Physiological Functions of Inulin and Its Application in Livestock and Poultry Production: A Postprint

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Abstract

Inulin is a class of plant-derived natural fructans that possess functions including modulating gut microbiota, regulating immune and lipid metabolism, and promoting mineral absorption. As a natural feed additive, inulin demonstrates efficacy in improving gut health and enhancing immunity in livestock and poultry, showing promising application prospects. This article reviews the physicochemical properties, extraction processes, main physiological functions of inulin, and its application status in livestock and poultry production, aiming to provide a reference for the application of inulin in animal feed.

Full Text

Physiological Functions of Inulin and Its Application in Livestock and Poultry Production

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Abstract: Inulin is a type of plant-derived natural fructan that can balance intestinal microorganisms, regulate immune and lipid metabolism, and promote mineral absorption. As a natural feed additive, inulin can improve intestinal health and immunity in livestock and poultry, demonstrating promising application prospects. This paper reviews the physicochemical properties, extraction processes, main physiological functions of inulin, and its application status in livestock and poultry production, aiming to provide references for the application of inulin in animal feed.

Key words: inulin; physiological function; prebiotics; feed additive

Inulin is a reserve polysaccharide in plants, primarily derived from sources such as dahlia tubers, chicory, and Jerusalem artichoke roots [1-2], but can also be obtained from certain bacteria or fungi. Numerous studies have demonstrated that inulin plays important roles in balancing intestinal microorganisms, regulating immunity, modulating lipid metabolism, and affecting redox systems in the body, and can serve as a substitute for fat and sugar as well as a prebiotic [3]. However, it is currently mainly applied in the food and pharmaceutical industries [4-5]. Analysis of Web of Science 检索 results for "Inulin" reveals that only 1.36% of all publications (10,650 articles) are in the field of zoology research, indicating that research on inulin in animal production is still in its infancy. With the increasingly serious problem of antibiotic abuse and growing awareness of livestock product safety, "antibiotic-free" farming will become an inevitable trend. Inulin, being natural, non-toxic, and capable of enhancing immunity and antioxidant capacity, possesses significant potential as a green plant-derived additive. Nevertheless, the appropriate dosage and mechanisms of action of inulin in livestock and poultry production remain unclear. Therefore, this paper summarizes the current research status of inulin both domestically and internationally, its main physiological functions, and applications in livestock and poultry production, aiming to provide theoretical references for its further development and application.

1.1 Physicochemical Properties

Inulin is a mixture of natural fructans. Fructans are carbohydrates composed of fructose monomers linked by -(2,1)-glycosidic bonds and terminated by a glucose monomer. Inulin molecules consist of approximately 31 -D-fructofuranose units and 1-2 pyranose residues, with a degree of polymerization (DP) ranging from 2 to 100. The -configuration prevents inulin-type fructans from being hydrolyzed by -glycosidic bond-specific digestive enzymes of monogastric animals, but they can be degraded by microorganisms [6]. Inulin can be hydrolyzed by endo-inulinase and exo-inulinase. Exo-inulinase removes terminal fructose residues from the non-reducing end of the chain, while endo-inulinase acts on internal linkages [7-8]. Inulin hydrolysis yields fructose and small amounts of glucose, and inulin with DP less than 10 is called fructooligosaccharides (FOS) [9]. The DP of inulin influences its important physical properties such as solubility, thermal stability, sweetness, and prebiotic activity. The DP of inulin depends not only on plant source, harvest time, and post-harvest storage conditions, but is also significantly affected by the extraction process [8]. The molecular formula of inulin is expressed as GFn [3], where G represents the terminal glucose unit, F represents fructose molecules, and n represents the number of fructose units. The chemical structure of inulin is shown in Figure 1 [Figure 1: see original paper]. Chicory-derived inulin is a white, transparent, tasteless powder. The sweetness of long-chain inulin and FOS is 10% [10] and 30%-50% [11] that of sucrose, respectively. Generally, inulin solubility decreases with increasing DP. Standard inulin has a solubility of only 10% at room temperature, while FOS solubility is approximately 80% at room temperature [12]. Wada et al. [13] reported the solubility changes of three types of inulin with different DP values at various temperatures, finding that enzymatically synthesized inulin had the highest solubility at all temperatures, followed by inulin with DP=10-12, and finally inulin with DP=23-25.

1.2 Extraction Process

In current industrial production, inulin is primarily extracted from Jerusalem artichoke and chicory. Jerusalem artichoke possesses many desirable growth characteristics, including cold and drought tolerance, wind and sand resistance, salt and alkali tolerance, strong reproductive capacity, and high disease and pest resistance, allowing cultivation in sandy soils and beaches. It has recently been considered an important source for industrial production of fructose and inulin [14]. The main processes for extracting inulin from chicory roots include traditional water extraction and ultrasound-assisted extraction, comprising three steps: extraction of water-soluble components, purification, and drying. During water-soluble component extraction, cut or ground chicory roots are typically boiled in water, with conditions such as pH, solid-liquid ratio, and boiling time affecting the DP of extracted inulin [8,15]. Inulin purification utilizes the solubility differences of various DP components in the extract, with final inulin content from chicory roots reaching up to 10% [16]. Xiao et al. [17] determined the optimal conditions for inulin extraction from Jerusalem artichoke using water extraction: extraction time of 100 min, temperature of 85 °C, and material-to-liquid ratio of 1:15. In addition to traditional water extraction, ultrasound-assisted extraction has been employed for high-yield inulin extraction, with main influencing factors including ultrasonic amplitude, temperature, and time. When extracting inulin from burdock root, increasing amplitude and amplitude time enhances inulin yield, while temperature has minimal effect. The optimal extraction conditions are: ultrasonic treatment time of 25 min, ultrasonic amplitude of 83.22%, and temperature of 36.76 °C [18]. It should be noted that ultrasound can fragment inulin molecules, altering their chemical composition. Subsequently, researchers proposed a new method for extracting inulin from Jerusalem artichoke tubers, achieving an extraction yield (16.39 g inulin per 100 g tuber) approximately 14% higher than traditional water extraction [19]. This method involves washing tubers with pressurized water to remove oil, natural drying, hot water treatment at 80 °C for 10 min to inactivate polyphenol oxidase, suspension in distilled water, three rounds of cutting and extraction, and final clarification of the resulting filtrate [19].

2.1 Prebiotic Effects

Typically, beneficial bacteria such as Lactobacillus and Bifidobacterium in the intestinal microbiota play important roles in protecting host health. Inulin can increase the quantity and activity of Bifidobacterium and Lactobacillus in the colon [20], thereby protecting intestinal health—a effect known as the prebiotic effect. The most common explanation in the literature for inulin-type prebiotics involves an indirect mechanism through the formation of short-chain fatty acids (SCFAs). Inulin and FOS are fermented in the hindgut to produce SCFAs (such as acetate, butyrate, and propionate), which lower intestinal pH and thereby stimulate the proliferation of beneficial bacteria [21-22]. SCFAs not only provide an energy source for the host but also have multiple functions, including regulating the proliferation, differentiation, and migration of intestinal epithelial cells, and influencing lipid and glucose metabolism. Additionally, SCFAs play a key role in maintaining intestinal homeostasis and affecting the intestinal mucosal barrier. Rebolé et al. [23] observed increased Lactobacillus counts in the cecum when adding 10 g/kg inulin to broiler diets; when the inulin level was increased to 20 g/kg, Bifidobacterium and Lactobacillus counts increased in the distal small intestine and cecum. The effect of inulin on modulating intestinal microbiota is influenced by its DP. Zhu et al. [24] found that FOS intervention was more effective than inulin in treating mouse intestinal microbiota, possibly because both FOS and inulin must be hydrolyzed into monosaccharides before being utilized by intestinal microorganisms. Fructans with low DP undergo relatively rapid microbial fermentation, while long-chain fructans are more resistant to fermentation and persist longer in the gastrointestinal tract [25]. Patterson et al. [26] reported that short-chain and long-chain inulin affect the growth and activity of intestinal microbiota to different degrees. Studies have shown that a 50:50 mixture of short-chain and long-chain inulin offers advantages in exerting prebiotic effects, reducing harmful gas production while enhancing prebiotic activity [27].

2.2 Immunomodulatory Effects

Current research on the immunomodulatory mechanisms of inulin primarily focuses on two aspects: first, inulin acts as a ligand that binds to Toll-like receptor 2 (TLR2) and Toll-like receptor 4 (TLR4), stimulating immune cells such as macrophages and monocytes to exert immunomodulatory effects; second, its fermentation products (SCFAs, H2) can serve as signaling molecules that influence AMP-activated protein kinase (AMPK) activity and nuclear factor- B (NF- B) signaling pathways. Vogt et al. [28] demonstrated that inulin-type fructans can modulate human peripheral blood mononuclear cell (HPBM) activity through TLR2, with lower DP inulin-type fructans increasing IL-10 and IL-12 secretion in HPBM cells. Studies have reported that in rat intestinal epithelial cells, oligosaccharides enhance immune responses by activating TLR4 and participating in NF- B signaling, thereby producing non-prebiotic effects [29]. Capitán-Cañadas et al. [30] also noted that in rat monocytes, prebiotic oligosaccharides directly regulate pro-inflammatory cytokine production by activating TLR4. Huang et al. [31] showed that adding 5-10 g/kg inulin to broiler diets significantly improved immune function at 21 days of age, but the improvement was less pronounced at later stages (42 days of age). The possible reason is that the intestinal and immune functions of broilers are not fully developed in the early stage, making the addition of inulin more effective during this period.

2.3 Lipid Metabolism Regulation

Among the SCFAs produced from inulin fermentation in the intestine, except for partial butyrate that is metabolized by colonocytes as an energy source, the remainder is transported to the liver. Propionate primarily serves as a precursor for gluconeogenesis [32], while acetate and butyrate are mainly involved in lipid biosynthesis [33-34]. In addition to serving as substrates, SCFAs can act as signaling molecules sensed by specific G protein-coupled receptors (GPRs) to participate in regulating lipid and glucose metabolism [35]. Adding fructooligosaccharides to rat diets leads to significant reductions in serum phospholipids and triglycerides, particularly very low-density lipoprotein (VLDL) content. This is mediated primarily by decreasing the activity of hepatic lipogenic enzymes such as malic enzyme, ATP citrate lyase, acetyl-CoA carboxylase, and glucose-6-phosphate 1-dehydrogenase [36-37]. Beylot et al. [38] concluded that rat studies have clearly demonstrated that inulin reduces triglyceride levels, with the most reasonable explanation being that inulin-type fructans reduce the expression and activity of lipogenic enzymes in the liver, thereby decreasing fatty acid and triglyceride synthesis. Kim et al. [39] reported that inulin reduces blood cholesterol levels in rats by increasing bile acid secretion and inhibiting the activity of 3-hydroxy-3-methylglutaryl-CoA (HMG-CoA) reductase, a rate-limiting enzyme in cholesterol synthesis. Yusrizal et al. [40] added inulin (10 g/kg) to broiler diets and found significantly reduced serum cholesterol levels. Sang-Oh et al. [41] observed that two experimental groups (with microencapsulated inulin added at 250 and 300 mg/kg) showed significantly lower total blood cholesterol and triglyceride levels in laying hens compared to the control group. However, Velasco et al. [42] reported that inulin supplementation did not reduce serum cholesterol, low-density lipoprotein cholesterol (LDL-C), or high-density lipoprotein cholesterol (HDL-C) levels. Dewulf et al. [43] found that in mice fed a high-fat diet, body fat gain was strongly correlated with GPR43 expression in subcutaneous adipose tissue, and inulin supplementation could reduce GPR43 expression and fat accumulation. Some researchers believe that inulin-type fructans cause differential changes in triglyceride metabolism depending on diet type [44]. The cholesterol-lowering effect of inulin remains controversial and requires further investigation.

2.4 Mineral Absorption Promotion

Studies have shown that adding inulin to livestock and poultry feed has positive effects on the absorption and metabolism of calcium, phosphorus, zinc, copper, and iron. Chen et al. [45] reported that adding fructooligosaccharides and inulin to laying hen diets increased serum calcium content and significantly increased total ash, calcium, and phosphorus content in tibiae. Ortiz et al. [46] similarly demonstrated that inulin supplementation in broiler diets increased the retention rates of calcium, zinc, and copper by 18.4%, 35.5%, and 46.6%, respectively, with no significant effect on magnesium and iron retention. Several mechanisms have been proposed to explain the enhanced mineral absorption by inulin: inulin produces SCFAs and organic acids in the intestine, lowering intestinal pH and thereby increasing mineral solubility. SCFAs may also affect calcium absorption through ion exchange systems [47]. Additionally, inulin promotes the proliferation of intestinal cells through microbial fermentation products, thereby increasing intestinal absorption surface area, enhancing calcium-binding protein expression, and releasing bone regulatory factors [48]. Yasuda et al. [49] and Tako et al. [50] both showed that inulin positively affects iron metabolism by influencing the expression of iron transporters, related enzymes, and ferritin-encoding genes in intestinal epithelial cells, as well as suppressing inflammation-related genes. Research indicates that inulin' s effect on mineral absorption and utilization is influenced by various factors such as animal age and physiological stage. The effects of inulin supplementation are more pronounced when animals are in rapid growth phases or have insufficient estrogen secretion and higher calcium requirements. In developing male rats, adding 5%-10% chicory inulin to the diet significantly enhanced whole-body bone mineral content (BMC) and bone mineral density (BMD) [51]. In adolescent females, three weeks of FOS and inulin administration increased calcium absorption by 18% [52]. Another study reported that appropriate dietary inulin supplementation significantly increased mean corpuscular hemoglobin (MCH) and packed cell volume (PCV) in pig erythrocytes (MCH is an effective indicator of iron status), but excessive supplementation had negative effects on MCH and PCV [20].

3 Application of Inulin in Livestock and Poultry Production

Weaning stress in piglets often disrupts intestinal morphology and microecological balance, leading to diarrhea and other diseases. Inulin can be utilized by Bifidobacterium and Lactobacillus in the intestine to produce SCFAs, lower intestinal pH, and stimulate immunoglobulin production, helping to competitively exclude pathogens [53] and thereby protect intestinal health. Tako et al. [50] found that adding 4% inulin to piglet diets significantly increased Bifidobacterium and Lactobacillus counts in cecal contents and mucin gene expression in the duodenum. Spencer et al. [54] demonstrated that inulin-type fructans significantly increased intestinal villus height and the villus height-to-crypt depth ratio in weaned piglets. Pierce et al. [55] also observed that adding 15 g/kg inulin to weaned piglet diets significantly decreased ileal pH and increased jejunal villus height. Additionally, Hansen et al. [56] found that adding 150 g/kg inulin to finishing pig diets reduced ammonia emissions by 33%. Petkevičius et al. [57] discovered that inulin significantly reduced fecal egg counts in pigs, demonstrating excellent anthelmintic effects.

These studies indicate that inulin-type fructans have multiple beneficial effects on pig intestinal health, and inulin has also received considerable attention in poultry production. Adding inulin to broiler diets can activate genes and pathways involved in immune processes, thereby modulating immune capacity [58]. Sang-Oh et al. [59] compared microencapsulated inulin and antibiotics in broiler diets, finding that the microencapsulated inulin group showed significantly increased serum immunoglobulin G (IgG), immunoglobulin M (IgM), and immunoglobulin A (IgA) levels. In the 0.20 and 0.25 g/kg microencapsulated inulin groups, broiler serum IgG levels increased by 155.6% and 168.5% compared to the control group, and by 125.1% and 135.5% compared to the 0.08 g/kg avilamycin group, respectively. Furthermore, Nabizadeh et al. [60] found that adding 5-10 g/kg inulin to broiler diets significantly increased total anti-sheep red blood cell (SRBC) and IgG levels. Some scholars have also suggested that inulin may potentially improve intestinal health by stimulating butyrate and mucin production [24].

Huang et al. [31] showed that inulin supplementation at 5 and 10 g/kg increased IgA levels in cecal contents of broilers at 21 and 42 days of age, and inulin at 10 and 15 g/kg enhanced mucin mRNA expression in the jejunum of 21- and 42-day-old broilers. However, literature reports on the effects of inulin on poultry growth performance are inconsistent. Ortiz et al. [46] added 5-20 g/kg inulin to broiler diets and found no significant changes in growth performance or intestinal morphology (duodenum, jejunum, ileum, and cecum) compared to the control group. Similarly, other researchers found that inulin supplementation in poultry diets did not significantly affect growth performance [61-62]. In contrast, Rebolé et al. [23] found that during the first phase (7-21 days), broilers fed 10 and 20 g/kg inulin had significantly higher weight gain than the control group, and the 10 g/kg inulin group also showed significantly increased overall body weight for the entire experimental period (7-35 days). The conflicting reports on inulin' s effects on poultry growth performance may be caused by multiple factors, such as inulin product quality, supplementation level, poultry breed, and rearing environment.

4 Conclusion

In summary, inulin possesses multiple physiological functions that help balance the intestinal microecology of livestock and poultry, inhibit pathogenic microorganisms, and modulate immunity. However, inconsistent research results have emerged regarding inulin' s effects on animal growth performance. This may be related to the fact that as a prebiotic, inulin' s effectiveness depends on factors such as the animal species, dosage, and duration of supplementation. Therefore, as the global movement toward "antibiotic-free farming" accelerates, there is an urgent need for further research on the optimal supplementation levels of inulin in various livestock and poultry production systems, its effects on different animal breeds, and its mechanisms of action, in order to provide a theoretical foundation for the application of inulin in animal husbandry and green livestock farming.

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Note: Figure translations are in progress. See original paper for figures.