

Fermented Agricultural Botanicals as Antibiotic-Sparing Interventions for Sustainable Broiler Production: A Systematic Review and Meta-Analysis

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Abstract: The search for practical antibiotic-sparing strategies in poultry is moving from single phytochemicals toward fermented plant matrices, where microbial biotransformation can modify nutrient availability, antimicrobial activity, and the delivery of bioactive compounds. This systematic review evaluated fermented agricultural botanicals in broiler production and performed a focused meta-analysis of feed conversion ratio (FCR). Searches through 20 September 2026 identified 23 *in vivo* reports meeting qualitative eligibility criteria; five non-overlapping trials provided compatible whole-period FCR data with measures of dispersion. The evidence covered fermented Ginkgo leaves, pine needles, Astragalus, ginger, grape and tomato pomace, mulberry, Chenopodium, dandelion, Artemisia, Moringa, chive, and shallot. Across studies, responses were more consistent for intestinal integrity, antioxidant status, pathogen control, and resilience under enteric or environmental challenge than for growth alone. Random-effects meta-analysis yielded a small point estimate favoring fermented botanicals (mean difference, -0.044 FCR units), but the Hartung-Knapp 95% confidence interval crossed zero (-0.093 to 0.005) and heterogeneity was high ($I^2=84.8\%$). Recent Allium studies illustrate a coherent development pathway linking host-derived probiotic selection, controlled fermentation, challenge testing, and practical delivery. Overall, fermented botanicals are promising components of antibiotic-sparing programs, but the evidence does not support universal replacement of therapeutic antimicrobials. Standardized fermentation, chemical and microbial quality control, direct antimicrobial-use outcomes, and multi-farm validation are priorities for the next phase of research.

Keywords: Antimicrobial Resistance, Broiler Chicken, Fermented Botanicals, Feed Additive, Phytogetic, Probiotic Fermentation, Sustainable Poultry.

INTRODUCTION

Antimicrobial growth promoters helped shape intensive poultry production, but their widespread use also contributed to the policy and consumer pressure that now surrounds antimicrobial resistance (AMR). The historical benefits of antibiotic growth promoters are well documented, as are the reasons many production systems have restricted them (Castanon, 2007). The practical question for broiler producers is no longer whether alternatives are needed. It is which alternatives remain effective when birds face variable diets, pathogen pressure, heat, litter challenges, and commercial stocking conditions. Probiotics, organic acids, enzymes and phytogenic products all have useful roles, but none is

uniformly effective across farms (Gadde *et al.*, 2017; Ntsongota *et al.*, 2025).

Agricultural botanicals are attractive because they can be sourced from crops, herbs and agro-industrial residues already present in feed chains. Their limitation is variability. A raw leaf meal or plant extract may contain phenolics, flavonoids, terpenes, organosulfur compounds, fibre and antinutritional factors in proportions that change with cultivar, harvest, storage and extraction. Fermentation offers one way to narrow that gap. Lactic acid bacteria, *Bacillus*, fungi and mixed starter cultures can acidify plant substrates, release cell-wall-bound compounds, generate microbial metabolites, reduce selected antinutritional factors and improve preservation. Yet fermentation can also consume

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desirable compounds or produce inconsistent products when temperature, moisture, inoculum and time are poorly controlled (Sugiharto and Ranjitkar, 2019; Zhang *et al.*, 2023).

The broiler literature has expanded from fermented Ginkgo leaves and pine needles to pomaces, medicinal leaves and Allium substrates. A 2024 meta-analysis reported favorable average effects of fermented herbal products on growth, breast meat traits and intestinal morphology, while a separate meta-analysis of fermented tropical leaf meals also suggested performance benefits (Adli *et al.*, 2024; Ogbuewu *et al.*, 2024). Those syntheses are valuable, but the field has moved quickly. New studies now combine host-derived probiotic strains with chive or shallot, test birds under bacterial, coccidial and heat challenge, and explicitly frame the technology as an antibiotic-sparing tool. At the same time, a recent probiotic meta-analysis shows that microbial chassis matter; *Bacillus*-based products can differ from *Lactobacillus*-based products in performance response (Bilal *et al.*, 2026).

This review therefore focused on fermented agricultural botanicals fed or administered to broiler-type chickens, with three aims: to map the current *in vivo* evidence; to quantify the direction and magnitude of the FCR response where data were sufficiently compatible; and to examine what the evidence actually supports regarding antibiotic replacement, gut health and sustainability. Particular attention was given to the emerging Allium-probiotic platform because it links strain selection, fermentation technology and challenge validation in a way that is unusually relevant to practical antibiotic-sparing programs.

MATERIALS AND METHODS

Search Strategy and Eligibility

Search strategy and eligibility. Reporting followed PRISMA 2020 principles (Page *et al.*, 2021). PubMed, Google Scholar, and publisher-indexed journal interfaces were searched from database inception to 20 September 2026. Search strings combined chicken OR broiler with ferment* and botanical terms including herb*, plant*, leaf, pomace, Allium, Ginkgo, Artemisia, Moringa, Astragalus, dandelion, Chenopodium, and ginger. Reference lists of eligible papers and recent reviews were hand-searched. Eligible *in vivo* studies used broiler-type chickens, compared a fermented botanical or plant-derived agricultural material with an unsupplemented or unfermented control, and reported at least one production, gut-health, pathogen, immune, antioxidant, or meat-quality outcome. Fermented complete feeds without an identifiable botanical component, conventional high-protein fermented meals, non-poultry studies, and purely *in vitro* assays were excluded from the *in vivo* synthesis. *In vitro* papers were retained only when they directly informed starter selection or fermentation of a botanical subsequently evaluated in poultry.

Study Selection and Extraction

Study selection and extraction. Twenty-three *in vivo* reports met the qualitative criteria. The final study set is enumerated in Table 1, allowing the evidence base to be audited despite the dynamic hit counts returned by Google Scholar and publisher search interfaces. For each report, the botanical substrate, fermenting organism, bird model, challenge status, exposure route, principal outcomes, and reporting of randomization or blinding were extracted. When several papers arose from related experimental programs, they were retained for qualitative interpretation but only one non-overlapping cohort was permitted in a given quantitative outcome. Risk of bias was assessed with domains adapted from the SYRCLE tool: sequence generation, baseline comparability, allocation concealment, blinding of caregivers or outcome assessors, incomplete outcome data, and selective reporting (Hooijmans *et al.*, 2014). Unreported procedures were classified as unclear rather than low risk.

Meta-Analysis

Meta-analysis. FCR was selected *a priori* because it links feed efficiency with resource use. Five independent reports provided compatible whole-period FCR means and pooled measures of dispersion: Cao *et al.*, (2012), Niu *et al.*, (2017), Xie *et al.*, (2021), Mao *et al.*, (2023), and Gungor *et al.*, (2024). Multi-dose treatment arms were combined to avoid repeated use of the same control. Where a pooled standard error of the mean was reported, arm-level standard deviations were approximated from the number of replicate pens; this conversion was treated as a sensitivity limitation. The effect size was the raw mean difference (fermented botanical minus control), so negative values favored fermentation. A random-effects model used Paule-Mandel estimation of between-study variance and a Hartung-Knapp-Sidik-Jonkman (HKSJ) t-based confidence interval, which is more conservative when few heterogeneous studies are combined (Int'Hout *et al.*, 2014). I² quantified inconsistency. Leave-one-out analyses examined influence of individual studies. Publication-bias tests were not undertaken because five studies provide little power for funnel-plot asymmetry tests.

Protocol and Data Availability

Protocol and data availability. The review was not prospectively registered. The numerical inputs used for the FCR meta-analysis are reported in Table 2 so that the pooled estimate can be independently reconstructed.

RESULTS

Evidence Landscape

Evidence landscape. The 23 *in vivo* reports spanned more than a decade and several fermentation platforms (Table 1). Early work centered on *Aspergillus*-fermented Ginkgo leaves, with studies reporting changes in growth, antioxidant status, intestinal morphology, microbial ecology, and responses to lipopolysaccharide

challenge (Cao *et al.*, 2012; Zhang *et al.*, 2012, 2013, 2015). Fermented pine needles also improved selected performance and meat-related traits (Wu *et al.*, 2015). Later work broadened the substrate base to fermented Astragalus and ginger stem (Park *et al.*, 2016; Qiao *et al.*, 2018), agro-industrial residues such as grape and tomato

pomace (Gungor *et al.*, 2021, 2024), and medicinal leaves including mulberry, Chenopodium, and dandelion (Ding *et al.*, 2021; Xie *et al.*, 2021; Mao *et al.*, 2023). More recent studies have examined Artemisia and Moringa systems, including colored-chicken models (Wang *et al.*, 2024; Fan *et al.*, 2024; Ni *et al.*, 2025).

Table 1: In vivo fermented-botanical studies included in the qualitative synthesis

Study	Botanical / fermentation platform	Bird model / exposure	Main finding relevant to this review
Cao <i>et al.</i> , (2012)	Ginkgo leaves; fungal fermentation	Broilers; dietary fermented Ginkgo	Growth, antioxidant and immune-related responses; one of earliest controlled broiler platforms.
Zhang <i>et al.</i> , (2012)	Ginkgo leaves; <i>Aspergillus niger</i>	Broilers	Improved intestinal morphology and microbial ecology in selected treatments.
Zhang <i>et al.</i> , (2013)	Fermented Ginkgo leaves	Broilers; LPS challenge	Modulated inflammatory/oxidative responses during immune challenge.
Zhang <i>et al.</i> , (2015)	Fermented Ginkgo leaves	Broiler chicks	Improved antioxidant capacity, intestinal morphology and microbial ecology.
Wu <i>et al.</i> , (2015)	Pine needles; microbial fermentation	Broilers	Selected growth, antioxidant and meat-quality benefits.
Park <i>et al.</i> , (2016)	Ginger stem; Lactobacillus fermentation	<i>Salmonella</i> -infected broilers	Reduced challenge-related effects and supported health responses.
Niu <i>et al.</i> , (2017)	Fermented Ginkgo leaves	Broilers; graded doses	Dose-related growth and meat-quality responses.
Qiao <i>et al.</i> , (2018)	Astragalus; fermentation	Broilers	Altered fecal microbiota composition.
Niu <i>et al.</i> , (2019a)	Fermented Ginkgo leaves	Broilers	Improved nutrient utilization in selected treatments.
Niu <i>et al.</i> , (2019b)	Fermented Ginkgo leaves	Broilers; graded doses	Dose-dependent serum biochemical and antioxidant responses.
Gungor <i>et al.</i> , (2021)	Grape pomace; solid-state fermentation	Broilers	Performance, antioxidant and meat-quality responses; circular-feed potential.
Ding <i>et al.</i> , (2021)	Mulberry leaf powder; fermentation	Broilers	Growth, antioxidant and intestinal responses.
Xie <i>et al.</i> , (2021)	<i>Chenopodium album</i> ; fermentation	Broilers	Improved growth-related and intestinal indices in selected groups.
Mao <i>et al.</i> , (2023)	Dandelion; fermentation	Broilers	Supported growth, antioxidant status and intestinal health.
Wang <i>et al.</i> , (2024)	<i>Artemisia argyi</i> ; fermentation	Broilers	Improved performance and gut/antioxidant indices in selected treatments.
Fan <i>et al.</i> , (2024)	<i>Moringa oleifera</i> ; Monascus fermentation	Broilers	Production performance, carcass and meat-quality responses.
Gungor <i>et al.</i> , (2024)	Tomato pomace; fermentation	Broilers	Improved feed efficiency and selected gut/antioxidant responses.
Hai <i>et al.</i> , (2025a)	Chive; <i>Lactobacillus plantarum</i>	<i>E. coli</i> -challenged broilers	Supported survival, performance and intestinal microbial balance.
Hai <i>et al.</i> , (2025b)	Chive; <i>L. plantarum</i>	<i>Eimeria acervulina</i> -challenged broilers	Reduced coccidial damage and improved intestinal responses.
Ni <i>et al.</i> , (2025)	<i>Artemisia argyi</i> ; fermentation	Hongyu roosters	Growth, intestinal and antioxidant responses in a colored-chicken model.
Hoang <i>et al.</i> , (2026a)	Shallot extract; <i>L. plantarum</i>	<i>E. coli</i> -challenged broilers; drinking water	Improved disease-resilience and gut-health indices.
Hoang <i>et al.</i> , (2026b)	Shallot bulb; <i>L. plantarum</i>	<i>Salmonella pullorum</i> -challenged broilers; drinking water	Improved survival and intestinal/immune outcomes.
Hai <i>et al.</i> , (2026)	Shallot extract; <i>L. plantarum</i>	Broilers under chronic natural summer heat	Improved growth-related and physiological stress responses.

The pattern across studies was not a simple growth-promotion signal. Some trials improved body weight gain or FCR, whereas others mainly altered antioxidant capacity, intestinal morphology, fecal or cecal microbiota, immune indices, meat quality or resistance to challenge. This distinction matters. A fermented botanical that does not improve FCR in an unchallenged flock may still have biological value under pathogen or environmental stress, but that value should not be recast as a guaranteed production response.

Fermentation systems also differed substantially in how the plant material was presented to the bird. Most Ginkgo, pine-needle, pomace and medicinal-leaf studies used fermented dry material incorporated into feed, whereas recent Allium studies used either a dried fermented ingredient or a fermented extract delivered through drinking water. Fungal systems were common in the earlier leaf-meal literature, while lactic acid bacteria dominate the more recent challenge studies. This matters because the administered product may contain different proportions of viable microbes, fermentation metabolites and transformed plant compounds. A dry fungal-fermented leaf meal is therefore not biologically equivalent to a Lactiplantibacillus-fermented Allium extract, even if both are placed under the same phytogetic label. The in vivo literature also differed in dose expression: percent of diet, grams per kilogram, inclusion in water, or graded dose series. Such variation prevented a meaningful dose-response meta-analysis across the entire evidence base and argues for reporting both the amount of fermented substrate and, where possible, the viable starter count or post-fermentation metabolite concentration delivered per bird.

Allium-based evidence has become more mechanistically connected. Before fermentation studies, chive and ginger extracts inhibited poultry *Escherichia coli* and *Salmonella* isolates in vitro, and chive extract influenced growth and Newcastle-disease immune status in broilers (Hai *et al.*, 2019; Hai and Hoa, 2020). Hai *et al.*, (2024) then screened chicken-derived *Lactobacillus* strains for purple-onion fermentation and anti-

Salmonella activity, while Phan *et al.*, (2025) identified indigenous *Bacillus subtilis* strains, including BSn5, with probiotic properties against Gram-negative enteropathogens. These strain-selection studies were not included as in vivo fermented-botanical trials, but they help explain the design logic of the later feeding work.

Challenge studies using *Lactobacillus*- or *Lactiplantibacillus*-fermented Allium products have generally shown a stronger disease-resilience signal than a uniform growth signal. Fermented chive supported performance, survival and intestinal microbial balance in *E. coli*-challenged broilers (Hai *et al.*, 2025a), and a related chive preparation reduced *Eimeria acervulina*-associated damage and improved intestinal responses (Hai *et al.*, 2025b). Fermented shallot delivered in drinking water has since been evaluated against *E. coli* and *Salmonella pullorum*, with improvements in survival, intestinal indices and pathogen-related outcomes (Hoang *et al.*, 2026a,b). Under chronic natural summer heat exposure, fermented shallot extract also improved growth-related and physiological stress responses (Hai *et al.*, 2026). These studies extend the field from 'plant as antimicrobial' toward 'fermented plant as a managed biological system.'

FCR Meta-Analysis

FCR meta-analysis. The five studies entered in the quantitative synthesis produced individual mean differences from -0.080 to +0.016 FCR units (Table 2; Figure 1). The random-effects point estimate favored fermented botanicals by 0.044 FCR units (MD=-0.044), roughly a 2-3% improvement relative to the control values represented in these trials. The HKSJ 95% CI ranged from -0.093 to 0.005 and therefore included no effect. Heterogeneity was high (I²=84.8%; tau²=0.00123). Leave-one-out estimates remained negative (-0.035 to -0.056 FCR units), although statistical certainty depended strongly on the study omitted; removing Niu *et al.*, (2017) produced the only leave-one-out HKSJ interval that excluded zero. A DerSimonian-Laird normal-theory sensitivity analysis was more optimistic, illustrating why the conservative HKSJ model was retained as the primary inference.

Table 2: Whole-period feed conversion ratio datasets included in the focused meta-analysis

Study	Control FCR	Fermented FCR*	MD	95% CI
Cao <i>et al.</i> , (2012)	2.00	1.920	-0.080	-0.114 to -0.046
Niu <i>et al.</i> , (2017)	1.88	1.896	+0.016	-0.009 to +0.041
Xie <i>et al.</i> , (2021)	1.78	1.720	-0.060	-0.096 to -0.024
Mao <i>et al.</i> , (2023)	1.73	1.655	-0.075	-0.142 to -0.008
Gungor <i>et al.</i> , (2024)	1.60	1.56	-0.040	-0.057 to -0.023
Random-effects pooled			-0.044	-0.093 to +0.005

*For multi-dose trials, fermented treatment arms were combined before comparison with the common control. MD = mean difference (fermented botanical - control). Primary pooled model: Paule-Mandel random effects with HKSJ confidence interval; I²=84.8%, tau²=0.00123.

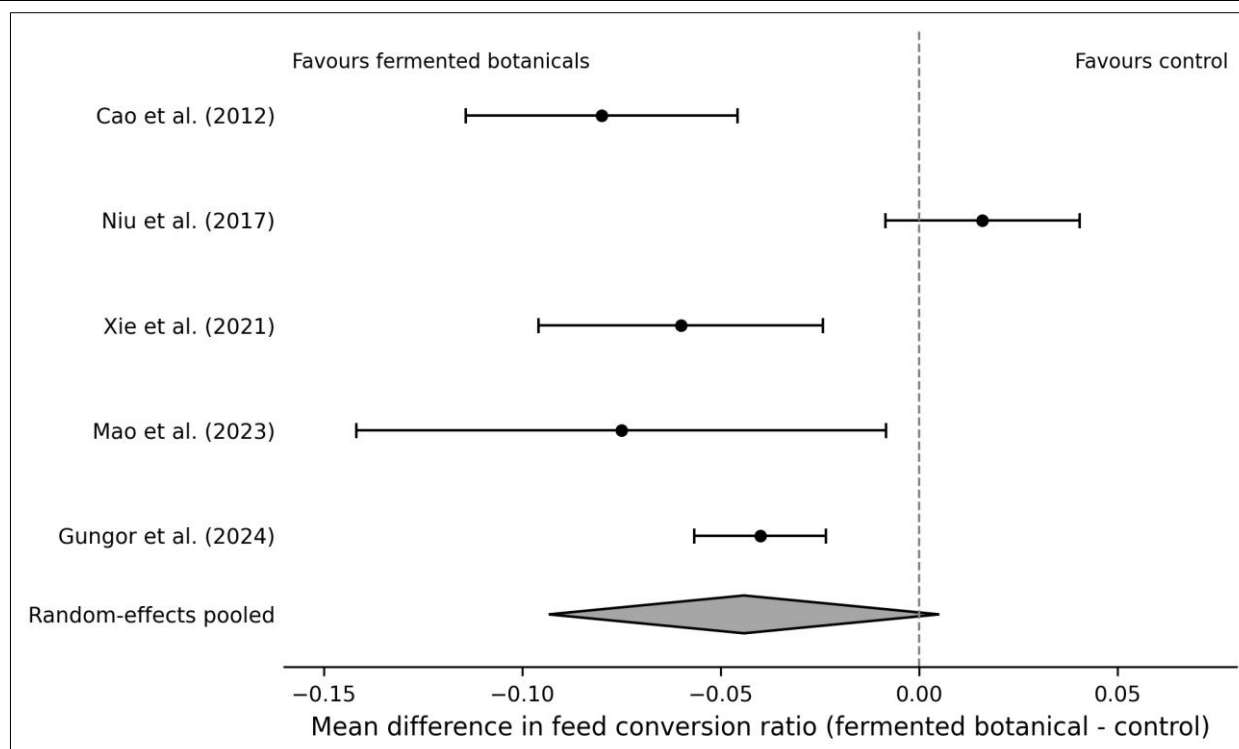


Figure 1: Forest plot of whole-period FCR. Negative mean differences favor fermented botanicals. The diamond shows the HKSJ random-effects estimate (MD -0.044; 95% CI -0.093 to 0.005; I²=84.8%)

Risk of Bias and Reporting Quality

Risk of bias and reporting quality. Random allocation was commonly stated, but sequence generation, allocation concealment and blinding were often poorly described. Objective outcomes such as feed intake, body weight and mortality were less vulnerable to assessor bias than lesion scoring, histology or subjective health observations. Attrition was usually traceable where mortality was reported, but selective-reporting risk remained difficult to judge because prospective protocols were rarely available. The main methodological weakness of the evidence base was not obvious misconduct; it was incomplete reporting of procedures that determine internal validity.

DISCUSSION

Fermentation should not be treated as a decorative processing step attached to a phytogetic additive. Its value lies in biotransformation. Plant cells are disrupted, fibre matrices are modified, pH changes, microbial metabolites accumulate, and the balance among soluble phenolics, organic acids, sulfur-containing compounds, and other bioactives may shift. Depending on the substrate and starter, fermentation can improve accessibility of useful compounds, reduce antinutritional factors, or consume constituents that were desirable before processing. This process dependence explains part of the heterogeneity seen here: fermented Ginkgo, fermented pomace, and fermented *Allium* are technologically different products even when all are placed under the same phytogetic label (Zhang *et al.*, 2023).

The FCR meta-analysis gives a useful reality check. The point estimate was favorable but small, and the conservative confidence interval crossed zero. That finding does not negate individual positive trials or the earlier broader meta-analysis by Adli *et al.*, (2024). It shows that once the evidence is restricted to non-overlapping whole-period FCR datasets with extractable variance, certainty falls quickly. Botanical species, inoculum, fermentation mode, dose, bird genetics and challenge status all modify the response. Treating those sources of variation as statistical noise would miss the biology. In feed-additive development, the more useful goal is to identify which fermentation-platform x bird-context combinations are reproducible.

Antibiotic sparing is also a stricter claim than improved growth. A product can improve villus architecture, lower Enterobacteriaceae, increase lactic acid bacteria or blunt oxidative stress without demonstrating reduced therapeutic antimicrobial use on farms. The strongest current rationale is therefore complementary: fermented botanicals may reduce pathogen pressure and strengthen gut resilience, helping producers maintain performance while routine antibiotic exposure is minimized. They should not be presented as replacements for clinically indicated therapy. This distinction is consistent with the wider antibiotic-alternative literature and protects the field from overselling promising challenge experiments (Gadde *et al.*, 2017).

The Allium program illustrates how an antibiotic-sparing platform can be developed more coherently. First, antimicrobial activity of the botanical matrix is established (Hai *et al.*, 2019). Second, host-derived microbes are selected for acid/bile tolerance, pathogen inhibition, enzyme production, and fermentation performance (Hai *et al.*, 2024; Phan *et al.*, 2025). Third, fermented products are tested under defined bacterial and parasitic challenge (Hai *et al.*, 2025a,b; Hoang *et al.*, 2026a,b). A separate summer trial extended the platform to chronic natural heat exposure (Hai *et al.*, 2026). The value of that sequence is not that Allium is necessarily superior to every other plant. It is that biological provenance, fermentation function, and animal outcome are linked in a traceable development pathway.

A second lesson from the Allium work is that the starter culture is part of the product identity. The 2024 purple-onion study selected chicken-derived *Lactobacillus* strains not simply for acid production but for survival under gastrointestinal conditions and inhibition of *Salmonella*, while the 2025 *Bacillus* study screened indigenous strains for extracellular enzymes, stress tolerance, antibacterial activity and persistence in the chicken intestine (Hai *et al.*, 2024; Phan *et al.*, 2025). Those steps are important because a generic claim such as 'fermented with *Lactobacillus*' hides strain-level differences that can alter acidification kinetics, substrate use and metabolite profiles. For future meta-analyses, the fermenting organism should be recorded at strain level whenever available. Without that information, studies that appear technically similar may in fact represent different biological interventions.

Sustainability claims need the same discipline. Fermenting low-value leaves, prunings and pomaces can support circular feed systems by converting materials such as grape or tomato pomace into more usable feed additives (Gungor *et al.*, 2021, 2024). Better FCR can reduce feed consumed per unit of gain, and a healthier gut may lower mortality and medication demand. But few studies measured antimicrobial use in mg per population-correction unit, life-cycle greenhouse-gas emissions, nitrogen excretion, land use, or full cost per kilogram of live weight. Sustainability is therefore plausible and partly supported, but not yet demonstrated across its full economic and environmental dimensions.

The same caution applies to AMR. Lower counts of *E. coli* or *Salmonella* and improved survival during challenge are relevant to antibiotic-sparing production, but they are surrogate steps rather than direct evidence of reduced selection for antimicrobial resistance. Very few fermented-botanical trials quantified therapeutic treatment days, total antimicrobial dose, resistance genes, phenotypic susceptibility, or the resistome before and after supplementation. A stronger sustainability trial would link animal performance to antimicrobial-use records and manure or litter

measurements in the same flock. That would allow researchers to test whether the intervention produces a genuine system-level gain rather than shifting benefit from one endpoint to another. Farm economics should also be measured prospectively, including starter culture, fermentation, drying, storage and labor costs. A botanical substrate can be locally abundant and still become uneconomic once moisture removal and quality control are added.

Quality control is the next bottleneck. Papers should report botanical identity, plant part, harvest or source, particle size, inoculum identity and dose, fermentation temperature, moisture, oxygen regime, duration, final pH, viable counts where relevant, drying conditions and storage stability. For medicinal or Allium-rich substrates, at least one chemical marker should be tracked before and after fermentation. Microbial safety also deserves more attention: absence of major pathogens, antimicrobial-resistance screening of starter strains, mycotoxin control in fungal fermentation, and limits for biogenic amines are not optional when products move from experimental pens to farms. The recent emphasis on indigenous *Lactobacillus* and *Bacillus* strains is useful, but strain identity alone does not guarantee batch consistency.

Fermentation design variables should therefore be reported as experimental factors, not background details. Moisture content and water activity determine which organisms dominate solid-state systems; aeration separates many *Bacillus* and fungal processes from lactic fermentations; temperature and time govern both microbial succession and chemical transformation. Drying is equally consequential. Excessive heat can reduce viable counts and alter volatile or sulfur-containing compounds, whereas insufficient drying compromises shelf life. At minimum, a publishable product description should allow another laboratory to reproduce the fermented material without contacting the authors. For applied work, a release specification can be even more useful than another mechanistic assay: viable count or marker organism, pH, moisture, one or more chemical markers, absence of pathogens, and stability over the intended storage period.

Future broiler trials should be designed around decisions producers actually make. A useful study would compare a standardized fermented botanical with an unsupplemented control and, where ethically appropriate, a clearly defined non-therapeutic comparator; record medication events and reasons for treatment; predefine mortality and FCR as core outcomes; and add intestinal pathology, microbiome or resistome endpoints only when they answer a mechanistic question. Multi-farm replication is especially important because litter, climate, feed formulation and pathogen ecology vary more than they do in university pens. For disease-challenge models, reporting both absolute survival and pathogen burden is

more informative than relying on a single growth measure.

This review has limitations. The quantitative synthesis was intentionally narrow and included only five FCR datasets, some of which required conversion from pooled SEM to approximate arm-level dispersion. Heterogeneity was high, and the evidence came from diverse botanicals rather than one standardized product class. Several research groups published multiple papers from related fermentation platforms, so qualitative evidence is richer than the number of fully independent experimental lineages. Search interfaces beyond PubMed do not all expose stable deduplicated records, and the review was not prospectively registered. These constraints make the pooled estimate exploratory, but they also point directly to what the field must standardize next.

CONCLUSION

Fermented agricultural botanicals are better viewed as a family of fermentation platforms than as a single feed-additive class. Current broiler evidence supports improvements in gut integrity, microbial ecology, antioxidant status, and resilience under enteric or environmental challenge, while the average FCR effect remains small and heterogeneous. The focused meta-analysis favored fermentation numerically, but the conservative confidence interval included no effect. The case for antibiotic sparing is therefore credible but conditional: standardized products may help reduce routine antimicrobial dependence when embedded in biosecurity, vaccination, and sound nutrition, yet they cannot replace clinically indicated therapy. Progress now depends on reproducible fermentation specifications, chemical and microbial release criteria, direct measurement of antimicrobial use, and multi-farm validation that includes economic and environmental endpoints.

DECLARATIONS

Ethics Approval: Not applicable. This study synthesized data from published reports and involved no new experiments on animals or humans.

Consent to Publish: Not applicable.

Competing Interests: The author declares no competing interests.

Author Contribution: PVH conceived the review, designed the search and eligibility criteria, extracted and interpreted the evidence, HC performed the focused meta-analysis, and wrote and revised the manuscript.

Availability of Data and Materials: All numerical inputs used in the meta-analysis are reported in Table 2 and were derived from the cited publications.

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Artificial Intelligence Disclosure: A generative AI language model was used for language drafting and formatting support. The author remains responsible for source verification, data extraction, statistical analysis, interpretation, and the final submitted text.

Abbreviations: AMR, antimicrobial resistance; CI, confidence interval; FCR, feed conversion ratio; HKSJ, Hartung-Knapp-Sidik-Jonkman; MD, mean difference; PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses; RoB, risk of bias; SSF, solid-state fermentation.

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