Open Journal of Animal Sciences, 2022, 12, 662-687
https://www.scirp.org/journal/ojas
ISSN Online: 2161-7627
ISSN Print: 2161-7597

Dietary Fiber in Poultry Nutrition in the Light of Past, Present, and Future Research Perspective: A Review

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How to cite this paper: Sekh, N. and Karki, D. (2022) Dietary Fiber in Poultry Nutrition in the Light of Past, Present, and Future Research Perspective: A Review. *Open Journal of Animal Sciences*, **12**, 662-687.
https://doi.org/10.4236/ojas.2022.124046

Received: July 14, 2022
Accepted: September 13, 2022
Published: September 16, 2022

Abstract

Dietary fibers (DF) largely represent carbohydrate polymers of plant origin which are able to escape endogenous enzymatic digestion in the small intestine of non-ruminant hosts like poultry. Traditionally, DF was considered as nutrient diluent, and as an anti-nutritional factor. Dietary fibers, however, have been shown to positively influence digestive system, immune function, microbiota, and also poultry behavior. After the ban of antibiotics and antibiotic growth promoters in many countries, nutritional strategies to meet the genetic potential of poultry breeds have been extensively investigated. Furthermore, increase use of unconventional or alternative feed resources to reduce the feed cost and human food competition have made the DF topic more interesting as such products are generally rich in fiber; therefore can alter the poultry performance. Thus, to produce poultry sustainably and eco-friendly, DF has to be carefully managed in poultry which further requires sound knowledge on feed formulation, source of fiber, type, subtype, form, inclusion rate, and other managerial aspects like exogenous enzyme supplementation. To sum up, this review paper has critically analyzed the dietary fiber related issues including positive and negative sides of DF in modern day's poultry nutrition. Finally, gaps in previous researches have been also identified and future direction has been suggested to better understand the topic considering therapeutic role of DF in poultry health.

Keywords

Dietary Fiber, Poultry, Digestive System, Unconventional Feed, Enzyme, Therapeutic

1. Introduction

The definition of dietary fiber (DF) has been historically debateful due to discrepancies in fiber analysis technique and thus, subsequent variations arose due to chemical compositions and physiological effects on hosts. However, one commonly accepted definition is that DF is carbohydrate polymers with three or more monomeric units, which are not hydrolyzed by endogenous enzymes in the small intestine of human [1]. The definition seems to lack sufficiency in context of animal nutrition. Moreover, new researches have suggested that DF can show high relevance with physiochemical and behavioral effect on animals [2] [3] [4]. Nowadays, insects as an alternative source of protein in poultry feed have been also studied with great interest [5] assuming that they can potentially replace expensive plant based protein sources for sustainable poultry production. Thus, novel dietary fiber from insect origin like chitin can get incorporated in the poultry feed. The role of such a new product requires further examination on poultry health and performance. In this paper, only plant or grain derived dietary fibers will be discussed in detail considering their role, and management strategy in modern day's poultry nutrition evidenced by previous and latest findings, and has also identified future research possibilities as direction to better understand the topic.

Broadly, DF are naturally present compounds that contain non-digestible (non-ruminant) fractions of feed ingredients, which can largely include carbohydrate polymers; cellulose, hemicellulose, pectin, gums, mucilage, B-glucan, Oligosaccharides, resistant starch, and other associated substances like lignin, wax, cutin, and suberin [6] [7]. As DF can escape digestion at major parts of small intestine at non-ruminant hosts, it can get fermented at distal parts of gastrointestinal tract (GIT), e.g. distal small intestine or/ and large intestine by microflora communities with varying degrees and proportions [6]. Gases, lactic acid, and short chain fatty acids (SCFA) are fermentation end products, among which the latter two can play significant roles in poultry gut health and performance [8] [9]. Traditionally, dietary fibers were measured with the aid of alkali and acid solution which later get expressed in terms of Crude Fiber (CF), Neutral Detergent Fiber (NDF), and Acid Detergent Fiber (ADF) [10] [11]. CF measures true cellulose and insoluble lignin present in the sample. Cellulose, hemicellulose, and lignin; widely present in plant cell wall are collectively termed as Neutral Detergent Fiber (NDF), whereas the residue that contains cellulose, lignin and insoluble mineral (silica rich) are termed as ADF [6]. However, the traditional method of fiber estimation in terms of CF, NDF and ADF have practically limited the role of DF at gut physiological level, and has also neglected consequence effects in terms of poultry health, performance and environmental aspect.

In this era of promotion of antibiotic-free poultry production, a more precise classification of DF would be based on its fermentation ability, its ultimate effect on the gastrointestinal tract (GIT), GIT related accessory organs, digestive and hormonal secretion, and microbiota. Poultry's response to different dietary fiber sources, inclusion levels, dietary and nutrient composition levels need further meticulous investigation. The GIT hosts wide range of microorganisms like bacteria, virus, fungus, and protozoa, which are believed to exist as a result of co-evolution [12]. So far, bacterial communities have been found extensively to act upon, and to utilize the dietary fiber [13]. Hence, based on the extent of fermentation by bacteria, dietary fibers can be generally divided as low or partial fermented, and easily or well fermented [14] [15]. Generally, fibers which are easily fermentable are soluble fibers as they express high aqueous solubility. Likewise, poorly or partially fermentable fibers are insoluble fibers. The common sources of soluble dietary fibers in poultry feed as ingredients are sugar beet pulp (SBP), apple pomace, and citrus peel [16]. Soluble fibers are rich in pectin, gum, and arabinoxylan that can significantly attract water molecules during the digestion process at the intestinal lumen, making the digesta viscous [17] [18] [19] [20] [21]. Meanwhile, the oat hull, soybean hull, sunflower hull, pea hull, wood shaving, and wheat bran are rich sources of insoluble dietary fibers in poultry. Insoluble fibers greatly contain cellulose, hemicellulose, lignin, and heteroxylans, and can add bulk to the feces due to their distinguished physiochemical properties from soluble fibers [20] [22] [23] [24]. Thus, soluble fibers and insoluble fibers can exhibit unlike effects on the host and vice-versa.

2. Paradigm Shift on Dietary Fiber

2.1. Traditional View

In reality, DF are spontaneously incorporated in the diet of animals even when very high-quality feed ingredients are used. Any feed ingredient like cereal, tuber, or agro-industrial product inherently contains some amount of dietary fiber. Despite of this, DF topic had acquired minor attention for many years in poultry nutrition. Moreover, insoluble DF were considered as a nutrient diluent, and even anti-nutritional factor due to their negative impacts on growth performance in poultry [8] [25]. This is further supported by the fact that mono-gastric animal like poultry do not digest feed rich in fiber as they do not produce several enzymes endogenously to break it [8]. Unlike ruminants, poultry species also do lack specific microbes at the GIT to ferment the DF efficiently. On other hand, total fiber content (gm per kg feed) can increase with incorporation of agro-industrial byproduct or low-cost alternative feed due to their higher fibers content. Thus, change in ingredient to reduce feed cost can increase the level of indigestible components like Non-Starch Polysaccharides (NSP) in feed which can be detrimental for poultry performance [15]. Furthermore, stress to digest high fiber diet is likely to be greater in modern-day's genetically improved breeds than previous generation with a lesser performance objective.

Likewise, soluble fibers had been criticized for their detrimental role on poultry performance. It has been reported that soluble fibers with high level of water soluble NSP can increase the viscosity of digesta in the intestinal lumen, causing reduction of digestion and nutrient absorption rate [13] [20] [23]. Besides, soluble fibers are readily available for fermentation to microbes which can lead to intestinal dysbacteriosis due to their rapid proliferation. Moreover, fermentation at small intestine is not considered desirable [26]. In addition, enterocytes have been shown to respond the soluble fibers by increasing goblet cells which can further increase the rate of mucin production [27]. As more mucin will be produced, the absorption rate of nutrients can reduce significantly. Eventually, more nutrients can get entry into the hindgut acting as a substrate which can favor proliferation of pathogenic bacteria like Clostridium, causing outbreaks of enteric disease like Necrotic Enteritis in poultry [28]. Above all, soluble fiber can decrease relative feed intake due to increase satiety ascribed to viscosity related gut-fill effect [29].

2.2. Modern Approach

There are shifts in paradigm on the role of DF in this intensive poultry production era. Presently, though it has been widely accepted that Crude Fiber (CF) is not absolute nutrient per se, dietary fibers may contribute to the nutritive value of diet directly as energy source and indirectly by improving digestive, and metabolic process when strategically incorporated [30]. In terms of physiochemical properties, DF can encompass hydration capacity (swelling, water holding, and binding), solubility, viscosity, bulking ability, gelation, and fermentability [7] [14]. Moreover, as insoluble fibers are minimally degraded by both microflora and host enzymes, they can principally provide physical effect at gut level which can later regulate the passage rate of digesta, fecal quality and can even enhance hindgut fermentation process [31]. Interestingly, insoluble fibers exert minor effect on viscosity of digesta at the intestinal lumen. In contrast, soluble fibers can get largely acted and utilized by intestinal microbes, mainly bacteria. In normal healthy birds, the fermentation site is distal part of small intestine and/ or large intestine [13] [32] [33]. The fermentation process can produce various end products of nutritionally important like lactate, and Short Chain Fatty Acid (SCFA) like Acetate, Butyrate, Propionate [34]. Furthermore, fermentable fibers when get utilized by lactobacilli can increase lactic acid level at hindgut which can prevent colonization of pathogens on intestinal wall thus can potentially improve the intestinal health [35] [36]. Moreover, it has been reported that fermentable fibers; mainly group of soluble fibers associated with oligosaccharides when get supplemented in feed can function as prebiotic regulating intestinal microbiota [18] [35] [36]. Besides, lactic acid and volatile fatty acids have shown to have crucial role to maintain eubiosis in the large intestine [37]. DF has also shown to reduce the adverse effect of coccidiosis in poultry [38]. Above all, ascribed to gut microbiota and gut pH modifying properties of some soluble DF salmonella colonization at the intestinal wall can be potentially reduced [39]. In addition, a fiber fermentation end product named butyrate has an important role on water re-absorption from the large intestine which can improve the dry matter content of excreta, therefore can reduce the wet litter condition in poultry farms [25] [40]. Wet or moist litter is a serious problem that can affect poultry health, performance, environment hygiene, and edible product quality like meat and egg.

3. Role of Dietary Fibers on Digestive System

Gastrointestinal tract (GIT) has drawn attention of researchers throughout the world. It may be due to the fact that GIT being largest group of organs that not only function for digestion of feed and absorption of nutrients, but also act as a physio-chemical barrier for pathogens and toxins [41]. Poultry have unique digestive system. They do not possess teeth but have peculiar organs like crop, proventiculus, gizzard, and a pair of modified ceca which altogether largely contribute to digestion and absorption process. In poultry, GIT contributes 70% of total immune cells of the body [13]. Thus, to maintain or improve poultry performance at least normal or enhanced digestive system with optimal immune function seems to be utmost important. Thus, several researches have examined the DF form, type, subtype, source, inclusion rate, particle size correlating their effect on GIT, microbiota and other accessory organs of digestion. Dietary fiber can affect various digestive organs of poultry as shown in **Table 1**. Although there are limited researches that have shown the impact of dietary fibers on largest glandular organ– liver, there are adequate reports concerned to influence on other organs like proventiculus, gizzard and cecum in poultry [43] [44]. Furthermore, the gizzard has received key attention.

DF role in terms of gizzard development due to gizzard's innate mechanical ability to crush the feed particles which can subsequently improve the nutrient digestibility and absorption has become topic of interest among researchers [45]. In addition, it has been suggested dietary fiber particles have to be accumulated in the gizzard for its own development. The growth of gizzard because of fiber inclusion is most likely due to the improvement of muscular activity [44] [46] [47]. Moreover, it has been suggested that particle size of fiber is crucial to enhance the gizzard function rather than fiber inclusion rate alone among which a study has suggested that feed particle size should be at least 1.5 mm [13] [45]. It has been also highlighted that coarsely ground fiber can stimulate the production of endogenous enzymes like HCl, Chyme, &, pancreatic enzyme at the GIT due to higher retention time of digesta, thus can improve digestibility of nutrients like carbohydrate (starch) and lipids [45]. Interestingly, it has been further mentioned that for dietary fiber to affect the gizzard, a considerably longer retention of feed particles in gizzard is required, and surprisingly such effect can lack for short retention period. For instance, the whole wheat feed improved the gizzard's development as compared to the traditional diet where the retention of feed particle was greater in former [48]. Thus, the effect of DF on gizzard's development can be determined by both feed particle size and period of feed retention

Table 1. Effect of DF on poultry digestive organ.

DF Source	Inclusion level	Species	Age and Duration	Effect	Diet type	Ref.
Wheat fiber	0, 0.5%, 1%, 1.5%	quail	Day 1 & 28 days	(+) relative wt and villi: crypt ratio of duodenum, jejunum, ileum at 1.5%, (−) relative wt of liver	Corn Soybean meal based	[44]
Inulin	0.5%, 1%	broiler	Day 1 & 42 days	(+) villi height by both level	Corn Soybean meal based	[104]
Pectin and sugar beet pulp	1.5% and 3%	broiler	Day 1 & 6 to 27 day	(−) wt of liver	Corn isolated soy protein based	[43]
Soyhull and cellulose	CF 2% to 8%	broiler	Day 1 & 20 days	(+) in villus height of small intestine by soyhull	Corn Soybean meal based	[105]
Oat hull, sugar beet pulp	3%	broiler	Day 1 & 21 days	Oat hull (+) relative wt of gizzard, (+) relative wt of proventriculus and ceca	Broken rice Soy protein concentrate based	[85]
Sugar beet pulp and rice hull	3%	broiler	Day 1 & 42 days	Rice hull (+) jejunal villi height & sugar beet pulp (+) relative wt of jejunum, ileum	Corn Soybean meal based	[106]
Oat hull, soyhull	3%	broiler	Day 1 & 21 days	(+) relative wt of gizzard, proventriculus; (−) relative wt of small intestine	Corn or Rice Soy protein concentrate based	[46]
Wood shaving	6%	broiler	Day 1 & 21 days	(+) relative wt of gizzard, proventriculus; (−) relative wt of small intestine	Wheat based diet	[47]
Sugar beet Pulp and Oat hull	7.5%	broiler	Day 1 & 18 days	(−) villi height at day 12 by Sugar beet pulp, (+) relative wt of gastrointestinal tract, (−) gizzard pH	Corn Soybean meal based	[107]
Sunflower meal and soyhull	CF 3%, 6%, 9%	turkey	Day 1 & 98 days	Inconsistent (+) in villi height and parameters in small intestine (duodenum, jejunum and ileum)	Not available	[108]
Oat and barley hull	15%	broiler	Day 1 & 17 to 32 day of age	(+) relative wt of gizzard and small intestine	Corn wheat Soybean meal based	[31]

(+) and (−) in Effect column denotes; increase or improvement, and decrease or reduction respectively

in gizzard.

Above all, the source of dietary fiber can influence the growth of digestive organ very differently as shown in Table 1. To illustrate it, a research has compared two unlike dietary fibers that comprised of Oat Hull (rich in insoluble fiber) and Sugar Beet Pulp (rich in soluble fiber) on digestive system. Oat hulls found to increase the growth and weight of gizzard but did not increase the weight of proventriculus and cecum as compared to the sugar beet pulp (SBP). However, both oat hulls and sugar beet pulp have decreased the relative fresh contents in proventriculus, and enhanced the growth of gizzard [45] [49].

4. Role of Dietary Fibers on Nutrient Utilization

Nutrient utilization is a very complex process through sophisticated digestive system. Moreover, there are evidences of negative effect of DF on nutrient utilization as shown in Table 2 when the inclusion level gets excess, *i.e.* higher than

Table 2. Effect of DF on nutrient digestibility.

	Inclusion level	Species	Age and Duration	Effect	Diet type	Ref.
Ligno-Cellulose	0.25%, 0.5%, 1%	broiler	Day 21 & day 42	Apparent ileal fat digestibility and total tract digestibility of total fatty acid not affected by 0.25% and 0.5% but (+) apparent fat digestibility by 1%	Corn-Soybean meal based	[109]
Ligno-Cellulose	0.8%	roaster	55 wks and 57 wks onwards	(+) true digestibility of protein by 6%	Corn-Soybean meal based	[65]
Ligno-Cellulose	0.8%	broiler	Day 1 & upto marketable age	(+) apparent and true dietary amino acid digestibility, (+) apparent protein digestibility by 5.5%	Corn-Soybean meal based	[66]
Ligno-Cellulose	1%, 2%	broiler	Day 1 & 35 days	No effect on protein and gross energy digestibility	Corn-Soybean meal based	[33]
Ligno-Cellulose	1%, 2%	broiler	Day 8 & 21 days	No effect on protein and gross energy digestibility	Wheat based diet	[48]
Citrus pulp pectin	1%, 3%, 5%	broiler	Day 1 & 31 days	(+) apparent metabolizable energy with pectin, (−) nutrient digestibility	Corn-Soybean meal based	[16]
Soyhull and cellulose	CF 2-8%	broiler	Day 1 & 20 days	Amino acid digestibility (+) by soyhull	Corn-Soybean meal based	[105]
Oat hull	3%	broiler	Day 1 & day 21	(+) total apparent retention of dry matter, organic matter, ether extract, nitrogen	Broken Rice-Soybean concentrate based	[85]
Oat hull	3%	broiler	Day 1 & day 21	(+) total tract apparent digestibility of dry matter, ether extract, nitrogen	Corn or Rice and Soy protein concentrate based	[110]
Cellulose	CF 3%, 8%	broiler	Day 1 & 21 days	(+) valine and arginine digestibility	Corn-Wheat-Soybean meal based	[111]
Oat hull	4%, 10%	broiler	Day 7 & day 14 days	Starch digestibility (+) and apparent metabolizable energy (−) by 10 %	Wheat based diet	[112]
Ligno-Cellulose	5%, 10%	broiler	Day 1 & day 23	(−) apparent ileal digestibility of CP, (−) apparent excreta digestibility of organic matter and gross energy	Wheat-Soybean meal-Corn based	[50]
Cellulose	6%	broiler	Day 1 & 21 days	(+) starch digestibility	Wheat based diet	[47]
Oat hull	10%	broiler	Day 11 & days 22	(+) starch digestibility	Wheat based diet	[113]
Oat and barley hull	15%	broiler	Day 1 & days 18 - 32	(+) starch digestibility, (−) apparent metabolizable energy	Corn-Wheat-Soybean meal based	[31]

(+) and (−) in Effect column denotes; increase or improvement, and decrease or reduction respectively.

usual low to moderate level [50]. This effect may be attributed to abrasive effect of DF on gut mucosa mainly insoluble fiber leading to several nutrients loss like protein, amino acid, mineral, & vitamin [3] [51]. Furthermore, the adverse impact of DF can be greater in younger birds than their older counterparts which likely to happen due to their immature digestive system, and immunity [49]. Besides, certain non-starch polysaccharides (NSP) can bind bile acid, cholesterol or fat that can eventually lower the apparent metabolizable energy (AME) value of poultry feed and thus, poultry performance can get affected [16] [19] [23]. In addtiion, DF can reduce availability of minerals and vitamins to hosts which may be due to the adsorption property of DF [3] [15]. For instance, Phytate which serve as store form of phosphorous in plant present in the DF can bind minerals like Zn, Cu, Ca, Mg, thus can affect their homeostasis [52] [53].

In contrast, dietary fiber, especially prebiotic fiber has been shown to improve mineral homeostasis. It has been mentioned that wheat grain derived prebiotic extract improved the iron status in iron deficient broiler [54]. Besides, it has been reported that three fiber sources oat hulls, alfalfa meal or soybean hulls equally increased retention of iron whereas Cu retention increased by soybean hulls only [55]. This might have happened due to high bioavailability of Fe in three fiber sources. Additionally, it has been reported that prebiotic fiber supplemented to poultry had no Ca deficiency related issue as compared to the low Ca diet fed control group of poultry [56]. Furthermore, it is noteworthy that not only quantity but quality of fiber for e.g., fiber composition matrix can affect the nutrient utilization. As discussed before, the generic term fiber includes diverse group of polymers ranging from carbohydrate to phenol. Thus, though crude fiber (CF) level which is still widely measured entity in feed can be similar, fiber fractions may fluctuate significantly. To illustrate this, one most commonly used energy source of poultry feed named corn and wheat are rich in NSP arabinoxylan, whereas the major poultry's feed of protein source named Soybean meal (SBM) is rich in B-mannan [57]. Similarly, oat and barley which are rich in highly soluble B-glucan can be incorporated in poultry feed depending on their availability, quality, and the cost factor. The total NSP can greatly vary from 9% in corn and up to 23.3% in oat; with lignin content 1.1% in corn and up to 6.6% in oat respectively [58]. Therefore, poultry feed can be dissimilar in terms of total dietary fiber (TDF) contents. Furthermore, the variations can exist within soluble and insoluble fiber portions. In conclusion, raw material, feed composition, nutrient composition, fiber's type, subtype, form, inclusion level can contribute to overall fiber matrix in the poultry diets which can differently affect the nutrient utilization process at the GIT because of their diverse physio-chemical attributes. The synergistic or antagonist effect to be emerge under combined form of different fiber fractions at gut level is yet to be extensively investigated.

5. Role of DF on Poultry Behavior

Cannibalism is a vice characterized by aggressive behavior in poultry which can start as simply as pecking followed by tearing of tissue, and in severe case consumption of organs of flock mates [59]. The problem has largely affected poultry industry by inflicting health and welfare issue; principally on laying hens [60]. Unfortunately, the exact cause of cannibalism is not well understood. However, ethologists have argued that poultry naturally spend significant of their time (61%) on searching food which is an innate instinct as foraging wild species [61]. However, modern poultry farming has limited such freedom of behavioral expression which is believed to be emerged once there is imbalance or any form of other stress to be on poultry. It has been suggested that cannibalism is easily preventable but once begins can be very difficult to control as it is a highly adaptable behavior that can spread to the entire flock [62]. Interestingly, cannibalism has been linked up with dietary factor too, out of several predisposing factors like poultry management, shed condition, genetic line, dominancy characteristics [59] [63] [64]. Moreover, today's diets of poultry are formulated with comparatively higher energy and lower in fiber level as compared to previous generation with lesser performance objective. Because of this, feed clearance time has reduced significantly which might have inflicted boredom favoring the pecking behavior in poultry.

Besides, conventional feed of chicken diluted with sand and fiber significantly reduced feather pecking behavior in one study when the diet was provided from very beginning of the trial [65]. However, such vice did not get improved when similar diet was provided at later stage instead of very beginning of the trial which suggested that the effect of DF could be limited by the time factor or duration of feeding as discussed before. Furthermore, cannibalism is more common in poultry that is offered pellet or crumble feed than mash as poultry generally takes longer time to select, and to eat feed particles in mash form thus, lengthening the total feed intake period and keeping it busy [66] [67]. On other hand, sudden change in the form of feed or palatability may be a contributing factor for the onset of cannibalism due to bird's reluctance to the feed invoking diet related stress. Traditionally, excess fiber inclusion has been considered to reduce palatability of the feed [68]. Thus, high fiber diet with imbalance nutrition may trigger the cannibalism.

In contrast, low to moderate level of dietary fiber, mainly insoluble, can prevent such vices as such feed can increase total feed intake volume up to certain limit due to the lowered in nutrient density. It has been shown that poultry can compensate nutrient's requirement by consuming more. Thus, DF can improve engaging time on feed consumption which can subsequently lower the risk of cannibalism when strategically used [60] [69]. Furthermore, with improvement in cannabalism, beak trimming practice may get reduced which will certainly benefit the poultry welfare.

Above all, it has been shown that either nutrient deficiency or absence of dietary protein, amino acid (methionine), salt (Na), or phosphorous (P) can favor the occurrence of cannibalism in poultry [70] [71] [72]. In aforementioned cases, dietary fiber can indirectly improve the nutrients homeostasis in bird. For instance, Methionine, an essential sulfur containing amino acid, has key role in the development of feathers [64]. Any marginal or severe deficiency can lead to poor feather development including at near vent areas resulting exposed body parts, thus likely to be attacked by flock mates. As shown in **Table 2**, a concentrated DF source named lignocellulose (LC) at 0.8% inclusion rate improved the true digestibility value of protein in rooster [73]. At that same level, LC increased apparent protein digestibility, apparent and true dietary amino acid digestibility in broilers [74].

In addition, DF can improve poultry behavior like preening which can lead into cannibalism. In fact, birds use the preen gland to preen their feathers [75]. The secretion consists of wax, lipid, and organic compounds near at the base of tail which tastes salty [76]. When poultry diet is deficient or absence in salt, it can overuse the preen gland resulting cut feathers, thereby exposing such rear vulnerable parts which can later trigger cannibalism. It has been mentioned that insoluble fiber source like oat hulls can increase Na and K retention [17] [55]. Furthermore, a DF fermentation end product named butyrate has shown to improve water absorption in large intestine which can also improve Na homeostasis [77].

6. Fiber Analysis and Optimal Inclusion Level

Like universal definition of DF, analysis of fiber has been debateful. Historically, the empirical method of fiber measurement was typically suited for human studies [78] [79]. The gravimetric method of fiber analysis in terms of Crude Fiber (CF), Neutral Detergent Fiber (NDF), and Acid Detergent Fiber (ADF) were extensively used in animal nutrition as well. This method measured well the degradability of specific fiber fraction in the animal [80]. CF, NDF and ADF analysis can quantify cellulose, hemicellulose and lignin which represent insoluble fiber. However, the detergent method can provide accurate measurement of insoluble DF but not soluble. Hence, soluble fibers like b-glucan in cereal, and some pectic polysaccharides can get excluded from the CF while other pectic polysaccharides that precipitate in strong acid can get included in ADF fraction which is principal limitation of detergent method of fiber analysis [80]. In addition, detergent method neglects major fractions of total dietary fiber in terms of soluble and insoluble NSP.

As discussed before, CF despite being routinely used in feed tests, is a poor measurement of dietary fiber that provides general indication in estimating energy value of feed as higher the CF level will represent lower metabolizable energy (ME) value of feed. Therefore, the most useful routine analysis of dietary fiber at present likely to be Total Dietary Fiber (TDF) which will let nutritionists to identify and compare both insoluble and soluble fiber portions [81]. As explained before, both soluble and insoluble fibers have been shown to distinguishly affect the GIT during digestion process, thereby can affect the poultry performance very differently which is highlighted in **Table 3**. However, for

Table 3. Effect of DF on poultry performance.

DF Source	Inclusion Level	Species	Age and Duration	Effect	Diet Type	Ref.
Wheat Fiber	0. 0.5%, 1%, 1.5%	quail	Day 1 & days 28	1.5% inclusion (+) body wt & feed efficiency by 5%	Corn-Soybean based	[44]
Inulin	0.5%, 1%	broiler	Day 1 & 42 days	1% inclusion (+) body wt gain (25 - 42 d) by 8%	Corn-Soybean based	[104]
Pectin and sugar beet pulp	1.5% and 3%	broiler	Day 1 & 6 - 27 days	3% inclusion level (−) body wt gain and feed efficiency by 28%	Corn-isolated soy protein based	[43]
Soyhull and cellulose	CF 2% - 8%	broiler	Day 1 & 20 days	(+) feed efficiency by 8% compared to cellulose	Corn-Soybean meal based	[105]
Sugar beet pulp	3%	broiler	Day 1 & 42 days	(−) feed efficiency by 9%	Corn-Soybean meal based	[106]
Oat hulls, sugar beet pulp	3%	broiler	Day 1 & 21 days	Oat hull (+) daily average body wt by 7.6%	Broken Rice-Soy protein concentrate based	[85]
Sunflower meal and soyhull	CF 3%, 6%, 9%	turkey	Day 1 & 98 days	6% CF level (+) body wt by 2.5%, however, 9% CF level (−) feed efficiency by 3.8%	-	[108]
Oat hull	4%, 10%	broiler	Day 7 & 14 days	10% oat hull (−) feed efficiency by 6%	Wheat or naked oat based & mash diet with or without Oat hull	[112]
Wood shaving	6%	broiler	Day 1 & 21 days	(+) feed efficiency by 4.7%	Wheat based	[31]
Oat hulls	10%	broiler	Day 11 & 22 days	(+) feed efficiency by 3%	Wheat based	[113]
Oat hulls and barley hull (fine/coarse)	15%	broiler	Day 1 & 17 - 32 days	Fine hulls (−) feed efficiency by 4.7%, and coarse hull (+) body wt gain by 2%	Corn-Wheat-Soybean based	[31]

(+) and (−) in Effect column denotes; increase or improvement, and decrease or reduction respectively

experiment or research purpose, enzymatic method can be employed where enzyme removes the starch first followed by the breakdown of NSP to concern sugars that can be measured by the gas chromatography [82]. Lastly, the sugar composition can help to predict dietary fiber's characteristic. However, the enzymatic method is laborious, time consuming, and expensive as well thus wouldn't be a good fit for routine feed analysis [11]. Today, an alternative technology named the near infra-red spectroscopy (NIR) can provide sound estimation of different portions of the dietary fibers more quickly and reliably provided the calibration has been done correctly for different feed resources [83].

Despite, the optimal inclusion level of dietary fiber in the poultry feed seems to be ambiguous. It may widely vary according to the feed ingredient type, nutrient composition, source of fiber, genetic line, poultry species, age, health status, and other management conditions [21] [49]. Generally, commercial poultry diets are formulated such that it contains crude fiber less than 30 gm per kg feed, especially for young broilers [23]. Furthermore, it has been suggested low to moderate level of fiber inclusion (up to 50 gm per Kg feed) might benefit gastrointestinal development, and poultry health; thereby enhancing nutrients digestibility, and growth performance [18]. Besides, insoluble fibers have received major attention than soluble fibers as shown in **Tables 1-3**. It has been further mentioned that inclusion of insoluble fiber for instance, cellulose at 30 - 50 gm per Kg feed can improve nutrient utilization due to gastric juice stimulation from proventriculus, and can cause improvement in gizzard [23]. In addition, one study has suggested that inclusion of a source of insoluble fiber named wood shaving at 40 gm per Kg feed can reduce Necrotic Enteritis in broilers fed wheat diet as main energy source [84]. However, wood shaving supplemented to corn-based diet in poultry didn't have such effect. In contrast, high inclusion level of insoluble dietary fiber may be detrimental. For instance, pea hull at inclusion rate of 75 gm per Kg feed had negative effect on total tract digestibility (TTD) whereas 50 gm per Kg feed didn't have such adverse effect [85]. Also, layer chicks have been found to utilize fiber rich feed ingredients (DDGS and wheat bran) efficiently as compared to the broiler chicks which may be due to reduced average daily feed intake (ADFI) and higher fiber utilization [86].

7. Enzyme for Breaking Fiber

Enzyme is a functional protein that stimulates or increases the rate of specific chemical reaction [87]. Interestingly, enzymes are naturally present at simplest life form to plant, and animal biological system. There are around 2500 classes of commercial enzymes in poultry [88]. Enzyme can provide benefits in term of poultry health, economic, and environmental aspect. Hence, exogenous enzyme supplementation has become popular in modern day's intensive poultry farming. There is no denying to the fact that poultry do not digest fiber rich feed to the large extent which is mainly due to its inability to produce several NSP enzymes to perform hydrolysis on NSP present at the cell wall of feed ingredients like cellulose, b-glucan, pectin, pentosan and phytate [18]. Hence, it has been widely accepted that enzyme addition can ease the breakdown process by complementing the action of endogenous system of poultry through disrupting the integrity of complex plant cell wall in the feed, followed by release of nutrients encapsulated by it [89]. Enzyme strictly acts under specific pH, and temperature on specific substrate. Once the biological reaction gets completed, enzyme acquires original state without getting spent [90]. Due to this, enzyme inclusion rate in the feed formulation is comparatively minor. Albeit, extreme temperature, pH, friction, and microbial action can easily destroy it, thus limiting their usefulness [91]. Considering these, commercially available enzymes in industry are carefully prepared by various methods like microbial fermentataion process for e.g. submerged liquid fermentation and solid state fermentation for quality and quantity production. In feed industry, only hydrolases class of enzymes like phytase, xylanase, b-glucanase, cellulase, amylase, and glyco-amylase are used extensively [92] [93].

Generally, poultry diets are formulated with low to moderate level of dietary fibers. This may have further created lesser opportunity for improving digestibility of fibers in expense of enzyme specially when feed are already lower in NSP like maize based [96]. On other hand, unconventional or alternative feed resources are being used greatly to reduce both human food competition and feed cost. As feed alone can impart the major cost (up to 70%) of poultry production, overcoming this cost factor would be a great advantageous [95]. However, the feed cost reduction can bring other challeneges side by side. For instance, a cheaper or fiber rich (low quality) feed product can increase the total NSP level. Consequently, the poultry performance may get reduced as there is negative relationship between NSP content and the nutritive value of feed [49] [96] [97].

Nowadays, exogenous enzyme supplementation has become hot topic among nutritionists. To elaborate this, a common poultry feed named Corn-SBM based died might have contained 43% arabinoxylan, 27% cellulose, 2% B-glucan and 28% other NSP [98]. Hence, two school of thoughts seem to have emerged on the exogenous supply of enzyme, either to use only one specific or cocktail/ multiblend enzyme which are elaborated in **Table 4** and **Table 5**. In above NSP compositions, a nutritionist may consider only major NSP fraction/s *i.e.* arabinoxylan or combination of any or all NSPs present after the feed test. Similarly, xylanase alone or xylanase rich cocktail enzyme can be supplemented to the Wheat, Rye, and Triticale. Likewise, B-glucanase alone or rich cocktail enzyme can be supplemented to Barley and Oat. B-galactosidase alone or rich cocktail enzyme can be supplemented to grain legumes like pea, peanut, lentil, and lupin which will be based on dominance of fiber types. On other hand, a nutritionist may also choose multienzyme blend considering all fiber fractions including NSP content variations as the same crop can be nutritionally dissimilar based on its genetic variety, growing conditions, management, harvesting or storage condition [68]. **Table 4** and **Table 5** have illustrated that enzyme supplementation on cereal grains with lower apparent metabolisable energy (AME) value like wheat, barley or lesser in crude protein provides greater benefit than higher AME value cereal grain or that of higher nutritional quality. Moreover, variation may exist among typical enzyme on itself. To elaborate it, the BioResource International's Technical Bulletin (2017) has mentioned that same xylanase enzyme named Bri' s modified GH11 Xylanase (Xylamax) reported to be more effective on corn based diet of poultry than standard GH10 and GH11 Xylanases. Thus, same named enzyme can exhibit unlike effects on poultry based on method used for their preparation. It is therefore concluded that, it is harder to compare efficacy of a enzyme (mono vs multi) for different researches and practical setups due to various factors discussed above. The ultimate decision should be based on cost-benefit analysis or return on investment (ROI) specially when less viscous feed ingredient like maize are primarily used in the poultry diet.

Table 4. Effect of monoenzyme supplementation on poultry.

Enzyme	Inclusion	Species	Enzyme Inclusion Period	Effect	Diet	Ref.
B-mannanase	0, 200, 400 PPM	Broiler	7 - 21 days	β-mannanase significantly (+) blood glucose and anabolic hormone homeostasis, FCR, digestible energy, and digestible amino acids	Corn-SBM based diet (Low and High SBM)	[114]
B-mannanase	400 gm per ton	Broiler (Challenged with coccidiosis at day 14)	Day 1 to 42	No improvement in performance but contributed to quality and intestinal health. Enzyme supplementation overall resulted worst FCR	Corn-Soya based	[115]
B-mannanase	800 IU per Kg Feed	Broiler	1 - 44 days	(+) BWT gain (day 2-22) but no effect on BW gain or Feed intake for entire research period	Corn-Soya based (Standard energy and low energy)	[116]
Xylanase	1 gm per Kg Feed	Broiler	7 - 21 days	(+) BWT gain at 21 days, (+) feed to gain ratio, (+) ileal digestibility of CP, Starch, Soluble & Insoluble NSP, (+) TTD of DM, CP, Starch, Soluble NSP	Wheat based diet	[117]
Xylanase (GH 11)	0.06% (600 UX/g)	Broiler	8 - 35 days	Supplementation did not affect the digestive utilization of rye or wheat diets, No improvement on FCR	Rye and Wheat based	[118]
Phytase	150, 300, 600, 1200, 2400, 24,000 U per Kg Feed	Broiler	1 - 16 days	(+) BWT gain, Toe ash %, Nutrient utilisation by above 150 U per g. Furthermore, the 24,000 U/kg of diet (+) toe ash percentage and the utilization of several nutrients beyond that of the lower doses of phytase.	Corn-soy based	[119]
Phytase (Ronozyme)	0, 250, 500, 750, 1000, 2000 FTU/Kg	Broiler	Day 0 to day 42	Phytase linearly (+) growth performance fed P and Ca deficient diet with 2000 FTV showing greatest (+) on BWT gain, FCR, Tibia ash, AR of Ca & P, AME relation to NC	Corn-Soybean	[120]
Phytase	2.5 AcPU/Kg phytase B-acid phosphatase activity	Layer	50 to 60 weeks layer	(+) mean egg wt., shell strength and Ca-P retention	Corn-Soybean (P deficient)	[121]

PPM, IU, UX, U, FTU, AcPU in Inclusion column denotes; Particle Per Million, International Unit, Unit Xyalanase, Phytase Unit, Acid Phosphatase Unit respectively. (+) and (−) in Effect column denotes; increase or improvement, and decrease or reduction respectively. FCR, BW, CP, NSP, TTD, DM, P, Ca, AR, AME, NC in Effect coulumn denotes; Feed Conversion Ratio, Body Weight, Crude Protein, Non-Starch Polysacchrides, Total Tract Digestibility, Dry Matter, Phosphoros, Calcium, Apparent Retention, Apparent Metabolisable Energy, Nitrogen Corrected respectively.

Table 5. Effect of multienzyme (cocktail) supplementation on poultry.

Enzyme	Inclusion level	Species	Enzyme Inclusion Period	Effect	Diet	Ref.
Natuzyme; containing Phytase (1500 u/g), Xylanase (10000 u/g), Cellulase (6000 u/g), Amylase (400 u/g), Protease (700 u/g), B-glucanase (700 u/g) & Mannanase (400 u/g)	0, 350, 700, 1000 gm per ton	Broiler	1 - 42 days	(+) gut morphology, (+) villus height in the duodenum, villus height, width, crypt depth in jejunum, (+) villus height width and number of goblet cell in the ileum, (+) nutrient digestibility by all supplementation level	Wheat-corn-soybean based diet	[122]
Natuzyme containing Phytase (500 u/g) Xylanase (1000 u/g) Cellulase (5000 u/g) Amylase (1800 u/g) Protease (6000 u/g) Glucanase (1000 u/g) Pectinase (140 u/g)	500 mg per kg feed	Layer	43 wks aged till next 8 weeks	No effect on feed intake, egg production, egg weight, egg qualities such as eggshell color or Haugh unit, total cholesterol, relative organ weights and cecal microflora profiles between any dietary treatments. However, enzyme supplementation to reduced CP and Energy diet significantly increased egg mass and eggshell qualities such as strength and thickness and reduced intestinal viscosity	Corn-Soybean based diet	[123]
Xylanase (150,000 BXU/gm), Cellulase (50,000 EU/g), Glucanase (10,000 BU/g), Pectase (10,000 U/g), Amylase (100 U/gm) and Glucoamylase (5000 U/g)	0, 50, 100, 150 mg/ kg	Broiler	36-days onward	(+) utilisation of nutrients and energy	Corn and Wheat based diet	[124]
XAP containing Xylanase (2000 U/kg), Amylase (200 U/kg), Protease (4000 U/kg)	100 gm per ton	Broiler	1 - 21 days	The supplemental XAP alone (+) digestibility of most of the amino acids compared with control. Moreover, XAP with probiotics (+) AID of most of all amino acids compared with control.	Corn-soybean based diet	[22]

U, BXU, EU, BU, in Enzyme column denotes; Unit, Bacterial Xylanase Unit, Enzyme Unit, Baker Unit respectively. (+) and (−) in Effect column denotes; increase or improvement, and decrease or reduction respectively. CP, XAP, AID in Effect column denotes; Crude Protein, Xylanase-Amylase-Protease, Apparent Ileal Digestibility respectively

8. Future Research Perspective

DF topic has received great attention in mono-gastric animal nutrition after many countries have banned the use of antibiotics or antibiotic growth promoters (AGP) in routine feed formulation to promote the one health [99] [100]. However, poultry industries have been facing several bacterial diseases outbreak in almost every part of the world from small scale farms to the large. Despite of this, poultry diet therapy or modification in case of several clinical conditions has not been well investigated. Furthermore, the role and management of soluble and insoluble dietary fiber in acute or chronic poultry diseases has not been adequeately researched. As an example, heat stress is a major challenge in poultry farm based on open-house system at tropical and sub-tropical regions like India & Nepal [101]. Meanwhile, it has been suggested to adopt dietary modification using highly digestible feed ingredients or less in crude fiber, and to increase nutrient density with aid of oil/ fat, vitamin, and mineral due to compromised feed intake [102]. As previously discussed, CF is poor indicator of dietary fiber measurement. Hence, the role of total dietary fiber, and typical fractions like soluble and insoluble in heat stressed birds needs further investigation. Besides, increment in dietary fiber has been suggested in pets like dog and cat to reduce the production and availability of nitrogen waste during hepatobiliary disorder which is further suggested to bind endotoxins [103]. The use of soluble and moderately soluble fiber are also suggested to reduce the colon pH and absorption of ammonia in pets. However, the role of dietary fiber during hepatic disorder of poultry is not adequately examined. In fact, the role and management of dietary fiber on other critical conditions like coccidiosis, nephritis (gout), malabsorption syndrome in the view of intestinal morphology (villi and crypt depth), GIT secretion, GIT regeneration, enzymatic activity, nutrient transport, and nutrient bioavailabilty are emerging research questions. Above all, presented research data on tables describing the effect of dietary fibers on growth performance, nutrient digestibility, nutrient utilisation, GIT development in poultry studies have been difficult to compare as meta analysis due to dissimilarity like different feed formulation (iso or non-isogenic), raw material variation, nutrient specification, fiber inclusion level, type, subtype, and source of origin, crop harvesting method. Thus, to allow more conclusive comparision on the effect of typical dietary fiber in the poultry, aforementioned sources of variations should be controlled or at least need to be minimized.

9. Conclusion and Recommendation

Poultry industry has revolutionized across the globe, and is becoming aware of role of dietary fiber, mainly insoluble fiber in context of better productivity, economic and environmental perspective. The strategical benefit of dietary fiber at low to moderate inclusion level may be due to a decrease in digesta passage rate at upper part of the GIT, thus enhancing digestibility and nutrients' utilisation. Furthermore, DF can improve fermentation process at the distal GIT, and can positively modify microbiota maintaining or even enhancing intestinal health and immunity. DF can also positively regulate poultry behavior by reducing the risk of vices like cannibalism and over-preening. Thus, it is strongly referred to precisely estimate both chemical and functional value of the DF, *i.e.* TDF pre-feed formulation as opposed to traditional method of fiber analysis. Interestingly, the optimal inclusion level of dietary fiber can greatly vary depending on chemical compositions, feed ingredient type, source of DF, health, age, and breed of poultry, and other management conditions like exogenous enzyme supplementation. At last, the latest technology like NIR can help to rationally use specific enzyme to target major or various NSP components in the feed. The DF role typically for the therapeutic diet of poultry is still underway in-depth investigation.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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