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Review Article

Nano-enabled Phytogenic Feed Additives for Sustainable Poultry Production: A New Frontier in Meat Quality, Growth Efficiency, and Antibiotic Alternatives

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Abstract

This review focuses on nano-enabled phytogenic feed additives (nPFAs) as innovative tools to enhance poultry growth performance, meat quality while potentially replacing the use of antibiotics. The excessive use of antibiotics in poultry production has raised significant concerns about antimicrobial resistance (AMR) and drug residues, which have increased interest in natural additives. However, conventional substances face challenges such as poor bioavailability instability and limiting their effectiveness. Nanoformulation technologies address these limitations by improving the stability, targeted delivery and controlled release of phytochemicals. This can significantly enhance biological efficacy even at reduced dosages. This review also elaborates recent advances in nPFA formulations, mechanisms of action at cellular and systemic levels as well as provides examples of their applications in poultry production. It highlights that using nano-encapsulation to deliver antioxidants, shape the gut bacteria and support the immune system leads to higher growth and better meat quality. Additionally, the environmental advantages of minimising antibiotic usage are emphasised. Despite having tremendous potential but the challenges with safety evaluation, regulatory frameworks, well as industrial-scale production still exist. Emerging research directions such as precision nutrition and multifunctional nanocarriers approaches are discussed as pathways to optimize nPFA applications. Ultimately, it demonstrates that by using nano-enabled phytogenic additives, the industry can achieve sustainable, antibiotic-free poultry production while giving consumers high quality protein.

Keywords

Nano-enabled Phytogenics, Feed Additive, Antibiotic Alternatives, Sustainable Poultry Production, Meat Quality, Poultry Nutrition

1. Introduction

1.1. Global Poultry Outlook & Antimicrobial Resistance Risk

Over the past several decades, the poultry sector has played an important role in stabilizing the world's food supply. According to the Food and Agriculture Organization (FAO), there is a steady rise in demand for poultry meat due to shifts in food preferences and increase in the world's population.

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This rise of poultry meat production is expected to surpass 135 million tons globally by the end of 2025 [1]. Furthermore, poultry production is projected to be nearly double by 2050 due to rising protein demand, affordability and efficiency in feed conversion ratio [2]. This rapid expansion has historically relied on antimicrobial growth promoters (AGPs) to optimize feed efficacy and reduce disease outbreak in intensive production environment. In the past, poultry received AGPs to promote healthy growth and efficient feeding. In addition, excessive use of antibiotics has brought about antibiotic-resistant strains that cause harm to people as well as animals [3]. However, as production continue increase on a larger scale, poultry industry faces a critical challenge from the threat of antimicrobial resistance (AMR).

Salmonella, *Campylobacter* and *Escherichia coli* have developed resistance to antibiotics due to the exploitative use of both therapeutics and growth promoters [4]. The World Health Organization (WHO) identifies antimicrobial resistance as a significant health issue, with potential implications for both human and animal [5]. As a direct response to this, several governments and organizations all over the world are imposing stringent regulation on limit use of antibiotics. For this reason, scientists are developing new methods to treat poultry and prevent AMR risk. As this emerging issue evolves, it is necessary to identify sustainable and new methods to tackle microbial diseases. The approach is to use natural substances like immunomodulators and advanced nanotechnology materials that focus on safer natural feed additives. Using these alternatives also helps poultry by reducing antibiotics, improving poultry health and disease resistance while simultaneously reducing the risks associated with antibiotic overuse.

1.2. Limitation of Conventional Poultry Feed Additives

Many now believe that phytogenic feed additives, derived from herbs, spices, and plants, offer a viable alternative to AGPs. It helps in improving the health of a chicken's gut and strengthens its ability to use nutrients and defend against bacterial and viral infections [6]. Although conventional feed additives have significantly enhanced production, increased growth and reduced disease risk while their limitations are now clearly evident in modern farming. Conventional PFAs such as vitamins, minerals, enzymes, probiotics and antibiotics are often subjected to deteriorate under harsh conditions [7]. It has been considered that the high temperature and high level of humidity during feed processing and production can cause deterioration of sensitive compounds, rendering them ineffective or diminishing their potency.

Another fundamental limitation of many poultry feed additives is associated with their poor solubility. Fat-soluble vitamins, essential amino acids and certain minerals are hard to dissolve effectively in water limiting their bioavailability and absorption in the gastrointestinal tract [8]. This can cause inconsistent dose level to poultry leading to suboptimal growth performance or even cause nutritional deficiencies. The lack of control in dosage or targeted release of these bioactive substances is also a significant challenge, as the nutrients may not be absorbed efficiently in the gut of a bird where it most needed.

In addition, the reliance on broad-spectrum AMRs to control diseases has led to the gradual emergence of resistance in bacterial strains to these drugs. Taking repeated low-dosage antibiotics results in the infectious pathogens being able to survive treatment, while it also disrupts the gut microbiome and increases the risk of foodborne diseases [9, 10]. Consequently, the poultry industry is being put under continuous pressure to transition away from the use of alternatives to traditional PFAs that are both environmentally sustainable and targeted solutions.

1.3. Nanotechnology's Promise in Poultry Feed Additives

Nanotechnology has emerged as a transformative approach to address many challenges which is associated with conventional poultry feed additives. The application of nanomaterials with the sizes ranging from 10-100nm helps in improving the stability, solubility and bioavailability of different feed additives [11]. Bringing together phytogenic and nanotechnology has made it possible to develop nano-enabled phytogenic feed additives (NPFAs). This intends to link the useful properties of PFAs with the advancements offered by nanotechnology. Based on recent studies, NPFAs are likely to improve how poultry grow, eat and respond to diseases while leading to a decrease in the use of antibiotics [3]. It has been proven that nano-encapsulation of substances benefits poultry because it keeps active compounds safe, helps them be absorbed in the body and assures controlled release for better results [12]. This encapsulation allows for the sustained release of active ingredients, ensuring that the nutrients are delivered into the GIT of poultry birds in a controlled and efficient manner. Encapsulating certain chemicals helps them resist environmental damage like heat, light, and oxidation [13]. It is possible to deliver nutrients to the digestive system at a controlled pace as well as release active substances over a long period.

The ability to enhance poorly water-solubility of certain compounds is one of the promising aspects of using nanotechnology in the poultry nutrition. When these feed additives are incorporated at the nanoscale, their surface area is significantly increased and tend leads to better dispersion and released on specific locations inside the digestive system [13, 14]. Therefore, this enhances the way nutrients are absorbed by the poultry birds. Moreover, changing the chemical and physical properties of nanoparticles allows the design of formulations that release their contents when needed even in response to pH changes or enzymatic activity, improving nutrient uptake while minimizing waste [15].

Additionally, nanoparticles hold unique antimicrobial abilities that serve as a direct alternative to antibiotics in poultry farming. For example, silver and zinc nanoparticles has exhibited strong antibacterial potential, since can suppress the growth of pathogenic microorganisms in the digestive system and also reduce the need of antibiotic interventions [15, 16]. The properties are advantageous in the context of AMR, providing a novel method for disease control that does not exacerbate the global health crisis of antibiotic resistance.

1.4. Objectives of Study

This work explores the use of nanotechnology to fill the gaps left by conventional poultry feed additives. Different types of nanoparticles used in poultry feed are discussed in this review. There are organic and inorganic nutrients sorted according to their functionalities. The research will examine how nanotechnology-based PFAs address challenges faced by conventional feed additives and measure their influence on essential nutrients, time-controlled activity, and overall health and growth in poultry. The review also looks at future trends and inventions in the field, highlighting the need for more studies and the challenges involved, such as adhering to rules, making the product usable for many animals, and highlighting the risks associated with applying nanotechnology in animal feed. The review aims to address key problems such as antibiotic resistance, sustainable farms, and poultry health, while focusing on how nanotechnology could help meet these challenges.

2. Phytogenic Feed Additives in Poultry Nutrition

2.1. Bioactive Components and Functional Roles

Phytogenic feed additives encompass a broad array of plant-derived bioactive compounds, including essential oils, herbs, spices, and other botanical extracts. These products are rich in diverse classes of phytochemicals – notably polyphenols (e.g. flavonoids, phenolic acids, tannins), terpenoids (especially in essential oils), glycosides, and alkaloids [17].

Commonly studied PFAs in poultry diets are derived from aromatic herbs such as oregano, thyme, garlic, cinnamon, clove, rosemary, and sage. Essential oils are a major subgroup of PFAs, providing compounds like thymol and carvacrol from oregano/thyme, eugenol from clove, and cinnamaldehyde from cinnamon [7]. Likewise, garlic contains organosulfur constituents (e.g. allicin and diallyl sulphides) and peppers provide pungent alkaloids (e.g. capsaicin); these contribute to the bioactivity of PFAs [19]. Collectively, the multitude of phytochemical components in PFAs underpins a range of functional properties in the animal.

Table 1. Common Phytogenic Compounds Used in Poultry Nutrition.

Phytogenic Compound	Source (Plant)	Key Biological Functions	References
Allicin	*Allium sativum* (Garlic)	Broad-spectrum antimicrobial (bacteria, viruses, parasites), immunomodulatory, enhances immune responses	Adjei-Mensah, et al. [20]
Capsaicin	*Capsicum annuum* (Chili Pepper)	Stimulates digestive enzyme secretion, improves gut motility, antimicrobial and antioxidant properties	Li, et al. [21]
Carvacrol	Oregano, Thyme	Broad-spectrum antimicrobial (effective vs. Clostridium perfringens, Salmonella), antioxidant, modulates gut flora	Spisni, et al. [22]
Cinnamaldehyde	*Cinnamomum verum* (Cinnamon)	Bacteriostatic and bactericidal, improves digestion, antioxidant and anti-inflammatory effects in gut	Pagliari, et al. [23]
Curcumin	*Curcuma longa* (Turmeric)	Potent antioxidant and anti-inflammatory, protects tissues from oxidative stress, modulates inflammation, improves immunity and performance	Boroumand, et al. [24]
Eugenol	*Syzygium aromaticum* (Clove)	Antibacterial, antifungal, antioxidant protecting lipids from oxidation	Maggini, et al. [25]
Gingerol	*Zingiber officinale* (Ginger)	Anti-inflammatory, antimicrobial, enhances digestion and absorption, improves growth performance	Abd El-Hack, et al. [26]
Rosmarinic Acid	*Rosmarinus officinalis* (Rosemary)	Strong antioxidant & anti-inflammatory, protects intestinal mucosa, supports immune function	Shang, et al. [27]
Thujone	*Artemisia absinthium* (Wormwood)	Antimicrobial and digestive stimulant; reduce pathogenic bacteria, enhances nutrient absorption	Szopa, et al. [28]

Phytogenic Compound	Source (Plant)	Key Biological Functions	References
Thymol	*Thymus vulgaris* (Thyme), *Origanum vulgare* (Oregano)	Disrupts bacterial membranes, antioxidant, improves gut health by reducing pathogenic bacteria	Nazzaro, et al. [29]

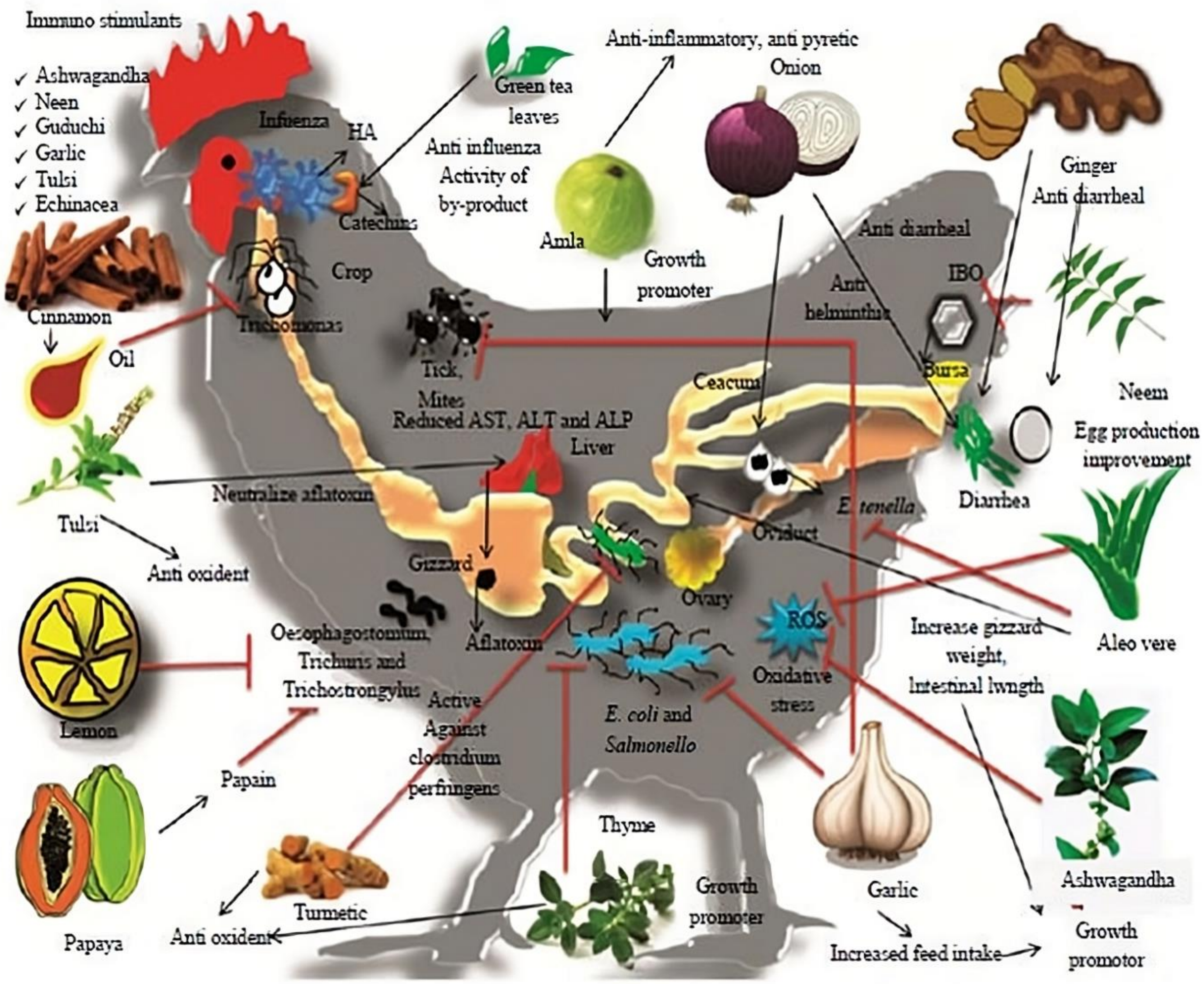

Figure 1. *Various phytogenic substances and their targeted beneficial effects on poultry physiological functions and growth promotion [18].*

Certain plant extracts can down-regulate proinflammatory mediators and enhance the immune response. For example, supplementation with anise seed was reported to increase phagocytic activity and lymphocyte counts in broilers [30]. Likewise, neem (Azadirachta) and green tea extracts have been shown to stimulate macrophages and improve antibody responses in poultry birds. Such effects contribute to a more balanced immune function and reduced inflammatory stress in the gut [31]. Overall, the diverse bioactive components in PFAs act in concert to suppress pathogenic bacteria, protect tissues from oxidative and inflammatory damage, and support the immune system, thereby promoting growth and health in poultry.

2.2. Challenges in Conventional Use of PFAs

Despite the promising benefits of phytogenic additives, several challenges have limited their consistency and efficacy in practice. A primary issue is the high variability in phytogenic products. Unlike synthetic feed additives, PFAs are natural extracts that can differ widely in composition depending on plant species, cultivar, growing conditions, harvest time, and processing methods. Because of the variability, the concentration of active compounds (for example, essential oil constituents and polyphenols) can be different from one preparation to another, even when they are the same additive [32]. Consequently, researchers frequently observe varied results; for example, an extract that performs effectively in one test may be ineffective in another. Puvača, et al. [33] studied that the variability in phytogenic mixes and concentrations among research renders the results incomparable due to differing biological effects.

The efficacy of a PFA is contingent upon the bird's genetics, its diet, and the management practices of the farm [34]. The precise number of phytogenics that affect growth and their interactions with the gut ecology remain unclear. This knowledge gap makes it challenging to predict responses and to optimize dosages. Another challenge lies in the stability, bioavailability, and practical applicability of PFAs. Many phytogenic compounds are volatile and sensitive to environmental conditions [35]. For instance, essential oils can partially evaporate or degrade during feed processing (e.g. the heat of pelleting) and storage, leading to reduced potency by the time the feed is consumed. Moreover, because most active compounds in PFAs (such as terpenoids and phenolics) are lipophilic, they may have poor water-solubility and stability in the gastrointestinal environment. This can limit their bioavailability and the fraction that actually reaches the lower gut where their action is needed. An additional hurdle is that the minimum inhibitory concentrations of many phytogenics against bacteria are relatively high; achieving those levels in feed may require high inclusion rates that could negatively affect feed taste [36]. Indeed, some essential oils have very pungent flavours and, at high doses, might reduce feed intake or cause transient stress to birds [37]. To fully capitalize on PFAs, these challenges must be addressed through standardization of extracts and improved delivery methods.

2.3. Innovative Delivery Technologies for PFAs

To overcome the limitations above, recent research and industry efforts have turned to advanced delivery technologies for phytogenic additives. A key strategy is encapsulation of phytogenic compounds, which protects sensitive bioactives and modulates their release in the gastrointestinal tract. For example, microencapsulation techniques (coating phytogenics in inert matrices or gel beadlets) can shield essential oils from volatility and degradation during feed processing and storage [38]. By encapsulating these compounds, their strong aromas are also masked, improving feed handling and acceptability to birds. Once ingested, the encapsulation matrix can be designed to dissolve or break down at specific gut pH or enzymatic conditions, thereby targeting the release of the active ingredients to the intestines [38, 39]. This targeted release ensures higher concentrations at the site of action (e.g. the distal gut) while minimizing losses or absorption in the upper digestive tract.

Beyond conventional microencapsulation, nanoencapsulation and novel nanoparticle delivery systems are being explored for PFAs. Nanotechnology-based carriers such as solid lipid nanoparticles (SLNs), nanoemulsions, and biodegradable polymer nanoparticles offer extremely small particle sizes (typically 50–300 nm) and a high surface area, which can enhance the solubility and uptake of phytochemicals [40]. Encapsulation of essential oil constituents (like thymol or cinnamaldehyde) in SLNs or liposomes has been shown to provide controlled, slow release and improved stability of these compounds. The lipid or polymer matrix protects the phytogenic from the acidic stomach environment and enzymatic degradation, effectively ferrying it to the gut where it can exert its effects [41, 42]. Another benefit is that nano-formulations can improve the uniform dispersion of oils in the feed and potentially increase the bioactive's residence time in the gut mucosa, thereby boosting efficacy at lower doses [43].

In addition to encapsulation, combination strategies are also employed: blending multiple phytogenic compounds or adding them alongside synergists (like organic acids or probiotics) can amplify their positive effects [39]. This synergistic approach leverages the complementary modes of action of different phytochemicals and can broaden the spectrum of activity (for instance, combining an essential oil with a saponin-rich extract to target both bacteria and gut protozoa). Overall, new delivery approaches such as essential oil beads and nano-carriers, are showing signs of making PFAs more reliable and effective. It ensures that the bioactives offered by phytogenics get delivered to the gut at the proper amounts which means more consistency and better poultry production practices.

2.4. Environmental and Sustainability Implications

The use of phytogenic supplements, rather than AGPs, is essential for both sustainability and "One Health" interests in poultry farming [44]. Since One Health connects human, animal and environmental health, the use of PFAs fits the idea by finding solutions to issues related to overusing antibiotics [45]. Concerns about antibiotic resistance and residues ending up in food and the environment have led the way to eliminate sub-therapeutic antibiotic use in poultry diets globally [4]. Phytogenics come from nature, can be considered safe and never cause harmful residues. By replacing antibiotics with PFAs, producers can help reduce the risk of generating antibiotic-resistant pathogens and avoid the contamination of soil and water with pharmaceutical residues [7]. This shift supports public health (by preserving antibiotic efficacy for human medicine) and environmental health (by preventing accumulation of persistent chemicals), exemplifying a One Health approach to poultry nutrition.

In addition to replacing antibiotics, PFAs may confer direct environmental benefits in poultry farming. Notably, certain phytogenic feed additives have been shown to reduce nitrogen excretion and ammonia emissions from poultry manure [46]. Ammonia gas from intensive poultry operations is a significant environmental pollutant and a welfare concern for birds and farm workers. Plant-based additives can ameliorate this issue by improving the birds' nutrient utilization – specifically, enhancing protein digestibility and retention – which means less undigested nitrogen is voided in the feces [33, 46]. For example, saponin-rich extracts (from plants like *yucca* or *quillaja*, often included under the umbrella of phytogenics) bind ammonia or inhibit urease activity in the manure, thereby lowering ammonia formation [47]. A recent report highlighted that phytogenic compounds improved the absorption of dietary nitrogen and directly reduced urease-driven ammonia release, leading to significantly lower ammonia levels in broiler houses. By curbing ammonia emissions, PFAs help improve air quality in poultry barns (benefiting animal respiratory health and worker safety) and reduce the environmental impact of poultry waste on surrounding ecosystems [48]. Furthermore, phytogenics are often derived from renewable plant sources and can be part of a circular agricultural economy (some are extracted from herbal agro-industrial by-products), adding to their sustainability profile.

3. Nanotechnology in Poultry Nutrition

3.1. Rationale for Nanoformulation of Feed Additives

Nanotechnology has become an important tool in poultry nutrition by addressing major limitations of conventional feed additives. Many phytogenic compounds and other bioactives used in poultry feeds are hydrophobic, volatile, or prone to degradation during feed processing and gastrointestinal transit [35]. Nanoformulation engineering these additives at the nanoscale (typically <100 nm) increases their surface area and improves solubility, stability, and interaction with the intestinal epithelium [49]. This results in enhanced absorption and bioavailability of active compounds. These enhancements allow nano-enabled feed additives to attain comparable or superior performance at lower doses than conventional versions, providing both economic advantages and minimised environmental consequences.

3.2. Common Types of Nanocarriers

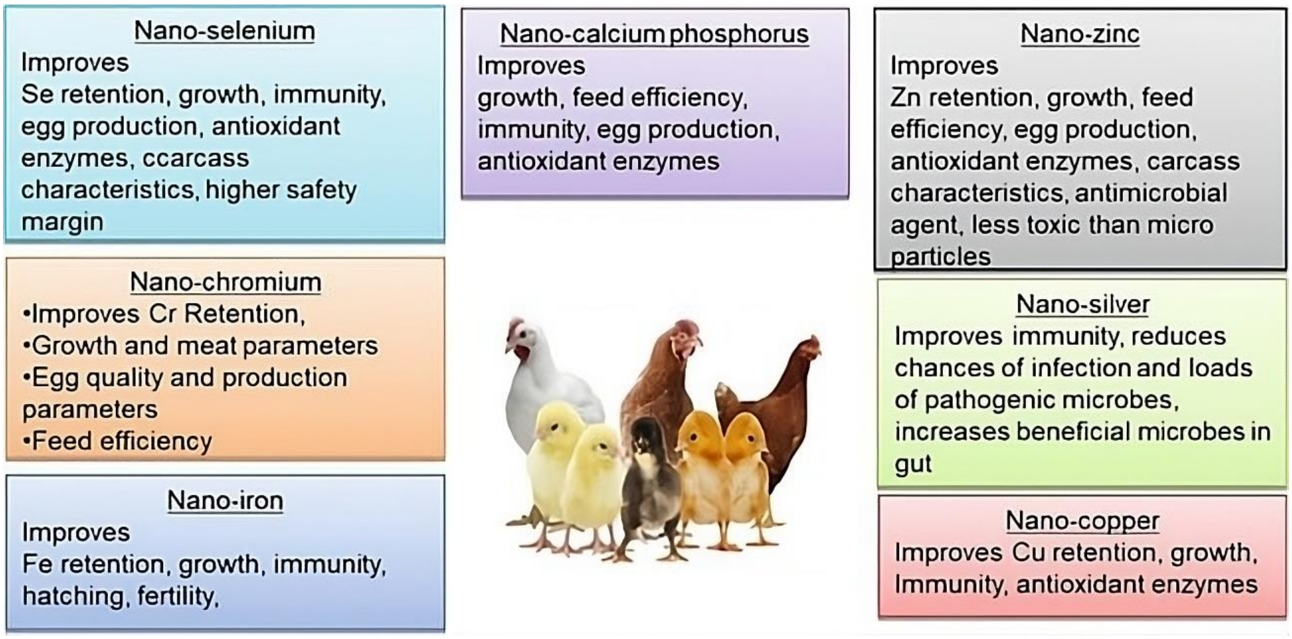

Figure 2. *Overview of the benefits of different nano-minerals on poultry health and performance.*

Several nanocarrier systems have been developed to deliver feed additives effectively in poultry nutrition. Lipid-based nanoparticles, including liposomes, solid lipid nanoparticles (SLNs), and nanostructured lipid carriers (NLCs), are widely employed due to their excellent biocompatibility and ability to protect sensitive bioactives such as essential oils from oxidation and degradation [50]. These lipid nanoparticles facilitate controlled release and improve mucosal penetration, thereby enhancing antimicrobial and antioxidant efficacy [51]. Polymeric nanoparticles made from biodegradable materials like chitosan, polylactic-co-glycolic acid (PLGA), and alginate have also gained prominence. Chitosan nanoparticles are particularly valued for their mucoadhesive properties, which prolong retention in the gut and provide intrinsic antimicrobial activity [52].

These carriers can be loaded with phytogenic compounds such as curcumin and oregano oil, leading to prolonged release and improved biological effects. [53, 54]. These nano-minerals exhibit higher bioavailability and stimulate antioxidant enzyme systems, thus supporting immune function and growth.

3.3. Production Methods of Nanoparticles

The production of nanoparticles suitable for poultry feed additives utilizes various physical and chemical techniques tailored to the properties of the bioactive compounds and desired product characteristics. Emulsion–diffusion methods involve preparing oil-in-water emulsions containing phytogenic compounds, followed by solvent removal to form nanoparticles [55]. High-pressure homogenization applies mechanical shear forces to reduce particle size in lipid or polymer suspensions and is commonly used for solid lipid nanoparticles [56]. Ionic gelation is a mild, aqueous-based technique particularly suited to biopolymer nanoparticles such as chitosan, where cross-linking with multivalent ions produces stable nanoscale beads [57]. Spray-drying converts nanoemulsions or suspensions into stable powders, facilitating storage and feed incorporation [58]. The choice of method depends on the chemical nature of the additive, desired release kinetics, and scalability for industrial production.

4. Nano-enabled Phytogenic Feed Additives in Poultry Nutrition

The application of nanotechnology in plant-derived feed additives (nPFAs) represents a significant recent advancement in poultry nutrition. Conventional phytogenic feed additives exhibit volatility, lack water solubility, and are susceptible to the detrimental conditions within the digestive system, resulting in inadequate bioavailability. Upon the emergence of these constraints, biological activity diminishes, rendering performance increasingly unpredictable.

4.1. Types and Forms of Nano-enabled Phytogenics

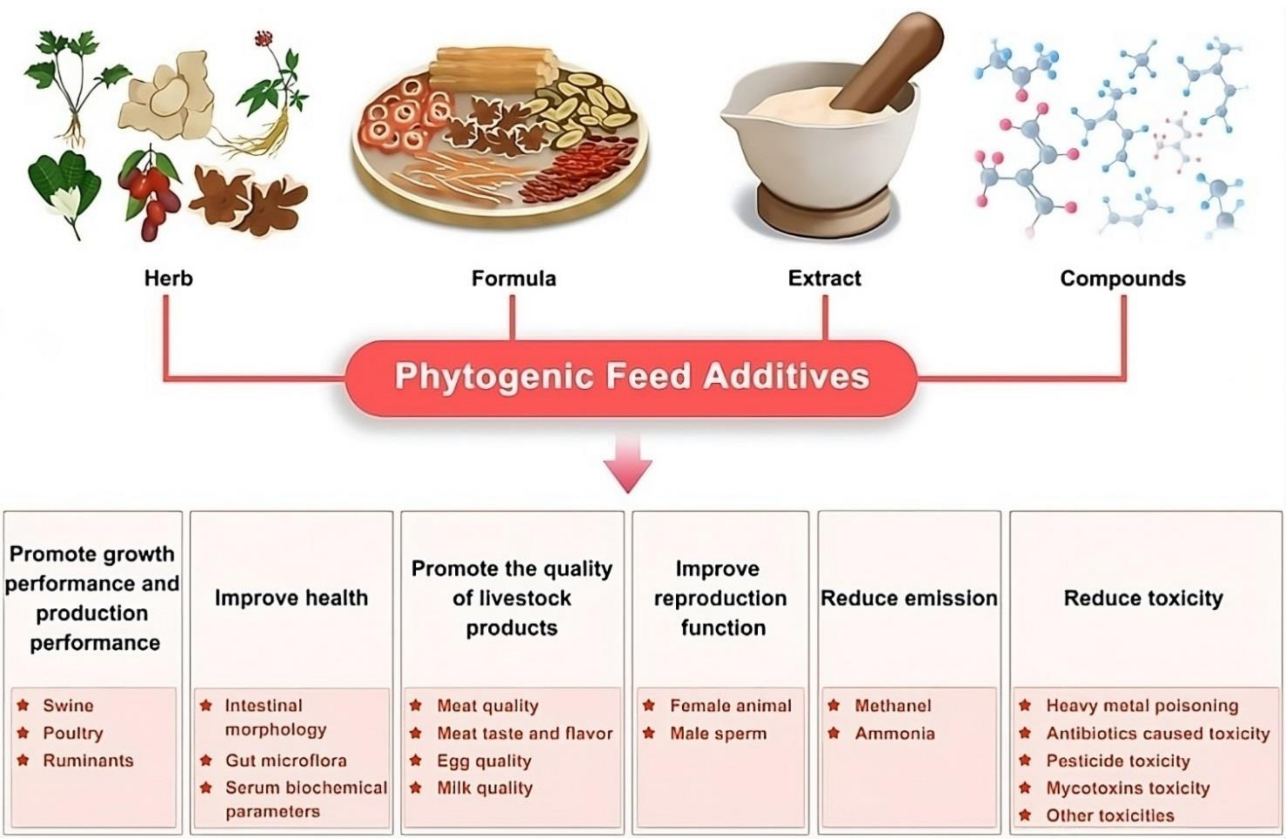

Figure 3. *Primary categories and functions of phytogenic feed additives.*

Nanoemulsions contain fine oil dispersed in water with droplets typically size between 20 to 200 nm [59]. It prevents phase separation and enhances delivering volatile essential oils including thymol, eugenol and carvacrol [22, 25]. Because of their small sizes, nanoemulsions interact well to the mucosal surfaces of the gastrointestinal tract which improves their absorption and bioavailability. The elevated chemical stability that nanoemulsions provide helps to reduce the amount of deterioration that occurs during the processing and storage of feed [60].

Lipophilic phytochemicals are protected by SLNs which encapsulate in a solid lipid matrix allows to release gradually as the matrix passes through the digestive track [40]. The slow and regulated delivery of these lipophilic compounds ensures a more prolonged physiological impact compared to free curcumin.

Polymeric nanoparticles made up of bio-compatible materials such as chitosan and polylactic acid provide additional advantages [52]. These polymers defend the phytochemicals from breakdown by enzymes and facilitate their controlled release, so their antimicrobial, antioxidant and immunomodulatory effects on poultry.

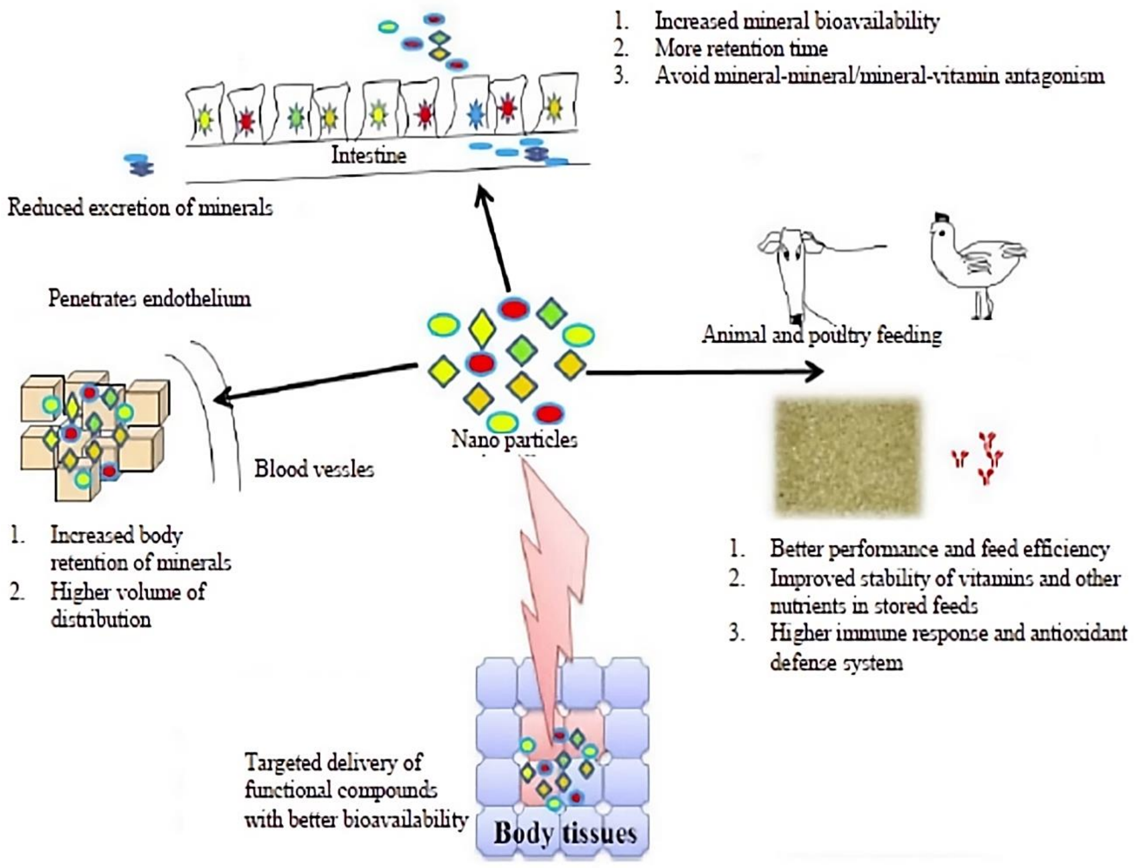

Figure 4. *Improved absorption, distribution, and effectiveness of nanoparticles in animal nutrition [61].*

4.2. Functional Benefits of Nano-enabled Phytogenics

The synergistic effect of nanotechnology and natural phytogenics in nPFAs manifests in multiple benefits for poultry production. Enhanced solubility along with improved penetration through microbial membranes make nano-encapsulated essential oils notably more effective antimicrobials. Hajibonabi, et al. [62] found that the nanoformulated carvacrol, oregano and thyme oils inhibit pathogenic bacteria such as *Escherichia coli*, *Salmonella*, and *Clostridium perfringens* more efficiently than the non-nano formulated supplements. Due to enhanced anti-bacterial properties of nPFAs serve as effective alternative to conventional AGPs. This approach also contributes to the sustainable poultry production as well as reduces public health risk associated with AMRs.

The broiler birds exhibited increased feed intake, an improved feed-conversion ratio, and greater weight gain, indicating enhanced growth associated with the application of nano-curcumin, nano-garlic, and comparable phytogenic products [63, 64]. An improvement in intestinal morphology, marked by increased villus length and deeper crypts, strengthens the body's capacity for nutrient absorption. The enhanced level of morphology promotes enzyme activity and maintains the integrity of the avian intestinal barrier, thereby contributing to the overall health of birds.

Table 2. Examples of nano-enabled phytogenic feed additives and their effects on poultry.

Nano-Formulation	Active Compound	Target Benefit	Reported Effects in Poultry	Reference
Nanoemulsion	Thymol	Antimicrobial	Inhibited E. coli and improved gut health	de Oca-Ávalos, et al. [59]
Solid Lipid Nanoparticles	Curcumin	Antioxidant, growth promoter	Increased body weight and antioxidant enzymes	Ani, et al. [40]
Polymeric Nanoparticles	Garlic extract	Immunostimulant	Improved immune organ development and serum Ig levels	Zhang, et al. [63]
Chitosan Nanoparticles	Green tea polyphenols	Antioxidant, anti-inflammatory	Reduced lipid peroxidation and enhanced intestinal morphology	Yang, et al. [52]

By increasing the ingestion of phytochemicals known to combat radicals, nPFAs effectively boost substantial antioxidant defences. When administered via nanoliposomes or comparable nanoformulations, the antioxidants found in green tea and turmeric significantly diminish lipid peroxidation in both the liver and muscles, while simultaneously enhancing the synthesis of SOD and GPx [40, 65]. Antioxidants play a crucial role in mitigating the detrimental effects of production-related stress, thereby safeguarding the tissue and inhibiting the spoilage of meat. Due to the various mechanisms through which nPFAs bolster the immune system, individuals suffering from infections typically exhibit enhanced responses and greater disease resistance.

4.3. Application Strategies and Dosage Optimization

The effective integration of nPFAs requires accuracy into dosage, feed composition and processing during poultry feeding. Nanoemulsions are used in feed at amounts of 100 to 500 mg per kilogramme to ensure the optimising effectiveness while ensuring safety [66]. The amounts of solid lipid and polymeric nanoparticles needed change based on the plant-based compound inside and the health of the birds, with younger birds usually needing smaller amounts because their digestive systems are still growing [67]. The physicochemical characteristics of nanocarriers affect their release kinetics and targeted action in the gastrointestinal system, which are essential for optimising bioavailability and reducing waste or toxicity [68].

5. Mechanisms of Action

The enhanced efficacy of nPFAs arises from their unique physicochemical properties and multifaceted mechanisms of action within the poultry body. These mechanisms include improved bioavailability, selective antimicrobial effects, antioxidant activity, immunomodulation, anti-inflammatory effects, and precise delivery.

5.1. Enhanced Bioavailability and Absorption

Phytogenic compounds generally possess poor water solubility and limited stability in the gastrointestinal tract, resulting in low absorption and bioavailability [35]. Nanotechnology reduces phytochemicals to nanoscale dimensions (less than 100 nm), dramatically increasing their surface area and dissolution rate [69]. For example, curcumin, which is otherwise poorly absorbed, shows significantly improved uptake when delivered in solid lipid nanoparticles. Enhanced absorption results in greater systemic availability, potentiating antioxidant and growth-promoting effects.

5.2. Modulation of Gut Microbiota

Nanoformulations enhance the antimicrobial activity of phytogenic compounds by facilitating better penetration of bacterial membranes and disruption of microbial quorum sensing and enzyme activity [49]. Nano-encapsulated essential oils from oregano, thyme, and clove have demonstrated effective inhibition of pathogenic bacteria, including *E. coli*, *Salmonella*, and *Clostridium perfringens*, while supporting the growth of beneficial gut flora such as *Lactobacillus* [22, 25, 29]. This selective modulation promotes a balanced microbiota essential for nutrient digestion and immune competence.

5.3. Antioxidant Mechanisms and Cellular Protection

Nanoformulation of phytochemicals like curcumin, quercetin and polyphenols improves their ability to fight oxidation by making less likely to quickly break down and ensuring their sustained release [70]. Adding these antioxidants to poultry feed supports the work of important enzymes, including superoxide dismutase (SOD), glutathione peroxidase (GPx), and catalase (CAT) in poultry tissues which defend the liver and muscles from oxidative stress [40, 65]. The defence system protects cells from harm, improves the immune system and results in better meat quality.

5.4. Immunomodulatory Effects

NPFAs support both innate and adaptive responses by carrying immune-stimulatory compounds directly to cells of the immune system such as macrophages, lymphocytes and dendritic cells [71]. Nanoformulated garlic and curcumin help boost the production of important immune system chemicals called cytokines: interleukin-2 (IL-2), interferon-gamma (IFN-γ), and tumour necrosis factor-alpha (TNF-α) [20, 24]. These chemicals are also crucial for pathogen defence and immune regulation. Due to their enhanced immune responsiveness, it reduces disease susceptibility in poultry production.

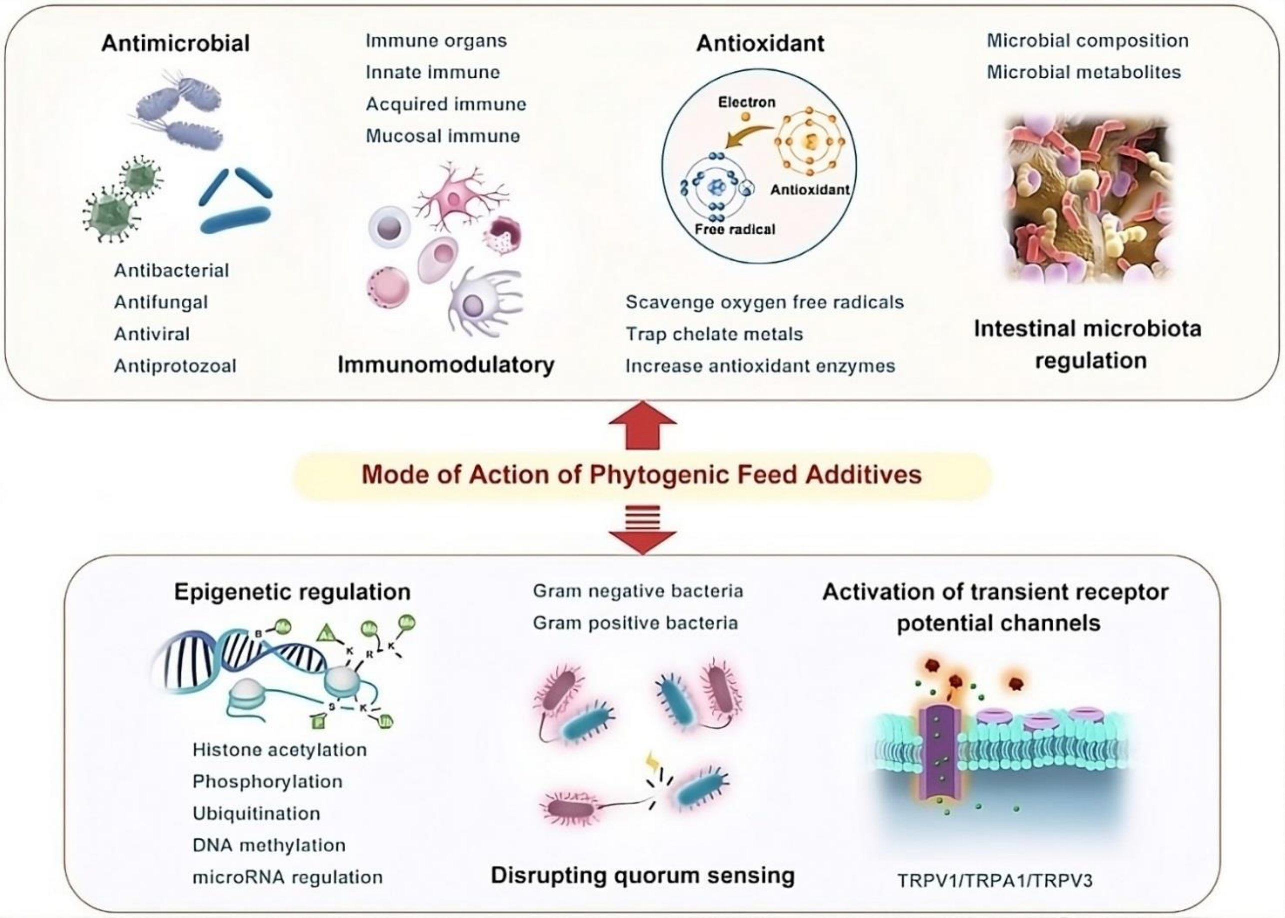

Figure 5. Overview of the multifaceted modes of action of phytogenic feed additives.

5.5. Anti-inflammatory and Gut Integrity Effects

The incorporation of phytogenics into nanoparticles results in a reduction of inflammatory mediators such as cyclooxygenase-2 (COX-2), inducible nitric oxide synthase (iNOS), and nuclear factor-kappa B (NF-κB) within cellular environments [72]. The anti-inflammatory properties of probiotics contribute to a reduction in gut inflammation, facilitate the recovery of the inner gut surface, and enhance the integrity of its walls [73]. Maintaining a robust gut is essential for preventing the entry of harmful pathogens and toxins, thereby promoting overall health and enhancing the body's ability to absorb nutrients.

5.6. Controlled Release and Targeted Delivery

Biodegradable nanocarriers such as chitosan, alginate, and solid lipids allow site-specific and controlled release of phytogenics in response to pH changes or enzymatic activity within the gastrointestinal tract [74]. This targeted release protects bioactives from degradation and maximizes their therapeutic effects at intended sites. Controlled release reduces feed additive wastage, minimizes dosing frequency, and increases cost-effectiveness and environmental sustainability.

6. Applications and Future Prospects of Nano-enabled Phytogenic Feed Additives in Poultry Production

6.1. Environmental and Economic Benefits

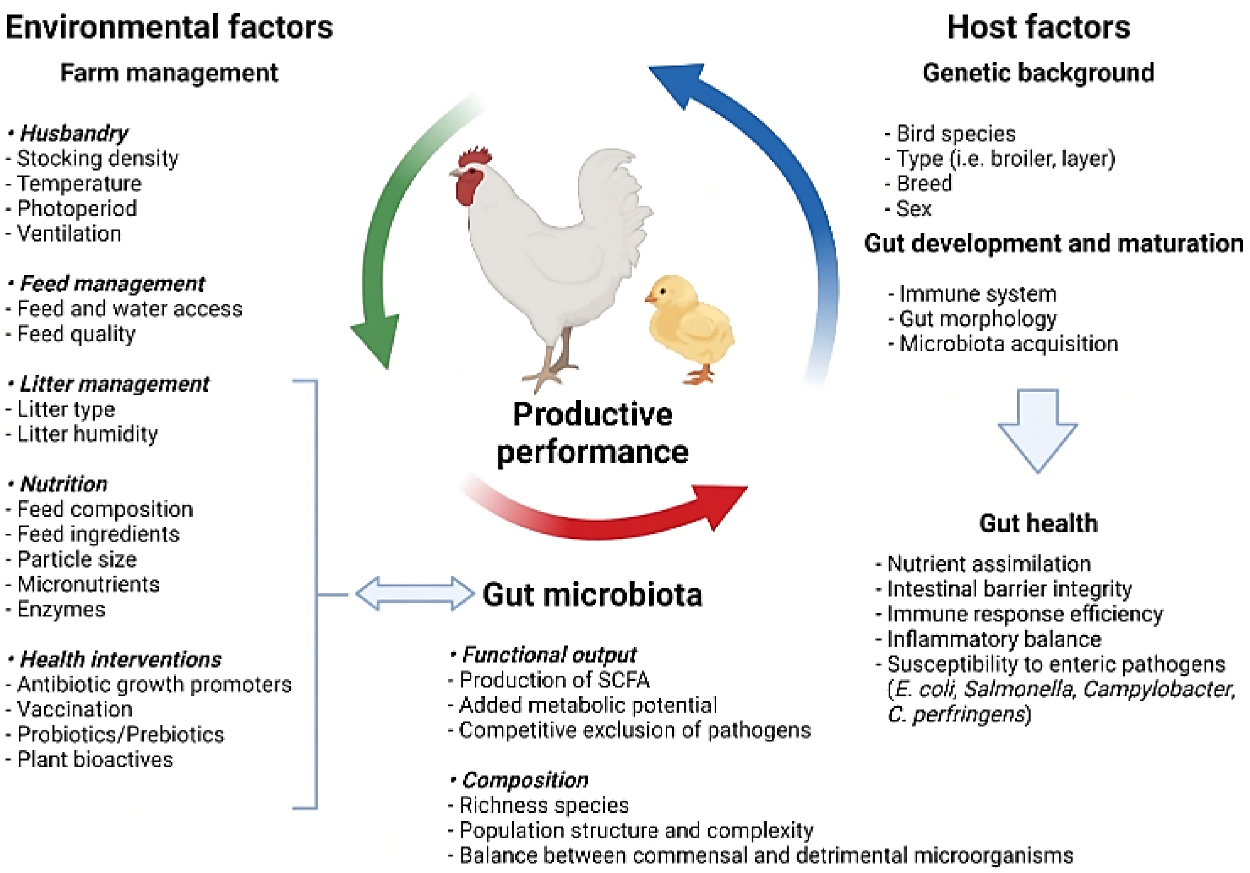

Figure 6. Environmental and host factors influencing gut microbiota composition and function, which collectively affect poultry gut health and productive performance.

NPFAs offer a multifaceted approach to enhancing poultry production efficiency while mitigating negative environmental impacts. Nano-sized mineral additives have enabled poultry to absorb nutrients more efficiently, allowing up to a four-fold reduction in traditional mineral inclusion without sacrificing performance [75]. In broilers and turkeys, supplementing nano forms of trace elements (e.g. copper, zinc, selenium) has yielded higher weight gain, improved feed conversion, and enhanced immune status compared to conventional forms [76]. Such feed efficiency gains not only mean more meat or eggs per unit of feed but also less manure output and nutrient waste. Dumlu [77] have investigated that replacing a portion of inorganic mineral supplements with nano-minerals can decrease mineral excretion and reduce the risk of environmental pollution. By minimizing nutrient runoff (nitrogen, phosphorus, etc.) and lowering drug residues in litter, NPFAs contribute to pollution control and a smaller ecological footprint for poultry operations.

From an economic perspective, the strategic use of NPFAs can offer cost benefits over the long term. Initially, nano-formulations may incur higher production costs due to advanced processing and encapsulation technologies. However, these costs can be offset by improved animal performance and the reduced quantity of additives required. Because nanoparticles have a higher surface area and reactivity, lower doses can achieve the same or superior effect compared to bulk additives [68]. For example, replacing up to 50% of conventional dicalcium phosphate with nano-calcium phosphate in broiler diets significantly improved weight gain and feed conversion, while cutting down on the expensive phosphorus content – effectively lowering feed costs [78]. Raising feed efficiency eventually decreases the amount of money spent on feed. Furthermore, as producers avoid using antibiotics for growth, that can cut costs associated with verifying and handling these substances and join markets that look for “antibiotic-free” products. All things considered, less waste, sustainable production and increased performance combine to create a positive cost-benefit balance for NPFAs.

6.2. Challenges and Regulatory Considerations

Several issues and licencing requirements must first be resolved to allow NPFAs to be used widely in the poultry industry. One big challenge is that standard rules for nanotechnology in animal feed are not consistent. Because food safety authorities have not yet developed standard methods for evaluating nanoparticles, there is uncertainty about how to use them in industries [79]. For instance, while the European Food Safety Authority (EFSA) has examined copper nanoparticles and seen that lower doses are effective, it also points out that the available information on their long-term safety and toxicity is lacking [80]. Because there are no consistent rules on this, products that can be traded in one place could be illegal in another, upsetting international business. While checking labels, testing products and assessing risks for "nano" ingredients in feed is still being shaped, officials tend to wait until thorough safety research is available before approving such ingredients for widespread use. Because toxicology is such a serious issue for nano-enabled products, companies should move with caution.

Another challenge lies in the variability and quality control of NPFA products. In the past, even conventional phytogenic additives showed inconsistent results across studies due to differences in product formulation, purity, and dosages [19]. The incorporation of nanotechnology needs to overcome, not add to, this variability. Ensuring that each batch of NPFA has a uniform particle size distribution and phytochemical content is crucial for reliable outcomes [53]. This ties into regulatory oversight: agencies will likely require robust characterization of nanomaterials (particle size, surface area, etc.) and reproducibility in manufacturing. Until toxicological profiles, residue studies, and environmental impact assessments are thoroughly addressed, regulatory approval will remain a cautious process [81]. In summary, the path to adoption of NPFAs involves navigating regulatory uncertainty, executing extensive safety studies on toxicity and bioaccumulation, and establishing standards that ensure these novel feed additives are as safe as they are effective.

6.3. Future Research Directions

Modern genomics, proteomics, and metabolomics can play a pivotal role in unravelling how NPFAs exert their effects at the molecular level. By analysing changes in gene expression, protein profiles, and metabolic pathways, researchers can identify the precise mechanisms through which nano-encapsulated phytogenic compounds influence growth, immunity, and metabolism [82]. Early studies have already shown that certain nanomaterials can modulate gene expression related to muscle development and cell proliferation in poultry. For example, diamond nanoparticles combined with functional nutrients were found to upregulate genes for muscle differentiation in chick cells, indicating a direct impact at the cellular level [83].

One of the most promising directions is the development of smart delivery systems for phytogenic additives. Current research indicates that simply adding an herb extract to feed may not guarantee its efficacy, due to degradation in the feed or stomach and poor release at the site of action [35]. Nanotechnology offers solutions here: by encapsulating phytogenic compounds in protective nanocarriers (lipid nanoparticles, polymers, or emulsions), we can achieve controlled release and target-specific delivery. Future "smart" nanocarriers might be designed to respond to environmental triggers in the gastrointestinal tract – for instance, pH-sensitive capsules that only release their cargo in the more neutral pH of the intestine, or enzyme-sensitive coatings that dissolve in the presence of certain gut enzymes [84]. There is evidence that even current microencapsulation techniques markedly improve efficacy of phytogenics. A notable example is the encapsulation of the essential oil compound carvacrol in alginate-whey protein microcapsules, which allowed it to bypass the upper gut and release in the intestines of broiler chickens [85]. The encapsulated carvacrol significantly reduced Clostridium-induced necrotic enteritis in broilers, achieving an outcome comparable to conventional in-feed antibiotics [67]. Additionally, pairing phytochemicals with synergistic nanoparticles (such as using a nano-clay to bind toxins while an encapsulated herbal antioxidant protects gut lining) could amplify benefits [43]. Research into biodegradable and food-grade nanomaterials (e.g., chitosan, alginate, liposomes) will also be crucial to ensure these delivery systems are safe and do not accumulate in the animal.

Another forward-looking concept is the tailoring of nano-phytogenic supplementation to the specific needs of flocks or even individual birds – essentially, precision nutrition enhanced by nanotechnology. Just as precision livestock farming uses data and sensors to optimize feeding, future NPFA applications could integrate with these digital tools to provide the right nutrient or bioactive at the right time and dose [86]. Nanotechnology's contribution here is the ability to fine-tune dosage and formulation. Because nanoparticles can be effective at low inclusion levels, nutritionists could adjust mineral or phytogenic additive levels for different breeds, life stages, or health statuses with high accuracy. For example, research has shown that turkeys-maintained muscle mineral homeostasis when only 10% of the conventional copper and zinc requirements were supplied in nano-form. This suggests that diets can be precisely formulated with minimal waste – a principle that aligns with personalized nutrition, where we avoid both deficiencies and excesses [54, 73]. While such integration of digital technology and nano-nutrition is still on the horizon, it represents a convergence of trends aimed at sustainable and efficient production.

The concept of personalized nutrition in poultry may ultimately involve customizing feed additive regimens to the farm or flock level: high-performing birds might receive different nano-supplements than heat-stressed or disease-challenged birds, all calibrated through data-driven decision systems [87]. Realizing this vision will require interdisciplinary research – bringing together animal nutritionists, nanotechnologists, and data scientists – to create frameworks for adaptive feeding strategies. In summary, future research will likely position NPFAs not as one-size-fits-all additives, but as flexible tools in a precision nutrition toolkit, deployed in smarter ways to meet the specific demands of modern poultry production.

7. Conclusion

Nano-enabled phytogenic feed additives represent a cutting-edge convergence of plant bioactive compounds with nanotechnology, offering a novel strategy to enhance poultry production sustainability. By enhancing the stability, bioavailability, and targeted delivery of phytogenics, NPFAs effectively improve nutrient utilization, immune function, antioxidant capacity, and gut health. These methodologies have resulted in enhanced growth, reduced waste, improved health outcomes, decreased antibiotic usage, and diminished pollution levels. The integration of nanoformulations enables a more precise control of biological pathways, thereby corroborating findings observed in experimental studies. The distinctive attributes of NPFAs suggest that they could be applied to address the challenges associated with antibiotic-free poultry while also satisfying the demands of consumers who seek high-quality and safe animal protein.

Despite their potential, several significant challenges remain to be addressed before widespread adoption can occur. It is essential that nanoparticle-based additives undergo thorough evaluation over time to address safety and toxicological concerns associated with health issues. The regulatory frameworks governing feed additives related to nanotechnologies remain underdeveloped and exhibit significant variation across different nations. The challenge of ensuring that each batch of nanomaterials meets high-quality standards while being produced in substantial quantities is significant. Furthermore, variations in the efficacy of treatments observed in studies indicate that a standardized approach and a deeper comprehension of the underlying treatment mechanisms are essential. Clarity and honesty in communication with the public, coupled with evidence-based judgments, are vital to increasing acceptance of emerging technologies. Advancements in NPFA technology will depend on the collaboration of scholars, regulatory bodies, and industry stakeholders to guarantee safety, develop optimal formulations, and demonstrate financial viability. The integration of these factors positions NPFAs as critical components in the development of healthy, efficient, and sustainable diets for poultry.

Abbreviations

AGPs	Antimicrobial Growth Promoters
AMR	Antimicrobial Resistance
GIT	Gastrointestinal Tract
nPFAs	Nano-enabled Phytogenic Feed Additives
PFAs	Phytogenic Feed Additives
SLNs	Solid Lipid Nanoparticles
PLGA	Polylactic-co-glycolic Acid
SOD	Superoxide Dismutase
GPx	Glutathione Peroxidase
CAT	Catalase
IL-2	Interleukin-2
IFN-γ	Interferon-gamma
TNF-α	Tumor Necrosis Factor-alpha
EFSA	European Food Safety Authority

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The authors declare that they have all the necessary data and are available where appropriate or requested by the editor.

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography

Muhammad Mubeen Jamal Anwar is a professionally trained food scientist with specialized expertise in functional nutrition, poultry meat science, and nano-enabled dietary strategies. He earned his M.Sc. (Hons.) in Food Science & Technology from The Islamia University of Bahawalpur, Pakistan in 2023, where my research focused on improving broiler growth and meat quality characteristics using *Moringa leaf extract-coated zinc nanoparticles*. I hold a B.Sc. (Hons.) in Food Science & Technology from the University of Agriculture, Faisalabad, Pakistan (2016-2020). My scientific contributions include peer-reviewed publications in areas such as probiotic development, antimicrobial activity of plant extracts, and nutritional modulation of livestock. I have participated in a nationally funded research project under the Pakistan Science Foundation and served in teaching and research roles across academia and government institutions. My technical proficiency spans advanced instrumental analysis, nanoformulations, feed additive development, food quality assessment, food safety and sensory evaluation, with a commitment to sustainable food production and science-driven innovation in food systems.

Research Field

Muhammad Mubeen Jamal Anwar: Food quality and safety, Poultry nutrition, Nanotechnology in food systems, Sustainable production, Meat science and technology, Natural bioactive compounds, Green technologies, Food waste Valorization, Sensory and instrumental analysis.