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Review

The Role of Phytogenics in Pig Production and Their Proposed Association with the Circular Economy and Life Cycle Assessment: A Narrative Review and Conceptual Framework

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Abstract

The intensification of global pig production has increased the pressure to reconcile productivity with animal health, food safety, and environmental sustainability. Phytogenic feed additives (PFAs)—plant-derived compounds including essential oils, oleoresins, phenolics, and polyphenol-rich extracts—have emerged as candidate alternatives to antibiotic growth promoters, with reported benefits of variable consistency for gut health, oxidative status, reproductive performance, and mycotoxin mitigation across the pig production cycle. In parallel, the pig sector is under increasing scrutiny for its environmental footprint, driving the adoption of circular economy (CE) principles and life cycle assessment (LCA) methodologies to quantify and reduce resource use and emissions. This narrative review synthesizes published evidence on the zootechnical, physiological, and health-related effects of phytogenics in swine, identified through literature searches of PubMed, Scopus, and Web of Science). It examines how their production, sourcing, and use intersect with circular economy strategies—particularly the valorization of agro-industrial by-products as phytogenic sources—and with the LCA-based evaluation of pig production systems. No specific study was identified through the search described that directly measured the environmental footprint of phytogenic feed additive use; the health/performance benefits of phytogenics and the environmental benefits of by-product substitution in pig diets are each independently well supported, but their combined net environmental effect remains unknown, and not all phytogenics originate from by-products; this review integrates the two bodies of evidence into a testable hypothesis—that phytogenics, via reduced morbidity/mortality and, where by-product-derived, circular sourcing, may contribute to a lower environmental footprint, rather than a demonstrated outcome. We regard phytogenics as a promising, mechanistically grounded candidate—rather than a confirmed lever—for reducing the environmental footprint of pig production and propose a concrete LCA methodology to test this hypothesis directly.

Keywords: phytogenic feed additives; pig production; circular economy; narrative review; life cycle assessment; sustainability; oxidative stress; by-products; swine nutrition

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1. Introduction

Pig production is one of the most resource- and emission-intensive branches of livestock agriculture, contributing substantially to feed-related land use, greenhouse gas (GHG) emissions, and nutrient losses associated with manure management [1,2]. At the same time, the restriction of antibiotic growth promoters in many jurisdictions and the rising consumer demand for antibiotic-free, "natural" pork have accelerated interest in phytogenic feed additives (PFAs) as functional alternatives that support gut health, immune function, and productive performance without contributing to antimicrobial resistance [3,4]. This concern extends beyond the farm gate: antimicrobial use in livestock production remains a recognized driver of resistant bacterial strains, with downstream public health implications via the food chain and environmental exposure routes, reinforcing the policy rationale for antibiotic-sparing alternatives such as phytogenics [5].

Phytogenics comprise a heterogeneous group of plant-derived substances—essential oils, oleoresins, flavonoids, tannins, and other phenolic compounds—extracted from herbs, spices, fruits, and agro-industrial residues. Their proposed modes of action include antimicrobial and antioxidant activity, the modulation of the gut microbiota, the stimulation of digestive secretions, and anti-inflammatory effects, which together translate into improved feed efficiency, reduced incidences of enteric disease, and better reproductive outcomes in sows [6,7].

Independently of the nutritional and health rationale, the pig sector is increasingly evaluated through the lens of the circular economy (CE), which seeks to close resource loops by re-introducing by-products, residues, and waste streams into productive use, and life cycle assessment (LCA), the standardized methodological framework (ISO 14040/14044) used to quantify the environmental impacts of a product or system across its life cycle [8,9]. Because many phytogenic sources are themselves agro-industrial by-products (e.g., olive mill wastewater derivatives, bakery residues, herbal processing residues), and because their inclusion in pig diets can influence feed conversion, health-related losses, and downstream waste burdens, phytogenics sit at a natural intersection between animal nutrition, circular bioeconomy strategies, and environmental sustainability assessment.

For clarity, and in response to peer review, this review distinguishes three related but non-equivalent categories of phytogenic- and by-product-related intervention discussed throughout: (i) a phytogenic extract obtained from an agro-industrial co-product, for which both the bioactive compound content and the by-product origin are documented (e.g., a polyphenolic extract purified from olive mill wastewater, Section 3.2); (ii) a plant residue or agro-industrial by-product incorporated and reported as a defined, standardized phytogenic feed additive (e.g., grape/olive extract-based anti-mycotoxin formulations, Section 3.3); and (iii) an agro-industrial by-product used primarily as a bulk feed ingredient, whose nutritional and environmental contribution is not attributable to phytogenic bioactivity and is therefore discussed as a circular economy feed substitution strategy (Section 4) rather than as phytogenic evidence (e.g., bakery meal inclusion). Not every by-product-derived ingredient reviewed here is a phytogenic feed additive, and environmental or circularity claims made in this review are limited throughout to the specific studies and products for which sourcing, processing, and inclusion rates are reported by the original authors.

This review brings together these three strands—phytogenic feed additives, CE, and LCA—as they apply to pig production. The health/performance evidence for phytogenics (Section 3) is drawn from the global primary literature, comprising controlled trials from Europe, Asia, and the Americas; the CE, organic farming, and LCA discussion (Sections 4 and 5) is more specifically focused on conventional and organic commercial systems in Europe, where most of the by-product valorization and LCA case studies cited

here were conducted. Smallholder and subsistence pig systems are outside the present scope. The primary objective of this review is to synthesize the evidence on phytogenic feed additives in pig production and to articulate, as a testable hypothesis, how their health/performance effects and their agro-industrial by-product sourcing may jointly relate to circular economy and life cycle assessment-based measures of environmental performance. Secondary objectives are to map the current phytogenic health/performance evidence base (Section 3), to characterize by-product valorization and circular economy framing in pig production (Section 4), and to review the LCA evidence relevant to interpreting these effects environmentally (Section 5). The geographic asymmetry between the globally sourced health/performance literature and the predominantly European circular economy and LCA literature reflects the current concentration of published by-product valorization and LCA case studies in European systems (Sections 4 and 5); this asymmetry should be borne in mind when extrapolating the review's integrative hypothesis to non-European production systems, where feed markets, by-product availability, and regulatory frameworks differ substantially.

2. Materials and Methods

2.1. Review Design and Protocol

This review is conceived as a narrative and exploratory literature synthesis. The search and selection process was informed by key principles of the PRISMA 2020 statement [10] to enhance transparency and consistency, but the overall methodology prioritized flexibility and integrative synthesis appropriate for mapping an interdisciplinary field spanning animal nutrition, the circular bioeconomy, and environmental assessment. Unlike a full systematic review, this approach enabled the inclusion of primary research, applied field studies, and review articles across three intersecting bodies of literature—phytogenic feed additives, CE/by-product valorization, and life cycle assessment—in order to construct the integrative argument developed in Sections 3–6. Specifically, the elements adapted from PRISMA 2020 were as follows: an a priori definition of eligibility criteria (Section 2.3), a structured and reproducible description of search sources and terms (Section 2.2), and the transparent reporting of the final included corpus (Section 2.2). A registered protocol, a formal PRISMA flow diagram, and per-domain quantitative counts of the records identified, duplicates removed, and full texts assessed for the phytogenic efficacy, by-product valorization, and LCA literature separately were not implemented; this omission is acknowledged as a limitation in Section 7.3. More broadly, this review offers a structured, thematic synthesis of selected studies illustrating the domains under review, and, consistent with its narrative and non-systematic design, it does not claim to capture the entirety of the available literature on phytogenic feed additives, the circular economy, or life cycle assessment in pig production.

2.2. Search Strategy and Data Sources

A literature search was conducted between January and July 2026 across three databases—PubMed, Scopus, and Web of Science—selected for their coverage of the peer-reviewed veterinary, agricultural, and environmental science literature. The search combined keywords grouped into conceptual categories (phytogenic compounds; target species and production system; CE and environmental assessment), using Boolean operators to optimize retrieval against title, abstract, and keyword fields.

Core search string (conceptual):

("phytogenic" OR "essential oil" OR "plant extract" OR "phenolic") AND ("pig" OR "swine" OR "sow" OR "piglet") AND ("circular economy" OR "by-product" OR "life cycle assessment" OR "sustainability").

This conceptual strategy was adapted to the syntax of each database's default interface. Additional search parameters were as follows: publication period, 2009–2026, with an emphasis on the last decade; document type, peer-reviewed journal articles; language, English. Foundational, methodological, or classic disciplinary review sources published before 2009 (e.g., ISO 14040/14044 [9]; the essential oil antibacterial review by Burt [7]; the phytogenic additive review by Windisch et al. [3]) were retained regardless of the publication date, on the grounds that they remain standard, frequently cited reference points for their respective methods or research areas, rather than results superseded by more recent primary data. We further acknowledge that the single, combined AND-based search string above—requiring phytogenic, pig, and sustainability/circular economy/LCA terms to co-occur in the same record—would be unlikely to retrieve, for example, a phytogenic efficacy trial that does not separately mention sustainability or an LCA study that does not mention phytogenics, even though both evidence types are central to this review. Coverage of such single-domain literature was supplemented, albeit not systematically, through the iterative snowball sampling described in Section 2.4. We did not conduct or log separate, database-specific searches restricted to each of the three domains (efficacy, by-product valorization, LCA) with distinct strings, fields, filters, and search dates; this is acknowledged as a further limitation in Section 7.3.

Records identified across the three databases were pooled, de-duplicated, and screened at the title/abstract level against the eligibility criteria defined in Section 2.3; the remaining full-text articles were then assessed for eligibility, and studies meeting the inclusion criteria were retained for narrative synthesis, together with additional records identified through snowball sampling (Section 2.4). In total, 65 references were retained: 62 primary research or review studies, plus 3 foundational methodological/regulatory references (the PRISMA 2020 statement, ISO 14040, and the EFSA FEEDAP efficacy assessment guidance) retained regardless of the publication date, consistent with the criterion stated above. Because this narrative review followed a flexible, exploratory identification strategy rather than a formal systematic review protocol (Section 2.1), granular per-database and per-stage record counts (records retrieved per database, duplicates removed, full texts screened) were not systematically logged during the search process; we therefore report the final included count precisely, while describing the upstream screening funnel qualitatively rather than presenting reconstructed per-stage figures that could not be verified against the original search records.

2.3. Study Selection and Eligibility Criteria

Titles, abstracts, and full texts were screened for thematic relevance to the review's three intersecting domains, rather than for formal methodological appraisal.

Inclusion criteria: primary research or review articles on phytogenic feed additives in pig nutrition and health; studies on circular economy valorization or agro-industrial by-product inclusion in pig diets; life cycle assessment studies of pig production systems; foundational methodological references for LCA or circular economy concepts; peer-reviewed journal articles.

Exclusion criteria: studies on species other than pigs, except where explicitly retained as mechanistic or comparative contexts and flagged as such (e.g., ref. [11], Section 3.3); non-peer-reviewed sources, unless no peer-reviewed equivalent was available for a directly relevant finding (e.g., ref. [12], a research station report also presented as a peer-reviewed conference abstract); publications addressing pig genetics, economics, or social aspects without a nutritional, circularity, or environmental assessment component.

This structured but non-exhaustive selection strategy allowed the inclusion of applied field studies alongside controlled trials, consistent with the review's narrative scope

(Section 7.3). Study selection was performed collectively by the author team (Investigation, Author Contributions) rather than through a formally duplicated, independent screening process with a pre-specified disagreement adjudication procedure; disagreements about borderline records were resolved by discussion among the authors until a consensus was reached. A quantitative log of documents entering the review by domain (phytogenic efficacy, by-product valorization/circular economy, LCA) and identification route (database search versus snowball sampling) was not retained; this is acknowledged as a limitation in Section 7.3. Tables 1 and 2 present the phytogenic health/performance studies and circular economy/LCA studies, respectively, that were judged most directly relevant and most completely reported (in terms of dose/duration or functional unit/system boundary/impact category, respectively) among the eligible records retrieved; this is a purposive rather than exhaustive subset of the eligible literature. Primary research articles are distinguished from review articles and other secondary sources in-text, and non-peer-reviewed sources are used only where explicitly flagged (Section 2.3).

Table 1. Summary of selected phytogenic effects in pig production. Entries are selected illustrative examples rather than an exhaustive or systematically weighted evidence synthesis (Section 2.5).

Production Stage	Phytogenic/Source	Reported Effect	n	Ref.	Inclusion Level/Duration
Weaning piglets	Oregano (*Origanum vulgare*) and garlic (*Allium sativum*) extracts	Reduced severity/duration of proliferative enteropathy	n = 288 piglets (3 groups)	[13]	1 kg Virbamix PE/tonne feed; 6 wk (42 d)
Weaned piglets	Polyphenolic product from olive mill wastewater	Reduced oxidative stress and post-weaning diarrhea	n = 100 piglets (2 groups)	[14]	1 kg/tonne feed; 40 d
Weaned piglets	Tributyrin combined with oregano or methyl salicylate	Improved intestinal morphology; altered microbiota/metabolites as antibiotic substitute	n = 48 piglets (4 groups)	[15]	1.4 g/kg (tributyrin) + 0.6 g/kg (oregano or methyl salicylate); 4 wk
Weaned piglets	Carvacrol, thymol, and cinnamaldehyde essential oil blend	Increased ADFI/ADG; reduced plasma cortisol; improved ileal villus height/crypt depth	n = 24 piglets (2 groups)	[16]	400 mg/kg; 28 d
Weaned piglets	Essential oils (carvacrol/thymol-based)—microbiome–metabolome study	Increased body weight gain; reduced diarrhea incidence; altered colonic microbiota	n = 96 piglets (3 groups)	[17]	62.5 mg/kg carvacrol + 7.5 mg/kg thymol; 30 d
Newly weaned piglets	Functional oil blend (cashew nutshell liquid and castor oil)	Improved daily weight gain and FCR; higher final live weight; reduced Campylobacter/*E. coli*	n = 225 piglets (3 groups)	[18]	0.35% (0.2% + 0.15% blend); 38 d

Table 1. *Cont.*

Production Stage	Phytogenic/Source	Reported Effect	n	Ref.	Inclusion Level/Duration
Weaned piglets	Coated plant essential oil (CEO)	Improved final weight/ADG; reduced diarrhea rate; increased antioxidant enzyme activity	n = 360 piglets (3 groups)	[19]	500 mg/kg; 4 wk
Weaned piglets (F18+ ETEC challenge)	Ground herb-based and essential oil-based phytobiotics	Improved intestinal health and performance under experimental F18+ *E. coli* challenge	n = 40 pigs (4 groups)	[20]	1% + 1% (~5 g/pig/d); 28 d
Primiparous sows (heat stress)	Phenolic phytogenic feed additives	Reduced TBARS/CARB; improved BCS, backfat, and reproductive parameters	n = 48 sows (3 groups)	[21]	5 g/sow/d; 14 d (7 d pre- + 7 d post-farrowing)
Primiparous sows (peripartum)	Phenolic phytogenic feed additive (top-dressing)	Improved redox status, hematology; reduced piglet mortality	n = 64 sows (2 groups)	[22]	10 g/d; 21 d (14 d pre- + 7 d post-farrowing)
Lactating sows	Curcumin/silymarin-based multi-component agent (with clays, postbiotics)	Reduced oxidative stress; improved health and reproductive performance	n = 160 sows (2 farms × 2 groups)	[23]	1.5–2.5 kg/farm (as reported); ~1 month pre-farrowing to end of lactation
Finishing pigs	Microencapsulated blend of organic acids and essential oils (MOE)	Improved growth performance, nutrient digestibility; linear increase in Lactobacillus; improved meat color	n = 75 pigs (3 groups)	[24]	0.05% MOE (Aviplus-S); 10 wk (70 d)
Fattening pigs	Litsea cubeba essential oil (LCO)	Improved blood antioxidant status, immune function, nutrient digestibility, and fecal microflora composition	n = 120 pigs (5 groups)	[25]	250 g/tonne (optimal dose); 35 d (+7 d acclimatization)
Finishing pigs	Plant essential oil (eucalyptus, oregano, thyme, lemon, garlic)	Improved ADG and nutrient digestibility; increased antioxidant capacity and intramuscular fat	n = 18 pigs (2 groups)	[26]	200 mg/kg plant essential oil; 42 d

Table 1. *Cont.*

Production Stage	Phytogenic/Source	Reported Effect	n	Ref.	Inclusion Level/Duration
Growing pigs	Herb and essential oil-based phytobiotic blend, alone or with antibiotic	Improved gain–feed without compromising weight gain; reduced jejunal inflammation	n = 96 pigs (4 groups)	[27]	0.05%; 42 d
Grow–finish pigs (commercial, n = 1245–1260)	Essential oil mixtures (caraway, garlic, thyme, cinnamon; oregano, citrus, anise)	Evaluated growth performance, carcass characteristics, and economic returns relative to control and ractopamine	n ≈ 1245–1260 pigs (2 groups)	[12]	Not disclosed (proprietary blend); 125 d
Growing–finishing pigs	Oregano essential oil (OEO)	Limited effects on carcass quality and hematology despite significant jejunal/ileal transcriptomic modulation—an example of biomarker-level response without corresponding zootechnical benefit	n = 86 pigs (2 groups)	[28]	1500 mg/kg feed (7.5% OEO); weaning (28 d) to 170 d (~142 d)
Organic pig farms	Mixed phytogenic feed additives	Alternative to antibiotics for enteric disease control and growth promotion	n = 200 piglets (2 groups)	[29]	1 kg/tonne feed or 50 ppm (cited primary studies); duration not specified (narrative review)

Table 2. Complementary contributions of phytogenic/by-product research and dedicated LCA studies to the environmental assessment of pig production. Entries are likewise a purposive selection of illustrative studies, not an exhaustive or systematically weighted synthesis of the LCA literature (Section 2.5).

Focus Area	Contribution	Ref.
[Review/synthesis] By-product/phytogenic valorization in pig diets	Synthesis of nutritional, environmental, and economic evidence for food industry by-products as circular feed ingredients	[30]
[Review/synthesis] Organic pig farming and SDGs	Critical assessment of environmental performance, animal health/welfare, and economic sustainability of organic pig systems	[31]
[Review/synthesis] Farrow-to-finish LCA review	Chronological synthesis of farrow-to-finish pig LCAs; alternative/organic systems generally use more land, with mixed effects on energy and emissions	[2]
[Primary case study (by-product/circularity)] Bakery meal LCA case study	Quantified ~30% land occupation reduction and improved FCR from 20% bakery meal inclusion (SimaPro-based LCIA)	[32]

Table 2. *Cont.*

Focus Area	Contribution	Ref.
[Primary case study (by-product/circularity)] Circularity indicators in pig LCA	Comparison of circularity indicators with conventional LCA impact categories across five circular strategies (manure/bread waste digestion, precision fertilization, cover crops, bread waste as feed)	[33]
[Primary case study (by-product/circularity)] Feed reformulation LCA	Multi-objective optimization of pig diets with black soldier fly meal, bakery by-product, and pea, evaluated across ten LCA impact categories; up to 9% impact reduction and 28% cost saving	[34]
[Contextual comparator] Genetic selection LCA	Quantified ~0.9%/year reduction in most environmental impact categories (2021–2030), attributable to genetic trends in reproduction/growth traits. Included as a comparator benchmark for the magnitude of annual environmental impact reduction achievable through non-nutritional (breeding) levers, alongside the feed substitution strategies above	[35]
[Contextual case study] National LCA case study	Cradle-to-slaughterhouse-gate LCA of pig/pork production; feed ingredient production identified as the largest contributor to the environmental burden across scenarios	[36]
[Contextual case study] Protein source comparison LCA	Comparative LCA of pork using different protein sources in pig feed; quantified differences in climate change, acidification, and eutrophication by protein source	[37]
[Contextual case study] Multi-farm LCA case studies	Cradle-to-gate LCA across seven case studies (four pig farms, one slaughterhouse, two processing facilities); identified system-specific environmental hotspots along the pork value chain	[38]

2.4. Iterative Search and Snowball Sampling

To ensure the adequate coverage of the interdisciplinary literature not fully indexed under a single controlled vocabulary, the identification process was iterative. An initial database search provided a core corpus; the reference lists of retrieved articles and key reviews were then hand-searched to identify additional relevant studies (snowball sampling). All publications identified through either route were evaluated against the same eligibility criteria described in Section 2.3.

2.5. Data Extraction and Thematic Synthesis

For studies on phytogenic health/performance effects (Section 3), extracted information included the production stage, phytogenic compound or source, reported outcome, sample size, and inclusion level (dose) and duration, as summarized in Table 1. For circular economy and LCA studies (Sections 4 and 5), extracted information included the focus area, methodological approach, and quantified environmental or economic contribution, as summarized in Table 2. Extraction was intentionally descriptive rather than standardized to a single fixed outcome metric, given the heterogeneity in compound classes, production stages, and impact assessment methods across the included literature. The extracted material was organized thematically into the three intersecting domains structuring Sections 3–6. The study design (e.g., randomized controlled trial versus observational field study), allocation method, experimental unit, comparator arm, health status or challenge model, attrition, and measures of statistical precision (e.g., confidence intervals) were not systematically extracted across all included studies and are therefore not reported in Table 1; this constrains the formal appraisal of validity and applicability and is acknowledged as a limitation in Section 7.3. Statements elsewhere in this review (e.g., Section 3.4) about the overall "balance" of the phytogenic evidence base should accordingly be read as the

qualitative, narrative characterization of the reviewed literature's general tenor, rather than a quantitatively weighted synthesis.

2.6. Quality Considerations and Synthesis Approach

In line with the narrative, non-systematic design, a formal risk-of-bias or quality scoring instrument (e.g., SYRCLE's risk-of-bias tool for animal studies) was not applied; this is acknowledged as a limitation in Section 7.3. Instead, quality was considered qualitatively during synthesis: findings that diverged from the broader pattern reported in the literature were retained and discussed explicitly rather than down-weighted (e.g., ref. [28], Section 3.4), and studies with disclosed commercial or industry funding were flagged transparently alongside independently funded studies (Section 3.4). This descriptive approach prioritizes interpretability and transparency over a numerically ranked appraisal, consistent with the review's integrative rather than quantitative synthesis objective. We consider this trade-off appropriate for a narrative, hypothesis-generating synthesis spanning three methodologically distinct bodies of literature (animal nutrition trials, circular economy case studies, and LCA modeling studies), for which a single standardized risk-of-bias instrument is not well suited; nonetheless, we acknowledge that this qualitative approach cannot fully substitute a formal appraisal, and we recommend that a future systematic review (Section 7.3) apply a validated tool such as SYRCLE's risk-of-bias tool to the phytogenic health/performance literature specifically.

2.7. Use of Generative Artificial Intelligence (GenAI)

Generative AI (ChatGPT Go, GPT-4o model, May 2024 version, OpenAI, San Francisco, CA, USA) was used during manuscript preparation in a strictly non-decisional, illustrative capacity. Full disclosure is provided in the Artificial Intelligence Statement following the Conclusions, in accordance with the journal's author guidelines.

3. Phytogenic Feed Additives in Pig Production

The evidence synthesized in this section sits within a rapidly expanding body of literature: recent reviews have similarly cataloged the growth performance, nutrient utilization, gut health, and meat quality effects of phytogenics specifically in swine [39], and a global systematic review across livestock species more broadly confirms the consistent, albeit compound- and dose-dependent, benefits for growth and immune responses [40]. The present synthesis is also consistent with the broader framing of phytogenics as one class within the wider family of natural bioactive feed additives being developed for sustainable and functional livestock production [41].

3.1. Control of Enteric Disease and Gut Health

The need for alternatives to antibiotics has gained particular urgency in the European Union following the 2022 withdrawal of pharmacological zinc oxide, historically the mainstay control for post-weaning diarrhea; producer perception surveys conducted around this withdrawal report substantial perceived increases in diarrhea incidence and treatment costs, underscoring the practical demand for effective phytogenic and other non-antibiotic alternatives [42]. Dietary extracts of oregano (*Origanum vulgare*) and garlic (*Allium sativum*) reduced the severity and duration of proliferative enteropathy in weaning pigs, supporting their antimicrobial and gut-protective activities as alternatives to conventional antimicrobial control strategies [13]. Independent studies have since reported broadly consistent gut health benefits from essential oil-based phytogenics in weaned piglets: dietary tributyrin combined with oregano or methyl salicylate improved the intestinal morphology and altered the gut microbiota and metabolites [15], and blends of carvacrol, thymol, and cinnamaldehyde increased feed intake and weight gain (e.g., average daily gain rising from

356 to 416 g/day, an approximately 17% increase, in ref. [17]; exact magnitude not stated in the published abstract/results excerpt for ref. [16]) while improving the ileal villus height and villus-to-crypt-depth ratio [16,17]. Mechanistically, these benefits are increasingly linked to phytogenic-driven shifts in short-chain fatty acid-producing taxa and epithelial barrier gene expression in the piglet gut, consistent with a broader synthesis of gut health mechanisms across monogastric species [43]. Directly illustrating this substitution potential, a recent controlled challenge study found that tannin-rich plant extracts, alone or combined with a reduced ("potentiated") zinc dose, lowered the enterotoxigenic *Escherichia coli* (ETEC) infection severity while also reducing the abundance of antimicrobial resistance genes in the gut microbiome relative to pharmacological zinc oxide, providing direct mechanistic and AMR-relevant support for phytogenic replacement strategies [44]. This is corroborated by a recent controlled F18+ *Escherichia coli* challenge trial in nursery pigs, in which ground herb- and essential oil-based phytobiotics improved intestinal health and performance under experimental infection pressure [20], and is consistent with a broader invited review of tannins specifically as an antibiotic-sparing strategy against coliform diarrhea in weaned pigs [45].

The evidence is not uniformly positive, however. A controlled trial of oregano essential oil in growing–finishing pigs found only limited effects on carcass quality and on standard hematological indices—significantly reduced hemoglobin, hematocrit, MCV, and MCH, together with an increased band neutrophil count, in the OEO-supplemented group at weaning (28 d), and an isolated increase in platelet count at mid-fattening (130 d), with no further differences at later sampling points—despite the significant modulation of jejunal and ileal gene expression, illustrating that transcriptomic or biomarker-level responses to phytogenics do not always translate into detectable zootechnical or carcass-level outcomes [28]. The practical use of phytogenic feed additives by pig farmers could serve as a tool for the prevention and control of enteric disease and as a natural growth promoter in the context of a rapidly expanding organic pig sector where, under EU organic production rules, the preventive use of synthetic antimicrobials and any use for growth promotion are prohibited, although veterinary medicinal products, including antibiotics, may still be administered therapeutically when clinically necessary and under veterinary responsibility [29]. This work highlights phytogenics not merely as a laboratory-tested intervention but as an applied, farm-level strategy already embedded in alternative production systems that explicitly prioritize environmental and welfare outcomes.

3.2. Oxidative Stress, Sow Performance, and Reproductive Outcomes

A growing, though still limited, body of recent phytogenic research in pigs has focused on the peripartal sow, a physiological stage characterized by heightened oxidative stress due to the metabolic demands of late gestation, farrowing, and lactation, often compounded by heat stress. Phenolic phytogenic feed additives reduced oxidative damage biomarkers—thiobarbituric acid-reactive substances (TBARS) and protein carbonyls (CARB)—and improved body condition, backfat retention, and reproductive parameters in primiparous sows exposed to heat stress under commercial field conditions [21].

A follow-up field study by the same group evaluated a phytogenic feed additive administered as a top-dressing before farrowing and through early lactation, reporting an improved redox status, favorable hematological indices (significantly higher packed cell volume and platelet count and near-significantly higher white blood cell/neutrophil counts, versus control), and reduced piglet mortality in primiparous sows, reinforcing the role of phenolic phytogenics as a practical tool for improving both sow welfare and litter survival under commercial conditions [22].

Complementary work from the same research group examined a natural polyphenolic product derived from olive mill wastewater—itself a circular economy-relevant by-product of olive oil production—and reported reductions in oxidative stress and post-weaning diarrhea incidence in piglets, illustrating how phytogenic bioactivity and by-product valorization can be addressed within the same experimental framework [14]. Similar antioxidant-mediated benefits have been reported by independent groups using structurally distinct phytogenics—for example, a commercial functional oil blend based on cashew nutshell liquid and castor oil improved weight gain and feed conversion and reduced pathogenic bacterial shedding in newly weaned piglets [18]—suggesting that antioxidant and gut-modulatory effects are not restricted to a single compound class, although direct head-to-head comparisons across compound classes remain scarce.

3.3. Mycotoxin Mitigation

Phytogenic compounds are also increasingly incorporated into multi-component detoxifying agents used to counter mycotoxin contamination in pig feed, a persistent challenge for feed safety and animal health. It was reported that a multi-component mycotoxin-detoxifying agent combining clays (bentonite, sepiolite) with phytogenic feed additives (curcumin, silymarin) and postbiotics (yeast cell wall, hydrolyzed yeast) improved the antioxidant capacity, health status, and reproductive performance of sows under field conditions [23]. Related work by the same group evaluated a structurally similar phytogenic-based liquid anti-mycotoxin agent (grape and olive extracts) in broilers rather than pigs; it is cited here specifically because it shared the same detoxifying agent formulation class as the sow study above [23] and reported an improved redox status and performance outcomes in large-scale commercial flocks (>45,000 birds) [11]. This cross-species evidence is included only as mechanistic context for a shared formulation strategy, not as direct evidence in pigs, and should be weighted accordingly by the reader. This mirrors a broader pattern in the poultry literature, where phytogenic feed additives are similarly reviewed as antibiotic-sparing strategies, reinforcing the notion that the mechanistic rationale for phytogenic use is not unique to swine production [46].

The mechanisms proposed to underlie these effects are summarized schematically in Figure 1. This is a conceptual synthesis drawn across multiple studies and compound classes rather than a pathway established within a single experiment; evidentiary strength varies across the pathways shown, from well-replicated (e.g., antimicrobial/antioxidant activity of essential oils) to preliminary (e.g., links to specific production outcomes).

3.4. Summary of Mechanisms, Heterogeneity, and Effects

As Table 1 illustrates, the phytogenic literature in pigs is highly heterogeneous across compound classes, doses, production stages, and measured outcomes, and the reported effects are not uniformly positive. The Hofmann et al. study [28] is a useful counter-example to the generally favorable findings summarized above: despite the significant modulation of intestinal gene expression, oregano essential oil produced only limited effects on carcass quality and blood hematology in growing–finishing pigs, illustrating that molecular- or biomarker-level responses to phytogenics do not necessarily translate into commercially relevant outcomes. More broadly, published meta-analyses and reviews of essential oils in weaned piglets report improved average daily gain and reduced diarrhea incidence on average but also flag considerable between-study heterogeneity and caution that high inclusion levels can reduce feed intake or have adverse effects [3]. Readers should treat the positive tenor of Table 1 as reflecting the general pattern observed among the selected studies rather than a uniform effect; compound, dose, and context specificity make direct comparison across studies difficult. A more recent systematic review and

meta-analysis spanning the nursery to finishing phases reached a similar conclusion: phytogenic effects on growth performance are inconsistent and context-dependent—diminishing under adequate amino acid supply and becoming more apparent under disease or stress challenge—while also noting that many primary studies omit essential methodological details, limiting quantitative synthesis [47]. Addressing this inconsistency has increasingly been framed as a formulation problem rather than a purely biological one, with recent work cataloging strategic technologies—including standardized extraction, blending, and stabilization approaches—aimed at improving the batch-to-batch efficacy of phytogenic feed additives [48]. Combining phytogenics with other functional additive classes is also gaining attention: a recent synthesis of postbiotic and phytogenic feed additives highlights potential synergistic effects on gut barrier integrity, immune signaling, and growth performance across monogastric species, suggesting combination strategies as a promising extension of the single-compound-class evidence reviewed here [49]. A recent review of probiotics, prebiotics, and synbiotics in pigs and poultry similarly highlights the gut health and performance benefits of such combination strategies, while additionally reporting environmental co-benefits (e.g., reduced nutrient excretion), reinforcing the relevance of this combination strategy literature to both the health and environmental strands of the present review [50].

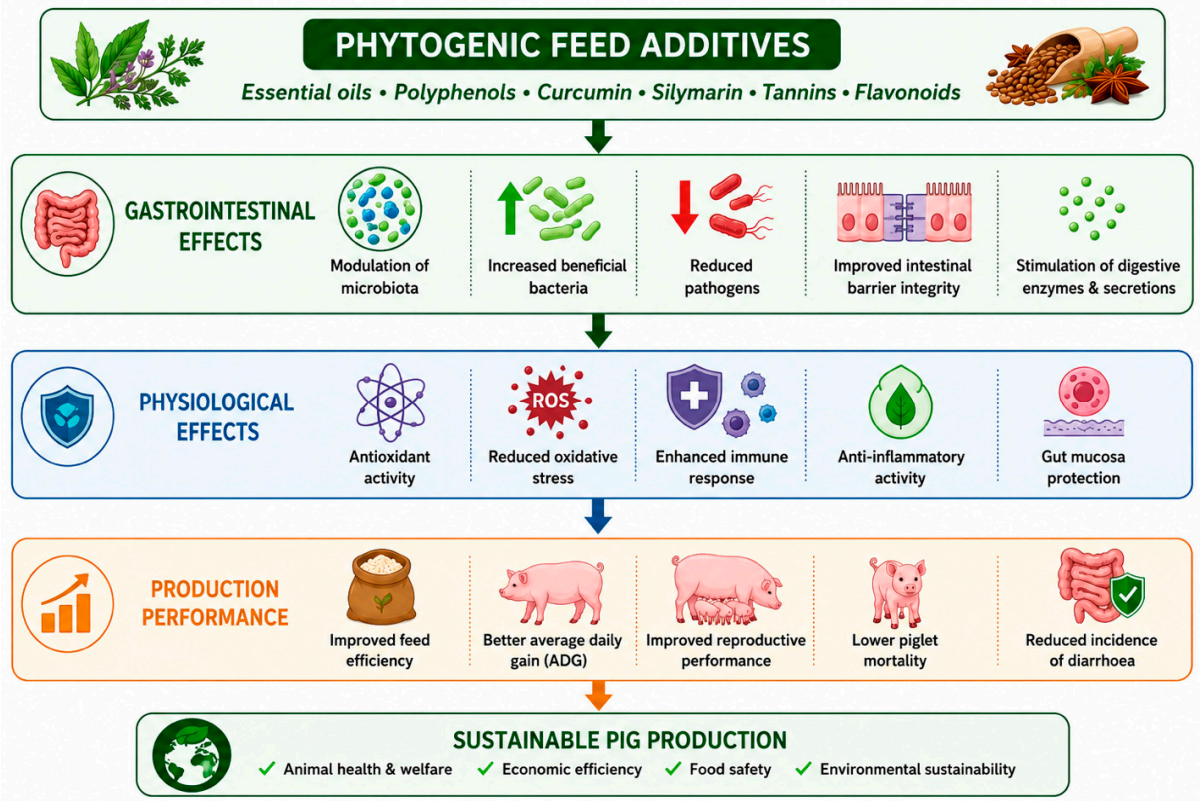


Figure 1. Conceptual, literature-derived synthesis of biological mechanisms linking phytogenic feed additives to gut health, oxidative status, immune function, and productive performance in pigs, integrating pathways reported across multiple, methodologically heterogeneous studies (Section 3.4).

A further consideration for interpreting this evidence base is the funding source. Several of the primiparous sow studies discussed in Section 3.2, including ref. [21], disclose partial funding or product provision from commercial phytogenic additive manufacturers (e.g., Life Circle Nutrition AG); this is disclosed transparently in the original publications and does not by itself invalidate the findings, but it is noted here in the interest of transparency, since a portion of the evidence base underpinning this review's central thesis is

derived from industry-supported trials. Readers seeking a fully independent replication should weigh this alongside the non-industry-funded studies also cited in Table 1.

Table 1 presents a purposive selection of studies that were judged most directly relevant and most completely reported among the eligible phytogenic health/performance literature retrieved (Section 2.3), rather than an exhaustive systematic evidence matrix; it predominantly reports favorable outcomes because such outcomes were more consistently and completely reported in the identified literature, and the Hofmann et al. study [28], which reported limited zootechnical effects, is retained as a documented counter-example (Sections 3.1 and 3.4). Reported sample sizes (n) denote the total animals allocated to the trial and do not indicate the experimental unit (individual animal versus pen/group), which was not consistently reported across the underlying studies and is not separately extracted here. The study design, comparator arm, health status/challenge, effect estimate, precision, and study-specific limitations are not tabulated for each row; this is a further limitation of the descriptive format adopted here (Section 7.3). Entries in the "Reported Effect" column reflect the outcome measures and conclusions as stated by the original authors and have not been independently re-derived from raw study data; readers should consult the cited primary sources directly for effect sizes, confidence intervals, and study-specific limitations. A systematic, row-by-row funding/conflict of interest disclosure comparable to the paragraph above was not compiled for every study in Table 1 and represents a further direction for a future, more formal evidence synthesis.

4. Phytogenics and the Circular Economy in Pig Production

The circular economy paradigm reframes agricultural and agro-industrial residues as resources rather than waste, seeking to "close the loop" between food processing and animal feeding [8,51]. Many phytogenic sources used in pig nutrition are, by nature, by-products of other supply chains: olive mill wastewater and pomace from olive oil production, grape extracts and marc from winemaking, and herbal or spice processing residues. Their inclusion in pig diets therefore serves a dual function—delivering bioactive, health-promoting compounds while simultaneously diverting agro-industrial residues away from disposal, in line with three of the core circular economy strategies described by Kirchherr et al. [51]: "closing" resource loops (recycling a residue back into a production system, e.g., feeding a processing by-product), "narrowing" resource loops (using fewer resources per unit of output, e.g., reducing feed inputs through improved efficiency), and "slowing" resource loops (extending a resource's useful life through reuse, repair, or multiple sequential service cycles before final disposal—a strategy that is less directly exemplified by the single-pass by-product-to-feed pathways discussed in this review, which more closely resemble "closing" or cascading resource loops). This framing is increasingly reflected at the policy level: recent analyses of livestock-sector circular bioeconomy policy note that circular economy and bioeconomy strategies have often been developed independently across jurisdictions, and they call for their deliberate integration—including the explicit recognition of livestock's capacity to upcycle agro-industrial biomass—within a coherent circular bioeconomy policy framework [52]. This is consistent with a broader conceptual shift recognizing livestock not as an inefficiency to be minimized but as an essential upcycling node within the circular bioeconomy—converting otherwise low-value biomass, by-products, and human-inedible feedstuffs into high-quality protein—a role that is increasingly emphasized in the sustainability literature [53].

Using an agro-industrial residue as a feed ingredient does not, by itself, guarantee a lower environmental impact. The outcome depends on the displaced counterfactual use of the residue (e.g., disposal, composting, or an alternative productive use), its waste versus co-product status and the environmental burdens assigned to it, the processing required to

render it usable (e.g., drying, extraction, stabilization), the transport distance, and the substitution rate actually achieved in the diet. Circularity indicators (e.g., material recirculation rate) and LCA impact categories (e.g., global warming potential, land occupation) capture different dimensions of this outcome and do not necessarily move in parallel (Section 5); throughout this review, an environmental benefit is claimed only where it is supported by a dedicated LCA study reporting these factors, and circularity per se is not treated as evidence of a reduced environmental impact.

This dual function is made explicit in the recent review by Papatsiros et al., which systematically examined the nutritional, environmental, and economic dimensions of incorporating food industry by-products—including bakery residues, fruit and vegetable processing residues, and other agro-industrial co-products—into pig diets as a strategy to reduce the environmental footprint of the sector [30]. The review, based on a structured search of Scopus, PubMed, and Web of Science combining terms such as "pig OR swine", "by-products OR co-products OR food waste", and "circular economy OR sustainability OR environmental impact", concluded that the sustainable valorization of food processing residues represents a viable option for reducing environmental pressure while addressing challenges related to feed safety, compositional variability, and regulatory harmonization [30].

Beyond formulation-level substitution, circular economy thinking has also been applied to whole-farm and territorial systems. Independent LCA-based research on the inclusion of bakery meal as a pig feed ingredient in Greece demonstrated environmentally beneficial outcomes, including an approximately 30% reduction in land occupation linked to the reduced use of wheat and soybean meal, alongside improvements in the feed conversion ratio [32]. Such findings reinforce the principle—consistent with the by-product valorization strategies [30]—that circular feed ingredients, including phytogenic-rich residues, can simultaneously advance feed efficiency and environmental performance when logistics and supply consistency are adequately managed.

Organic pig farming provides a further point of convergence between phytogenics and circular economy principles, since organic systems prohibit synthetic growth promoters and rely more heavily on natural feed additives, including phytogenics, while also emphasizing closed-loop nutrient cycles, pasture-based systems, and reduced reliance on imported concentrate feed [29,31]. However, organic status alone does not guarantee superior environmental or circularity outcomes; continued improvements in feed sourcing, land use efficiency, and quantitative sustainability indicators—including LCA-based metrics—are required for organic and phytogenic-supported systems to substantiate their sustainability claims [31].

Beyond agro-industrial by-products, other circular protein and bioactive sources are increasingly discussed alongside phytogenics within the same circular bioeconomy framing: insect meals produced on organic side-streams are an actively researched circular protein source for monogastric diets, illustrating the breadth of circular feed ingredient strategies being developed in parallel with by-product-derived phytogenics [54]. At the policy level, recent analyses of EU protein self-sufficiency similarly identify circular, non-conventional feed sources—including by-products, insects, and novel plant proteins—as central to reducing the livestock sector's reliance on imported, land-intensive protein feedstuffs, situating the phytogenic and by-product sourcing strategies discussed in this review within a broader EU feed security context [55].

5. The Relevance of Life Cycle Assessment for Evaluating Phytogenic Feed Additives in Pig Production

LCA has become the reference methodology for quantifying the environmental performance of pig production, typically covering feed production, on-farm rearing, and, in cradle-to-gate or cradle-to-slaughterhouse-gate studies, downstream processing [9,56].

Across the literature, feed production consistently emerges as the dominant contributor to several impact categories in conventional pig systems, commonly reported to account for roughly 60–80% of the climate change impact and an even higher share of land occupation in cradle-to-farm-gate studies, although the exact proportion varies with the system boundary, feed composition, and impact assessment method used [34]. This is why feed reformulation—including the substitution of conventional protein sources with alternative or by-product-derived ingredients—is a central lever for environmental improvement [9,34]. (The 60–80% range above reflects pig- and livestock-specific estimates reviewed within [34]—e.g., feed alone accounting for roughly 55–75% of the climate change impact and feed crop cultivation for up to approximately 67%—rather than the ISO 14040 standard itself, which defines the LCA methodology but is not itself an empirical data source.) A recent systematic review of the livestock LCA methodology, encompassing 93 studies, including 29 on pig production, similarly highlights persistent harmonization challenges across functional units, system boundaries, and impact assessment methods, reinforcing the need for the standardized reporting emphasized throughout this review [57]. This range is drawn from cradle-to-farm-gate pig production LCA studies using varying functional units (e.g., per kg live weight or per kg carcass weight) and system boundaries [9,34]; a single, harmonized estimate with a consistently matched functional unit, system boundary, geography, and method was not extracted for this narrative synthesis, and it should be read as an order-of-magnitude benchmark from the general pig LCA literature rather than a phytogenic-specific or precisely comparable figure.

The environmental LCA evidence reviewed above also sits alongside a broader movement to extend life cycle thinking in pig production beyond purely environmental impact categories. A recent application of social life cycle assessment (S-LCA) to the pig value chain in Ireland demonstrates how social dimensions—labor conditions, community impacts, and animal–worker interactions—can be systematically incorporated alongside conventional LCA [58], while a complementary methodological proposal argues for explicitly embedding animal welfare indicators within life cycle assessments of livestock systems [59]. Neither social nor welfare dimensions have yet been linked specifically to phytogenic feed additive use, but both represent natural extensions of the LCA methodology proposed in Section 7.2. On the environmental side specifically, a recent systematic review of life cycle greenhouse gas accounting in intensive pig farming reinforces the notion that feed production and manure management remain the dominant, and most heterogeneously reported, contributors to the sector's carbon footprint, underscoring the importance of the standardized reporting emphasized throughout this review [60].

The review by Papatsiros et al. [30], focusing on food industry by-products, explicitly situates its nutritional and economic analysis within this environmental impact framework, arguing that by-product inclusion reduces the environmental footprint of pig diets by lowering the demand for conventional, resource-intensive ingredients such as cereals and soybean meal, whose cultivation is strongly associated with land use and greenhouse gas emissions in LCA studies of pig production [30,34]. Although this review is primarily a synthesis of nutritional and economic evidence rather than a primary LCA study, its framing directly aligns phytogenic- and by-product-based feeding strategies with the environmental hotspots identified by dedicated LCA research on pig production systems [9,32].

More broadly, recent LCA research on pig feed reformulation has shown that introducing alternative ingredients—such as insect meal, bakery by-products, and legumes—into multi-objective optimized diets can reduce environmental impacts across several categories, although trade-offs between environmental benefit, cost, and nutritional adequacy must be carefully balanced [34]. Similarly, work applying circularity indicators alongside conventional LCA impact categories in pig production systems has shown that strategies such as

the anaerobic digestion of manure and bread waste, precision fertilization, and the use of by-products as feed can simultaneously improve both circularity metrics and traditional environmental impact scores, although the two types of indicators do not always move in parallel and require joint reporting for a complete sustainability picture [33].

It is important to distinguish the environmental benefits attributable to feed substitution as a general circular economy strategy—for example, replacing soybean meal or other conventional ingredients with agro-industrial by-products, which is the mechanism quantified in most of the LCA studies discussed above [32–34]—from those that could be specifically attributable to the phytogenic bioactive compounds themselves. Phytogenics may plausibly confer an additional, mechanistically distinct environmental benefit through improved nutrient digestibility and gut health, which can reduce nitrogen and phosphorus excretion and alter the manure composition independently of any by-product substitution effect; however, this phytogenic-specific pathway has not yet been isolated or quantified in a dedicated LCA study, and the feed substitution and phytogenic-specific contributions to environmental performance should therefore not be conflated when interpreting the evidence reviewed in Sections 4–6.

Selected quantified examples of these feed-substitution-associated environmental and economic benefits, reported individually alongside their original study context rather than combined into a single comparable metric, are summarized in Table 3.

Table 3. Selected quantified environmental and economic benefits associated with circular by-product inclusion in pig diets, reported individually with their original study context (replacing the earlier bar-chart presentation of these data, whose internal reference labels did not match the manuscript's reference numbering and which plotted non-commensurable metrics on a shared percentage axis). Values are not directly comparable to one another, since each is derived from a different functional unit, system boundary, and study; they illustrate the order of magnitude of the reported benefits only, and none are phytogenic-specific. The environmental reduction and cost saving values above have been corrected to specify that, although both are derived from the same multi-objective optimization study, they correspond to different ingredient substitution scenarios and outcome metrics within that study and should not be read as two benefits of a single formulation.

Metric	Reported Value	Study Context	Ref.
Land occupation reduction	≈30%	Cradle-to-farm-gate LCA of 20% bakery meal inclusion replacing wheat and soybean meal in pig diets (Greek circular bioeconomy case study)	[32]
LCA impact category reduction (across ten categories assessed)	up to 9%	Multi-objective optimization of pig diets incorporating black soldier fly meal, bakery by-product, and pea; the ~9% reduction (across ten LCA impact categories) corresponds specifically to the bakery-by-product-substituted diet scenario, evaluated separately from the other tested ingredients	[34]
Feed cost saving	up to 28%	Same multi-objective optimization study as above; however, the ~28% saving corresponds specifically to the pea-substituted diet scenario—a different ingredient and outcome from the environmental impact reduction reported above, not a combined-formulation result	[34]

6. Integrating Phytogenics, Circular Economy, and LCA: Toward a Coherent Framework

Taken together, the evidence reviewed here suggests three complementary pathways through which phytogenics contribute to more circular and environmentally accountable pig production. First, at the health and productivity level, phytogenics reduce losses associated with enteric disease, oxidative stress, and mycotoxin exposure [13,21–23], and reduced morbidity and mortality translate directly into a lower environmental burden per unit of pig meat produced, since resources invested in animals that die prematurely or perform poorly are effectively wasted from an LCA perspective [9]. This principle has recently been demonstrated empirically, if not yet for phytogenics specifically: a large-scale LCA of Porcine Reproductive and Respiratory Syndrome (PRRS) across North American sow and wean-to-finish farms found that PRRS-negative farms had a 4–9% lower environmental footprint than PRRS-positive farms, driven primarily by worsened feed conversion and productivity losses in affected herds [61]. This disease-specific evidence directly substantiates the causal mechanism proposed here for phytogenics—that health-related productivity losses translate measurably into a higher environmental burden per unit of pig meat produced—even though the phytogenic-specific link itself remains to be tested directly (Section 7.2).

Second, at the ingredient-sourcing level, many phytogenic actives originate from agro-industrial by-products—olive mill wastewater, grape and olive extracts, and other processing residues—whose use as feed additives exemplifies circular economy "closing the loop" strategies while simultaneously supplying bioactive compounds with a demonstrated zootechnical benefit [11,14,30]. This dual-purpose sourcing distinguishes phytogenics from purely synthetic feed additives and positions them as a natural fit for circular bioeconomy strategies in the pig sector. It is important to note that this ingredient-sourcing benefit reflects the general circular economy strategy of by-product valorization, common to any by-product-derived feed ingredient; the extent to which the phytogenic bioactivity of these particular sources confers an additional, compound-specific environmental benefit—for example, through altered nutrient digestibility or manure composition (see Section 5)—remains a distinct and, as yet, separately unquantified question.

Third, at the systems evaluation level, the explicit framing of by-product and phytogenic use within circular economy and environmental footprint terminology [30,31] signals a shift from viewing phytogenics purely as a health and performance intervention toward viewing them as a component of a sustainability strategy that should, in principle, be quantified using a standardized LCA methodology. To date, however, dedicated LCA studies quantifying the specific environmental impacts of including phytogenic feed additives in pig diets—as distinct from broader by-product or ingredient substitution studies—remain scarce, representing an important gap for future research.

Figure 2 summarizes this proposed integration schematically. Like Figure 3, it is a conceptual synthesis organizing the review's argument, rather than a depiction of jointly measured outcomes: the environmental footprint items shown (e.g., GHG emissions, manure output, land use) are drawn from the by-product substitution and organic farming LCA literature (Sections 4 and 5) and have not yet been quantified specifically for phytogenic feed additives—the research gap that is addressed methodologically in Section 7.2. Figures 2 and 3 present highly similar integrations; rather than consolidating them in this section, each figure's caption states explicitly that its links are each supported by evidence within an individual domain, and the complete, integrated pathway shown remains conceptual and hypothetical, not yet evaluated jointly within a single study (Section 7.2).

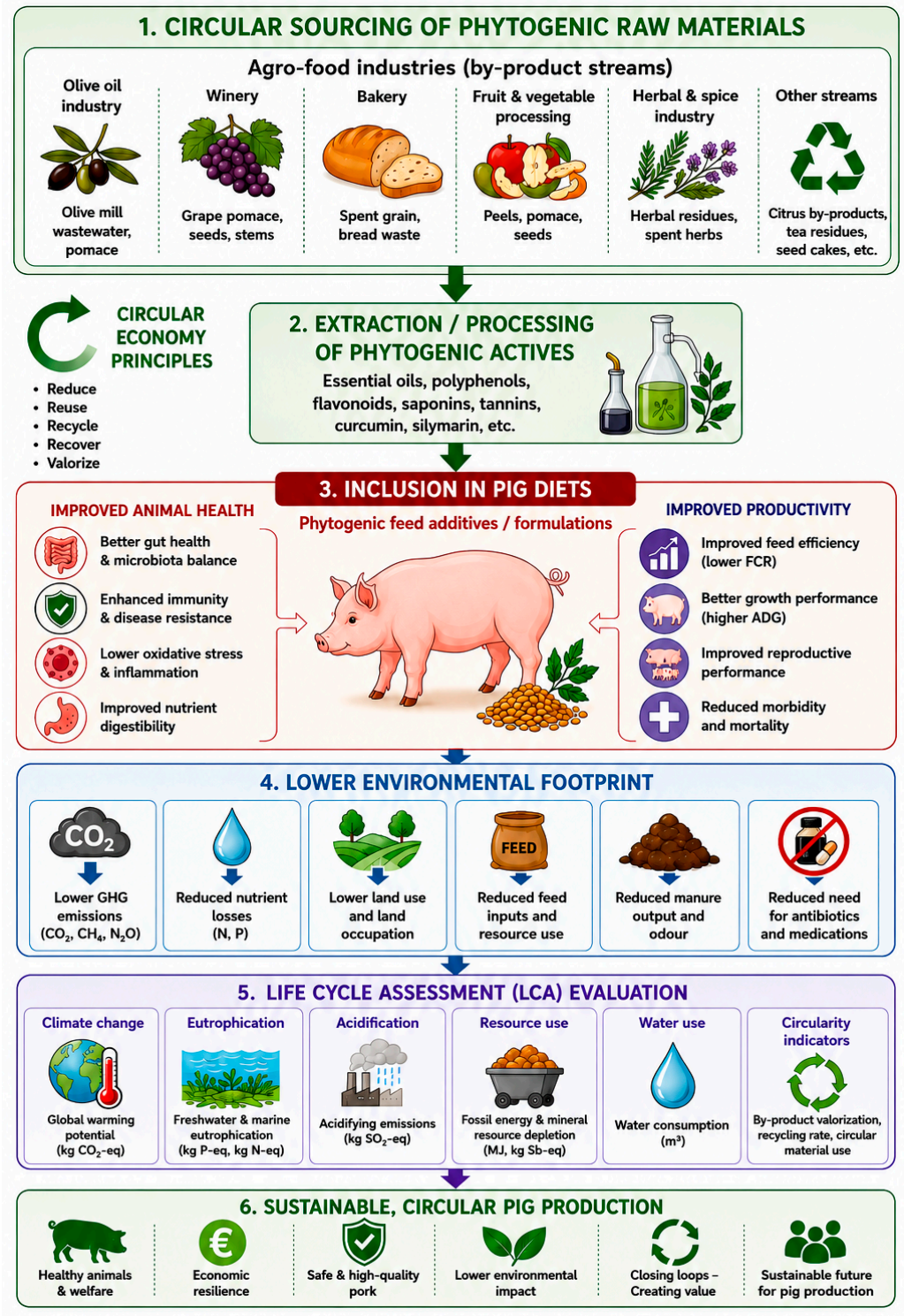


Figure 2. Conceptual, author-proposed framework illustrating how agro-industrial by-products could be converted into phytogenic feed additives that improve pig health and productivity while reducing environmental burdens, with life cycle assessment (LCA) as the methodology for quantifying these benefits. Outcomes shown are drawn from separate bodies of literature (by-product substitution LCA studies; phytogenic health/performance studies) and have not yet been jointly measured within a single phytogenic-specific LCA study (Sections 6 and 7.2). We clarify here, in the caption, that stages 4 ("Lower environmental footprint") and 6 ("Sustainable, circular pig production") represent hypothesized, not yet empirically demonstrated, integrated outcomes: each link is supported by evidence within an individual domain, but the complete pathway shown has not been evaluated jointly, across domains, within a single study.

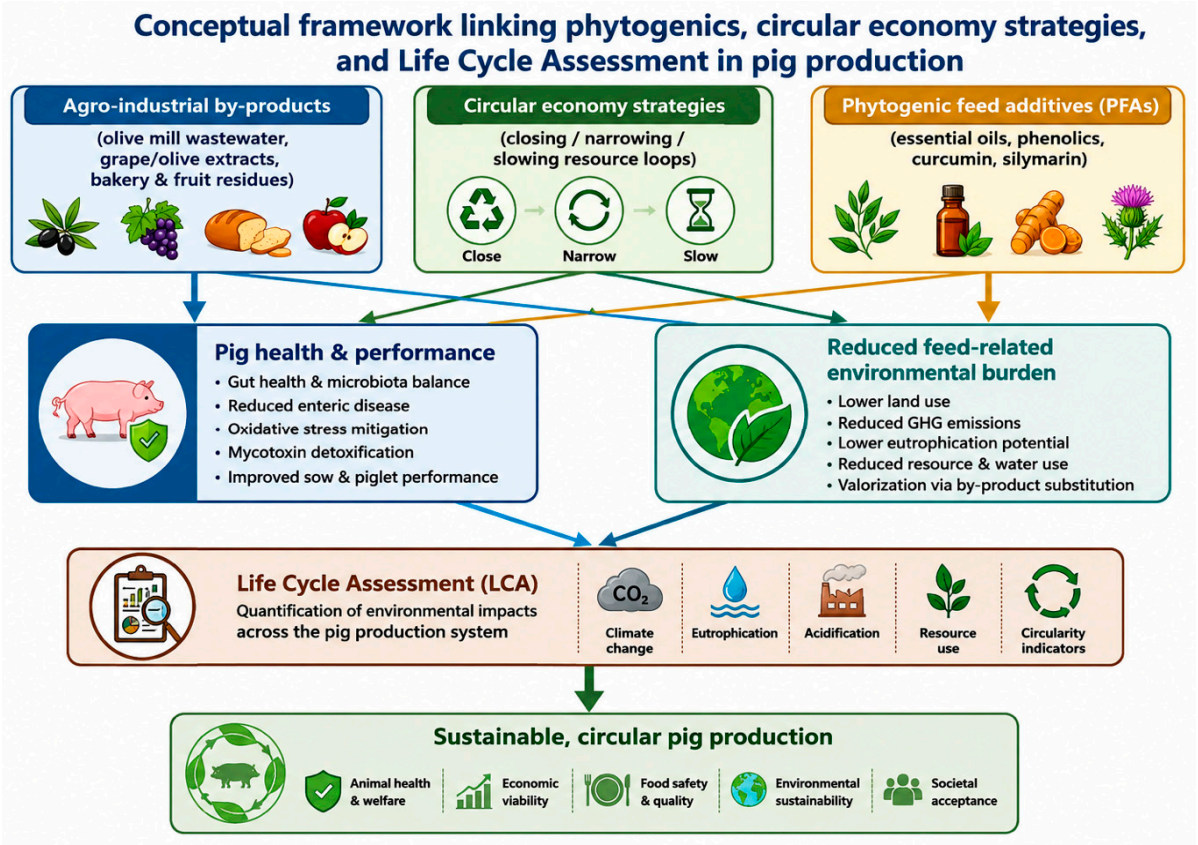


Figure 3. Conceptual framework, proposed by the authors, linking phytogenic feed additives, circular economy strategies, and life cycle assessment (LCA) in pig production, synthesized from the literature reviewed in Sections 3–6. Agro-industrial by-products and circular economy sourcing supply phytogenic actives that improve pig health/performance and reduce feed-related environmental burdens; both pathways would, in principle, feed into LCA-based quantification supporting more sustainable, circular pig production—a hypothesis developed and tested methodologically in Section 6. Solid arrows in this figure denote pathways supported by the literature within each domain shown; none of the arrows reflect a relationship measured jointly across domains within a single study. To avoid the figure being read as depicting an established, jointly demonstrated outcome, we clarify here, in the caption, that the links shown are each supported by evidence within an individual domain (phytogenic health/performance literature; circular economy and LCA literature) but have not been evaluated jointly, across domains, within a single study; terminal outcomes such as "reduced feed-related environmental burden" and "sustainable, circular pig production" are accordingly hypothesized, not yet empirically demonstrated, integrated outcomes (Section 7.2).

7. Challenges, Limitations, and Future Perspectives

7.1. General Challenges

- Standardization and quality control: Phytogenic products vary considerably in active compound concentration depending on the plant source, extraction method, and processing, which complicates both dose–response research and their consistent representation in LCA feed input data [3,30]. Encapsulation and controlled-release technologies are increasingly being proposed to address this variability directly, improving the stability, bioavailability, and dose consistency of essential oil-based phytogenics under feed-manufacturing and gastrointestinal conditions; a recent systematic review catalogs these approaches across poultry and swine applications, although the phytogenic-specific LCA implications of encapsulation itself (e.g., additional processing energy and material inputs) remain unexamined [62].

- Scarcity of dedicated LCA data: While by-product inclusion is increasingly framed in circular economy and environmental footprint terms [30], few studies isolate the specific LCA contribution of phytogenic additives themselves, as opposed to broader ingredient substitution; targeted cradle-to-farm-gate LCA studies of phytogenic-supplemented diets are needed [9,34].
- Supply chain logistics: The environmental benefit of by-product-derived phytogenics depends on the transport distance and collection logistics, which can offset the gains if sourcing hubs are not regionally optimized [32].
- Regulatory and safety considerations: Variability in composition and potential contaminant carryover from agro-industrial residues require robust safety and traceability frameworks before wider adoption [30]. This is particularly relevant where the phytogenic source is itself a variable-origin by-product (e.g., olive mill wastewater, bakery or herbal processing residues), since batch-to-batch differences in active compound concentration and the possible carryover of heavy metals, pesticide residues, or mycotoxins from the parent process both need routine monitoring against maximum residue limits (MRLs), rather than being assumed constant across suppliers, seasons, or geographic origins. In the EU specifically, any phytogenic feed additive intended for commercial use must, in any case, satisfy the EFSA FEEDAP Panel's efficacy and safety assessment framework, which explicitly requires robust, reproducible dose–response and safety data—a regulatory reality that reinforces, from a compliance perspective, the standardization and traceability needs identified above [63].
- Economic feasibility: The health/performance studies reviewed in Section 3 rarely report the purchase cost of the phytogenic relative to the value of the efficiency gains (feed conversion, morbidity/mortality, avoided veterinary costs); a simple cost–benefit module, reported alongside the LCA design in Section 7.2, would strengthen the practical case for adoption [3,30].
- Need for integrated indicators: Combining circularity indicators—which are not standardized and can measure different aspects depending on the system boundary and goal [64]—with conventional LCA impact categories, as demonstrated in theoretical pig production systems, offers a more complete sustainability picture than either approach alone and should be extended to phytogenic-specific case studies [33].
- Socioeconomic sustainability: As emphasized in recent assessments of organic and sustainable pig systems, environmental and health benefits must be considered alongside economic viability and social acceptability for phytogenic- and circularity-based strategies to be adopted at scale [31]. This is consistent with consumer research showing that the willingness to pay for sustainability attributes in pork (including a reduced carbon footprint) varies considerably across markets and is often secondary to animal welfare considerations, underscoring that phytogenic- and circularity-based strategies will need to be communicated alongside, rather than instead of, welfare credentials to gain broad consumer traction [65].

7.2. A Proposed Methodology for a Phytogenic-Specific LCA

As established in Section 6, the single largest gap identified by this review is the absence of a dedicated LCA that jointly quantifies the health/performance benefits and the environmental costs and benefits of phytogenic feed additive use in pigs. We propose the following methodological outline, adapted from established pig LCA practice [9,32,34], as a starting point for such a study: a functional unit of 1 kg of pig live weight at the farm gate as the primary functional unit, with 1 kg of carcass weight at the slaughterhouse gate reported only as a secondary, cradle-to-slaughterhouse-gate scenario (further specified below); a cradle-to-farm-gate system boundary at a minimum, with the cradle-to-slaughterhouse-gate

extension corresponding to this secondary scenario; comparator arms contrasting a conventional diet, a phytogenic-supplemented diet at the manufacturer-recommended dose, and, ideally, a by-product-derived versus purpose-cultivated phytogenic source to isolate the circularity contribution from the health/performance contribution; primary zootechnical data (feed conversion ratio, morbidity/mortality, reproductive performance) combined with emissions and resource use factors for the phytogenic ingredient's production pathway, which is a current gap in databases such as ECOALIM [56]; allocation between the primary product and the by-product-derived phytogenic extract—using system expansion (substitution) where feasible or economic or mass allocation as a fallback—explicitly specified and justified in accordance with the hierarchy of approaches prescribed by ISO 14044 [66]; global warming potential, land occupation, and eutrophication as minimum impact categories, with circularity indicators [33,64] reported alongside as a secondary metric; and a study design set a priori via power analysis on the smallest biologically meaningful difference in the pre-specified primary outcome, analyzed with mixed-effects models accounting for the pen-based hierarchical structure detailed below.

Executing this design would directly test the hypothesis proposed in Figures 1 and 3 of this review—that reduced morbidity/mortality and by-product-based sourcing jointly translate into a measurable reduction in environmental footprint per unit of pig meat produced—rather than leaving it as an inference from separate bodies of literature, as it necessarily remains in the present review.

To address several methodological gaps identified in peer review, we further specify the following elements of the proposed design. The two functional units mentioned above are not interchangeable; we propose 1 kg of pig live weight at the farm gate as the primary functional unit, with 1 kg of carcass weight at the slaughterhouse gate reported only as a secondary, cradle-to-slaughterhouse-gate sensitivity scenario, together with a matched reference flow, an explicit time horizon (e.g., a single production cycle from birth to market weight, or a defined annual reference period for herd-level assessment), study geography, a target product quality specification, and an explicit statement on whether land use change is included in the system boundary. The phytogenic ingredient life cycle inventory should further specify the following: raw-material origin or cultivation (wild-harvested versus cultivated; agro-industrial by-product versus purpose-grown); pretreatment, extraction method, and solvent/energy use; active compound concentration and standardization; carrier material; encapsulation or stabilization processing where used; drying, packaging, and transport distances and modes; processing losses; and the in-feed dose. We propose structuring the study according to the four ISO 14040/14044 phases—goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation—with allocation rules for the by-product-derived phytogenic extract defined and justified a priori (system expansion where feasible; otherwise, economic or mass allocation, as per the ISO 14044 hierarchy, as already noted above) and with a sensitivity analysis (e.g., varying allocation method, functional unit, and key inventory assumptions) and an uncertainty analysis (e.g., Monte Carlo propagation of inventory data variability) reported alongside the central impact estimates, consistent with standard LCA reporting practice [9].

Regarding the proposed zootechnical trial design specifically, treatment should be assigned at the pen (or pen group) level rather than the individual animal level, consistent with standard practice in production-scale pig trials; the pen is therefore the experimental unit, with individual animals as nested observational units, and the statistical model should include the pen nested within the batch/farm as a random effect, rather than the farm/batch alone, to correctly account for this clustering. Growth performance (e.g., average daily gain—a continuous, approximately normally distributed outcome), reproductive performance (e.g., litter size or farrowing rate—a count or proportion outcome), and

mortality/morbidity (a binary or time-to-event outcome) are statistically distinct outcome types and require correspondingly distinct model families (e.g., linear mixed-effects models, generalized linear/count models, and survival or binomial generalized linear mixed models, respectively) rather than a single shared model; a single primary outcome (e.g., morbidity/mortality incidence, as the outcome most directly linked to the environmental-footprint hypothesis under test) should be pre-specified for the purpose of the power analysis, with the remaining outcomes treated as secondary. This zootechnical trial power analysis, sized to detect the smallest biologically meaningful difference in the primary outcome, should be conducted and reported separately from the sensitivity and uncertainty analysis of the accompanying LCA (described above), since the two address distinct sources of variability—biological/sampling variability in the trial versus inventory and model-parameter uncertainty in the LCA—and conflating them would misrepresent the precision of either component.

For clarity, where morbidity/mortality incidence is adopted as a composite primary outcome, it should be explicitly defined a priori—for example, as the proportion of pigs per pen experiencing either a protocol-defined morbidity event (e.g., veterinary-treated clinical disease meeting pre-specified diagnostic criteria) or mortality within the observation period—and justified on the grounds that both events similarly curtail an animal's productive life and therefore similarly increase the environmental burden per unit of pig meat produced under the hypothesis tested here (Section 6); where morbidity and mortality are expected to respond differently to treatment, they should instead be analyzed and reported as separate secondary outcomes. Because treatment is assigned at the pen level, the power calculation for this primary outcome must be based on the number of independent pens, not the number of individual pigs, as the unit of replication, using an estimate of the intrapen correlation (intraclass correlation coefficient) to correctly inflate the required sample size relative to a naive individual animal-level calculation.

7.3. Limitations of This Review

This review has several limitations. First, the literature search (Section 2) was not systematic and did not follow a registered protocol; study selection, while intended to be representative, may have been subject to selection bias. Second, no formal risk-of-bias or study quality assessment (e.g., SYRCLE's risk-of-bias tool for animal studies) was applied to the primary studies discussed, and design features such as the sample size, blinding, and randomization were not systematically extracted or reported. Third, the review draws substantially on the published output of one research group for the phytogenic health effects and circular economy/LCA sections (Sections 3 and 4); independent studies are integrated throughout and discussed critically where they diverge (Section 3.4), but readers should weigh this concentration when assessing the overall evidence base. Fourth, no quantitative synthesis (meta-analysis) was attempted, given the methodological heterogeneity of the studies compared in Table 1. These limitations motivate the concrete methodological proposal in Section 7.2 and suggest that a future systematic review or meta-analysis, following PRISMA guidance, would usefully complement this narrative synthesis.

8. Conclusions

Phytogenic feed additives have accumulated more than a decade of supporting evidence in pig production, spanning enteric disease control in weaning pigs, oxidative stress mitigation and reproductive support in sows, and mycotoxin detoxification. To date, no study has directly measured the environmental footprint of phytogenic feed additive use itself; the reduced footprint hypothesis rests on combining two independently well-supported bodies of evidence—the health/performance benefits of phytogenics and the

environmental benefits of by-product substitution—rather than on direct measurement. This review's contribution is to articulate this hypothesis explicitly and to provide a concrete LCA methodology for its testing. Phytogenics should accordingly be regarded as a promising, mechanistically well-grounded lever for reducing the environmental footprint of pig production, meriting the targeted empirical work outlined above.

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Abbreviations

The following abbreviations are used in this manuscript:

ADFI	Average daily feed intake
ADG	Average daily gain
BCS	Body condition score
CARB	Protein carbonyls
CE	Circular economy
ETEC	Enterotoxigenic *Escherichia coli*
FCR	Feed conversion ratio
GenAI	Generative artificial intelligence
GHG	Greenhouse gas
ISO	International Organization for Standardization
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
MRL	Maximum residue limit
PFA	Phytogenic feed additive
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
SCFA	Short-chain fatty acids
SDG	Sustainable Development Goal
TBARS	Thiobarbituric acid-reactive substances

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