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Impact of Nano-encapsulated Cinnamon and Coriander on Quail Performance and Gut Absorption

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Abstract

This article reviews scientific papers on Nano-encapsulation of cinnamon and coriander extract, including their bio stability and how well birds absorb them through their intestines as well as how they've affected quail production. Although there have been several studies conducted involving the use of Cinnamon and Coriander to enhance growth rates, feed conversion ratios and egg production, the major limitation has been the relatively low levels of stability and bioavailability of the herbals. By using Nano-encapsulation to increase the amount of active ingredient protected so that it has a longer time to be absorbed into the bird's system more effectively than with conventional methods, researchers have found that this method may allow for improved intestinal absorption due to improved interaction with the avian gut system and potentially improved intestinal health and immune response. However, relative to the direct studies performed on avian species, there are limited amounts of material available exploring this concept. This review will provide a summary of both the advantages and current gaps in our understanding and will highlight the need for additional research studies looking at the stability of commercial feeds containing these additives over extended periods, potential safety issues regarding long-term use of these additives and opportunities for the use of these additives to develop economically viable feed sources in our poultry businesses, particularly in developing natural nutrition programs using these nano-encapsulated forms as a complement to existing conventional feeds.

Keyword: Nano-encapsulation • Chitosan encapsulation • Phytogenic additives • Quail • Plant extracts • Halloysite nanotubes (HNTs).

Introduction

Overview of Quail Production and Nutritional Challenges

The rapid growth of quail farming as one of the more quickly changing areas in the world of agriculture will see its development take place in many tropical regions where the surrounding environment can present a different set of challenges.

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Modern quail genotypes produced through selective breeding to improve productivity are placed under significant thermal stress due to their elevated metabolic rate, making them highly susceptible to their environment.Temperatures in excess of 40°C will reduce their THERMO-comfort range of approximately 22°C to 26 °C[1]. High thermal stress causes quail physiologic stress responses, reduced feed intake, increased water intake, and decreased production of both egg quantity and quality[1]. Because of the economic values associated with maximum productivity, and because of the environmental stressors that a high-yield quail may experience, developing sound feeding practices is essential. There is a need to combine genetic advances and use management strategies that are effective to increase the production of quail. Some of the main reasons including body weight and amounts of eggs produced show a need for the use of economically sound technology[2]. The implementation of nutritional strategies can be a more economically feasible and practical alternative compared to the expense of the costly environmental control systems (such as cooling systems) associated with quail production; particularly since environmental control systems are a significant financial burden. A converter to nutritional strategies can mitigate the negative effect of environmental stressors and maintain good performance levels regardless of climate, therefore, the development and implementation of novel additives is an opportunity to further enhance quail production in challenging environmental conditions commercially.

The Significance of Phytogenic Additives in Animal Nutrition

In response to rising concerns over the proliferation of antibiotic-resistant bacteria strains and the presence of antibiotic residues in products derived from animals, the livestock industry has begun to shift from the use of Antibiotic Growth Promoters (AGPs)[3]. Regulatory agencies, including the European Union and the FDA, have already banned or placed significant limitations on AGP use, creating an urgency to develop safe, natural, and effective alternatives[4]. Promising alternatives to AGPs are Phytogenic Feed Additives (PFAs). PFAs are derived from plant sources. They possess many of the same properties as AGPs, including antibacterial, antioxidant, immune-modulating and gut micro-biota-enhancing properties. Essential Oils (EOs) from plants produce a range of physiological, pharmacological, and antimicrobial effects. EOs can stimulate the activity of digestive enzymes, improve nutrient absorption and strengthen intestinal health, leading to improved livestock performance[4]. The two phytogenic additives cinnamon (*Cinnamomum zeylanicum*) and coriander (*Coriandrum sativum*) contain important bioactive compounds[4]. Through these bioactive compounds, including trans-cinnamaldehyde, eugenol and carvacrol, cinnamon has antiseptic, antibacterial, and antioxidant effects, and is a very good source of a wide variety of vitamins and minerals[5]. Linalool, folate, vitamins A, B12 and C and phenolic compounds and petroselinoic acid make coriander an excellent source of antioxidants, antibacterial activity and anti-inflammatory activity[6]. Because of the above-mentioned properties, cinnamon and coriander have the potential to be effective natural alternatives to antibiotics for the sustainable and health-oriented production of livestock[7].

Essential oil and powder from cinnamon (*Cinnamomum zeylanicum*) possesses volatile bioactive compounds such as cinnamaldehyde and eugenol which have an antimicrobial effect on pathogenic bacteria and may improve meat quality, antioxidant status, and immune function in poultry making it a good alternative to AGPs in feed[8]. Coriander (Coriandrum sativum) is high in bioactive phytochemicals like linalool, and has been researched as a potential feed additive. Studies on broiler performance have shown that adding coriander has had a positive impact on immune response, blood biochemical markers, and carcass traits; thus supporting that phytogenic products containing coriander can provide health benefits to livestock raised without antibiotics[9]. ·Coriander and cinnamon phytogenic feed additives are a viable, eco-friendly, safe alternative to AGPs in livestock production, and can help minimize the use of antibiotics and reduce the development of antibiotic-resistant bacteria. However, there is a need for standardized dosages and formulations of phytogenic products to provide consistent efficacy in livestock production[10].

Introduction to Nanoencapsulation Technology

Bioactive compounds can be contained in nanoencapsulation technology through nanoscale carriers, which is a new and advanced technology with carriers ranging in size from 1-100 nanometers[5]. Using nanoencapsulated BACs offers many advantages over raw essential oils because of their low level of solubility in water, high degree of volatility, and ability to degrade by environmental conditions as well as strong odors that can affect feed palatability negatively[4].

Nanoparticles can be encapsulated to provide the following benefits[11]:

1. Greater bioavailability and improved distributions of hydrophobic components.
2. Physical protection of sensitive agents from light, heat and other environmental effects, such as elevated levels of oxygen, and variations in pH and stress conditions.
3. Prolonged activity of essential oils through inhibition of evaporation, leading to a reduction of undesirable feed odors.
4. Directed and controlled releases of active compounds at specific locations in the digestive tract increases therapeutic efficacy.
5. Enhanced bioavailability and cellular uptake due to reduced particle size and increased surface area.
6. Potential reductions in dose, enabling cost-effective feed formulations with reduced residues in animal products.

Using nanoecapsulatment of bioactive materials can reduce the required dose of these products while allowing for improved or equal therapeutic and production performance. The bioactive substances will have much greater stability, bioavailability, and controlled release when encapsulated with nanoscale carriers (e.g. nanoparticles, nano-emulsified particles,or enticular nano-liposomal particles). Additionally, due to the advantages of nanoecapsulation, and the decreased amount of the bioactive substance needed, the overall performance of the animals in terms of growth, feed efficiency, gastrointestinal (GI) health/immunity, and antioxidant status will be improved compared to those animals fed with no encapsulated product. Nanoecapsulated bioactive materials will also be protected from degradation during feed processing and animal digestion; thus assuring the consistent, and targeted delivery of these bioactive compounds to the animal. Additionally, nanoencapsulation changes how the bioactives are processed and how they behave in the body, which helps regulate when they are released from the feed and how effectively they are applied within the cell. The result is better therapeutic and production results from these complex biological systems (e.g., poultry nutrition), thus making nanoencapsulation a powerful tool in modern animal feed programs.

Objectives of The Review

In this review, a thorough examination of all available scientific data on the nanoencapsulation of cinnamon and coriander extract was carried out. To meet this end, the following areas were explored and addressed:

– The impact of nanoencapsulation on preserving the bioactivity of these phytocontacts.

– The mechanisms associated with how nanoencapsulated extract can be absorbed through bit intestinal epithelium in birds.

– Effects of nanoencapsulation on productive performance by poultry.

The information for this review was compiled from credible literature references, which includes published research in the databases Scopus, Elsevier and PubMed, with the aim of providing a comprehensive presentation of what is currently known regarding this area. The reader will be provided with identified benefits, challenges and opportunities for future investigations in the area of sustainable poultry production.

Nanoencapsulation of Cinnamon and Coriander Extracts: Principles and Biostability

General Nanoencapsulation Techniques and Materials for Essential Oils

There are many different methodologies utilized in the development of nanoencapsulation of essential oils using a variety of methods and carriers. This diversity in methodology is indicative of the evolution of technology and flexibility within this field, allowing for the creation of products that are tailored to the individual physicochemical properties of the various bioactive substances. There are careful considerations taken into account in the design of these methodologies to achieve the highest level of encapsulation efficiency and controlled-release capabilities, in order to increase the functional stability and availability of the essential oils in animal nutrition. Biopolymer-Based Encapsulation Systems. Systems of encapsulation are typically composed of biopolymers that are considered to be safe for human consumption and derived from natural sources, in either their unmodified form or altered chemically. Most commonly used biopolymers include whey protein, casein, zein, gelatin (all proteins), starch, chitosan, cyclodextrin, pectin, and alginate (all polysaccharides)[12]. Depending on the final formulation, biopolymer systems can lead to two principal categories of nanostructures: nanocapsules, where the central oily core is surrounded by a polymeric shell containing essential oils; and nanospheres, where the bioactive substance is evenly dispersed throughout a solid polymer matrix[12].

Different nanoencapsulation techniques for manufacturing and encapsulating biopolymer materials are described below:

1. **Complex Coacervation**: Utilizing the oppositely charged nature of two polyelectrolytes to create a coacervate as a means for encapsulating the core bioactive[12].
2. **Freeze Dryer (lyophilization)**: Freeze drying (lyophilization) is best for compounds that are heat-sensitive. This technique retains the integrity and activity of the product during sublimation of the frozen solvent directly from solid to vapour in a vacuum[13].
3. **Spray Drying:** One of the most common and lower cost methods of encapsulating bioactive compounds, where a liquid emulsion or suspension is sprayed atomised into a hot dry chamber, causing the rapid evaporation of the solvent and forming dry nanoparticles[12].
4. **Ionic Gelation:** Although usually combined with chitosan, this method uses ionic cross-linkers under mild conditions, so as not to alter any characteristics of the original material being encapsulated[11].

Biopolymers such as polysaccharides are biodegradable, cost-effective and stable across a variety of pH ranges, with low toxicity levels. Oligosaccharides with a cyclic structure such as cyclodextrins create inclusion complexes that protect core molecules against light and oxygen degradation and also mask the odor of some essential oils. Chitosan is a cationic polysaccharide that can serve as a valuable option for a variety of nanocarriers due to its biodegradability, pH sensitivity, and ease of chemical modifications[12]. In contrast, proteins are able to adapt their structures to specific conditions in the environment and possess exceptional emulsifying abilities, solubility, and ability to change food textures, making them other suitable candidates, for many types of nanocarriers. Complexing biopolymers (e.g. polysaccharides and proteins) often results in nanocarriers that have improved properties compared to those derived from only one type of biopolymer[12]. Many different techniques for nano-encapsulating bioactives will impact the rate of controlled release and how stable the bioactive is throughout time when stored. Spray drying is considered to be one of the most common methods of encapsulating bioactive products because it provides viable solutions for large-scale production and provides a more stable environment for volatile compounds when they are converted to a solid powder; this helps to protect the volatile from oxidation and degradative reactions due to the surrounding environment. Although the particles produced from spray drying can exhibit controlled release of the encapsulated constituents, when heat-sensitive constituents are included in the formulations, high temperatures used in the spray drying process can negatively influence their overall stability unless the proper wall materials are used[14]. The use of the complex coacervation technique to encapsulate essential oils will yield even better protective characteristics due to the formation of a polymer shell around the droplets under more moderate conditions, while also producing sustained or controlled-release patterns of bioactive release because of the interactive biopolymer matrix that will delay or reduce the rate of diffusion of the encapsulated bioactive constituents[15]. Ionic gelation is another method that will also improve the stability of the encapsulated bioactive by trapping the bioactive within an ionic polymer gel (biopolymers, such as alginate or chitosan) and reducing the rate of volatility and degradation while typically resulting in controlled release patterns controlled by diffusion, which is useful for producing activity over a more extended time period[16].

Nanocarrier design methods must be effective to improve the stability of orally administered bioactive compounds for goats (livestock) and their bioavailability and the systemic distribution of these bioactive compounds. The selection of materials is an important factor in the development of nanocarrier systems, since biocompatible and biodegradable polymeric substances (such as chitosan, PLGA) and lipids provide a protective matrix against the detrimental effects of acid pH, enzymatic activity, and the premature release of bioactives from the gastrointestinal (GI) tract, as well as enhancing the solubility and absorption of these bioactives[17].

Lipid-Based Systems: Because of their high encapsulation efficiency, low toxicity, and superior biodegradability, lipid-based nanocarriers are attractive for use in the industrial sector[12].

• Nanoemulsions consist of liquid droplets, at the nanoscale, that are dispersed throughout another immiscible liquid phase. The production of nanoemulsions can occur via either high-energy processes (e.g., high-shear mixing; microfluidization) or low-energy methods based on physiochemical changes[12]. The droplet size is typically < 100 nm and as such, nanoemulsions are characterized by unique properties such as kinetic stability and optical clarity, making them ideal for use in the food/beverage industries[12].

Nanoliposomes are vesicular constructions that contain a lipid bilayer of phospholipids, which contain an active ingredient within. The advantages of nanoliposomes include their ability to deliver substances to targeted sites, their biocompatibility (i.e., compatibility with living organisms), their minimal toxicity, and their increased stability of bioactive compounds[12]. Equipment-Based Methods: To create nanofibers and use nanofibers as scaffolds, you need special equipment, such as what is found in advanced techniques, for example; creating fine fibers/nanoparticles using electrospinning/electrospraying with charged jets (one small jet produces many fine fibers)[12]. The great opportunity that these techniques present for food packaging is due to their ability to produce large amounts of high-surface-area material, contain heat-sensitive compounds, and create cost-effective and scalable production methods for these products.

Other methods, for increasing mucus permeability, include coating the particles with mucus-adhesive (or multi-adhesive) materials, optimizing their size to range from ~50-200 nm, and designing them using core-shell (or other reactive) methods. These approaches also provide mechanisms for targeting the delivery of bioactive compounds through clathrin-and cross-linked caveolin-mediated endocytosis and will help to deliver these bioactive compounds to their intended site of action within the intestinal tract efficiently[18].

Enhancement of Biostability through Nanoencapsulation

The application of nanoencapsulation significantly increases the biostability of bioactive materials by providing a protective medium against environmental factors, including ultraviolet radiation and heating (thermal), oxidation, and changes (increased or decreased) to the pH of elements that are recognised as harmful to the nutritional and functional properties of bioactive substances[13]. In the same way, nanoencapsulation will reduce the losses of volatile compounds while providing essential oils protection against physical damage, allowing for the continued efficacy of the functional characteristics of essential oils[5]. The mechanism of nanoencapsulation also increases the physicochemical stability of the encapsulated bioactive compounds, providing long-term protection of their molecular structures, and therefore, a means to maintain their biological activity[11]. The protective nature of this technology enables the extended shelf life of sensitive bioactive compounds, including Vitamin A, Vitamin B, Antioxidants and Probiotics, when incorporated into food products[13].

The examples of omega 3 fatty acids, which are prone to oxidative degradation and negative sensory characteristics, are indicative of the effectiveness of nanoencapsulation to protect these compounds from deterioration and to improve their sensory acceptability. Nanoencapsulation also enhances the bioactivity of curcumin and resveratrol, two poorly soluble and unstable compounds, thus demonstrating the link between increased bioactivity and improved functional performance resulting from enhanced protection of the compound via nanoencapsulation[13].

Biostability refers to the ability of a compound to retain its biological activity during production, storage, and digestion. With increased biostability, active ingredients are delivered to the body consistently and efficiently; thus, biostability increases the potential for optimal physiological benefits and cost avings from the use of feed additives. Nanoencapsulation helps to retain the functional integrity and strength of a bioactive compound and thereby improve its biological efficacy in animals.

Specific Findings on Nanoencapsulation and Biostability of Cinnamon Extract

The successful incorporation of cinnamon essential oils (CEO) into the nanoparticles (CEO-NPs) has been established using chitosan and whey protein isolates (WPI) as wall materials through the technique of nanoprecipitation. Under ideal conditions, CEO-NPs were found to have a mean particle size of 195.17 ± 1.35 nm with a very large encapsulation efficiency (EE) of 91.74 ± 1.10% according to a certain investigation[19]. The FTIR (Fourier Transform Infrared Spectroscopy) results confirmed that the encapsulation of CEO took place due to the detection of unique chemical interactions. In addition, DSC (Differential Scanning Calorimetry) results demonstrated a greater degree of thermal stability in both samples of CEO-NPs, thereby enabling better resistance to heat degradation. Gas

Chromatography-Mass Spectroscopy (GC-MS) findings showed that greater than 90% of the CEO components were maintained inside the nanocapsules. Furthermore, no significant changes in the essential volatile components were detected before or during the encapsulation stage. The antimicrobial properties of CEO-NPs were determined through both MIC (minimum inhibitory concentration) and DIZ methods.

The use of disc inhibition zone (DIZ) analysis is a standard technique to preliminary confirm the antimicrobial effectiveness of CEO-NPs. The greater the diameter of the DIZ around disks containing CEO-NPs, the better the ideal suppression of microbial growth and therefore the better the antimicrobial properties of CEO-NPs. Many studies have shown that CEO-NPs produce larger inhibition zones than the same free (non-encapsulated) cinnamon oil due to the improved stability, dispersion and penetration of the active ingredients (for example: cinnamaldehyde) into the microbial cells. Additionally, while DIZ does provide qualitative and semi-quantitative evidence for antimicrobial potential, it does not provide the exact minimum inhibitory concentration (MIC) or bactericidal values[20].

Although the original antimicrobial activity was slightly lowered, CEO-NPs demonstrated improved and longer-lasting antimicrobial effects on foodborne pathogens (i.e., S. aureus, E. coli, P. fragi, and S. putrefaciens) over a ten day period[19].

It's clear from findings that nanoemulsion products do not appear to limit the immediate bioavailability of volatile compounds required for bacterial inhibition. Therefore, it seems essential to find a suitable balance between short-term effectiveness and long-term stability when developing formulations of this type. The use of nanoencapsulation increases biostability as well as provides a method for controlled release, but there doesn't seem to be guaranteed rapid antimicrobial activity associated with nanoencapsulated products; therefore, application-specific strategies are important when considering the use of nanoemulsions as a product. For instance, a sustained modulation of gut microbiota in poultry could be preferred over the immediate eradication of pathogens using nanoemulsions. In addition to biopolymer materials, other natural nanotube materials such as halloysite nanotubes (HNTs) were researched as potential carriers of CEO. HNTs are a naturally occurring nanotube material with a loading capacity of approximately 11% and a retention rate of approximately 33% after 20 days of being held at room temperature, which provides further evidence for the long-acting, controlled-release delivery potential of CEOs[19].

Specific Findings on Nanoencapsulation and Biostability of Coriander Extract

To date, current studies in the field of coriander essential oils (EOs) and their effectiveness against phytopathogens, specifically Colletotrichum nymphaeae (See **Table 1**), have focused mainly on the use of nanoencapsulated coriander EOs. One particular study indicated that the use of copper oxide nanoparticles (CuO-NPs) to nanoencapsulate coriander EOs resulted in a significant increase in antifungal activity with an inhibition rate of over 90% of mycelial growth.[22] Therefore, this finding demonstrates how the use of nanoencapsulation can enhance the bioactivity of coriander-derived compounds. However, much of the available information regarding the application of coriander oil to animal nutrition is lacking with respect to the specific methodology used in the nanoencapsulation of coriander oils and quantitative measurement for important factors affecting biostability. There are few published data regarding encapsulation efficiency, particle size, release kinetics and long-term stability in feed matrices[21].

Limited knowledge about the nature of the chemical and physical properties of coriander oil creates barriers for the use of this product in animal feed throughout the entire world. It is clear that the antimicrobial effects of this product are well documented when using it with plants, but the absence of adequate scientific data on these types of products restricts their ability to be adequately utilized for animal feed. To resolve this issue, future investigations related specifically to coriander essential oil should provide support for the use of coriander essential oil as an approved phytogenic supplement based on scientific data. Although there is a specific gap of available information, the findings from the use of alternative essential oils to create nanoencapsulated oils suggest the method increases or improves the stability, release rate, and antibacterial activities of encapsulated materials. For example, research has shown that silica hollow nanospheres (HNS) have significantly improved particle uniformity, oil capacities (up to 4.18 mg/g), and slow release patterns (up to 102 days) compared with non-encapsulated products[22]. Furthermore, coriander essential oil is almost entirely composed of oxygenated monoterpenes, specifically linalool, which makes up around 81.29% of coriander essential oil[23]. Thus, the chemical composition of coriander essential oil allows for it to be transformed into a bioactive agent if it is properly introduced into or encapsulated in a stable nanoencapsulation structure. HNTs, with their hollow tubular structure, are an example of an aluminosilicate nanocarrier that occur naturally and provide effective means of loading and delivering coriander essential oils through their hollow channels while helping protect against physical damage and reducing the amount that evaporates into the air. The primary mechanism for releasing ceo from HNTs is through diffusion, and this is typically a slow rate of release that allows significant amounts of coriander essential oils to be released for an extended period of time, enabling long-lasting antimicrobial concentrations to be maintained over time. By facilitating sustained release from HNTs, the long-term antimicrobial efficacy against pathogens is improved compared to unencapsulated oils, which often have rapid losses of activity shortly after application[24]. Encapsulation of ceo into HNTs may slightly decrease the immediate antimicrobial activity because of a longer time to release, but the fact that HNTs provide more stable and prolonged antimicrobial activity creates a more appropriate balance between efficacy and durability[25].

Table 1. Summary of nanoencapsulation methods and biostability findings for cinnamon and coriander essential oils.

Extract	Nanoencapsulation Method(s)	Wall Materials/Carriers	Particle Size (if available)	Encapsulation Efficiency (if available)	Key Biostability Findings	Sources
CEO	Nanoprecipitation	Chitosan, WPI	195.17 ± 1.35 nm	91.74 ± 1.10%	Enhanced thermal stability; Slightly decreased initial but more long-lasting and strong antibacterial activity (10-day storage); >90% ingredients encapsulated with no significant change in volatile constituents.	[19]
CEO	HNTs	HNTs	Not specified	~11% loading efficiency	33% retention after twenty days, indicating long-acting controlled-release effect.	[19]
CEO	CuO-NPs	CuO-NPs	Not specified	Not specified	Synergistic antifungal effects (>90% inhibition of mycelial growth against *C. nymphaeae*).	[21]
CEO	*General Nanoencapsulation Principles*	*Various (e.g., silica hollow nanospheres)*	*Not specified for animal nutrition context*	*Not specified for animal nutrition context*	*Generally, enhances stability, release behavior, and antimicrobial properties (based on other EOs); Linalool (81.29%) is major constituent.*	[22]

Nanoprecipitation, HNTs and CuO-nanoparticle systems are examples of nanoencapsulation approaches. These nanoencapsulation processes, and the general principles of encapsulation, produce stable and controlled-release formulations of Coriandrum sativum essential oil that remain bioactive over time. Compared to free oils, nanoencapsulation improves the physicochemical stability of the essential oil, protects against oxidation and volatilization, and allows for controlled-release properties as an important factor in preserving the antimicrobial and antioxidant activity of the essential oil[26]. In particular, nanoprecipitation creates polymeric nanoparticles that have controllable sizes and morphologies, which is necessary for the effective encapsulation of volatile compounds, and thus for a prolonged and regulated release of these compounds, resulting in increased functional stability and bioavailability[27]. The HNTs' unique hollow tubular shape allows for high loading capacity, and the release from HNTs will be controlled through diffusion, which will significantly reduce the rate of evaporation and extend the antimicrobial effect of the essential oil for several days[28].

Intestinal Absorptionof Anoencapsulated Compounds in Avian Species

Overview of The Avian Gastrointestinal Tract and Nutrient Absorption

An avian's digestive tract consists of an incredibly effective, specialized mechanism that transforms food into the essential nutrients (to maintain life, grow, form egg and meat products) that provide sustenance, allow reproductive activities in 3 ways: 1) produce meat; 2) produce Table Eggs; 3) produce Fertile Eggs. The integrity of the digestive tract's structure and function is extremely important in protecting the health of an avian and helping it achieve maximum productivity. Digestion of nutrients and nutrient absorption primarily occurs in the small intestine, where most nutrient absorption happens[3]. However, the mucosa of avian intestines is very sensitive to many environmental and physiological stresses. After being exposed to stresses such as heat stress, overcrowding, lack of good hygiene practices and/or inadequate nutritional / dietary levels can create oxidative stress and cause injury to the intestinal epithelium[29]. Injury to the intestinal epithelium will damage the intestinal barrier, and therefore will decrease the efficiency of the nutrient absorption process, thus negatively impacting production and health of the avian. The avian gut acts as both a site of nutrient absorption and as an immunological/metabolic center. Therefore, feed additives (with special emphasis on new and innovative nanoscale compounds) should be evaluated for both their ability to be absorbed into the body (bioavailability) and also for their impact on the avian gut's structure (gut morphology), the ability of the gut to protect the animal from pathogens and other harmful substances (Barriers), and also how they affect the overall microbe balance within the avian gut (Microbes). All of these factors are interrelated to how well nutrients are utilized, how well the immune system functions, and how well an individual chicken/cock bird grows. Research clearly shows that for optimal absorption of nutrients to occur, the avian gut must maintain a healthy and functional environment, which includes: normal developing intestinal villi; intact junctions between cells (tight junctions); and a stable population of microorganisms (normal Microbes). Understanding this integrated perspective is necessary to truly evaluate the effects of nutritional practices on the performance and well-being of chickens.

Mechanisms of Nanoparticle Uptake and Transport Across The Intestinal Barrier

Nanocarriers have been meticulously designed for oral administration to enhance the absorption of active pharmaceutical ingredients, their bioavailability and therapeutic effectiveness. Nevertheless, the multiple levels of physical complexity and physiological barriers found in the intestines severely limit their ability to deliver effectively.[31] The barriers include the mucosal barrier which is made up of the mucosal membranes, epithelial cells that are tightly packed, immune cells and vascular beds. To successfully penetrate and interact with intestinal mucosal cells, nanoparticles have to survive the harsh conditions of the GI tract that include pH variability, digestive enzymes, and an extensive network of electrolytes that can cause nanoparticles to degrade before they are absorbed[30].

Nanoparticles are designed with the specific purpose of serving as a barrier to the very demanding environment of the gastrointestinal (GI) tract and, therefore, reduce the likelihood of the degradation of the active ingredient before it can be absorbed through the intestinal epithelium[31]. There are different ways nanoparticles can be taken up by intestinal epithelial cells (Enterocytes).

- Clathrin-Mediated Endocytosis: This pathway is characterized by the cell membrane forming an invagination to form vesicles containing nanoparticles, then merging with the early endosomes in order to allow the particles to be transported into the cell[30].
- Caveolin-Mediated Endocytosis: Like clathrin-mediated endocytosis, caveolin-mediated endocytosis also allows the inside of the cell to access the nanoparticles, using caveolae, which are small cave-like structures found in the plasma membrane[30].
- Mucus Penetration: Nanoparticles are able to penetrate through the mucus layer produced by goblet cells and come into contact with the epithelial cells, which allows them to be internalized by the epithelial cells[30].

Microfold (M) Cells are specialized epithelial cells located above lymphoid follicles, which are potential targets for oral vaccines; however, the role of enterocytes in the systemic bioavailability of orall administered particulate nanoparticle) formulations, particularly those that fall within the sub-micron size range, is likely more significant[32]. Less frequently mentioned methods for taking up nanoparticles include: (1) Paracellular Permeability, which allows the particles to bypass the intestinal cells and enter the bloodstream directly; (2) Persorption as a result of damage to intestinal cells caused by the ingestion of nanoparticles; and (3) Uptake by migratory immune cells for transport to the lymphatic system[32].

Endocytosis through clathrin is by far the most common and efficient means of taking up nanoparticles in the intestines, while endocytosis via caveolae has some advantages when it comes to preventing degradation of nanoparticle formulation. The ability of nanoparticles to penetrate through the mucosa is also a crucial factor that determines whether they will be able to reach epithelial cell,since this will be a complementary pathway in addition to providing a mechanism for cellular uptake through endocytosis[32, 33].

Further, the systemic distribution of particular types of nanoparticles may occur as a result of passage through the lymphatic link to the interstitial compartment, which typically happens via the transport systems for uptake via bile acids or transport of lipid emulsions in chylomicrons[34]. The size and surface features of nanoformulations are anticipated to have a considerable effete on their interactions with the GEO, thereby determining bioavailability[11]. Smaller particles are generally more efficiently absorbed than larger; therefore, the size of the particle should correspond to some degree with the amount of absorption[11]. To achieve absorption and distribution throughout the systemic circulation of birds, nanoparticles must travel through several endocytic pathways, lymphatic transport mechanisms and various physicochemical influences; thus, nanoencapsulation will provide a flexible mechanism for providing targeted delivery of nutritional and therapeutic goods. Investigations moving forward should revolve around the design of nanocarrier systems that can penetrate through the intestinal tract and target specific types of cells in order to optimize both the nutritional and therapeutic benefits associated with the delivery of these materials. Such a novel approach to the delivery of nutraceutical ingredients is anticipated to represent a major advancement in the area of animal nutrition.

Influence of Nanoparticles on Gastrointestinal Health and Structural Integrity

Nanoparticles not only boost the bioavailability of encapsulated compounds, but also contribute to the health and structural stability of the avian gastrointestinal tract. Thus, nanoparticles deliver bioactive compoun and simultaneously improve gut morphology and barrier function by increasing mammalian intestinal surface area and enhancing anti-inflammatory properties. All these characteristics of nanoparticles indicate synergistic interactions that may potentially increase nutrient absorption and improve overall resilience of avian species; thus, making nanoparticles a more effective means of delivering nutrient content than traditional non-encapsulated methods. Baicalin (a plant flavonoid) reduces the morphological changes in the duodenum, jejunum, and ileum following the administration of DON-contaminated feed to broilers[35]. It increased the expression of tight junction proteins, including ZO-1, claudin-1, and occludin, reducing DON-induced intestinal permeability and preserving gastrointestinal tract barrier function[35].

Essential oils from herbal sources that have been nanotechnology encapsulated stimulate the production of digestive enzymes, regulate the microbiome of the intestines, enhance the development of small intestinal absorptive mucosal cells, and improve bile acid production[5]. All of these effects combined improve digestion and overall gastrointestinal health and indicate that the use of nanoparticle technology to effect the intestinal environment of birds positively will contribute to increasing bird resilience and improving the efficiency of nutrient absorption. The nanoencapsulation technique can maximize the targeted delivery of nutrients and therapeutics to specific intestinal cells in poultry. This can improve the efficacy and bioavailability of the nutrient or therapeutic and minimize loss from degradation in the gastrointestinal tract. Bioactive compounds (e.g., vitamins, amino acids, essential oils, antimicrobial agents) are protected from the acidic conditions of the stomach, enzymatic degradation, and premature release by encapsulating them in biopolymeric nanoparticles, lipid-based carriers, or inorganic nanocarriers. Additionally, the surface functionalization of nanoparticles can facilitate receptor-mediated or site-specific uptake of the nanoparticles by intestinal epithelial, enterocytes, or goblet cells in order to achieve a targeted delivery of the nanoparticles to specific areas of the intestine[31, 33]. The nanoencapsulation technique can improve the absorption of nutrients and therapeutic agents by reducing the required dosage of nutrients and therapeutic agents, minimizing the incidence of off-target effects, and promoting gut health and growth performance in poultry. Research in poultry has shown that nanoencapsulated probiotics, essential oils,and micronutrients exhibit improved retention in the gut, controlled release, and enhanced systemic uptake when compared to their free form[32]. **Table 2** reresents the intestinal absorption mechanisms and gut health impacts of nanoparticles in avian species

Table 2. Overview of intestinal absorption mechanisms and gut health impacts of nanoparticles in avian species.

Category	Component/Mechanism	Description/Observed Impact	Sources
Gut Barrier Components	Mucus layer	Extracellular mucus secreted by goblet cells; can hinder NP movement but also diffuse through it.	[30]
	Intestinal epithelial layer (Enterocytes)	Tightly regulated barrier; primary site for nutrient absorption and NP uptake, especially for sub-micron particles.	[30]
	Tight junctions	Protein complexes (ZO-1, Claudin-1, Occludin) that seal intercellular space; vital for barrier integrity; NP can increase their expression.	[29]
	M cells (Microfold cells)	Specialized cells for antigen sampling; valid target for oral vaccines, but enterocytes play greater role in systemic bioavailability.	[30]
Nanoparticle Uptake Mechanisms	Clathrin-mediated endocytosis	Cell membrane invagination forming vesicles that encapsulate NPs for translocation.	[30]
	Caveolin-mediated endocytosis	Another endocytic pathway for cellular uptake.	[30]
	Diffusion through mucus	NPs can diffuse through the mucus layer to reach epithelial cells.	[30]
	Paracellular permeability	Passage of particles between intestinal cells (less common).	[32]
	Lymphatic transport (Chylomicron pathway)	Transport to systemic circulation via gut lymphatic system, often with bile-acid conjugation.	[34]
Factors Influencing Uptake	Particle size	Directly impacts distribution and bioavailability; decreasing size increases bioavailability.	[11]
	Surface properties	Affect interactions with GIT systems and bioavailability.	[36]
	Resistance to pH/enzymes	Desirable NPs resist degradation by electrolytes, pH, and digestive enzymes.	[30]
Impact on Gut Health/Integrity	Increased villus height (VH) & VH/crypt depth ratio (VH/CD)	Enhanced absorptive capacity.	[29]
	Increased tight junction protein expression	Strengthened intestinal barrier function (e.g., ZO-1, ZO-2, Occludin, Claudin-1, Claudin-3).	[29]
	Reduced inflammatory markers	Decreased IL-1β, IL-8, and reactive oxygen species (ROS) in jejunum.	[29]
	Increased goblet cell numbers & Mucin-2 (Muc2) levels	Enhanced mucus production for gut lubrication and protection.	[29]
	Stimulated digestive enzymes & healthy bacterial population	Improved nutrient digestibility and gut microbiota balance.	[11]
	Enhanced mucosal absorptive cell development & bile acid secretion	Improved nutrient absorption and overall gut function.	[11]

Productive Performance Parameters in Quail Farming

A wide range of key performance indicators used to measure the effectiveness of feed additives in quail farming ultimately determine the economic viability and environmental sustainability of this industry. The various productive parameters that have been measured in research related to quail production demonstrate that poultry production is a complex and multifactorial activity. In order to optimize performance, a holistic approach needs to be developed. When evaluating feed additives, it must include consideration of their effects on growth rates, egg production, feed conversion efficiencies, egg quality (internal and externalcharacteristics), carcass characteristics, physiological health and immune system health indicators.The most important parameters used to measure quails:

- Growth performance (i.e., body weight, weight gain, growth rate, and performance index) and how efficiently they have been fed by looking at feed intake and feed conversion ratios (FCR)[5].

– Egg production (i.e., egg count, egg mass, average egg weight), and egg quality (specific gravity, colour, shell ratio, weight of yolk and albumen, Haugh units)[5].

– Carcass Aspects: The main carcass-related characteristics of quails raised for meat are carcass yield, liver weight, and percentage of body fat[37].

– Health Indicators; Physiological and Immunological: Blood profiles (e.g., cholesterol, LDL, HDL, triglycerides, uric acid, VLDL) and enzyme activity (e.g., amylase, lipase, trypsin), followed by antioxidant levels (e.g., TBARS, GSH-PX), and immune activity (e.g., IgA, IgM, IgG), are all important indicators of the host's internal condition[38].

– Intestinal Microbiome: The balance between the beneficial and harmful microbes within the intestines (i.e., Lactobacillus spp. vs. E. coli and Salmonella) is a significant factor influencing gut health status and, therefore, the overall well-being of the individual[39].

Effects of Cinnamon Extracts (Nanoencapsulated and Non-encapsulated) on Quail Performance

Researchers have looked deeply into how cinnamon extracts affect the performance of quails. Studies have shown that non-encapsulated cinnamon extracts consistently produced superior productive performance metrics than those that were encapsulated (See **Table 3**). However,until now, very few studies have directly investigated the effects of nanoencapsulated cinnamon on quail performance. There is a significant research void regarding this area, as other studies have shown that nanoencapsulation offers many advantages, including improving the bioavailability and controlling the release of a supplement while providing greater stability than the use of standard encapsulated essential oils.Therefore,it is reasonable to suspect that similar or improved benefits of nanoencapsulation could also be experienced by quail; however, these potential advantages must be tested in controlled experiments to determine if this is true.

Table 3. Key Productive Performance Parameters of Quails Supplemented with Cinnamon Extracts.

Cinnamon Form/Type	Dosage/Concentration	Quail Type	Key Performance Parameters	Observed Effect	Statistical Significance (if noted)	Sources
Powder Extract (CPEx)	250, 500 ppm/kg	Growing Japanese	Live Body Weight, Body Weight Gain, Growth Rate, Performance Index	Highest	$P \leq 0.01$	[39]
Powder Extract (CPEx)	250, 500 ppm/kg	Growing Japanese	Feed Conversion Ratio (FCR), Feed Intake	Best FCR, Lowest Feed Intake	$P \leq 0.01$	[39]
Powder Extract (CPEx)	250, 500 ppm/kg	Growing Japanese	Total Cholesterol, LDL, Triglycerides, ALT, AST, TBARS, *E. coli*, *Salmonella*	Reduced	$P \leq 0.01$	[39]
Powder Extract (CPEx)	250, 500 ppm/kg	Growing Japanese	HDL, Amylase, Lipase, Trypsin, IgA, IgM	Increased	$P \leq 0.01$	[39]
Powder Extract (CPEx)	150 ppm/kg	Growing Japanese	GSH-PX, IgG	Highest levels	Not specified	[39]
Aqueous Extract	10 ml/L (drinking water)	Japanese	Productive Performance	Significant improvement	Not specified	[40]
Dried Cinnamon	800 mg/kg	Laying Japanese	Laying Rate, Egg Numbers, Egg Mass, Feed Conversion Ratio	Enhanced	$P < 0.05$	[38]
Dried Cinnamon	800 mg/kg	Laying Japanese	Body Weight Change, Mean Egg Weight	Improved	$P < 0.05$	[41]
Cinnamon Powder	9 g/kg	Laying Japanese	Feed Conversion per Egg Mass (FC/MASS)	Lower (better)	$P = 0.0126$	[6]
Cinnamon Powder	9 g/kg	Laying Japanese	Egg Weight, Yolk/Shell/Albumen %, Posture %, Feed Intake, Egg Mass	No significant effect	$P > 0.05$	[6]
Cinnamon Powder	6.0, 12.0 g/kg	Laying Japanese	Egg Specific Gravity, Yolk Color	Increased linearly	Not specified	[5]
Cinnamon Powder	6.0 g/kg	Laying Japanese	Purchase Intention of Eggs	Higher	Not specified	[5]
Cinnamon Powder	9 g/kg	Laying Japanese	Pancreas Weight, Intestine Weight	Lower	$P = 0.0418$, $P = 0.0209$	[6]
Cinnamon Powder	9 g/kg	Laying Japanese	Ovary Weight	Higher	$P = 0.0389$	[6]
Cinnamon Powder	9 g/kg	Laying Japanese	Triglycerides, Uric Acid, VLDL	Higher	$P = 0.0207$, $P = 0.0003$, $P = 0.0252$	[6]

Non-encapsulated Cinnamon

Many studies show that using cinnamon powder extract (CPEx) can significantly enhance the growth performance of developing Japanese quails. The doses of CPEx of 250 and 500 ppm/kg added to the diets of the Japanese quails resulted in a statistically significant effect ($P \leq 0.01$) for the following growth performance measurements: live body weight, weight gain, growth rate, and performance index. In addition, these two dose levels produce the highest FCRs (feed conversion ratios) and the lowest feed intakes, indicating that these two doses produce the best feed efficiency. Along with increased growth, the addition of CPEx to the diets of Japanese quails decreased total cholesterol, LDL, triglycerides, ALT, AST and TBARS levels and increased the levels of HDL as well as the activity levels of digestive enzymes (amylase, lipase, and trypsin) and immune parameters (IgA and IgM). Furthermore, the addition of CPEx to the diets of Japanese quails decreased the numbers of pathogenic isolates of Escherichia coli and Salmonella. Interestingly, the addition of 150 ppm CPEx per kg diet produced the highest level of glutathione peroxidase (GSH-PX) and immunoglobulin G (IgG). Lastly, providing cinnamon extract (10 ml/L in drinking water) also improved overall productivity[40].

Laying Japanese Quails

When quails were given a diet supplemented with 800 grams of cinnamon powder per kilogram (800 g/kg), there was a statistically significant increase in their critical egg-laying performance parameters (i.e. egg output, egg weight, and number of eggs produced). In addition, this heightened egg-laying performance was associated with changes in average body weight and average egg weight as well[41]. In another study, quails receiving 9 grams of cinnamon powder per kilogram feed produced statistically heavier eggs than Quails given feed without added cinnamon. However, the daily feed ingested or the total egg output was not significantly different[6]. Adding cinnamon increased the amount of specific gravity of eggs as well as the amount of pigment in yolk[5]. Evaluation of sensory characteristics showed that evaluators preferred to purchase eggs from Quails that had eaten 6 grams of cinnamon daily[6]. Physiologically, the effects of cinnamon were observed by decreases in the weights of the pancreas and intestines, but increased ovary weights. Levels of triglycerides, uric acid, and VLDL were higher in serum[6].

Nanoencapsulated Cinnamon

Currently, no studies have been conducted directly evaluating how nanoencapsulation of cinnamon affects the production and performance of quails. However, encouraging results have been observed among various species of poultry, including broiler chickens. For example, one study evaluated the effect of chitosan nano-encapsulated CEO on broilers and reported significant increases in body weight gain and feed conversion ratios (FCR)[42]. In general, nano-encapsulated herbal essential oils in poultry production are recognised for their ability to improve production, stimulate the immune system, and enhance the antioxidant ability through multiple biological pathways[11]. The above results highlight the need for research studies that specifically assess nano-encapsulated cinnamon on quails. There is a strong possibility that quails will experience similar, or possibly even greater, benefits as well.

Impacts of Coriander Extracts (Nanoencapsulated and Non-encapsulated) on Quail Performance

Significant numbers of studies have been conducted on the impact of coriander extract on the growth and development of quail(See **Table 4**). Many of these studies have confirmed that the use of coriander extract, in an unencapsulated state, improves growth and feed conversion ratios and improves egg quality for birds in the quail industry. However, there are still very limited amounts of published research on the impact of using coriander extract in a nanocapsule form and how it enhances quail production. This lack of information provides an excellent opportunity for future research to determine how using both forms of coriander extract together will improve quail production. Given the positive benefits established through research conducted to date on the use of coriander and the potential increase in absorption and preservation of bioactive compounds due to nanocapsulation, it would seem likely that combining the two will produce even greater improvements in quail production.

Non-encapsulated Coriander

Cultivating Japanese Quail: Adding coriander seed to the diet has shown many benefits for raising Japanese quail. At a level of 2% in the diet, birds fed a diet with this concentration had increased overall body weight gain, better feed conversion ratios (FCR) and increased carcass weights and liver weights compared to birds fed the control diet. The birds receiving a diet with a 2% inclusion of coriander also had the lowest amount of abdominal fat when compared to birds fed the control diet. The birds fed the 2% coriander diet had an increase of 8.3% in their daily live weight gains and a 4.3% increase in their FCR compared to the control diet[37]. These increases were largely attributed to the desirable taste and digestive properties of coriander essential oils such as linalool. Although there was increased feed consumption when coriander was included in the diet, particularly at 4% inclusion, birds that received the 0.5% inclusion had similar consumption levels compared to birds fed the control diet[37].

Laying Japanese Quails: The addition of 1% and 2% ground coriander to the diets of quails resulted in significantly improved values for all measured performance traits including: egg weight, feed conversion ratio (FCR), and nutrient retention (dry matter), organic matter, crude protein and ether extracts[43]. In addition to improved performance, the addition of coriander at 1% and 2% resulted in increased yolk and albumen weights which were an indication of higher quality eggs. Quails that were provided with coriander in their diet also had greater feed consumption compared to the quails in the control group. However, when using higher amounts of coriander's essential oils (e.g., 4%), they may be toxic to quails and cause reduced performance[43]. Further evidence of coriander's effectiveness being dose dependent is shown as well as indicating that proper inclusion levels need to be determined for optimal performance results.

Nanoencapsulated Coriander: Like nanoencapsulated Cinnamon, there appears to be a lack of research available for evaluating the effect of nanoencapsulated Coriander on quails's production performance directly; although most of the current research has been directed toward exploring the antifungal activity of Coriander on vegetable pathogens, rather than animal nutrition applications[21]. Despite this, the many advantages to using nanoencapsulated Herbal Essential Oils within avian species including improved growth rates, increased immune function & increased antioxidant potential make it possible for Nanoencapsulated Coriander to be beneficial for Quail Production.Therefore,this area may prove to be advantageous for future studies and/or practical use from this aspect of poultry nutrition[11].

Table 4. Key Productive Performance Parameters of Quails Supplemented with Coriander Extracts.

Coriander Form/Type	Dosage/Concentration	Quail Type	Key Performance Parameters	Observed Effect	Statistical Significance (if noted)	Sources
Coriander Seed	4%	Growing Japanese	Feed Intake	Highest	P < 0.05	[37]
Coriander Seed	2%	Growing Japanese	Daily Live Weight Gain	Highest (8.3% improvement vs. control)	P < 0.05	[37]
Coriander Seed	2%	Growing Japanese	Feed Conversion Ratio (FCR)	Best (4.3% improvement vs. control)	P < 0.05	[37]
Coriander Seed	2%	Growing Japanese	Carcass Yield, Liver Weight	Highest	P < 0.05	[37]
Coriander Seed	1%, 2%, 4%	Growing Japanese	Abdominal Fat Percentage	Lowest (especially 2%)	P < 0.05	[37]
Coriander Seed	0.5%	Growing Japanese	Feed Intake	Similar to control	P > 0.05	[37]
Ground Coriander Seeds	1%, 2%	Laying Japanese	Egg Weight, Yolk Weight, Albumen Weight	Highest	P < 0.05	[43]
Ground Coriander Seeds	1%, 2%	Laying Japanese	Feed Conversion Ratio (g feed/g egg)	Best	P < 0.05	[43]
Ground Coriander Seeds	1%, 2%	Laying Japanese	Nutrient Retention (Dry Matter, Organic Matter, Crude Protein, Ether Extract)	Improved	P < 0.05	[43]
Ground Coriander Seeds	0.5%, 1%, 2%, 4%	Laying Japanese	Daily Feed Intake	Higher than control	P < 0.05	[43]
Coriander Essential Oil	High concentrations (e.g., 4%)	Laying Japanese	Performance	Potential toxicity, lower performance	Not specified	[43]

Discussion

Synergistic Effects and Comparative Efficacy of Nanoencapsulated Extracts

The benefits gained through nanoencapsulation of bioactive compounds are reflected in their increased bioavailability, increased controlled release, and increased targeted delivery[11]. Nanoencapsulated bioactive compounds exhibit enhanced bioefficacy and an associated decrease in effective dose relative to their non-encapsulated counterparts, providing both biological and economic/environmental benefits. The use of lower doses of nanoencapsulated essential oils, for example, results in reduced production costs and lower levels of residues in animal products, thus leading to a lower ecological footprint. Therefore, the poultry sector has a more economical and sustainable alternative when it uses nanoencapsulated essential oils. Therefore, the efficient use of nanoencapsulated essential oils provides feed manufacturers and animal producers with both financial and environmental benefits.Essential Oils have the potential to serve as viable alternatives to traditional antibiotics for Poultry production. The overall benefits of these compounds are primarily due to their ability to improve animal production, improve immune response and antioxidant status through a variety of biological interactions or pathways.[11] Another anticipated benefit of combining essential oils with other bioactive agents is the potential enhancement of synergism or the demonstrate greater effects than either agent alone when used for raising quail.This finding represents a significant advancement in the development of multiple-component Nanoformulations that contain various bioactive agents or delivery systems to promote enhanced health and performance of animals[44]. Such synergistic strategies may usher in new levels of efficiency and sustainability in the area of animal nutrition.

Challenges and Limitations in Current Research

Although the nanoencapsulated extracts pose a significant promise, there are several substantial challenges and limitations remaining within the current research field. Firstly, one of the main drawbacks of the current research field might consider the lack of direct research regarding the impacts of nanoencapsulated cinnamon and coriander extracts on the production performance of quails. The existing literature clearly shows a substantial dominance of research either regarding nonencapsulated variants or nano-variants tested on other poultry breeds like broiler chicken. This indicates the urgent need for specific research as the theoretical promises of nanoencapsulation are yet to be confirmed within quail production systems.In connection with the data gap found in the specific species, it must be recognized that there is already an identified need for more in-depth studies concerning the mechanisms and possible adverse effects, such as toxicity, of nanoencapsulated herbal essential oils[5]. The relationship between nanoparticles and biological entities is in itself complex, and in-depth safety testing must be ensured prior to large-scale and sound use in animal production.There are also practical issues in relation to the stability of the nano-formulation in complex matrices of the animal feed. Such issues include the possibility of interaction with the components of the animal feed. These components include proteins, carbohydrates, lipids, minerals, as well as vitamins. There might also be physical instability during the processing of the animal feed. Such processing entails the mechanisms of grinding, mixing, and pelleting[45]. The process of optimizing bioavailability for its enhancement still poses some challenges, given that size and surface properties of nano-formulations, along with their interaction with the gastrointestinal environment, play significant roles in determining the efficiency of its absorption[45].The formulation of nano-particles, therefore, has to be done in a meticulous manner with respect to optimizing itsbioavailability for a range of physiological conditions.

Nano-supplemented feed calls for comprehensive toxicological assessment to ascertain its safety for both animal and human populations. Potential long-term effects and bioaccumulation within the food chain need to be well comprehended and mitigated in order for such feed to be used responsibly and in a sustainable manner. Another formidable challenge relates to the economics surrounding the formulation and production of nanoformulated delivery systems. To realize economic feasibility, nanoformulated delivery systems will need to offer clear and measurable improvements in the health and productivity of animals that justify the higher production costs, ideally to reduce overall costs when compared to traditionally formulated feed additives.The long-term environmental impacts of incorporating nanoparticles in animal feed are unclear. Further study is needed to alleviate concerns regarding the accumulation of nanoparticles in the environment and the food chain. Emphasis should be placed on using degradable, environmentally friendly formulations that minimize ecological impacts as much as possible. Safety concerns, cost-effectiveness, stability in feed matrices, and environmental issues are major hindrances to the commercialization acceptance and approval of nanoencapsulated feed additives. Overcoming these complex barriers is vital to the translation of promising laboratory discoveries into useful industrial applications.

Future Directions and Research Gaps

These current research gaps accentuate the need to move forward from proof-of-concept studies towards a more emphasized focus on optimization, safety, and the potential for commercial viability. This represents a kind of coming of age in the field, leading to a need for an interdisciplinary approach which combines expertise in animal science, nanotechnology, toxicology, and economics.

Key Areas for Future Research Include:

- **Direct Efficacy Studies:**There is an urgent need to conduct direct research in regard to the use of nanoencapsulated cinnamon and coriander in quails. Further research needs to focus on the impact on the performance of the organism and the mechanisms of absorption in the intestines.
- **Formulation Optimization:** Research must be performed to understand the effects of surface properties of an essential oil on bioavailability[13]. Investigate the best dietary inclusion ratios for nanoencapsulated plant extracts, 43 and simultaneously develop the specific designs of nanocapsules for appropriate end-use[36].
- **Mechanism Elucidation:** The objective is to define how nanoencapsulated plant extracts cross and interact with the avian GI tract. In order to accomplish that, in vitro and in vivo testing will be required, along with clinical testing of the safety and efficacy throughout[36].
- **Scalability and Cost:** To ensure the commercial viability of nano-formulations in poultry nutrition, studies aimed at improving cost effectiveness will be needed to support the scale-up of production[45].
- **Safety and Environmental Impact:** Conducting comprehensive long-term toxicological evaluations, keeping animal welfare and environmental sustainability in mind, is important. There should be a focus on using biodegradable or environmentally friendly materials to reduce the risk of environmental impacts and accumulation in the food chain[45].
- **Target Delivery and Personalized Nutrition:** Exploring new methods of nanoencapsulating bioactive compounds is a valuable approach to providing targeted delivery of these compounds to specific locations in the gastrointestinal tract of the bird. In addition, developing personalized nutritional programs that are based on the individual health status and nutritional needs of quails will represent the future of precise poultry nutrition[13].

Conclusion

Nanoencapsulation technologies represent an innovative method to improve the bioavailability of natural plant extracts (e.g., Cinnamon and Coriander) due to limitations in stability with respect to their non-encapsulated counterparts. This innovation is likely to play an important role in improving animal nutrition, and developing the feed industry. There have been many studies demonstrating the advantages of using non-encapsulated Cinnamon and Coriander on the performance of quail; for example, these products improve the growth rate, efficiency of feed conversion, quality of eggs and improve gut health. There does not appear to be a substantial amount of direct evidence to support that Nanoencapsulated Cinnamon and Coriander will have the same beneficial effects on quail. Nanoparticle absorption through the avian digestive tract involves a series of complex processes and pathways within cells. These nanoparticle interactions aid in the uptake of nutrients, as well as, maintaining the health and integrity of the avian intestinal tract.

While nanoencapsulated extracts possess great promise for use as sustainable replacements for conventional antibiotics in poultry, there are still a number of obstacles to overcome. Specifically, these challenges include demonstrating feed stability; performing long-term safety evaluations;

demonstrating commercial viability and cost efficiency; assessing environmental impact.

The strategic implementation of nanoencapsulated cinnamon and coriander may reveal the full potential of therapeutic and productive uses of these spices in quail production by addressing existing limitations in research and facilitating greater efficiency and sustainability in animal protein production.

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