage; reduced nutrient and N utilization cautions against extensive replacement in high-producing cows	[9]
Ensiled Citrus Pulp	32 mid-lactation Holstein cows; 28-d feeding study	3 kg DM/d ensiled CP replacing 3 kg DM/d alfalfa cubes	Rumen pH NS; enteric CH_4 production and CH_4 yield NS	DMI and total-tract digestibility were not central reported endpoints	Milk yield 26.20 kg/d vs 27.40 kg/d control (NS); milk composition, fat yield and protein yield NS vs control	NR; no CH_4-mitigation benefit was detected under this forage-replacement design	[51]
Dried Citrus Pulp (DCP)	12 mid-lactation Murciano-Granadina goats; incomplete crossover; metabolism cages + indirect calorimetry	Complete replacement of a diet containing 605 g corn grain/kg DM with DCP (soybean-hull diet as an additional comparator)	CH_4: 34.80 g/d for DCP/soybean-hull diets vs 24.70 g/d for corn; direct VFA outcomes not emphasized	DMI NS (~1.53 kg/d); total replacement with fibrous by-products ↑ fibre digestibility; metabolizable-energy intake for DCP was intermediate	Milk yield NS (~1.72 kg/d); DCP generally intermediate for milk fat and energy output	All treatments had negative energy balance; DCP did not improve CH_4 or energy partitioning relative to corn	[14]
Dehydrated Orange Pulp (DOP)	Payoya dairy goats followed throughout lactation; companion metabolism trial	0%, 40% or 80% replacement of cereal in the concentrate with DOP	No evidence of adverse rumen-function responses in the companion nutrient-utilization assessment; detailed microbiome data NR	DMI, apparent nutrient utilization and N balance were broadly maintained across diets	Milk yield and major components were maintained; DOP80 improved margin over feed cost by approximately EUR 3.27 (approximately USD 3.81) /goat	Haematological and biochemical indicators remained within physiological ranges; no detrimental metabolic response	[52]
Dried Citrus Pulp ± Soybean Oil	10 mid-lactation Holstein cows; 5 × 5 changeover Latin square; 28-d periods	0 g DCP/kg, 86.50 g DCP/kg or 173 g DCP/kg diet DM; with or without 17.30 g soybean oil/kg DM	NR	DMI and digestibility of DM, OM, CP, NDF and ADF: NS; ether-extract digestibility was greatest with oil + 86.50 g DCP/kg DM	Milk production NS; DCP increased milk total phenolics, and DCP + oil shifted milk fat toward more unsaturated FA	Blood metabolites were not adversely altered; functional-product effects occurred without a production penalty	[44]

Table 3. Effects of citrus processing by-products and their phytochemicals on rumen fermentation, nutrient utilization, animal performance, and metabolic health (continued)

Citrus Material/ Active Fraction	Animal or Experimental Model	Dietary Treatment / Dose	Rumen Fermentation and Microbiota	Nutrient Intake and Utilization	Animal Performance	Metabolic Health / Resilience	Ref.
B. Whole and Processed Citrus By-Products							
Dried Citrus Pulp	Santa Inês sheep; factorial comparison with wet brewer grain	DCP totally replaced corn in the concentrate; wet brewer grain tested independently	DCP vs corn: ruminal pH, VFA pattern and acetate: propionate ratio NS	DCP vs corn: intake and apparent digestibility NS; Depressions reported with wet brewer grain should not be attributed to DCP	Final BW, ADG and feed efficiency: NS for DCP vs corn	NR	[53]
Sun-Dried Citrus Pulp	40 male Lohi lambs; randomized block; 120 d	10%, 20% , 30% or 40% DCP in concentrate; diets contained 30% forage and 70% concentrate	NR	Nutrient intake, apparent digestibility and N balance: NS across inclusion levels	ADG and feed conversion: NS; feed cost declined and economic efficiency improved as DCP increased	NR	[54]
C. Citrus Flavonoids and Flavonoid-Rich Extracts							
Citrus Flavonoid Extract (CFE)	8 multiparous lactating dairy cows; replicated 4 × 4 Latin square; 25-d periods	0 g CFE/d, 50 g CFE/d, 100 g CFE/d or 150 g CFE/d	Total VFA 93.97 mmol/L → 103.79 mmol/L (linear ↑); acetate, propionate, butyrate and microbial CP ↑; ruminal LPS ↓; pH and NH_3-N NS; cellulolytic taxa enriched and methanogens reduced at 150 g/d	DMI NS; direct total-tract digestibility NR	Milk yield 31.90 kg/d → 34.37 kg/d at 100 g/d; energy-corrected milk greatest at 100 g/d; milk lactose ↑ and SCC ↓	Antioxidant capacity improved; rumen-derived hesperetin/naringenin and host metabolic pathways were altered	[11]
Citrus Peel Extract (Hesperidin-Rich)	30 transition Holstein cows (15/treatment); -21 d to + 21 d relative to calving	4 g CPE/d by intragastric administration; hesperidin > 50% with neohesperidin, synephrine and diosmin	Total VFA, acetate, propionate and butyrate ↑; Prevotella, Butyrivibrio, Bacteroidales_RF16 and Methanobrevibacter enriched	Digestibility NR; ruminal energy-supply signals improved	Milk yield, milk protein and lactose ↑ during early lactation	Glucose ↑; NEFA, BHBA, serum amyloid A and haptoglobin ↓; hepatic lipid accumulation and adipose inflammation ↓; insulin sensitivity/gluconeogenesis improved	[55]
Citrus Flavonoid Extract	8 mid-lactation Holstein cows on a high-starch diet; replicated Latin-square experiment	0 g CFE/d, 50 g CFE/d, 100 g CFE/d or 150 g CFE/d; mechanistic comparison emphasized 0 g/d vs 150 g/d	Hindgut rather than rumen focus: fecal total VFA, acetate and butyrate ↑; Bifidobacterium, Faecalibacterium and Bacteroides enriched; bacterial endotoxin-related taxa suppressed	Direct total-tract digestibility NR	Milk yield/lactose ↑ and SCC ↓ in the shared dose-response experiment	Fecal and serum LPS and pro-inflammatory cytokines ↓; sphingolipid/ceramide metabolism shifted toward improved immunometabolic homeostasis	[49]
Bitter-Orange Bioflavonoids	20 lactating Mediterranean buffaloes under hot weather; 35-d randomized trial	20 g extract/d (~0.10% DMI); 22.28% total flavonoids (naringin 7.38%, hesperidin 5.62%, neohesperidin 3.05%, nobiletin 1.26%)	pH, NH_3-N and individual/total VFA NS; microbial CP 12.25 mg/dL → 14.36 mg/dL; α-diversity tended to ↑; Lachnospiraceae taxa enriched and Segatella ↓	ADF apparent digestibility ↑; DMI and most other digestibility coefficients NS	Milk yield, 4% FCM, milk protein, lactose and solids-not-fat ↑	Respiration rate and TNF-α/IL-1β/IL-6 ↓; catalase, IgM and HSP70 ↑, indicating greater heat-stress resilience	[56]
Citrus Aurantium Flavonoid Extract (Bioflavex)	Holstein bulls fed high-concentrate diets; commercial feedlot conditions	0.04% of diet DM (approximately 400 mg/kg DM)	Improved pH stability, rumination/eating behaviour and rumen-wall health; expression of inflammatory genes including TLR4-related pathways ↓	Concentrate required per unit of gain ↓; full digestibility data NR	ADG/final BW broadly maintained while concentrate efficiency improved	Local rumen inflammation ↓; systemic metabolic biomarkers were not a principal endpoint	[40]

Table 3. Effects of citrus processing by-products and their phytochemicals on rumen fermentation, nutrient utilization, animal performance, and metabolic health (continued)

Citrus Material/ Active Fraction	Animal or Experimental Model	Dietary Treatment / Dose	Rumen Fermentation and Microbiota	Nutrient Intake and Utilization	Animal Performance	Metabolic Health / Resilience	Ref.
C. Citrus Flavonoids and Flavonoid-Rich Extracts							
Naringin	24 male Boer goats fed a high-concentrate finishing diet	0 g or 0.50 g naringin/kg diet DM (treatment groups within a three-diet design)	Butyrate proportion ↑ and valerate ↓; Bacteroidetes and Rikenellaceae_RC9_gut_group enriched; high-grain-associated rumen dysbiosis was partly attenuated	NR	Growth effects were not the principal reported benefit	Plasma IL-6 and TNF-α ↓; antioxidant-enzyme activities ↑ and inflammatory response attenuated	[57]
Bioflavex (Naringin-Dominant Extract)	36 growing male Awassi lambs; 56-d randomized study	0 g, 0.40 g or 0.80 g Bioflavex/kg diet DM	Rumen papilla length, width, surface area and total absorptive surface ↑; fermentation and microbiome NR	DMI NS; apparent digestibility NR	Growth indicators and hot/cold carcass weight ↑; feed conversion improved, with strongest overall response at 0.80 g/kg DM	No blood metabolic-health panel; improved rumen morphology supports greater absorptive capacity	[46]
Bioflavex or Purified Naringin /Hesperidin	8 rumen-cannulated Friesian steers *in vivo*; parallel in-vitro component	450 mg Bioflavex/kg diet DM; purified components tested singly and in combination *in vitro*	Bioflavex prevented a post-feeding pH collapse and improved fermentation efficiency; component responses were not simply additive, underscoring matrix/synergy effects	Direct total-tract digestibility NR	Performance was not the primary endpoint	NR	[58]
D. Citrus Essential Oils							
Sweet-Orange Essential Oil (OEO; 78.84% D-Limonene)	6 rumen-cannulated crossbred beef heifers; replicated 3 × 3 Latin square; *in vitro*/in situ support experiments	0%, 0.25% or 0.50% of DMI; bermudagrass-based diet (forage: concentrate 70 : 30)	*In vivo* pH and major VFA largely NS; valerate ↓ at 0.50%; CH_4 139.60 g/d → 122.70 g/d (-12%) at 0.50%; CH_4 yield showed only a tendency	DMI NS; 0.25% caused no adverse utilization response, whereas 0.50% reduced gross-energy intake and apparent DM digestibility (653 g/kg → 613 g/kg)	Growth performance NR in the short Latin-square study	No systemic health panel; mitigation at 0.50% was accompanied by a digestibility cost	[13]
Orange-Peel Essential Oil (OEO; ~95% D-Limonene)	28 lactating Chios ewes (7/treatment)	0 mg, 150 mg, 300 mg or 450 mg OEO/kg concentrate	Rumen fermentation and microbiome NR	Intake response was dose-dependent; no direct total-tract digestibility dataset	Milk yield, milk-fat yield and feed efficiency improved, with responses reported up to the upper tested dose; milk composition responses were dose-specific	Plasma glutathione peroxidase/reductase and SOD, and milk lactoperoxidase activity ↑, indicating improved antioxidant defence	[59]

NOTE: 1. The table prioritizes controlled *in vivo* studies and recent quantitative syntheses. It is an evidence map rather than a formal systematic review; absence of an outcome from a row must not be interpreted as evidence of no effect; **2.** Arrows indicate direction and $P < 0.05$ unless a tendency ($0.05 \leq P < 0.10$) is stated explicitly. Numerical magnitudes or treatment means are reported when they could be extracted from the source; an arrow alone denotes a statistically supported direction for which a comparable effect size was not available. NS: no statistically significant difference; NR: not reported or not measured; **3.** Doses are reported exactly as used by the authors. Percentages may refer to diet DM, concentrate, DMI, or replacement of a conventional ingredient and are therefore not directly interchangeable. Extract doses cannot be compared without considering total flavonoid content, marker compounds, carrier, extraction method, and bioavailability; **4.** Responses to bulk citrus pulp reflect both nutrient substitution (starch replaced by pectin, soluble fibre and sugars) and residual phytochemicals. Responses to isolated extracts or essential oils more directly reflect flavonoid/terpene exposure, but matrix interactions and microbial adaptation remain important; **5.** The same CFE dose-response experiment generated complementary rumen/lactation and hindgut/immunometabolic publications[11,49]; these rows should not be treated as independent animal populations in quantitative synthesis; **6.** Results from mixed by-product diets or factorial designs are attributed only where the citrus contrast was separable. In the Gilaverte *et al.*[53] study, adverse effects associated with wet brewer grain are not assigned to DCP; **7.** Abbreviations: ADF: acid detergent fibre; ADG: average daily gain; BHBA: β-hydroxybutyrate; BW: body weight; CFE: citrus flavonoid extract; CH_4: methane; CP (ingredient): citrus pulp; CP (nutrient): crude protein; DCP: dried citrus pulp; DM: dry matter; DMI: dry matter intake; DOP: dehydrated/dried orange pulp; ECM: energy-corrected milk; FA: fatty acid(s); FCM: fat-corrected milk; LPS: lipopolysaccharide; MCP: microbial crude protein; N: nitrogen; NDF: neutral detergent fibre; NEFA: non-esterified fatty acids; NH_3-N: ammonia nitrogen; OEO: orange essential oil; OM: organic matter; SCC: somatic cell count; SOD: superoxide dismutase; VFA: volatile fatty acids.

5.1. Feed Intake, Productive Performance, and Feed-Use Efficiency

At moderate inclusion rates, citrus pulp can replace part of the cereal fraction without compromising animal performance. Its readily fermentable pectin and soluble carbohydrates provide rumen-fermentable energy while reducing dietary starch load. A meta-analysis of dairy-cow studies showed that low citrus-pulp inclusion (> 0%−10% of dietary dry matter) increased milk yield without depressing dry matter intake (DMI), whereas inclusion above 10%–20% progressively reduced DMI and milk yield; nevertheless, the accompanying increase in milk fat often maintained milk energy output[7]. Thus, citrus pulp should be regarded as a lipogenic energy source rather than as a nutritionally equivalent replacement for starch-rich cereals.

The importance of substitution rate was confirmed in high-yielding cows under tropical conditions. Replacing 60% of dietary corn meal with citrus pulp slightly reduced DMI, apparent nutrient digestibility, milk production, and economic return, although milk yield per unit of DMI was maintained[9]. Such findings indicate that high substitution may limit glucose precursor supply or reduce dietary energy density, especially in cows with high lactose-driven glucose requirements. In contrast, replacing corn with dried citrus pulp at up to 20% of the total mixed ration maintained weight gain and normal hematological and biochemical indices in growing goats[45]. Differences among studies probably reflect animal species, production level, basal forage quality, physical processing, citrus-pulp composition, and the nutrients displaced by its inclusion.

Concentrated citrus phytochemicals may improve production without contributing substantial dietary energy. In a replicated Latin-square experiment, supplementation with 50–150 g/d of citrus flavonoid extract did not affect DMI but increased milk yield, ruminal volatile fatty acid production, and microbial protein synthesis; the greatest energy-corrected milk response was observed at 100 g/d[11]. However, the experiment involved only eight cows, and its production estimates therefore require confirmation in larger herds. Similarly, supplementation of finishing lamb diets with 0.40 g/kg or 0.80 g/kg dry matter of a commercial Citrus aurantium flavonoid preparation increased weight gain and improved feed conversion, carcass weight, and ruminal papilla development[46]. Collectively, these studies suggest that citrus phytochemicals may enhance nutrient-use efficiency by coordinating microbial fermentation, ruminal absorptive capacity, and host metabolism. Nevertheless, responses are not universal: a low-dose citrus extract did not alter milk yield in lactating cows, although it transiently reduced plasma non-esterified fatty acids (NEFA) and modified insulin responses[60].

5.2. Energy Metabolism and Metabolic Health

The transition period provides a particularly relevant model for evaluating citrus phytochemicals because excessive adipose-tissue lipolysis, hepatic lipid accumulation, oxidative stress, and systemic inflammation frequently occur around calving. Supplementation with 4 g/d of citrus peel extract from three weeks before to three weeks after calving increased milk yield, milk protein, lactose, serum glucose, and ruminal volatile fatty acid production. Simultaneously, it reduced circulating NEFA, β-hydroxybutyrate (BHB), insulin, aspartate aminotransferase, alanine aminotransferase, and haptoglobin[55]. Adipose- and liver-tissue analyses indicated reduced lipolysis and inflammation, improved insulin signaling, decreased hepatic lipid accumulation, and enhanced gluconeogenic capacity. Because the extract was administered intragastrically and the study included 30 cows, however, commercial responses under conventional feeding conditions remain to be established.

Evidence from individual citrus flavanones further supports an adipose-centered mechanism. Feeding 30 g/d of naringin from approximately 21 d prepartum to 35 d postpartum increased milk and milk-protein yields without affecting DMI. It also reduced serum NEFA, lipopolysaccharide (LPS), malondialdehyde, C-reactive protein, IL-1β, IL-6, and hepatic enzyme activities, while increasing glutathione peroxidase activity and adipose-tissue adiponectin and total antioxidant capacity[47]. Lipidomic and proteomic analyses revealed lower ceramide accumulation and downregulation of pathways associated with lipolysis, inflammation, and cellular stress. These results connect a specific citrus phytochemical with the regulation of lipotoxic lipid species rather than merely with nonspecific antioxidant activity.

More recent evidence showed that 30 g/d of highly purified hesperidin supplied to periparturient cows did not change DMI or total milk production but increased milk-protein concentration and yield and decreased milk urea nitrogen[48]. Hesperidin reduced circulating NEFA and BHB, increased adiponectin and estimated insulin sensitivity, and lowered ceramides and acylcarnitines in serum and adipose tissue. Concurrent increases in sphingomyelins, glycerophospholipids, mitochondrial fatty-acid oxidation, and antioxidant-related proteins suggest coordinated remodeling of adipose-tissue metabolism. Detection of hesperetin, hesperetin glucuronide, and hesperetin sulfate in circulation and adipose tissue also provides evidence that ruminal or intestinal metabolites of citrus flavanones reach peripheral tissues.

The available bovine data support a provisional rumen-gut-host signaling sequence. Greater ruminal volatile-fatty-acid supply and lower gut lipopolysaccharide exposure can increase insulin responsiveness, while absorbed flavanone metabolites may act in peripheral tissues[48,49,61-63]. In transition cows, citrus peel extract increased adipose AKT signaling and PPARα-associated lipid oxidation, reduced phosphorylation of hormone-sensitive lipase and NF-κB, and lowered hepatic SREBP-1c-associated lipid accumulation[61]. Naringin and hesperidin studies further linked higher adiponectin and antioxidant proteins with lower ceramides, acylcarnitines, inflammatory cytokines, NEFA, and β-hydroxybutyrate[62,63]. These observations are consistent with coordinated attenuation of TLR4/NF-κB inflammatory signaling, restraint of lipolysis, and improved mitochondrial fatty-acid use; however, they do not prove direct binding of flavonoids to these targets. The multi-omics studies used small cohorts, mostly single doses and short sampling windows, and relied heavily on correlations among taxa, lipids, and host proteins[48,49]. Causal validation requires pharmacokinetics of aglycones and conjugates, isotope tracing, tissue-specific pathway inhibition, absolute microbiome measurements, and independent replication.

5.3. Oxidative, Immune, and Environmental-Stress Resilience

Biological resilience can be defined as the capacity to maintain production or recover rapidly during nutritional, thermal, metabolic, or inflammatory challenges. Citrus phytochemicals are relevant because flavanones and polymethoxylated flavones can modulate antioxidant enzymes, inflammatory signaling, epithelial integrity, and microbial endotoxin production rather than simply scavenging reactive oxygen species.

Under hot-weather conditions, supplementing lactating buffaloes with 20 g/d of citrus bioflavonoids increased milk yield from 6.76 kg/d to 7.32 kg/d and 4% fat-corrected milk from 10.66 kg/d to 11.74 kg/d. Supplementation also increased catalase, immunoglobulin M, and heat-shock protein 70, decreased TNF-α, IL-1β, and IL-6, and reduced respiratory rate and body-surface temperature[56]. Naringin supplementation similarly improved productive performance, antioxidant status, and immune responses in heat-stressed lambs[64]. These results indicate that citrus flavonoids may preserve production by limiting oxidative and inflammatory costs during thermal challenge, although replication across climates, breeds, and heat-load intensities remains limited.

Citrus extracts may also improve resilience to high-concentrate feeding. In finishing bulls, Citrus aurantium flavonoid extract improved concentrate efficiency and feeding behavior while reducing ruminal inflammation and modifying epithelial gene expression associated with barrier function[40,41]. A broader meta-analysis of flavonoid supplementation in small ruminants reported increased average daily gain, antioxidant enzyme activities, and total antioxidant capacity, together with reduced feed conversion ratio and malondialdehyde concentration[65]. However, because that analysis included flavonoids from multiple botanical sources, it provides supportive rather than citrus-specific evidence.

A practical dose hierarchy emerges across interventions. For bulk citrus pulp, dairy-cow evidence is most favorable at ≤ 10% of dietary dry matter; inclusion above 10%–20% increasingly depresses intake or milk volume, although milk fat can partly preserve energy-corrected yield[10,11]. For a citrus flavonoid extract tested at 50 g/d, 100 g/d, and 150 g/d, milk yield increased from 31.90 kg/d to 34.37 kg/d at 100 g/d, whereas the highest dose produced stronger microbiome shifts without a larger production response[14]. For orange essential oil, 0.25% of dietary dry matter did not reduce methane, while 0.50% reduced methane by 12% but lowered digestibility[16]. These non-linear responses argue against a universal dose. Trials should report the delivered amounts of hesperidin, naringin, polymethoxylated flavones, and D-limonene, and should include at least three doses plus a control, an adaptation period, and productivity and safety endpoints.

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Biological resilience can be defined as the capacity to maintain production or recover rapidly during nutritional, thermal, metabolic, or inflammatory challenges. Citrus phytochemicals are relevant because flavanones and polymethoxylated flavones can modulate antioxidant enzymes, inflammatory signaling, epithelial integrity, and microbial endotoxin production rather than simply scavenging reactive oxygen species.

Under hot-weather conditions, supplementing lactating buffaloes with 20 g/d of citrus bioflavonoids increased milk yield from 6.76 kg/d to 7.32 kg/d and 4% fat-corrected milk from 10.66 kg/d to 11.74 kg/d. Supplementation also increased catalase, immunoglobulin M, and heat-shock protein 70, decreased TNF-α, IL-1β, and IL-6, and reduced respiratory rate and body-surface temperature[56]. Naringin supplementation similarly improved productive performance, antioxidant status, and immune responses in heat-stressed lambs[64]. These results indicate that citrus flavonoids may preserve production by limiting oxidative and inflammatory costs during thermal challenge, although replication across climates, breeds, and heat-load intensities remains limited.

Citrus extracts may also improve resilience to high-concentrate feeding. In finishing bulls, Citrus aurantium flavonoid extract improved concentrate efficiency and feeding behavior while reducing ruminal inflammation and modifying epithelial gene expression associated with barrier function[40,41]. A broader meta-analysis of flavonoid supplementation in small ruminants reported increased average daily gain, antioxidant enzyme activities, and total antioxidant capacity, together with reduced feed conversion ratio and malondialdehyde concentration[65]. However, because that analysis included flavonoids from multiple botanical sources, it provides supportive rather than citrus-specific evidence.

A practical dose hierarchy emerges across interventions. For bulk citrus pulp, dairy-cow evidence is most favorable at ≤ 10% of dietary dry matter; inclusion above 10%–20% increasingly depresses intake or milk volume, although milk fat can partly preserve energy-corrected yield[10,11]. For a citrus flavonoid extract tested at 50, 100, and 150 g/d, milk yield increased from 31.90 kg/d to 34.37 kg/d at 100 g/d, whereas the highest dose produced stronger microbiome shifts without a larger production response[14]. For orange essential oil, 0.25% of dietary dry matter did not reduce methane, while 0.50% reduced methane by 12% but lowered digestibility[16]. These non-linear responses argue against a universal dose. Trials should report the delivered amounts of hesperidin, naringin, polymethoxylated flavones, and D-limonene, and should include at least three doses plus a control, an adaptation period, and productivity and safety endpoints.

6. Translation into Ruminant Product Quality

The effects of citrus processing by-products on ruminant-derived foods arise from both nutrient substitution and phytochemical exposure. Replacing starch with pectin can change ruminal acetate supply and lipid biohydrogenation, while flavanone metabolites, carotenoids, and tocopherols may be transferred to tissues or stimulate endogenous antioxidant defenses. Product responses must nevertheless be distinguished from plasma biomarkers because improved systemic antioxidant status does not guarantee longer shelf life or sensory acceptance. **Table 4** compares milk, dairy-product, meat, and carcass outcomes, whereas **Figure. 3** summarizes the ruminal and host pathways that link citrus matrices with product quality.

Table 4. Effects of citrus processing by-products and their phytochemicals on milk, dairy products, meat, and carcass quality

Citrus Material / Active Fraction	Animal and Product	Dietary Treatment / Dose	Composition and Processing Traits	Fatty-Acid Profile / Bioactive Transfer	Oxidative Stability / Shelf Life	Sensory Quality / Carcass Traits	Ref.
A. Milk							
Dehydrated Orange Pulp (DOP)	44 Payoya goats; milk to 55 d postpartum	0%, 40% or 80% replacement of cereal in concentrate	Milk yield and gross composition: NS	Milk α-tocopherol: 21.70 μg/100 g → 32.80 μg/100 g → 42.30 μg/100 g; TPC: 63.50 mg GAE/L → 84.10 mg GAE/L → 102 mg GAE/L; TAC: 6.63 μmol TE/mL → 11.10 μmol TE/mL → 12.80 μmol TE/mL	Antioxidant enrichment increased dose-dependently; storage stability was not tested	Milk sensory traits NR; suckling-kid carcass quality was NS in this early-lactation study	[66]

Table 4. Effects of citrus processing by-products and their phytochemicals on milk, dairy products, meat, and carcass quality (continued)

Citrus Material / Active Fraction	Animal and Product	Dietary Treatment / Dose	Composition and Processing Traits	Fatty-Acid Profile / Bioactive Transfer	Oxidative Stability / Shelf Life	Sensory Quality / Carcass Traits	Ref.
A. Milk							
Pelleted Citrus Pulp (PCP) ± Soybean Oil	4 lactating Holstein cows; milk	Control; 3% soybean oil; soybean oil + 9% or 18% PCP (diet DM)	Milk yield and 4% FCM: NS; Soybean-oil diets lowered milk fat and total solids; the PCP-specific contribution cannot be separated completely	PCP increased milk polyphenols, flavonoids and FRAP; 18% PCP shifted fat toward ↑ MUFA and ↓ SFA	Greater reducing capacity indicated improved antioxidant potential; shelf life NR	Sensory traits NR	[15]
Dried Citrus Pulp (DCP) + Soybean Oil	4 Serra da Estrela ewes; milk and cheesemaking milk	450 g/kg corn silage + 550 g/kg concentrate; cereal concentrate vs DCP concentrate, both with 5% soybean oil	Milk yield ↑; composition and technological cheesemaking properties mostly NS, except lactose ↓	Milk 18 : 0 and cis-9 18 : 1 each ↓ ~3 percentage points; trans-11 18 : 1 ↑ 4.19 points and cis-9, trans-11 CLA ↑ 1.68 points	NR	No reported adverse milk-processing response	[67]
Orange-Peel Essential Oil (OEO; Limonene-Rich)	28 Chios ewes; milk	0, 150, 300 or 450 mg OEO/kg concentrate	Milk yield improved up to 300 mg/kg; feed efficiency improved up to 450 mg/kg	Up to 300 mg/kg, milk SFA ↑ and UFA ↓ — a nutritional-quality trade-off	Milk lactoperoxidase activity and systemic antioxidant-enzyme status improved	Sensory traits NR	[59]
DOP	44 Payoya goats; milk across 180 d lactation	0%, 40% or 80% replacement of cereal in concentrate	Milk yield and major components were maintained	α-Tocopherol, TPC and TAC ↑ with DOP; DOP80 milk α-tocopherol 45.2 vs 21.1 μg/100 g control; MUFA/SFA, PUFA/SFA, 18 : 3n-3 and cis-18 : 2n-6 ↑, but late-lactation total CLA ↓ (0.59–0.65 vs 0.76 g/100 g FA); TI slightly ↓	Antioxidant status improved throughout lactation; direct shelf-life testing NR	Sensory traits NR	[61]
DCP ± Soybean Oil	10 mid-lactation Holstein cows; milk	0, 86.5 or 173 g DCP/kg diet DM; with or without 17.3 g soybean oil/kg DM	Milk production and major composition: NS	DCP ↑ milk TPC; soybean oil + DCP produced the strongest shift toward unsaturated FA (↓ SFA and 18 : 0; ↑ MUFA/trans-18 : 1)	Functional enrichment occurred without a production penalty; shelf life NR	Sensory traits NR	[44]
Citrus-Bioflavonoid Premix (Naringin, Hesperidin, Neohesperidin and Nobiletin)	20 lactating buffaloes under hot conditions; milk	0 g or 20 g premix/d (~0.1% DMI) for 60 d	Milk yield, 4% FCM, protein, lactose and SNF ↑	Milk C14 : 0, C15 : 0, C16 : 0 and C18 : 0 ↓; UFA, PUFA and CLA ↑; SFA/UFA ↓	Milk antioxidant indices improved concurrently with systemic heat-stress resilience	Sensory traits NR	[68]
B. Dairy Products							
DOP	Raw Payoya goat milk; 18 artisanal cheeses	Goats received 0%, 40% or 80% cereal replacement; animal or vegetable coagulant; fresh and ripened cheeses	Diet caused limited changes in physicochemical traits; coagulant type and ripening were stronger determinants of volatile and compositional variation	No consistent nutritionally adverse FA shift was identified	Oxidative shelf life was not directly challenged	No broad sensory penalty attributable to DOP; coagulant/ripening effects predominated	[69]

Table 4. Effects of citrus processing by-products and their phytochemicals on milk, dairy products, meat, and carcass quality (continued)

Citrus Material / Active Fraction	Animal and Product	Dietary Treatment / Dose	Composition and Processing Traits	Fatty-Acid Profile / Bioactive Transfer	Oxidative Stability / Shelf Life	Sensory Quality / Carcass Traits	Ref.
B. Dairy Products							
DOP	Artisanal raw-milk goat cheeses	0%, 40% or 80% cereal replacement; animal vs vegetable rennet	Rennet did not change FA or antioxidant outcomes; cheese FA composition was NS among DOP diets	Cheese α-tocopherol and TPC ↑ dose-dependently; TAC correlated with TPC ($r = 0.73$) and α-tocopherol ($r = 0.62$)	TAC ↑ with DOP, demonstrating antioxidant transfer into cheese; storage stability NR	Sensory outcomes were outside the principal endpoint set	[70]
C. Meat and Carcass Quality							
Fresh Citrus Pulp (FCP)	36 British-breed steers; longissimus lumborum and carcass	0%, 15% or 30% diet DM for 104 d	Meat pH, colour, cooking loss and proximate traits: NS	Muscle α-tocopherol and retinoids ↑ linearly; FCP30 produced ~3-fold control α-tocopherol	Lipophilic ORAC was greatest at FCP15; no direct retail-display challenge	HCW, ribeye area, backfat, marbling and Warner-Bratzler shear force: NS	[71]
DCP	24 Angus steers; longissimus thoracis retail display	150 g DCP/kg diet DM for 90 d (control and grape-pomace comparators)	DCP steaks were lighter (↑ L*); other basic quality traits were not materially impaired	Muscle α-tocopherol was greatest with DCP	Antioxidant activity ↑; TBARS, protein carbonyls and coliform counts ↓ over 9 d display; Grape pomace generally produced the strongest protection	No reported sensory penalty in this shelf-life paper	[72]
DCP	Same Angus-steer cohort; cooked beef sensory and volatile profile	150 g DCP/kg diet DM for 90 d	Control beef contained more aldehydes, ketones and alcohols; most sensory attributes were NS	DCP ↑ 18 : 2n-6, 20 : 4n-6, 18 : 3n-3, total CLA and total n-3/n-6 PUFA; control ↑ cis-9 18 : 1	Companion evidence indicates reduced oxidation during display	DCP beef was slightly less tender than control; other sensory attributes were maintained	[73]
DCP	26 male Comisana lambs; meat stored aerobically at 4 °C	0%, 24% or 35% diet DM replacing barley	Basic carcass endpoints were not the focus	Tissue antioxidant deposition was not quantified in this paper	DCP reduced protein radicals and carbonyl formation and preserved thiol groups during 6 d storage	Sensory traits NR	[74]
DCP	Lamb meat; related barley-replacement feeding experiment	High DCP inclusion replacing cereal concentrate	Meat colour stability was not consistently altered	NR	DCP reduced lipid oxidation during 6 d aerobic refrigerated storage, irrespective of inclusion level	Sensory and carcass traits NR in this endpoint paper	[75]
DCP (Phenolic- and Vitamin-E-Rich Matrix)	17 lambs; liver, plasma and longissimus muscle	35% DCP vs barley control for 56 d	Basal meat-quality traits were not the primary endpoints	DCP diet supplied 45.70 vs 10.30 mg α-tocopherol/kg DM; α-tocopherol ↑ in liver, plasma and muscle	Basal TBARS were NS, but TBARS after induced muscle peroxidation ↓; hydrophilic antioxidant capacity was NS, implicating vitamin E as the major mediator	Sensory/carcass traits NR	[62]
DCP ± Cistus Ladanifer (Rockrose)	32 lambs; carcass and longissimus meat	2 × 2 design: cereal vs DCP, with/without 150 g rockrose/kg DM; oil-supplemented diets	Most physicochemical traits and total SFA/PUFA : NS	DCP altered odd-chain and minor biohydrogenation intermediates; with no rockrose, 18 : 0 ↑ and trans-10, cis-12 CLA ↓; Trans-11 18 : 1 and rumenic acid were maintained	Lipid stability was not the main discriminating response	Dressing percentage, tenderness and juiciness ↓ with DCP; most other carcass traits NS	[76]

Table 4. Effects of citrus processing by-products and their phytochemicals on milk, dairy products, meat, and carcass quality (continued)

Citrus Material / Active Fraction	Animal and Product	Dietary Treatment / Dose	Composition and Processing Traits	Fatty-Acid Profile / Bioactive Transfer	Oxidative Stability / Shelf Life	Sensory Quality / Carcass Traits	Ref.
C. Meat and Carcass Quality							
Naringin	20 Assaf lambs; longissimus muscle	0 g or 1.50 g naringin/kg diet DM for 7 wk	Meat composition and principal physicochemical traits: NS	Direct muscle deposition of naringin metabolites NR	Despite improved hepatic antioxidant status, meat oxidation and colour stability were NS	Carcass and sensory traits were not materially improved	[77]
Hesperidin or Naringin	44 male Chios lambs; refrigerated meat	2.50 g hesperidin or naringin/kg feed for 35 d; control and 200 mg α-tocopheryl acetate/kg comparators	Basic meat-quality traits were largely maintained	Flavanone metabolite transfer was not quantified	Both flavanones reduced meat MDA during storage up to 8 d, although vitamin E afforded stronger protection	No major adverse carcass or sensory response reported	[62]
Citrus-Bioflavonoid Premix (Bioflavex)	36 male Awassi lambs; carcass and longissimus meat	0 g/kg, 0.40 g/kg or 0.80 g/kg diet DM for 56 d	Cooking loss 42.89% → 41.12% → 39.59%; shear force 7.91 N/cm^2 → 6.34 N/cm^2 → 5.20 N/cm^2; The reported water-holding and myofibrillar-fragmentation metrics decreased and are method-specific	FA profile and flavonoid deposition NR	Direct shelf-life challenge NR	Hot/cold carcass weight ↑; backfat and body-wall fat ↓; carcass redness ↓; Hardness, springiness and cohesiveness: NS	[45]

NOTE: ↑ and ↓ indicate an increase or decrease at $P < 0.05$ unless a tendency ($0.05 \leq P < 0.10$) is identified explicitly. Treatment means, percentage changes, or fold changes are given where extractable from the cited report; an arrow alone indicates direction when a comparable magnitude was not available. NS: no statistically significant difference; NR: not reported or not measured; CLA: conjugated linoleic acid; DCP: dried citrus pulp; DMI: dry-matter intake; DOP: dehydrated orange pulp; FA: fatty acid; FCM: fat-corrected milk; FCP: fresh citrus pulp; FRAP: ferric-reducing antioxidant power; GAE: gallic-acid equivalents; HCW: hot carcass weight; MDA: malondialdehyde; MUFA: monounsaturated fatty acids; OEO: orange-peel essential oil; ORAC: oxygen-radical absorbance capacity; PCP: pelleted citrus pulp; PUFA: polyunsaturated fatty acids; SFA: saturated fatty acids; SNF: solids-not-fat; TAC: total antioxidant capacity; TBARS: thiobarbituric-acid-reactive substances; TE: Trolox equivalents; TI: thrombogenicity index; TPC: total phenolic compounds; UFA: unsaturated fatty acids. Doses are expressed on a diet-DM basis unless stated otherwise. Companion publications from the same animal cohort are identified and must not be counted as independent experiments. Values are rounded as reported in the source articles.

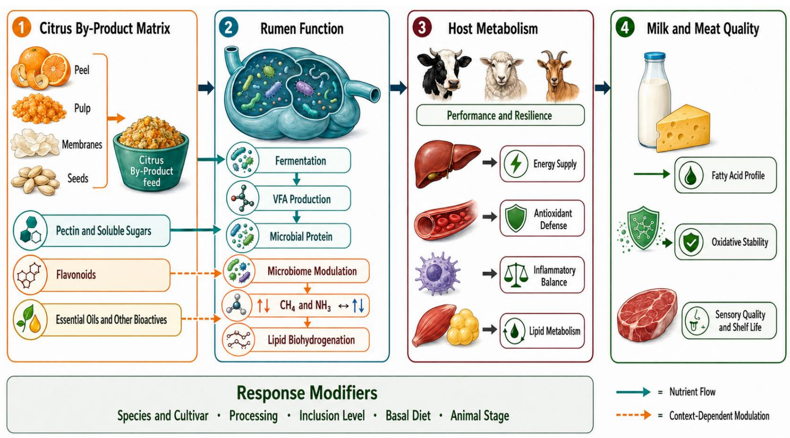

Figure. 3 Nutrient-phytochemical mechanisms linking citrus processing by-products to rumen function, animal metabolism, and milk and meat quality. Citrus peel, pulp, membranes, and seeds provide a fermentable nutritional matrix rich in pectin and soluble sugars, together with flavonoids, essential oils, and other bioactive compounds. Fermentation of the carbohydrate fraction supplies volatile fatty acids and supports microbial protein synthesis, thereby contributing to host energy and protein metabolism. Citrus phytochemicals may conditionally modulate the rumen microbiome, methane and ammonia formation, and lipid biohydrogenation. These ruminal responses may subsequently affect energy supply, antioxidant defense, inflammatory balance, and lipid metabolism, with potential consequences for animal performance, biological resilience, and the fatty-acid profile, oxidative stability, sensory quality, and shelf life of milk and meat. The magnitude and direction of these responses depend on citrus species and cultivar, processing method, dietary inclusion level, basal diet, and animal physiological stage. Solid arrows represent principal nutrient flows, whereas dashed arrows indicate context-dependent phytochemical modulation. **NOTE:** CH_4: methane; NH_3: ammonia; VFA: volatile fatty acids. Copyright: Created with BioRender.

6.1. Milk Composition and Lipidomic Quality

Citrus pulp generally exerts a lipogenic effect on milk because ruminal fermentation of pectin favors acetate and butyrate production over propionate. A meta-analysis found that low dietary inclusion of citrus pulp increased milk and milk-fat yields, whereas higher inclusion reduced milk volume but frequently maintained milk energy output through increased fat concentration[7]. Effects on protein and lactose are less consistent because excessive replacement of cereal starch may restrict propionate supply and hepatic gluconeogenesis.

Changes in milk fatty acids become particularly evident when citrus pulp is combined with unsaturated lipid sources. Replacing cereal grains with dehydrated citrus pulp in a soybean-oil-supplemented diet increased vaccenic acid (trans-11 18 : 1) and rumenic acid (cis-9, trans-11 conjugated linoleic acid; CLA)) in ewe milk[78]. This response was attributed to changes in ruminal biohydrogenation, including a greater accumulation of vaccenic acid and its subsequent mammary conversion to rumenic acid by Δ^9-desaturase. However, the study involved only four ewes in a Latin-square design, and whether comparable effects occur without supplemental oil remains uncertain.

Evidence from dairy goats indicates that citrus pulp can also increase the antioxidant value of milk. Replacing 40% or 80% of dietary cereals with dried orange pulp increased milk α-tocopherol, total phenolic compounds, and total antioxidant capacity, while effects on the overall fatty acid profile were relatively small[79]. These results imply that citrus pulp may improve milk oxidative status without necessarily causing extensive lipid remodeling. More pronounced effects have been reported for concentrated citrus phytochemicals. Supplementation of dairy cows with up to 150 g/d citrus peel extract increased milk yield, CLA and total unsaturated fatty acids and enhanced milk antioxidant capacity[56]. Lipidomic analysis revealed changes in triglycerides, phosphatidylcholines, phosphatidylethanolamines, and sphingomyelins, indicating that citrus phytochemicals may influence mammary lipid synthesis beyond conventional fatty acid indices. Nonetheless, this study used eight cows, and targeted validation of the proposed lipid biomarkers is still required. Transition-cow studies have similarly reported increased milk protein or lactose following citrus peel extract, naringin, or hesperidin supplementation, but changes in gross composition were generally more consistent than changes in total milk yield[47,48,55].

6.2. Cheese Composition, Oxidative Status, and Sensory Properties

The translation of dietary effects from milk to cheese depends on milk composition, partitioning of bioactive compounds into curd and whey, microbial metabolism, coagulant type, and ripening conditions. In Payoya goats, replacement of 40% and 80% of cereal ingredients with dehydrated orange pulp increased cheese α-tocopherol, total phenolic content, and total antioxidant capacity while cheese fatty-acid composition did not differ among diets[80]. Cheese antioxidant capacity was correlated with total phenolics and α-tocopherol at r = 0.73 and r = 0.62, respectively. This supports the retention of diet-responsive antioxidant components during cheese manufacture, although the study did not directly assess lipid oxidation or microbial shelf life during prolonged storage.

Earlier work showed that orange-pulp feeding could alter goat-cheese pH, water activity, fat concentration, color, hardness, adhesiveness, and the intensity of goat and salty flavors. Some of these changes were associated with greater consumer acceptance and purchase intention[81]. In contrast, a subsequent experiment using raw Payoya milk and animal or vegetable coagulants found only minor differences in physicochemical properties, volatile compounds, and sensory attributes among cheeses produced from goats receiving different amounts of dried citrus pulp[66,69]. Thus, citrus feeding does not impart a uniform "citrus" sensory signature. Effects appear to depend on inclusion level, cheese type, ripening period, milk microbiota, and manufacturing technology. Importantly, the presence of volatile terpenes in the diet does not guarantee their deposition at concentrations exceeding sensory thresholds.

6.3. Carcass Traits, Meat Composition, and Oxidative Stability

Most studies indicate that moderate citrus-pulp inclusion maintains carcass yield and conventional meat-quality attributes, whereas its clearest benefit is improved oxidative stability during refrigerated storage. Feeding dried citrus pulp at 24% or 35% of concentrate reduced thiobarbituric acid-reactive substances in lamb meat during six days of aerobic storage, without consistently affecting meat color[75]. In the same experimental context, citrus pulp decreased protein-radical and carbonyl formation and preserved protein thiol groups, demonstrating protection against both lipid and protein oxidation[74].

This protection has often been attributed to citrus phenolics, but tissue studies suggest a more complex mechanism. Lambs fed 35% dried citrus pulp exhibited greater antioxidant capacity in muscle and liver; however, α-tocopherol appeared to contribute more strongly than the measured phenolic compounds[62]. The antioxidant value of citrus pulp may therefore reflect interactions among tocopherols, carotenoids, flavonoid metabolites, and endogenous enzymatic defenses rather than direct deposition of intact flavonoids.

Purified citrus flavanones provide complementary evidence. Supplementation with 2.50 g/kg feed of hesperidin or naringin reduced malondialdehyde formation in lamb meat stored at 4 ℃ for up to eight days, although the protection was weaker than that achieved with α-tocopheryl acetate. Neither flavanone changed growth, carcass characteristics, pH, color, cooking loss, or tenderness[72]. Thus, their principal product-level value may be preservation rather than alteration of fresh-meat composition.

Cross-study contrasts caution against attributing product effects to "citrus antioxidants" as a single mechanism. Fresh citrus pulp at 15%–30% of dietary dry matter increased muscle α-tocopherol to approximately three times the control value without changing carcass traits[82], and 15% dried citrus pulp reduced lipid and protein oxidation during a nine-day beef display[83]. In another cattle experiment, however, replacement of 40% or 80% of barley did not increase muscle α-tocopherol, total phenolics, or antioxidant capacity[73]. Lamb studies more consistently show protection against lipid or protein oxidation at 24%–35% dried pulp[53,54,84], but purified naringin improved hepatic antioxidant status without improving meat quality[58]. Differences in pulp composition, basal antioxidants, tissue deposition, storage challenge, and species probably explain more of this heterogeneity than inclusion level alone. Future studies should quantify feed and tissue metabolites, use standardized retail-display protocols, and include trained sensory panels.

7. Environmental Sustainability and Circular Bioeconomy Implications

7.1. Waste Diversion and Displacement of Conventional Feed Resources

The incorporation of citrus processing by-products into ruminant diets can contribute to environmental sustainability through two complementary pathways: avoiding burdens associated with residue disposal and displacing conventionally cultivated feed ingredients. Citrus juice production generates large quantities of peel, pulp, membranes, seeds, and soluble solids that are characterized by high moisture content and rapid biological deterioration. When these materials are inadequately stored or disposed of, their high organic load may contribute to odor, leachate formation, oxygen depletion in receiving waters, and greenhouse-gas emissions during uncontrolled decomposition. Their conversion into feed therefore represents a form of biological upcycling in which ruminants transform biomass unsuitable for direct human consumption into milk, meat, and manure nutrients[1].

The principal system-level benefit may arise from replacing feeds such as maize grain, beet pulp, or other energy concentrates, thereby reducing food-feed competition and potentially avoiding land occupation, irrigation, fertilizer use, and emissions associated with crop production. However, these avoided burdens depend on the actual substitution ratio and the feed ingredient displaced. Citrus pulp cannot be assumed to replace maize on an equal-mass basis because differences in moisture, digestible energy, protein, storage losses, and animal response determine its effective nutritional substitution. Consequently, environmental comparisons should be based on nutritionally equivalent diets and animal-product outputs rather than on tonnes of feed alone.

Recent citrus-specific life-cycle assessments emphasize that valorization does not automatically guarantee a lower environmental footprint. Dilek *et al*.[17] reported that producing a non-hydrolyzed orange-peel feed ingredient generally had lower impacts than conventional feed production and disposal through landfilling or composting. Enzymatic hydrolysis increased energy and material requirements, whereas incineration with heat recovery performed favorably under some assumptions[17]. Drying is particularly important because wet citrus residues are bulky, perishable, and costly to transport. A recent systematic review identified dehydration — frequently conducted using fossil-fuel-fired industrial kilns — as a major environmental hotspot in citrus valorization chains[5]. Local use of fresh pulp, rapid ensiling, mechanical dewatering, solar-assisted drying, or drying with recovered process heat may therefore provide greater benefits than centralized production of extensively dried feed.

7.2. Enteric Methane, Nitrogen Use, and Pollution Trade-Offs

Environmental effects occurring within the animal system must be distinguished from the avoided impacts of waste management and conventional feed production. Whole citrus pulp is rich in pectin and fermentable fiber but contains relatively low concentrations of the essential oils and flavonoids that are often studied as rumen modifiers. Accordingly, feeding citrus pulp should not be considered intrinsically antimethanogenic. In lactating goats, complete replacement of maize grain with dried citrus pulp increased methane emissions from 24.7 to approximately 34.8 g/day without increasing milk yield[14]. This response is consistent with a shift from starch fermentation toward acetate-producing fermentation of pectin and fiber, which may increase the availability of metabolic hydrogen for methanogenesis.

By contrast, concentrated citrus phytochemicals may directly modify methanogenic pathways. Supplementation with orange essential oil at 0.5% of dietary dry matter reduced daily methane emissions by approximately 12% in heifers without depressing dry-matter intake, although the experiment included only six animals and requires confirmation under larger and longer-term production conditions[13]. *in vitro* research has similarly shown that combinations of naringin, hesperidin, and citrus flavonoid extract can suppress both methanogenesis and ammonia formation more effectively than individual flavonoids, accompanied by changes in methanogens, protozoa, and other rumen microorganisms[12]. Nevertheless, these findings were obtained at relatively high experimental doses and should not be directly extrapolated to commercial feeding. Microbial adaptation may also attenuate the response to continuous essential-oil exposure, suggesting that dose, delivery pattern, and adaptation period are important determinants of efficacy[85].

Nitrogen-related outcomes are equally conditional. Rapidly fermentable pectin could theoretically improve microbial capture of ruminal ammonia when synchronized with degradable protein, thereby reducing urinary nitrogen losses. Conversely, insufficient dietary nitrogen, reduced intake, or asynchronous nutrient supply may restrict microbial protein synthesis. In high-producing tropical dairy cows, replacing 60% of maize meal with citrus pulp reduced nutrient digestibility, microbial nitrogen capture, and milk production[9]. Thus, lower feed-related emissions may be offset by poorer production, increasing impacts when expressed per kilogram of energy-corrected milk or live-weight gain. Future experiments should simultaneously quantify methane yield, methane intensity, fecal and urinary nitrogen, ammonia volatilization, manure-derived nitrous oxide, and product output. Extraction energy and solvents must also be included when environmental benefits are attributed to purified citrus phytochemicals.

7.3. Circular Biorefinery Design and Sustainability Assessment

A circular strategy should prioritize the highest feasible value retention rather than treating feed use as the sole destination for all citrus residues. In an integrated biorefinery, essential oils, flavonoids, pectin, carotenoids, or limonoids may first be recovered when technically, economically, and environmentally justified; the remaining carbohydrate-rich matrix can subsequently be used as ruminant feed, while unsuitable fractions may enter anaerobic digestion, composting, or nutrient-recovery systems. Such cascading use can increase resource efficiency, but every additional extraction, purification, drying, and transport step introduces energy, chemical, water, and infrastructure requirements. The optimal cascade is therefore region-specific and may favor minimally processed feed in livestock-producing regions but higher-value extraction near large processing facilities.

Robust evaluation requires explicit system boundaries, counterfactual waste-management scenarios, transport distances, allocation procedures, and assumptions regarding displaced feed. Attributional life-cycle assessment describes the footprint of the existing supply chain, whereas consequential assessment is better suited to estimating market-mediated changes caused by large-scale adoption. This distinction is important because policies that reduce the price of low-opportunity-cost feeds may stimulate livestock production and partially offset environmental gains through rebound effects[86]. Recent reviews also show substantial methodological heterogeneity among assessments of food-loss and waste-derived feeds, particularly regarding allocation, substitution credits, functional units, and alternative uses[18].

Circularity indicators should consequently complement rather than replace conventional environmental assessment. Relevant metrics include the proportion of low-opportunity-cost biomass in the diet, human-edible feed conversion, land-use ratio, nitrogen and phosphorus recycling, renewable-energy use, and avoided waste disposal. These should be interpreted alongside climate change, eutrophication, acidification, water use, land occupation, and biodiversity-related impacts because a more circular system is not necessarily environmentally superior in every category[87]. Overall, citrus by-products are most likely to deliver genuine sustainability gains when they are sourced locally, stabilized with minimal fossil energy, incorporated at nutritionally appropriate levels, and demonstrated to maintain animal productivity while reducing whole-system greenhouse-gas and nutrient losses.

8. Knowledge Gaps and Future Research Priorities

8.1. Standardization, Dose-Response Relationships, and Mechanistic Validation

A major limitation is the poor characterization of citrus-derived interventions. Generic terms such as citrus pulp, peel extract, or citrus flavonoids conceal variation in species, cultivar, anatomical fraction, maturity, storage, drying, essential-oil recovery, and extraction solvent. Future studies should report complete nutrient composition together with marker phytochemicals — especially hesperidin, naringin, nobiletin, tangeretin, D-limonene, and total phenolics — using validated chromatographic methods. Batch-to-batch stability and processing history should be documented so that biological differences can be separated from ingredient variability.

Dose-response experiments must distinguish pectin-driven nutrient substitution from exposure to concentrated phytochemicals. For whole pulp, the response inflection observed near 10%–20% of dietary dry matter depends on the starch source displaced and animal production potential[10,11]. Extract studies should express dose as both product mass and analyzed marker compounds; otherwise, 100 g/d of one preparation cannot be compared with 100 g/d of another. Essential-oil studies also require an adaptation phase because antimicrobial responses may attenuate with continuous exposure[16,88]. Future trials should use multiple doses, pre-specified non-inferiority criteria for intake and production, and simultaneous measurements of digestibility, microbial protein, methane, nitrogen excretion, health, and product quality. This design would identify the lowest effective dose and the dose at which nonselective antimicrobial or substitution costs emerge.

8.2. Safety Assessment and Long-Term Feeding Constraints

Safety assessment should begin with batch-specific screening of pesticide residues, mycotoxins, heavy metals, pathogenic or spoilage microorganisms, and lipid- or terpene-oxidation products. Peel-associated contaminants can become concentrated when water and juice are removed, and measured mineral and contaminant profiles vary by tissue and processing history[38,41]. Regulatory maximum levels and withdrawal requirements should be applied to the final feed material, not inferred from fresh fruit. Traceability should include orchard treatments, extraction solvents, storage temperature, and time between processing and stabilization.

Essential oils and flavonoid extracts require additional dose-specific evaluation. D-limonene is membrane-active and can alter rumen bacteria; cattle data show biological activity against Fusobacterium necrophorum, but not a uniform improvement in fermentation[89]. In heifers, 0.50% orange essential oil reduced methane but also lowered apparent dry-matter digestibility[16]. Direct evidence that dietary limonene causes chronic rumen-epithelial injury is currently insufficient, so this risk should be tested rather than assumed. Safety conclusions issued for a standardized bitter-orange extract are preparation- and dose-specific and cannot be transferred to uncharacterized pulp or oil[90]. Long-term studies should therefore assess intake, rumen histology and barrier function, liver and kidney indices, reproduction, bioactive-metabolite residues in milk and meat, and possible accumulation or adaptation across a complete production cycle.

8.3. Translation to Commercial Systems and Whole-Chain Sustainability

Future research should move beyond short-term, single-site experiments toward multicenter studies encompassing cattle, sheep, and goats under contrasting diets, climates, production stages, and genetic backgrounds. Recent positive responses to standardized citrus flavonoids in lambs[46] coexist with evidence that high citrus-pulp replacement can reduce intake, nitrogen capture, and milk yield in high-producing cows[9]. Defining species- and production-specific optimal inclusion ranges is therefore more informative than proposing a universal supplementation rate.

Sustainability assessments should integrate animal performance with methane and nitrogen emissions, processing energy, storage losses, transport distance, displaced feed ingredients, and alternative uses of the residue. Drying and additional hydrolysis can alter the environmental advantage of citrus-feed systems[8,77]. Harmonized life-cycle assessments should employ multiple functional units, including product output, nutritional value, land use, and waste managed, while clearly specifying allocation and counterfactual assumptions[91]. Finally, techno-economic feasibility, seasonal supply, farmer adoption, regulatory compliance, consumer acceptance, and traceability require concurrent evaluation to determine whether experimentally effective citrus interventions can deliver durable benefits at commercial scale.

9. Conclusions

Citrus processing by-products represent heterogeneous feed resources in which fermentable nutrients and bioactive phytochemicals interact to influence ruminant production. The pectin-rich carbohydrate matrix can partially replace conventional energy concentrates, whereas flavanone glycosides, polymethoxylated flavones, essential oils, phenolic acids, carotenoids, and limonoids may modulate rumen fermentation, microbial ecology, oxidative status, and lipid metabolism. These combined properties provide opportunities to maintain animal performance, enhance metabolic resilience, and improve selected attributes of milk and meat, including fatty-acid composition, oxidative stability, sensory characteristics, and shelf life.

Nevertheless, responses are strongly dependent on citrus species, by-product fraction, processing method, phytochemical concentration, dietary inclusion level, basal ration, and animal physiological state. Whole citrus pulp should therefore not be considered equivalent to purified citrus extracts, nor should *in vitro* antimicrobial or antimethanogenic effects be directly extrapolated to commercial production. Excessive replacement of cereal concentrates may reduce intake, nutrient utilization, or productivity, potentially offsetting environmental benefits when impacts are expressed per unit of animal product.

The strongest circular-bioeconomy potential is likely to arise from locally integrated and minimally energy-intensive systems that recover high-value phytochemicals where appropriate and subsequently utilize the residual nutrient-rich matrix as ruminant feed. However, avoided waste disposal alone does not establish environmental superiority; drying, extraction, transportation, feed displacement, animal productivity, and alternative residue uses must be considered across the complete life cycle.

Overall, citrus by-products and their phytochemicals offer a promising platform for linking ruminant nutrition with functional animal products and agro-industrial circularity. Their successful implementation will require standardized chemical characterization, dose-response validation, long-term *in vivo* studies, and integrated assessments of animal performance, product quality, emissions, safety, economic feasibility, and environmental sustainability.

Author Contributions

Yuchao Zhao: Writing review & editing, Writing original draft; Linshu Jiang: Supervision, Conceptualization.

Conflicts of Interest

The authors declare that they have no competing interests.

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