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Effect of extrusion processing on starch gelatinisation and performance in poultry

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Starch, the major source of carbohydrates in commercial avian diets, is the most abundant storage polysaccharide in plants. Native starches differ in granule size, amylose to amylopectin ratio and amylose structure. Extrusion in simple terms is a process of cooking under pressure, moisture and elevated temperature. There are several effects of extrusion processing on protein, lipid and starch by changing physical, chemical and nutritional properties. Yet, starch plays a key role during extrusion, and undergoes several significant structural changes, which include starch gelatinisation, melting and fragmentation.

Related literature gives no consensus on the impact of extrusion processing; hence this review will give an overview on factors affecting gelatinisation degree of starch and the effects of extrusion processing on performance and nutrients digestibility in poultry.

Keywords: extrusion; starch gelatinisation; performance; digestibility; poultry

Introduction

Starch, the major source of carbohydrates in commercial avian diets, is the most abundant storage polysaccharide in plants. Native starches differ in granule size, amylose to amylopectin ratio and amylose structure **(**Eliasson and Gudmundsson, 1996). A nutritional classification of starch into rapidly digestible (RDS), slowly digestible (SDS) and resistant starch (RS) has been proposed (Englyst *et al.*, 1992), where RDS and SDS are digested in the small intestine and RS is the part of the starch fraction that escape digestion in the small intestine and is slowly fermented in large intestine.

Chemically, starches are glucose polysaccharides, composed of two types of α-glucans: amylose and amylopectin. Starch with high amylose content is often considered to be less digestible. The ratio of the two polysaccharides varies according to the botanical origin, which is of great importance for the chemical and functional properties of a starch. This influence might be attributed to the granule size distribution, to the crystallinity, to the organisation of the molecules within the granule or to the chemical nature of the starch polymers (Fredriksson *et al.*, 1998). The interior of the starch granule is composed of

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alternating crystalline and amorphous regions; thermo-mechanical processing chemically alters several ingredients of feed. When starch is heated in the presence of moisture; it absorbs water, swells and disruption occurs of the organised structure - a process called gelatinisation. Gelatinisation or 'starch melt' is a homogeneous phase formed under heat treatment. Viscosity increases during gelatinisation, and the properties of starch gels are very sensitive to factors such as shearing, temperature, heating or cooling rate and of course the source of starch and the presence of other components. The viscosity and gel formation properties are important for four major reasons:

1) Delay in gastric emptying (Johansen *et al.*, 1996)
2) Possible reduction of absorption rates in the small intestine (Johnson and Gee, 1981)
3) Increased endogenous secretions (Low, 1989)
4) Proliferation of microorganisms in the lower digestive tract (Choct, 1997).
5) Generally, increased gut viscosity decreases the rate of diffusion of substrates and digestive enzymes and hinders their effective interaction at the mucosal surface.

Factors affecting gelatinisation

LIPIDS

Internal lipids in native cereal starches have been shown to affect swelling and gelatinisation properties of the granules (Morrison, 1995). Lin *et al.* (1997) reported that increasing the fat content significantly decreased the degree of starch gelatinisation of the extrudates. Also, Becker *et al.* (2001) found that the presence of amylose-lipid complexes in the granular starch particles played a key role in restriction of water penetration into the particles of these complexes due to the ability of the amylose fraction of starches to bind compounds of the lipid fraction such as fatty acids (Mercier *et al.*, 1980). Similar observations have been reported in other studies (Mälkki *et al.*, 1984). Amylose-lipid interactions and crystallite reorientation have also been found to occur on heat-moisture treatment (Hoover and Manuel, 1996). The extent of amylose-lipid complex formation is dependent upon both starch and lipid type present in a food. Monoglycerides and free fatty acids are more likely to form complexes than are triglycerides (Bhatnagar and Hanna, 1994).

AMYLOSE TO AMYLOPECTIN RATIO

Cereals with high amylose content are more resistant to gelatinisation during processing than moderate to high amylopectin cereals. Starch that is high in amylose swells more slowly than the starch rich in amylopectin, and exhibits a loss of order within the granule, followed by its destruction (Colonna and Mercier, 1985). In contrast, Swanston *et al.* (2001) found that the temperature required for gelatinisation was higher for both high-amylopectin and high-amylose barleys compared to mid-range barley.

MOISTURE CONTENT

Excess moisture in the feed results in complete starch gelatinisation if combined with elevated temperature. Therefore, increasing moisture usually results in a higher degree of starch hydrolysis (Hakulin *et al.,* 1983*)*. Wood (1987) determined that high moisture content (30-50%) is required for efficient gelatinisation. Furthermore, Sun *et al.* (2002) found that, when limited amounts of water or other solvents are present, more heat is needed to complete gelatinisation and gelatinisation occurs over a wider range. In contrast, several researchers have reported that an increase of water content resulted in

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a lower degree of starch gelatinisation for different products during extrusion (Bhattacharya *et al.*, 1988; Lin *et al.*, 1997). Lund (1981) reported that, generally, a water: starch ratio of about 1.5:1 is required for complete gelatinisation, and a ratio about 0.3:1 would be required for minimal gelatinisation to begin.

PROCESSING/SCREW SPEED

Chiang and Johnson. (1977) and Della Valle *et al.* (1987) reported that increasing screw speed during processing decreased starch gelatinisation. They hypothesised that the increase of screw speed decreased the retention time of the sample in the extruder, which decreased the extent of its cooking and hence resulted in the decrease of starch gelatinisation. Increased screw speed may have increased the protein digestibility of extruded corn-gluten, because the increase in shear forces in the extruder denatures the proteins more easily, thus facilitating enzyme hydrolysis (Bhattacharya and Hanna, 1985). Changes of screw speed resulted in changes of products temperature, thus affecting starch gelatinisation (Lin *et al.*, 1997).

During extrusion, shear forces are suspected to play an important role in changing the nutritional value of proteinaceous materials (Marsman *et al.*, 1993). Normally, shear forces are varied by changing the screw speed. However, by changing the screw speed the residence time is largely affected (Van Zuilichem *et al.*, 1988).

GRANULE SIZE

Granule size has also been found to affect gelatinisation. Large starch granules within the endosperm have a higher gelatinisation enthalpy than small granules, reflecting greater crystallinity of large than of small starch granules (Peng *et al.*, 1999; Chiotelli and Le Meste, 2002). This means that it is easier to gelatinise large than small starch granules. Extrusion makes starch more accessible for digestive enzymes by the reduction of particle size and changes the crystalline structure of the starch (Thomas *et al.*, 1999; Goelema *et al.*, 1999). Some of the beneficial effects of feed particle size may arise from their influence on intestinal morphology, but the published data on these aspects are scarce. The morphological modulations of the intestine will affect function, secretion of digestive enzymes and absorption of nutrients.

Effect of particle size on digestibility and performance

Amerah *et al.* (2008) found that wheat particle size had no effect on villus height and crypt depth. These findings are consistent with previous reports in broilers (Amerah *et al.*, 2007*b*). The effect of particle size on the size and pH of gastrointestinal organs was studied by Nir *et al.* (1994), who found that the pH of the gizzard content decreased with increasing grain particle size in broiler. Dikeman and Fahey (2006) reported that decreasing the particle size resulted in decreased apparent viscosity. Moreover, Yasar, 2003 addressed that particle size reduction has been shown to decrease water holding capacity of excreta in broiler chickens.

Studies which relate particle size to digestibility of nutrients are limited, and show inconsistent results with broiler performance. Cabrera (1994) found no effect of diet particle size on growth performance of broiler chicks. Lott *et al.* (1992) reported that larger particle size resulted in reduced growth performance of broilers. On the other hand, Nir *et al.* (1994) has shown that increasing corn particle size increased broiler performance.

Data from Carré and Melcion (1995) showed a higher apparent protein digestibility when chickens were fed a fraction of ground peas remaining on a 3-mm sieve compared

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to being fed a fraction from a 0.5mm sieve. On the other hand, Kalmar *et al.* (2007) demonstrated that particle size had no significant effect on apparent digestibility of CP, EE, and NFE in African grey parrots. Comparable results were observed with Peron *et al.* (2005) who revealed that no significant effect of wheat particle size for protein and lipid digestibility values in chickens. Impact of feed particle size on apparent digestibility coefficients can be explained by its influence on passage rate through the alimentary tract, which in turn results in altered digestion and absorption times of nutrients.

Effects of feed processing on starch availability

Starch structure is considered to have an impact on the rate of starch digestion in cereals, and is therefore an important factor in regard to optimise the starch quality in animal feed. Starch digestion is affected by animal-related factors, including age, feed intake, and passage rate. Hence, the digestibility of starches in the GI tract of poultry will be dependent on a number of factors including the amylose to amylopectin ratio. The carbohydrate quality may be modified by thermo-mechanical treatments through the gelatinisation of starch (Lankhorst *et al.*, 2007) or a shift to the development of resistant starch (Dust *et al.*, 2004).

Under condition of excess water, hydrogen bonds in the less ordered amorphous regions of the granule are disrupted first, allowing water to associate with free hydroxyl group. Donovan *et al.* (1983) postulated that the effect of heat moisture treatment may be due to either to new crystallisation or recrystallisation and perfection of the small crystalline regions of starch granules.

High moisture and temperature extrusion results in complete gelatinisation and in a significant increase in *in vitro* (Murray *et al.*, 2001; Dust *et al.*, 2004 and Ljokjel *et al.*, 2004) and *in vivo* (Svihus *et al.*, 2005) starch availability (Bjorck *et al.*, 1984). Camire *et al.* (1990) found that extrusion enhanced both the *in vitro* and *in vivo* digestibility of starch. Likewise, Camire *et al.* (1990) reported an improvement in starch digestibility using extrusion processes. On the other hand, the results by Plavnik and Sklan (1995) indicated no significant differences in apparent starch digestibility in broiler fed extruded diet in comparison to unprocessed feeds (Zimonja and Svihus, 2009). Increases in susceptibility for enzymatic starch breakdown resulting in the higher gelatinisation degree of the starch were reported by Zimonja and Svihus (2009).

It is important to optimise processing conditions in the barrel to maximise gelatinisation. If the temperature is outside the range of optimum, starch conversion can be expected to be lower. However, retrogradation of starch after processing is a factor that needs to be taken into account. Retrogradation occurs when the molecules within gelatinised starch start to reassociate. For example, amylopectin retrogradation happens very slowly and needs a long storage time to develop (Lii *et al.*, 2004), whereas amylose retrogradation is thought to be more immediate and important. The retrogradation process generally depends on water content (Zeleznak and Hoseney, 1986). From a nutritional point of view, it is well established that retrograded starch is resistant to digestion in monogastrics (Eerlingen *et al.*, 1994).

Effect of extrusion on digestibility and performance

Extrusion is a useful processing method, which causes a modification in the starch structure (Van den Einde *et al.*, 2005), and nutritive value of extruded poultry feeds can be improved by facilitating its enzymatic degradation (Holm and Bjorck, 1988).

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Definition of extrusion

Extrusion technology is characterised as a high-temperature, short dwell time process (Dziezak, 1989), where the feed is exposed to a high temperature (80-200°C) for a relatively short periods of time (10-270 s), and is concurrently exposed to high pressure and shear forces (Bjorck and Asp, 1983). The ingredients during the extrusion process are ground, mixed and heat-treated. Extrusion can optimise the beneficial effects of heat treatment as well as minimise its detrimental impacts (Serrano, 1996). Mild extrusion processing usually enhances the digestibility of plant proteins (Srihara and Alexander 1984; Hakansson *et al.*, 1987).

There are two types of extruders: single screw and twin-screw extruders (Harper and Jansen, 1981). Each type of extruder has its own operating conditions, with advantages and disadvantages. Heat processing typically alters the composition and availability of nutrients and other components in native materials (Dellavalle *et al.*, 1994) by starch gelatinisation, protein denaturation, and inactivation of anti-nutritional factors, especially trypsin inhibitors, haemagglutinins, tannins and phytates - all of which inhibit protein digestibility (Armour *et al.*, 1998; Alonso *et al.*, 2000a and Singh *et al.*, 2007). Undesirable effects of extrusion cooking involve losses of heat-labile vitamins (*e.g.* vitamin A, E, thiamine), oxidation of lipids (Lin *et al.*, 1997), destruction and reduction in the availability of amino acids, in particular, of lysine which is related to the Maillard reaction (Camire *et al.*, 1990; Moughan and Rutherfurd, 1996). The processing conditions must therefore be controlled during extrusion in order to maximise the desirable effects on feed quality. Araba and Dale (1990) and Marsman *et al.* (1995) reported that over-processing may decrease the nutritional value of SBM due to Maillard reactions.

During extrusion, protein structures are disrupted and altered under high shear, pressure, and temperature (Harper, 1981). Jones *et al.* (1995) revealed that the extrusion process caused some protein and amino acid destruction in broiler feed diets. Therefore, extruded rations should be formulated at slightly higher nutrient density to redress nutrient destruction.

Several reviews of chemical or nutritional changes (*Table 1*) during extrusion cooking of foods have been published (Bjorck and Asp, 1983; Camire, 1998; Camire *et al.*, 1990; Cheftel, 1986).

Table 1 General changes in foods during extrusion cooking.

Chemical changes	Physicochemical changes
Cleavage	Binding smaller molecules
Recombination of fragments	Loss of native structure
Thermal degradation	Losses due to die size

Effect of extrusion processing on performance

Extruder conditions which result in different degrees of starch gelatinisation may cause variations in growth performance. Previous research (Meyer and Froseth, 1988; Marsman *et al.*, 1997; Nageswara *et al.*, 2004) on the effects of extrusion on the performance of poultry have been inconsistent results. Meyer and Froseth (1988) found an improved body weight gain and feed conversion ratio in broiler chicks fed a diet containing

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extruded versus toasted soybeans. Moreover, Marsman *et al.* (1997) reported the positive effect of SBM extrusion on growth performance in broiler chicks. Similarly, body weight and body weight changes tended to be different between the degree of starch gelatinisation due to dwell time for pigeons (Abd El Khalek *et al.*, 2009). Weurding (2002) reported that a diet with slowly digestible starch resulted in a better feed conversion ratio (FCR) of broiler chickens compared with a diet with rapidly digestible starch. On the other hand, Sloan *et al.* (1971) found that the extrusion process had no effect on body weight gain and feed: gain ratio of 28 day old broilers. Nageswara *et al.* (2004) noticed that the processing of maize-soy or maize-soy-palm kernal diets by pelleting, extrusion cooking or expander extrusion was not beneficial in improving the performance of layers, but extrusion processing of the maize-soy diet improved feed utilisation efficiency.

Effect of extrusion processing on digestibility

Extrusion and/or gelatinisation values do not always correspond to increased digestibility of test ingredients (Davis and Arnold, 1995). Heat processing of food influences protein digestibility in different ways:

1) Denaturation of protein, thus increasing protein digestibility (Cheftel, 1979).
2) Side chains of amino acids may be modified, thus delaying the action of digestive enzymes, (Sagum and Arcot, 2000).

Table 2 shows the effects of extrusion process on digestibility and utilisation of nutrients.

Table 2 Impact of extrusion processing on digestibility coefficient and utilisation of nutrients.

Authors	Process	Species	Results
Spais, 1997	Extrusion	Poultry	↑ starch, fat and protein utilisation
Dahlin and Lorenz (1993)	Extrusion	In vitro	↑ protein digestibility
Alonso *et al.*, 2000	Extrusion	In vitro	↑ protein & starch digestibility
Mujahed *et al.*, 2003	Extrusion	Broiler	↑ Fat digestibility
Abd El-Khalek *et al.*, 2009	Extrusion (low gelatinised starch)	Pigeons	↑ DM, CP, EE, CA, and NFE digestibility

Heat processing (HP) of cereals gelatinises a proportion of the grain, which many result in improved nutrient availability. However, there is some controversy about effects of heat processing on digestibility. Marsman *et al.* (1997) demonstrated a significantly higher apparent ileal crude protein (CP) digestibility in extruded soybean meal compared with toasted soybean meal (87.2 *vs.* 82.2%) in broiler. Arija *et al.* (2006) similarly showed that extrusion kidney bean significantly improved the ileal digestibility of CP and amino acids in chicken. Lichovnikova *et al.* (2004) reported that the extrusion process significantly increased total tract apparent digestibility (TTAD) of fat, nitrogen retention and TTAD of essential amino acids, except for lysine and histidine, in laying hens diet. Still, the decrease in TTAD of these two amino acids was not significant. Also, Dänicke *et al.* (1998) found that increasing the temperature of the thermal treatments resulted in an increase in crude fat digestibility in broilers and laying hens.

On the other hand, many studies have shown that increased heat processing can have a

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negative effect on amino acids bioavailability in feedstuffs (Parsons *et al.*, 1992). One of the important amino acids that is affected during the extrusion process is lysine, mostly the first limiting amino acids in cereal diets for many animal species. Lysine is very sensitive to heat, due to the presence of a free ε-amino group which can easily react with other nutrients such as sugar. As a result of the Maillard reaction, which occurs during the extrusion process, lysine is damaged and protein digestibility decreases. (Hurrell and Carpenter, 1981, Chiang, 1983).

Ljokjel *et al.* (2000) reported that digestibility of CP and most amino acids were significantly reduced after heat treatment of soyabean meal (SBM) at 120°C and further at 130°C in a monogastric (mink) diet. Also, Skrede and Krogdahl (1985) showed that heat treatment of SBM by autoclaving at 135°C for 30 minutes caused a decline of total tract digestibility of all amino acids compared to untreated SBM. Ljokjel *et al.* (2004) evaluated different extrusion processes on the digestibility of a fish meal based diet fed to mink, where they noticed that digestibility of crude protein and total amino acids decreased when increasing extrusion temperature from 100 to 125°C ($P< 0.05$). Martinez Amezcua and Parsons (2007) studied the influence of increased heating on amino acids digestibility, and found that amino acid digestibility was greatly reduced by increasing heating, particularly for lysine. On the other hand, Fernandez Figares *et al.* (1995) observed that after heat treatment (autoclaving), there was a significant increase in the digestibility of amino acids of growing broilers.

Conclusion

In conclusion, the information available on the effects of the extrusion process on nutrient digestibility and performance in poultry is unequivocal, but whether benefits are seen is highly dependent on processing techniques and extrusion conditions.**References**

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