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Herbal medicine as an alternative for coccidiosis control in poultry: From tradition to science

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Abstract

Coccidiosis continues to rank among the most economically devastating parasitic diseases in poultry, stemming from infection by various *Eimeria* species that inflict intestinal damage and hinder growth performance. Historically, control measures have depended on synthetic anticoccidial drugs and live vaccines. Yet, growing concerns over drug resistance, tightening regulatory policies, and consumer preference for antibiotic-free poultry have spurred interest in alternative approaches. Herbal medicine, with its rich array of bioactive compounds, has gained traction as a viable solution, offering not only anticoccidial effects but also immunomodulatory, anti-inflammatory, and antioxidant benefits. Plant-based extracts-such as those derived from *Artemisia annua*, garlic (*Allium sativum*), turmeric (*Curcuma longa*), and oregano (*Origanum vulgare*) have shown notable efficacy against *Eimeria* in both experimental trials and field applications. These natural agents disrupt the parasite's life cycle, promote beneficial gut microbiota, and strengthen host immunity, all while avoiding harmful residues. Moreover, their biodegradability aligns with sustainable farming goals, minimizing ecological harm. Despite promising results, hurdles persist in adopting herbal remedies. Inconsistent plant composition, undefined dosing standards, insufficient large-scale validation, and practical challenges like shelf stability and palatability pose obstacles. Moving forward, research must prioritize standardized formulations, rigorous commercial-scale trials, and investigations into synergistic effects with vaccines or probiotics. This review underscores the potential of herbal medicine as either a standalone or complementary strategy for coccidiosis control. By overcoming current limitations through targeted research and regulatory support, the poultry sector can advance toward more sustainable, effective, and consumer-accepted disease management practices.

1. Introduction

Coccidiosis is a major parasitic disease in poultry caused by *Eimeria* species, leading to intestinal damage, poor growth, and high mortality especially in young birds (Chapman *et al.,* 2013). It presents with symptoms like diarrhea, reduced feed efficiency, and increased susceptibility to other infections. With over 50 billion chickens raised annually, controlling coccidiosis is vital for food security and economic sustainability (Gilbert *et al.,* 2011). Seven *Eimeria* species infect poultry, each targeting specific gut regions. Their life cycle spans 4 to 7 days and involves both sexual and asexual stages within the host. Rapid replication and environmental resilience make them difficult to control (Chapman, 2014).

Traditionally, control has relied on anticoccidial drugs and live vaccines. However, widespread drug resistance and increasing consumer demand for antibiotic-free meat have limited chemical use, particularly in markets like the European Union (Chapman *et al.,* 2010; Abbas *et al.,* 2012). Herbal medicine has emerged as a promising alternative. Extracts from plants such as *A. annua* and *A. sativum* (garlic) show anticoccidial effects through mechanisms like disrupting parasite metabolism, enhancing immunity, and supporting gut health (Bozkurt *et al.,* 2013; Arab *et al.,* 2006; Del Cacho *et al.,* 2010; Kim *et al.,* 2013; Broom, 2021). These natural compounds align with trends toward sustainable and organic poultry production. Many herbal substances also offer anti-inflammatory, antioxidant, and immunomodulatory benefits. Flavonoids, tannins, saponins, and essential oils not only interfere with *Eimeria* development but also protect gut integrity and support a healthy microbiome (Rizwan *et al.,* 2022; Muthamilselvan *et al.,* 2016). The transition from laboratory research to practical implementation of herbal anticoccidial agents encounters several significant barriers. One fundamental challenge stems from the inherent variability in phytochemical profiles across plant sources, which when combined with differences in extraction protocols and administration regimens, frequently produces inconsistent therapeutic outcomes (Abbas *et al.,* 2012; El-Shall *et al.,* 2022; Ola-Fadunsin and Ademola, 2013). Current scientific understanding of how these botanical compounds mediate their effects remains incomplete, particularly concerning

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their complex interplay with avian immunological pathways and intestinal microbial ecosystems (Felici *et al.,* 2021). The promising results obtained in controlled experimental settings have not been sufficiently replicated in commercial poultry operations (De Almeida *et al.,* 2012). Safety considerations present additional obstacles to widespread adoption. Although, numerous medicinal plants demonstrate favorable safety profiles, emerging evidence indicates that extended use of certain botanicals may induce adverse effects or negatively influence production parameters (Idris *et al.,* 2017; Molan and Faraj, 2015). These concerns are compounded by the current lack of standardized quality assurance measures for herbal products, leaving open possibilities for contamination or inconsistent potency.

Investigations into potential complementary effects between plant-derived compounds and established control measures represent a particularly promising research direction. Allen (2003) and Janardhana *et al.* (2009) have provided preliminary evidence that specific botanicals like *Echinacea purpurea* may augment vaccine efficacy, while certain carbohydrate compounds appear to stimulate microbial populations capable of inhibiting parasitic development.

This comprehensive evaluation examines contemporary research on plant-based anticoccidial interventions, systematically analyzing their therapeutic potential as either standalone or adjunctive treatments. The assessment encompasses multiple critical dimensions including the spectrum of bioactive plant species and their constituent compounds, established mechanisms of action, documented safety characteristics, and demonstrated effectiveness across various experimental and production environments. Concurrently, the analysis identifies persistent knowledge deficits regarding product standardization, mechanistic elucidation, and implementation challenges (Abbas *et al.,* 2012; Mesa-Pineda *et al.,* 2021; Muthamilselvan *et al.,* 2016). Despite growing interest in botanical alternatives for coccidiosis control, current research lacks integrated, long-term evaluations of their efficacy, mechanisms, and practical use in sustainable poultry systems. There is also limited evidence on their role within holistic, reduced-pharmaceutical management strategies that maintain productivity and animal welfare.

2. Pathogenesis and pathology of *Eimeria* spp. clinical signs and economic implications

2.1 Pathogenesis and disease impact

Avian coccidiosis develops through a complex interaction between *Eimeria* parasites and the host's intestinal epithelium. These intracellular parasites invade and systematically damage avian intestinal cells, severely impairing digestive and absorptive functions. Following epithelial invasion, *Eimeria* species replicate within host cells, causing widespread cellular destruction and inflammation (Muthamilselvan *et al.,* 2016). The resulting epithelial damage disrupts nutrient absorption and creates conditions favorable for secondary bacterial infections, further compromising bird health (El-Shall *et al.,* 2022). Pathological severity depends on the *Eimeria* species involved and their location in the gastrointestinal tract. Highly virulent species like *E. tenella, E. necatrix, E. maxima, and E. brunetti* induce severe clinical disease and extensive intestinal lesions (Conway and McKenzie, 2007). Additionally, these parasites weaken the host's immune defenses, increasing susceptibility to secondary infections such as *Salmonella* and *Clostridium perfringens* (Koinarski *et al.,* 2005).

2.2 Life cycle of *Eimeria* species

The *Eimeria* life cycle consists of exogenous (sporogony) and endogenous phases, both critical for disease persistence (Mesa-Pineda *et al.,* 2021). Unsporulated oocysts excreted in feces (Figure 1) require warm (25-30°C), humid conditions to sporulate, maturing into infectious oocysts within 24-48 h (Del Cacho *et al.,* 2014). Each sporulated oocyst contains four sporocysts, with two sporozoites per sporocyst. Upon ingestion by birds, sporozoites are released in the gut, invading intestinal epithelial cells and initiating schizogony. This asexual phase produces merozoites, which spread infection by invading new cells (Lopez-Osorio *et al.,* 2020). Subsequent gametogony generates microgametes and macrogametes, whose fusion forms zygotes. These mature into oocysts, excreted to restart the cycle. The rapid 4-7 days lifecycle facilitates swift outbreaks in poultry farms.

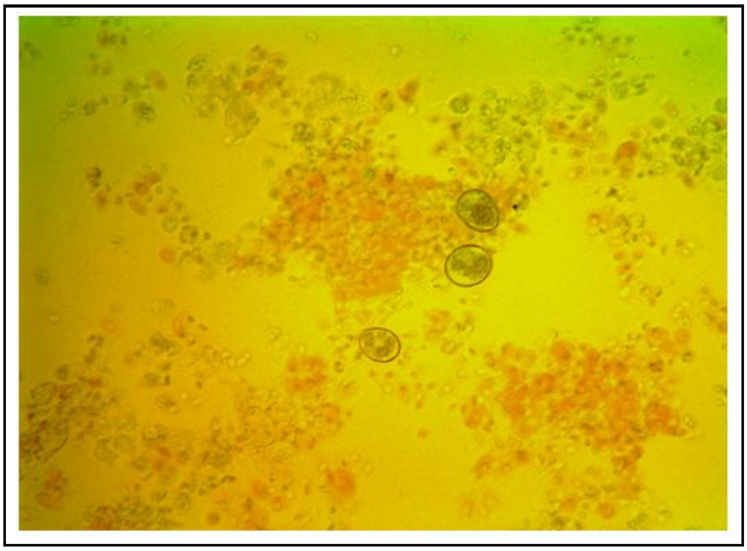

Figure 1: Oocyst of *Eimeria* in poultry.

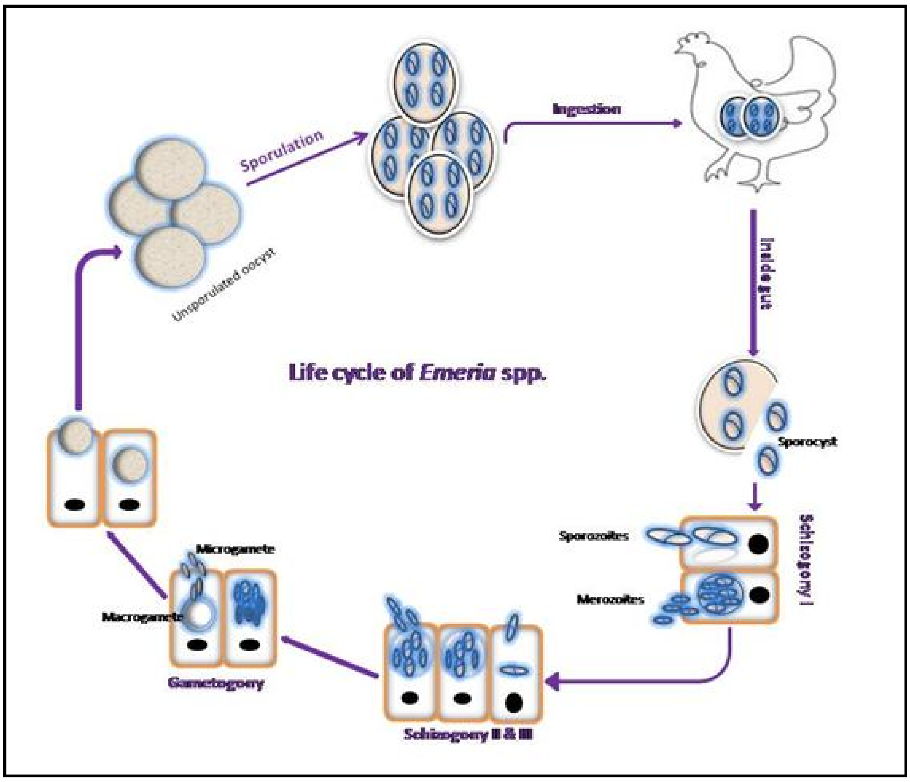

Figure 2: Life cycle of *Eimeria* in poultry.

2.3 Clinical signs and economic implications

Coccidiosis manifests variably, from subclinical infections to acute disease, depending on parasite load, host immunity, and environmental factors (Blake *et al.,* 2020). Subclinical cases, though asymptomatic, reduce feed efficiency and growth, causing substantial economic losses (Remmal *et al.,* 2011). Severe infections trigger bloody diarrhea (especially with *E. tenella*), weight loss, dehydration, and mortality (McDougald, 2003). Necropsies reveal intestinal hemorrhages that revels salt and pepper appearance (Figure 3), blood tinged ingesta in lumen (Figure 4), necrosis, and mucosal thickening.

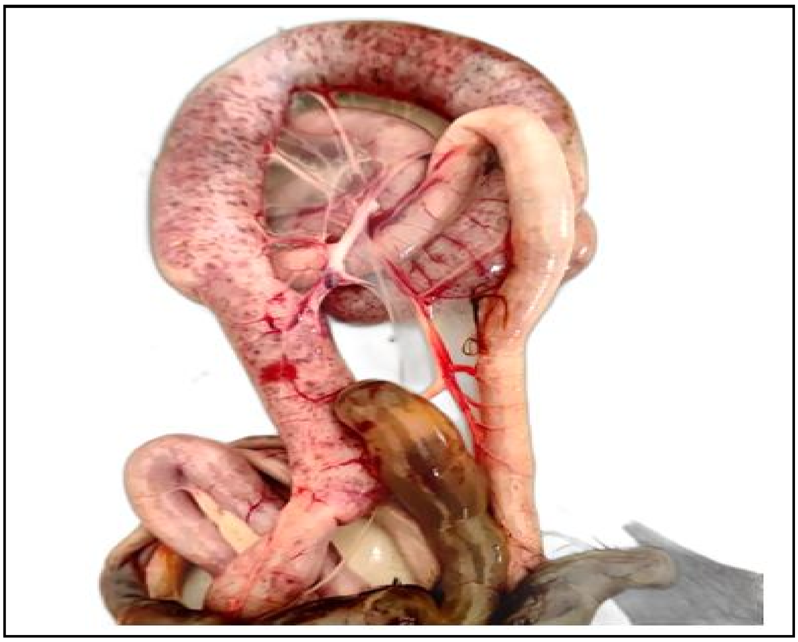

Figure 3: Intestinal hemorrhage in coccidial infected poultry (salt and pepper appearance in intestine).

Figure 4: Intestine filled with the blood tinged feed material.

3. Conventional anticoccidial drugs: Commonly used chemical agents, mechanisms of action, and challenges of resistance, residues, and regulations

The global poultry industry spends billions annually on prophylaxis, treatment, and managing the fallout of avian coccidiosis (Blake *et al.,* 2020). To combat this disease, conventional anticoccidial drugs have been the cornerstone of control strategies for decades. These drugs are broadly classified into synthetic chemicals, ionophores, and mixed products, each with distinct mechanisms of action (Chapman, 1999). However, their prolonged use has led to significant challenges, including drug resistance, residues in poultry products, and stringent regulatory restrictions (Noack *et al.,* 2019).

3.1 Conventional anticoccidial drugs and their mechanisms of action

The poultry industry has long relied on synthetic coccidiostats to manage *Eimeria* infections. Common drugs like amprolium, decoquinate, diclazuril, and nicarbazin each target different aspects of parasite physiology (Rybicki, 2020). Amprolium works by mimicking thiamine (vitamin B1) effectively starves the parasites of this essential nutrient (James, 1980). Other compounds take different approaches - decoquinate disrupts the parasite's energy production (Felici *et al.,* 2021). Diclazuril appears to block cell division, though its precise mechanism continues to be studied (Rybicki, 2020). The dual-component drug nicarbazin shows clear anti-parasitic effects, but researchers still debate its exact biochemical targets (Clarke *et al.,* 2014).

A second important drug category comes from natural sources. Ionophores like monensin and salinomycin originate from Streptomyces bacteria (Dembitsky, 2022). Rather than killing parasites outright, these compounds alter ion balance in parasite cells. Monensin, for instance, causes sodium and calcium buildup that disrupts cellular function (Rybicki, 2020). Interestingly, this partial effect allows some parasites to survive, which actually helps birds develop immunity (Kadykalo *et al.,* 2018). This unique characteristic makes ionophores particularly useful for long-term disease management.

Some of the most effective treatments combine both approaches. Products like Maxiban® (nicarbazin/narasin) and Lerbek® (meticlorpindol/methylbenzoquate) pair different drug types for enhanced effectiveness (Chapman, 1999). Poultry producers often rotate these combinations in "shuttle" programs to prevent drug resistance (Peek and Landman, 2003), a strategy that has helped maintain their usefulness over time.

3.2 Challenges: Drug resistance

One of the most pressing challenges in coccidiosis control is the emergence of drug-resistant *Eimeria* strains. Resistance can be complete, where increasing drug doses are ineffective, or relative, where higher doses retain some efficacy. The widespread use of anti-coccidial drugs has led to resistance in regions such as the United States, Europe, and China. Resistance develops due to genetic mutations in parasite populations, often accelerated by prolonged exposure to a single drug (Chapman and Rathinam, 2022). For example, decoquinate-resistant *Eimeria* strains have been reported in commercial poultry farms, necessitating drug rotation strategies (Felici *et al.,* 2021).

To mitigate resistance, rotation and shuttle programs are commonly employed. Rotation involves alternating different anti-coccidial drugs every few months, while shuttle programs use multiple drugs within a single production cycle. These strategies reduce the selective pressure on parasite populations, delaying resistance development (Peek and Landman, 2003). However, no method entirely prevents resistance, and the limited number of drug classes further complicates management efforts (De Gussem, 2007).

3.3 Public health concerns of drug residues: Residues in poultry products

Consumers face potential health risks from coccidiostat residues in poultry products. Studies show drugs like nicarbazin can accumulate in meat and eggs, raising toxicity concerns (Roila *et al.,* 2019). While agencies like the EU enforce maximum residue limits (Martins *et al.,* 2022), improper withdrawal periods before processing sometimes lead to violations (Owusu-Doubreh *et al.,* 2022). Some compounds may even pose cancer or birth defect risks, leading to strict bans for example, nicarbazin is prohibited in egg-laying flocks (Roila *et al.,* 2019). These safety issues have increased consumer preference for drug free poultry, pushing producers to explore alternatives (Chapman *et al.,* 2010).

4. Regulatory challenges

Global regulations continue tightening for coccidiostat use. The EU's Directive 70/524/EEC strictly controls these feed additives, with proposals for complete bans on preventive use (Martins *et al.,* 2022; Kadykalo *et al.,* 2018). Similarly, the FDA oversees U.S. approvals while shifting focus toward non-pharmaceutical solutions. This regulatory evolution forces the industry to rethink disease management (El-Shall *et al.,* 2022).

5. Emerging alternatives

Vaccines show promise as sustainable solutions. Live vaccines using weakened parasites work well but offer limited cross-protection (Blake and Tomley, 2014), while newer subunit vaccines face efficacy challenges (Dalloul and Lillehoj, 2006). Plant-based options are gaining traction too compounds like artemisinin (from wormwood) and allicin (from garlic) demonstrate antiparasitic effects through multiple mechanisms (Elkhtam *et al.,* 2014). Oregano and turmeric oils also boost immunity against infection (Giannenas *et al.,* 2003).

Gut health supplements offer another approach. Probiotic bacteria enhance intestinal defenses (Dalloul *et al.,* 2003a), while prebiotics like MOS block harmful pathogens and stimulate immunity (Elmusharaf *et al.,* 2006). These natural solutions meet growing demand for safer poultry production methods.

5.1 Herbal solutions for poultry coccidiosis: A sustainable approach

Modern poultry farming faces growing challenges with conventional coccidiosis treatments. While synthetic drugs and ionophores have historically controlled outbreaks effectively, issues like parasite resistance, drug residues in food products, and environmental impact are driving the search for alternatives (Martins *et al.,* 2022; Blake *et al.,* 2020). Plant-based medicines are emerging as promising solutions, offering multiple benefits including parasite control, immune support, and alignment with organic farming principles (Muthamilselvan *et al.,* 2016).

5.2 Meeting market demands for herbal anticoccidial drug

Consumer preferences are shifting toward cleaner poultry products, and herbs fit this trend perfectly. With regulations tightening on drug residues (Martins *et al.,* 2022), plants like oregano and thyme offer antimicrobial protection without safety concerns (Bozkurt *et al.,* 2016). These natural options allow producers to meet both regulatory standards and customer expectations for drug-free meat and eggs.

6. Advantages of herbal medicines in poultry health

6.1 Safety profile of herbal anticoccidials

Herbal anticoccidials offer a distinct advantage in terms of safety compared to synthetic alternatives. Conventional treatments, such as ionophores and chemical coccidiostats, frequently leave harmful residues in poultry meat and eggs, raising concerns about human health risks and contributing to antimicrobial resistance (Martins *et al.,* 2022). In contrast, plant derived treatments are generally considered safe for consumption, with a low likelihood of residue accumulation. For example, turmeric (*C. longa*) and its active component, curcumin, exhibit strong antioxidant and anti-inflammatory effects without causing adverse reactions in poultry (Allen *et al.,* 1998). Similarly, *Bidens pilosa* has demonstrated efficacy in reducing coccidial infections without promoting drug resistance in *Eimeria* species (Yang *et al.,* 2015).

The safety of herbal medicines also makes them highly compatible with organic and sustainable farming practices. As consumer demand for organic poultry grows, natural alternatives such as *Aloe vera* and *Moringa oleifera* have gained prominence for their ability to improve bird health without synthetic chemicals (Gadzirayi *et al.,* 2005; Guo *et al.,* 2004). This shift toward natural remedies reflects broader industry trends prioritizing food safety and sustainability, positioning herbal solutions as a key component of future poultry health strategies.

6.2 Environmental sustainability

Another major benefit of herbal anticoccidials is their biodegradability, which reduces ecological harm. Synthetic drugs used in poultry production often persist in the environment, contaminating soil and water through manure runoff (Felici *et al.,* 2021). In contrast, bioactive compounds from medicinal plants, such as those found in *B. pilosa* and *A. annua*, break down naturally while maintaining therapeutic effectiveness (Chang *et al.,* 2016). This environmentally friendly characteristic aligns with global agricultural initiatives aimed at minimizing pollution and promoting sustainable farming practices.

The ecological advantages of herbal medicines are especially relevant in large-scale poultry operations, where excessive use of synthetic drugs can lead to widespread environmental contamination. By incorporating plant based alternatives, producers can reduce ecological risks while still effectively managing coccidiosis. For instance, essential oils derived from *Oreganum compactum* and *Anredera cordifolia* have been shown to effectively neutralize *Eimeria* oocysts and sporozoites without leaving persistent residues (Muthamilselvan *et al.,* 2016). These properties highlight the dual benefits of herbal medicines supporting both poultry health and environmental conservation.

7. Common anticoccidial medicinal plants and their bioactive compounds

Traditional control methods, such as synthetic anticoccidial drugs, have been effective but are increasingly challenged by drug resistance and consumer demand for residue-free products. This has spurred interest in medicinal plants as natural alternatives, many of which exhibit anticoccidial properties through bioactive compounds that disrupt parasite life cycles, modulate immune responses, or exert antioxidant effects. Several medicinal plants have demonstrated efficacy against avian coccidiosis, including *Azadirachta indica* (neem), *A. annua* (sweet wormwood), *C. longa* (turmeric), *A. sativum* (garlic), *O. vulgare* (oregano), *Emblica officinalis* (amla), and *Punica granatum* (pomegranate), among others.

A. indica , commonly known as neem, is a fast-growing evergreen tree native to the Indian subcontinent and belongs to the *Meliaceae* family. The tree is characterized by its dense canopy of pinnate leaves and small, white flowers. Various parts of the neem tree, including leaves, seeds, and bark, are used for medicinal purposes. The primary bioactive compounds in neem include azadirachtin, nimbin, and nimbidin, which are known for their antimicrobial, antifungal, and anti-inflammatory properties (Tipu *et al.,* 2002). Neem has demonstrated significant anti-coccidial efficacy in poultry. Studies by Tipu *et al*. (2002) and Nweze and Obiwulu (2009) reported that neem leaf and fruit extracts reduced oocyst shedding and improved weight gain in chickens infected with *E. tenella*. The mechanism of action involves the disruption of the oocyst wall, inhibiting sporulation and the release of sporozoites. Additionally, neem extracts enhance the host's immune response by stimulating both humoral and cellular immunity, which aids in combating the infection (Abdel-Tawab *et al.,* 2020).

A. annua, or sweet wormwood, is an annual herb native to Asia and a member of the Asteraceae family. The plant is distinguished by its aromatic, feathery leaves and small yellow flowers. The aerial parts, particularly the leaves and flowers, are used medicinally. The most notable bioactive compound in sweet wormwood is artemisinin, a sesquiterpene lactone with potent anti-parasitic properties (Oh *et al.,* 1995). Artemisinin has shown strong efficacy against *E. tenella* and *Eimeria maxima,* reducing lesion scores and oocyst output in infected chickens (Allen *et al.,* 1997a). However, its effectiveness against *Eimeria acervulina* has been inconsistent (Arab *et al.,* 2006). The anticoccidial activity of artemisinin is attributed to its ability to generate reactive oxygen species (ROS), which damage parasite cellular structures. It also interferes with calcium ATPases in gametocytes, disrupting their metabolic functions (Del Cacho *et al.,* 2010).

C. longa, or turmeric, is a perennial herb belonging to the Zingiberaceae family, native to Southeast Asia. The plant is recognized for its bright yellow rhizomes, which are the primary part used for medicinal and culinary purposes. The active compound in turmeric is curcumin, a polyphenol with antioxidant, anti-inflammatory, and antimicrobial properties (Allen *et al.,* 1998). Turmeric has demonstrated anticoccidial effects, particularly against *E. maxima*, improving weight gain and reducing lesion scores in infected chickens (Khalafalla *et al.,* 2011). Curcumin inhibits sporulation and sporozoite invasion while modulating the host's immune response, enhancing macrophage activity and reducing oxidative stress (Abbas *et al.,* 2010).

A. sativum , or garlic, is a perennial herb from the Alliaceae family, native to Central Asia. The cloves of the garlic bulb are the primary medicinal part, rich in sulfur containing compounds such as allicin, ajoene, and diallyl disulfide, which exhibit antimicrobial and antioxidant properties (Kim *et al.,* 2013). Garlic extracts have shown promise in reducing oocyst shedding and enhancing immune responses in chickens infected with *Eimeria* species (El-Khtam *et al.,* 2014). The mechanism involves disruption of the parasite's membrane potential, leading to cellular apoptosis, and modulation of the host's immune system to combat infection (Pourali *et al.,* 2014).

O. vulgare , commonly known as oregano, is a perennial herb native to the Mediterranean region and a member of the Lamiaceae family. The leaves and flowers are used for their medicinal properties, primarily due to the presence of carvacrol and thymol, which have strong antimicrobial and anti-inflammatory effects (Giannenas *et al.,* 2003). Oregano essential oils have been effective against *E. tenella*, reducing lesion scores and oocyst shedding (Tsinas *et al.,* 2011).

Other noteworthy herbs such as *Aloe vera*, ginger, and eucalyptus have also shown potential as anticoccidial agents. *A. vera* gel contains acemannan, which modulates gut immunity and reduces oocyst shedding (Desalegn *and* Ahmed, 2020). Ginger, rich in gingerols, enhances antioxidant status and inhibits parasite replication (Muthamilselvan *et al.,* 2016). Eucalyptus essential oil, containing eucalyptol, disrupts protozoan metabolism and improves intestinal health (Akhtar *et al.,* 2012).

The mechanisms of action of herbal anticoccidials are diverse and multifaceted. The emergence of drug resistance among *Eimeria* species and growing consumer demand for antibiotic-free poultry products have created an urgent need for alternative control strategies (Chapman, 1999; Dalloul and Lillehoj, 2006). The increasing interest in herbal anticoccidials stems from their potential to offer sustainable, natural alternatives to conventional treatments while addressing concerns about chemical residues in food products (Abbas *et al.,* 2012). These botanical compounds demonstrate remarkable versatility in their approach to combating coccidiosis, employing multiple mechanisms of action that work synergistically to control parasitic infections. Understanding these diverse mechanisms is crucial for developing effective herbal-based strategies that can serve as viable alternatives or complementary approaches to traditional anticoccidial treatments.

One of the most direct mechanisms by which herbal anti-coccidials exert their effects involves the disruption of various developmental stages within the *Eimeria* life cycle. This interference occurs at multiple critical points, preventing successful parasite proliferation and maturation within the host. The complexity of the *Eimeria* life cycle, which includes both asexual and sexual reproductive phases, provides numerous targets for herbal intervention. Saponins, naturally occurring compounds found in plants such as *Yucca schidigera* and *Quillaja saponaria*, demonstrate particularly effective mechanisms of parasite disruption. These bioactive molecules interact directly with cholesterol present in the cell membranes of *Eimeria* parasites, leading to membrane perforation and subsequent death of sporozoites and merozoites (Bafundo *et al.,* 2020). This mechanism is particularly significant because it targets the invasive stages of the parasite, preventing initial infection and subsequent development within intestinal epithelial cells.

The phenolic compounds known as tannins represent another important class of anticoccidial agents that disrupt parasite development. Present in various concentrations in plants such as Emblica officinalis, tannins exhibit the ability to penetrate the protective oocyst wall of *Eimeria* species, causing structural damage that inhibits the crucial sporulation process (Kaleem *et al.,* 2014). This interference with sporulation effectively prevents the formation of infective sporozoites, thereby breaking the transmission cycle of the parasite. Essential oils derived from aromatic plants contribute to parasite disruption through their effects on membrane integrity and metabolic processes. Compounds extracted from Myristica fragrans demonstrate significant sporicidal activity by disrupting membrane sterols essential for parasite survival (Thabet *et al.,* 2022). Similarly, garlic (*A. sativum*) contains allicin, which has been shown to hinder the sporulation process of *Eimeria* oocysts, effectively preventing the completion of the parasite's developmental cycle (El-Khtam *et al.,* 2014). The artemisinin rich extracts from *A. annua* represent a particularly well studied example of herbal compounds that disrupt parasite development through oxidative mechanisms. These extracts generate reactive oxygen species through the degradation of iron-implicated peroxide complexes, inducing oxidative stress that proves detrimental to *E. tenella* development (Allen *et al.,* 1997b). The oxidative stress created by these compounds interferes with essential metabolic processes within the parasite, ultimately leading to cell death and preventing successful infection establishment.

7.1 Modulation of gut microbiota by herbal anticoccidial compound

The complex interplay between gut microbiota composition and resistance to parasitic infections has become a pivotal consideration in coccidiosis management. Plant-derived anti-coccidial agents exhibit a pronounced ability to reshape the intestinal microbial landscape, fostering conditions that hinder *Eimeria* colonization and replication while simultaneously supporting the growth of advantageous bacterial communities.

Certain phytogenic compounds exert prebiotic effects that are instrumental in this microbial restructuring. Mannan oligosaccharides, obtained from yeast cell walls and present in various botanicals, have been documented to impede pathogenic microorganism adhesion to intestinal receptors while concurrently boosting immune activity (Spring *et al.,* 2000). When incorporated into poultry diets, these substances have led to observable decreases in *E. tenella* infection severity, primarily by reinforcing gut barrier integrity and inhibiting pathogenic bacterial attachment (Elmusharaf *et al.,* 2006; McCann *et al.,* 2006).

Garlic-derived flavonoids and organosulfur compounds have been widely investigated for their dual capacity to encourage beneficial gut flora while suppressing harmful microbes. These bioactive agents introduce selective pressure within the intestinal milieu, preferentially supporting *Lactobacillus* and *Bifidobacterium* proliferation while restricting opportunistic pathogens (Kim *et al.,* 2013). Such targeted modulation establishes an intestinal ecosystem that is intrinsically less hospitable to *Eimeria* establishment.

Essential oils, particularly those extracted from oregano (*O. vulgare*), play a key role in sustaining an optimal microbial equilibrium. Their broad spectrum antimicrobial properties effectively neutralize pathogenic bacteria without disrupting commensal microbiota (Mohiti-Asli and Ghanaatparast-Rashti, 2015). The resulting stabilized microbiome enhances coccidial resistance via competitive exclusion and strengthened intestinal barrier performance.

Some herbal formulations also exhibit probiotic like effects by either containing or stimulating beneficial microorganisms. Research involving *Lactobacillus*-based probiotics has reported diminished intestinal invasion and lower oocyst output in *E. acervulina*-infected poultry (Dalloul *et al.,* 2003). Likewise, supplements incorporating *Bacillus subtilis* and similar beneficial strains have shown potential in enhancing overall gut health and lowering coccidiosis prevalence (Ritz *et al.,* 2014).

7.2 Immune-enhancing effects by natural anticoccidial medicine

In addition to their direct antiparasitic properties, herbal medicines play a vital role in enhancing poultry immunity through immunomodulation. Many medicinal plants contain bioactive compounds that strengthen both innate and adaptive immune responses, thereby improving resistance to infections such as coccidiosis. For example, *Echinacea purpurea* has been shown to activate macrophages and stimulate cytokine production, bolstering host defenses against *Eimeria* species (Allen, 2003). Supplementation with *E. purpurea* in poultry diets has also been associated with reduced lesion scores and mitigated weight loss following multi-species *Eimeria* infections.

Polysaccharides extracted from medicinal mushrooms such as *Lentinus edodes* and *Tremella fuciformis*, as well as from *Astragalus membranaceus*, enhance both humoral and cell-mediated immunity. These compounds improve T lymphocyte and natural killer cell function, promote antibody production, and contribute to faster parasite clearance in *E. tenella* infected birds (Guo *et al.,* 2004). Similarly, saponins known for their potent immunostimulatory and adjuvant properties-support immune organ development and boost antibody synthesis, thereby reinforcing host defenses and enhancing the effectiveness of coccidiosis vaccines (Oelschlager *et al.,* 2019; Lee *et al.,* 2020).

Herbs such as *Prunus salicina* (plum) and *A. vera* have been shown to upregulate immune related genes like IFN-γ and IL-15, thereby strengthening the gut associated lymphoid tissue (GALT), which is critical for intestinal immunity (Lee *et al.,* 2008; Gadzirayi *et al.,* 2005). The maintenance of gut health through immunomodulation is particularly advantageous in managing coccidiosis, where parasite burden directly impacts growth performance. As a result, herbal treatments not only reduce parasite load but also improve key production metrics, including weight gain and feed conversion efficiency.

Other botanicals, including *A. annua* and garlic, further demonstrate immunoregulatory potential. *A. annua* stimulates T cell responsiveness and cytokine secretion, while garlic metabolites have been linked to increased resistance against *E. acervulina* through targeted immune modulation (Fatemi *et al.,* 2017; Kim *et al.,* 2013). These immune-enhancing effects contribute to the development of acquired immunity, offering longer-term protection and reducing the impact of recurrent infections (Del Cacho *et al.,* 2010).

Overall, the immunomodulatory properties of plant-derived compounds represent a core mechanism in the prevention and control of coccidiosis. Rather than functioning solely as direct antiparasitic agents, herbal bioactives amplify host immune defenses, facilitating more effective pathogen recognition and clearance. Their multifaceted benefits including safety, sustainability, and compatibility with consumer preferences-position herbal medicines as a promising alternative to conventional coccidiosis control strategies in modern poultry production.

7.3 Antiinflammatory and antioxidant effects

Coccidiosis triggers intense inflammatory reactions and oxidative stress within the intestinal environment, contributing to tissue damage and clinical disease progression. Plant derived anticoccidial agents counteract these pathological mechanisms through robust anti-inflammatory and antioxidant activity, safeguarding intestinal structure and promoting gut health.

Curcumin, the primary bioactive component of turmeric (*C. longa*), exerts powerful anti-inflammatory effects by suppressing nitric oxide synthase activation in macrophages (Brouet and Ohshima, 1995). This suppression attenuates inflammatory cascades and minimizes tissue injury during coccidial infections. Research confirms that dietary curcumin supplementation markedly decreases intestinal inflammation and oxidative stress in poultry infected with *E. tenella* (Khalafalla *et al.,* 2011).

Flavonoids isolated from *M. oleifera* and *Musa paradisiaca* act as effective antioxidants, neutralizing reactive oxygen species produced during coccidiosis (Anosa and Okoro, 2011; Mgbojikwe *et al.,* 2022). These phytochemicals protect intestinal epithelial cells from oxidative damage, preserving barrier function and alleviating clinical disease severity.

Polyphenol rich green tea extracts exhibit notable antioxidant capacity, shielding intestinal cells from oxidative injury induced by coccidial parasites (Jang *et al.,* 2007). Their free radical scavenging properties inhibit lipid peroxidation, maintaining membrane stability and cellular function under oxidative duress.

Essential oils extracted from *Pistacia lentiscus* display significant anti-inflammatory properties that mitigate *Eimeria* induced pathological changes (Rahmani *et al.,* 2021). These oils regulate inflammatory signaling pathways, curbing pro-inflammatory mediator release and accelerating inflammation resolution.

7.4 Synergistic interactions of phytochemicals

The therapeutic potential of botanical anticoccidials is frequently amplified through synergistic relationships among diverse phytochemicals, whether within single plants or in carefully blended formulations. Such interactions often produce combined effects surpassing individual component efficacy, delivering more robust protection against coccidiosis.

Essential oil blends demonstrate particularly strong synergism against *Eimeria* species. Studies reveal that oregano-citrus oil combinations exert superior anticoccidial activity compared to isolated components, likely through complementary modes of action targeting distinct parasitic vulnerabilities (Gordillo *et al.,* 2021). Similarly, formulations combining oregano oil with thymol, eugenol, curcumin, and piperine enhance coccidiosis vaccine efficacy in broilers (Giannenas *et al.,* 2003).

The interplay between saponins and tannins in mixed herbal preparations shows particular promise, with documented additive or synergistic improvements in weight gain and lesion score reduction (Pop *et al.,* 2019). These findings suggest that multi-component phytogenic treatments offer broader protection than single-compound therapies.

Specific botanical pairings, such as garlic with turmeric, provide stronger defense against *Eimeria* than individual applications (El-Khtam *et al.,* 2014). Likewise, *A. annua* and *C. longa* extract combinations exhibit heightened anticoccidial effects by simultaneously disrupting multiple parasite life cycle stages (de Almeida *et al.,* 2014).

While many phytochemical combinations generate novel mechanisms absent in isolated compounds, not all interactions prove beneficial. Further investigation remains crucial to identify potential antagonistic effects and refine formulations for optimal therapeutic outcomes.

8. Natural compounds in avian coccidiosis control

Extensive research has investigated the effectiveness of plant-based solutions for managing coccidiosis in poultry production systems. Among these, garlic (*A. sativum*) has emerged as a particularly potent natural intervention which has capacity to neutralize ROS and free radicals (Juman *et al*., 2024), research by Kim *et al*. (2013) revealed that incorporating garlic metabolites into poultry diets enhanced resistance to *E. acervulina* infections, evidenced by decreased oocyst excretion, lower intestinal lesion severity, and improved growth rates. Complementary findings by Youn and Noh (2001) demonstrated that botanical extracts from *Ulmus macrocarpa* and *Pulsatilla koreana* substantially decreased mortality and pathological damage in *E. tenella* infected broilers, reinforcing the value of phytogenic approaches in coccidiosis management.

A. annua represents another promising botanical intervention due to its artemisinin content. Investigations by Coroian *et al*. (2022) and Fatemi *et al*. (2015) documented that *A. annua* supplementation reduced parasitic oocyst output while supporting better growth metrics in challenged flocks. The therapeutic mechanism appears linked to oxidative stress induction and developmental interference within the parasite (Fatemi *et al.,* 2017). Plant derived essential oils particularly those containing carvacrol, thymol, and eugenol - have shown remarkable ability to compromise *Eimeria* oocyst integrity (Remmal *et al.,* 2011). Practical applications demonstrate oregano oil's effectiveness in mitigating *E. acervulina* and *E. maxima* infections, with measurable improvements in both intestinal health and production parameters (Tsinas *et al.,* 2011).

8.1 Mechanistic insights from botanical research

Scientific investigations into herbal anticoccidial agents have provided valuable mechanistic insights, confirming the efficacy of traditional plant-based remedies through modern research methodologies. For example, Muthamilselvan *et al.* (2016) demonstrated that the anticoccidial activity of artemisinin, a compound derived from *A. annua*, is mediated by the generation of reactive oxygen species (ROS), which interfere with the sporulation of *Eimeria* oocysts. This oxidative disruption not only reduces parasite viability but also minimizes intestinal damage, leading to improved growth performance in treated birds.

Further advancing this understanding, Saeed and Alkheraije (2023) reported that saponin rich botanicals such as *Yucca schidigera* and *Quillaja saponaria* exert comparable efficacy to synthetic anticoccidials. Their mechanisms include antimicrobial actions, membrane disruption, and direct effects on parasite viability, offering a multifaceted approach to parasite control.

Historically, the use of medicinal plants to combat poultry parasites dates back centuries, particularly in traditional healing systems. Contemporary studies now validate these practices, revealing that herbal compounds can act at multiple points in the *Eimeria* life cycle. Unlike synthetic drugs, which typically target a single stage or molecular pathway, plant-based bioactives interfere with sporozoite invasion, inhibit oocyst formation, and impair parasite reproduction simultaneously (Abbas *et al.,* 2012). This multi-targeted activity reduces the risk of treatment failure and minimizes the emergence of drug resistance.

Of particular importance is the role of botanicals in addressing the growing problem of anticoccidial resistance. The overuse of conventional drugs has led to the selection of resistant *Eimeria* strains (Abbas *et al.,* 2011). In contrast, herbal compounds such as allicin from garlic and artemisinin from wormwood exhibit broad-spectrum mechanisms that hinder the development of resistance (Kim *et al.,* 2013). These phytochemicals-alongside flavonoids, tannins, and essential oils-act synergistically to overwhelm parasite defenses, making it more difficult for resistance to evolve (Muthamilselvan *et al.,* 2016).

For instance, artemisinin induces oxidative stress that compromises oocyst integrity (De Almeida *et al.,* 2012), while garlic not only exhibits antiparasitic effects but also enhances host immunity, providing a dual line of defense against infection. This combination of direct parasiticidal action and immunomodulation underpins the growing interest in botanicals as sustainable and effective alternatives to synthetic anticoccidials.

8.2 Practical application considerations

Implementation protocols for phytogenic coccidiosis controls show considerable variation in practice. Garlic interventions typically range from 0.5-1% dietary inclusion, delivering consistent reductions in parasite load alongside growth benefits (Kim *et al.,* 2013). *A. annua* formulations demonstrate efficacy at 1-2.5 mg/kg feed concentrations against multiple *Eimeria* species (Fatemi *et al.,* 2015), with purified artemisinin showing activity at 50 mg/kg feed levels (Muthamilselvan *et al.,* 2016). Saponin-based preparations achieve therapeutic effects at 0.1-0.5% inclusion rates, matching conventional drug performance in some instances (Saeed and Alkheraije, 2023).

Administration methods extend beyond feed incorporation. Tannic acid extracts from *Rhus chinensis* (0.2% feed inclusion) improved both production metrics and coccidiosis indicators (Kaleem *et al.,* 2014). Essential oil blends (*O. vulgare Citrus* combinations) at 0.1-0.2% concentrations enhanced immune function while controlling infection severity (Reisinger *et al.,* 2011). The predominance of feed-based delivery reflects practical advantages in homogeneity and operational simplicity within commercial production settings.

8.3 Comparative performance relative to conventional anticoccidials

Research evaluating plant derived alternatives against synthetic coccidiostats has produced divergent outcomes. Investigations with *Artemisia sieberi* extracts revealed comparable efficacy to monensin, with equivalent reductions in oocyst excretion and similar growth performance enhancements (Kheirabadi *et al.,* 2014). Phytogenic compounds including carvacrol and cinnamaldehyde have matched synthetic drugs in immunomodulatory capacity (Lillehoj *et al.,* 2011). Artemisinin demonstrated parity with monensin in suppressing parasite proliferation and supporting weight gain (Muthamilselvan *et al.,* 2016), while saponin-based formulations achieved performance benchmarks equivalent to ionophore antibiotics (Saeed and Alkheraije, 2023). Not all botanical interventions achieve this standard of efficacy. Artemisinin exhibited inconsistent activity against *E. acervulina* and marginal effectiveness against *E. maxima* when benchmarked against lasalocid (Arab *et al.,* 2006). *C. longa* preparations showed species-dependent activity, demonstrating effectiveness against *E. maxima* but limited impact on *E. tenella* infections (Allen *et al.,* 1998). These observations underscore the pathogen-specific nature of phytogenic efficacy, highlighting the need for targeted formulation development.

8.4 Critical evaluation metrics

Coccidiosis intervention studies typically assess four cardinal parameters: parasitic load quantification, growth performance metrics, pathological scoring, and survival rates. Oocyst enumeration serves as the primary indicator of parasitic replication and environmental contamination potential. *A. annua* interventions achieved 70% reductions in oocyst output alongside 20% improvements in growth rates (Fatemi *et al.,* 2015). Oregano oil formulations decreased intestinal lesion severity by 50% while enhancing weight gain by 10 percentage points (Tsinas *et al.,* 2011). Botanical extracts have demonstrated mortality reductions from 30% in control groups to below 10% in treated flocks (Youn and Noh, 2001).

Pathological assessment of intestinal and cecal tissue damage remains a crucial evaluation component. Betaine salino mycin combinations improved both growth metrics and feed efficiency in challenged poultry (Augustine *et al.,* 1997). *Echinacea purpurea* supplementation mitigated both pathological damage and growth retardation (Allen, 2003). Probiotic interventions featuring *Lactobacillus* and *Saccharomyces* strains enhanced gut immunity while reducing parasitic shedding (Dalloul *et al.,* 2003; Lee *et al.,* 2007). This multidimensional evaluation framework provides comprehensive therapeutic assessment.

9. Safety considerations and regulatory status of phytogenic interventions

9.1 Toxicological assessments of herbal anticoccidials

Plant-derived interventions for coccidiosis control have garnered significant interest due to their favorable safety profiles and multifaceted modes of action compared to synthetic anticoccidials. Numerous botanicals exhibit potent antiparasitic properties, disrupting *Eimeria* development through various mechanisms. For instance, *A. annua* derivatives generate reactive oxygen species that interfere with oocyst sporulation (Del Cacho *et al.,* 2010), while pine-derived tannins compromise oocyst integrity by inducing cytoplasmic disruption (Molan and Faraj, 2015). Garlic's organosulfur compounds, such as allicin and diallyl sulfides, reduce parasite excretion and intestinal pathology (Alnassan *et al.,* 2015), and green tea polyphenols inhibit key enzymes essential for sporulation (Jang *et al.,* 2007).

The superior safety margins of these botanicals stem from their natural, biocompatible active constituents. Garlic compounds provide not only antiparasitic effects but also immunomodulatory and antioxidant benefits without notable toxicity (Kim *et al.,* 2013; Pourali *et al.,* 2014). Similarly, *Artemisia* extracts demonstrate effective parasite suppression alongside excellent tolerability in poultry (Fatemi *et al.,* 2017). *B. pilosa* has shown benefits in modulating gut microbiota and enhancing immune responses during prolonged administration, with no documented adverse outcomes (Chang *et al.,* 2016; Yang *et al.,* 2019).

Despite these promising results, thorough toxicological evaluations are essential to confirm the long-term safety of botanical anticoccidials. Existing safety assessments often rely on indirect parameters such as mortality rates, growth performance, lesion scores, and oocyst shedding. For example, *A. annua* has been shown to boost immune function without inducing clinical toxicity (Del Cacho *et al.,* 2010), and garlic and pine bark derivatives exhibit favorable safety profiles when appropriately dosed (Molan and Faraj, 2015; Alnassan *et al.,* 2015). However, excessive intake of certain compounds may result in gastrointestinal irritation, underscoring the importance of precise dosage control.

Crucially, major gaps remain in the toxicological literature. Few studies have conducted comprehensive evaluations involving histopathological analyses, hematological profiling, or liver enzyme assays to assess organ-specific toxicity (Allen *et al.,* 2005; Abd El-Hack *et al.,* 2021). For instance, although *C. longa* (turmeric) and its active constituent curcumin are generally considered safe and immunostimulatory, data on their chronic effects in poultry remain scarce (Allen *et al.,* 1998; Abbas *et al.,* 2010). Likewise, essential oils derived from oregano and thyme possess potent antiparasitic and antimicrobial activities, yet their potential systemic effects—such as alterations in plasma nitric oxide levels-warrant further investigation (Giannenas *et al.,* 2003).

9.2 Challenges and limitations in the application of herbal remedies for avian coccidiosis control

The use of herbal remedies for avian coccidiosis control presents several challenges, primarily due to variability in bioactive compound composition. The efficacy of these remedies depends on the concentration of active constituents, which can fluctuate based on cultivation conditions, processing methods, and storage. For example, allicin, the key anticoccidial compound in garlic (*A. sativum*), varies significantly depending on environmental and post-harvest factors (Kim *et al.,* 2013). Similarly, artemisinin levels in *A. annua* differ across plant sources, affecting therapeutic consistency (Ferreira *et al.,* 2010). Such variability complicates the reliability of herbal treatments.

Another critical issue is the lack of standardization and quality control in herbal product manufacturing. Unlike pharmaceutical drugs, herbal remedies often evade stringent regulatory scrutiny, leading to inconsistencies in potency, purity, and safety. Contaminants or adulterants in herbal extracts may compromise both efficacy and animal health (Abbas *et al.,* 2015). The absence of standardized extraction and formulation protocols further hinders reproducibility, making it difficult to assess therapeutic potential accurately.

Clinical validation remains a major limitation. While in vitro and small-scale studies highlight the anticoccidial properties of herbs like oregano essential oil (Tsinas *et al.,* 2011), large-scale field trials are scarce. Without robust clinical evidence, determining optimal dosages, treatment durations, and administration methods remains speculative, limiting practical adoption in poultry farming. Shelf-life and palatability also pose significant challenges. Many bioactive compounds degrade over time due to exposure to light, heat, or oxygen. For instance, garlic's active components lose efficacy under improper storage (El-Khtam *et al.,* 2014). Additionally, strong odors or bitter tastes in some herbs may reduce feed intake, negatively impacting poultry growth (Ogunlana *et al.,* 2008).

Addressing these challenges requires a multifaceted approach. Standardization through quality control measures and regulatory frameworks is essential to ensure consistent product efficacy. Developing uniform extraction methods, purity assessments, and storage guidelines will enhance reliability. Furthermore, extensive clinical trials are necessary to validate herbal treatments under real-world conditions and establish best practices for their application.

9.3 Variability and standardization issues in herbal remedies

The effectiveness of herbal treatments for coccidiosis is heavily influenced by the inconsistent composition of bioactive compounds. Factors such as plant species, geographic origin, and harvesting techniques contribute to this variability. For example, artemisinin levels in *A. annua* vary with growth conditions and plant maturity (Zhang *et al.,* 2012). Additionally, synergistic or antagonistic interactions among phytochemicals complicate the isolation of active components (Efferth and Koch, 2011), necessitating comprehensive phytochemical profiling often absent in current research.

The lack of standardized production protocols exacerbates these challenges. Unlike synthetic drugs, herbal products lack strict regulatory oversight, leading to inconsistencies in extraction methods, active compound concentrations, and purity (Rossi *et al.,* 2020; Tsiouris *et al.,* 2021). While compounds like quercetin, curcumin, and berberine show promise against *E. tenella*, discrepancies in study designs and dosages hinder definitive conclusions (Idris *et al.,* 2017; Sánchez-Hernández *et al.,* 2019). Without standardized formulations, reproducibility and regulatory approval remain difficult.

Most supporting evidence for herbal anticoccidials comes from in vitro or small-scale studies rather than large-scale field trials (Song *et al.,* 2020; Abbas *et al.,* 2012). Laboratory findings often fail to account for real-world variables such as host immunity and environmental stressors (Marugan-Hernandez *et al.,* 2020). Moreover, methodological flaws-small sample sizes, short durations, and lack of controls-undermine result reliability (Tsiouris *et al.,* 2021). Without rigorous clinical validation, stakeholders remain skeptical of herbal alternatives compared to conventional drugs.

Many herbal compounds degrade rapidly under suboptimal storage conditions (Marchiosi *et al.,* 2020). Essential oils, for instance, lose potency when exposed to light or oxygen, requiring costly stabilization methods (Wani *et al.,* 2021; Moghaddam and Mehdizadeh, 2017). Additionally, unpalatable flavors may reduce feed intake, necessitating encapsulation or flavor-masking techniques-areas needing further research (Perin *et al.,* 2019; Ghaniei *et al.,* 2022).

10. Future prospects and recommendations for herbal remedies in avian coccidiosis control

The increasing demand for natural alternatives highlights a promising shift in avian coccidiosis management, though several obstacles must be addressed to optimize herbal treatments.

10.1 Need for standardized research

While many studies support the efficacy and safety of herbal remedies against avian coccidiosis, inconsistent results remain a significant issue. These variations often arise from a lack of standardized protocols in preparation, formulation, and quality assurance (Abbas *et al.,* 2015; Rossi *et al.,* 2020). Unlike synthetic drugs, which follow strict regulatory guidelines, herbal treatments frequently lack precise standards for active compound concentrations, extraction methods, and purity (Tsiouris *et al.,* 2021). Such inconsistencies undermine reliability and complicate scientific validation.To resolve these challenges, uniform extraction techniques, quality control measures, and storage guidelines must be established (Quiroz-Castañeda and Dantán-González, 2015). Standardization ensures consistent therapeutic effects across different batches and plant sources, facilitating reproducible research and reliable treatment protocols (Zhang *et al.,* 2012). Additionally, expanded clinical trials are essential to confirm real-world efficacy, determine optimal dosages, and refine administration methods (Song *et al.,* 2020; Abbas *et al.,* 2012).

10.2 Integration with conventional therapies

Herbal remedies offer a viable alternative to synthetic anticoccidial drugs, but their integration into existing management systems is crucial for maximizing benefits. A combined approach-using herbal treatments alongside vaccines or pharmaceuticals-can enhance coccidiosis control by leveraging both natural and conventional strategies (Chapman, 1999; Dalloul and Lillehoj, 2006). For example, immune-boosting herbal extracts may complement vaccines by strengthening host defenses, while synthetic drugs remain reserved for severe outbreaks (Chapman, 2003). Rotating herbal remedies with conventional drugs in shuttle programs may also delay resistance development (Peek and Landman, 2003). This approach reduces selective pressure on parasite populations, extending the effectiveness of both treatment types (De Gussem, 2007). By incorporating herbal solutions into existing protocols, the poultry industry can benefit from their advantages while mitigating risks related to drug resistance and residues.

10.3 Biotechnology's role in optimizing phytochemical extraction and formulation

Advances in biotechnology offer significant potential for improving the potency and stability of herbal remedies. Modern extraction techniques such as supercritical fluid extraction, ultrasonic-assisted extraction, and microwave-assisted extraction-can enhance the yield and purity of bioactive compounds (Bafundo *et al.,* 2021; Rossi *et al.,* 2020). These methods not only increase active ingredient concentrations but also preserve delicate phytochemicals, ensuring consistent therapeutic effects (Efferth and Koch, 2011).Innovative formulation and delivery methods, including microencapsulation and nanoencapsulation, protect bioactive compounds from degradation while improving bioavailability (Wani *et al.,* 2021; Moghaddam and Mehdizadeh, 2017). Such advancements can also enhance the palatability of herbal feed additives, addressing a key challenge in poultry nutrition (Perin *et al.,* 2019; Ghaniei *et al.,* 2022). By adopting these technologies, the industry can overcome critical limitations of herbal treatments, making them more practical for coccidiosis control.

10.4 Synergistic potential of herbs and vaccines

Combining herbal remedies with vaccines presents a compelling strategy for improving coccidiosis management. Certain herbal extracts stimulate immune function, potentially enhancing vaccine-induced protection (Lee *et al.,* 2020). For instance, saponins from Yucca schidigera and Quillaja saponaria act as natural adjuvants, promoting immune organ development and boosting antibody production (Oelschlager *et al.,* 2019). This immunomodulatory effect may improve vaccine efficacy, reducing infection severity and enhancing flock health. Additionally, herbal compounds that influence gut microbiota can create a more favorable environment for vaccine performance. Prebiotics and probiotics derived from plants may encourage beneficial bacteria, limiting *Eimeria* colonization (Spring *et al.,* 2000; Elmusharaf *et al.,* 2006). This dual action-targeting both parasites and host immunity-supports a comprehensive approach to coccidiosis control.

11. Conclusion

Advancing coccidiosis control in poultry will require moving beyond preliminary trials to standardized, field-ready herbal formulations supported by rigorous validation. Future work should focus on improving consistency through advanced extraction and delivery technologies, while exploring synergistic use with vaccines, probiotics, and selective drugs. Regulatory frameworks that establish clear quality and safety standards will be essential for commercial adoption. Ultimately, integrating phytogenic remedies into sustainable health management offers a pathway to reduce reliance on synthetic drugs, meet consumer demand for residue-free products, and strengthen the resilience of poultry production systems.

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Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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