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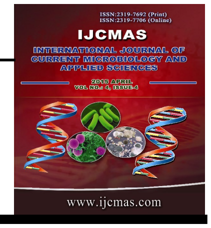

Review Article

Extrusion of Feed/Feed Ingredients and Its Effect on Digestibility and Performance of Poultry: A Review

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A B S T R A C T

Keywords

Extrusion processing, Nutritional value, Growth

In modern poultry farming system the major emphasis is on reducing the feed cost by adopting modern processing techniques and by enhancing feed efficiency. Extrusion process is one of the best processing techniques not only to enhance the nutritional value of the ingredients and feed but also efficiency of the feed. In modern feed milling operations, extrusion is to be considered the basic process to enhance the profitability of the feed. Extrusion process benefits in term of enhanced nutritional value and efficiency of ingredients and feed, depending upon many factors like structure and chemical composition of the ingredients, processing conditions and machinery used in processing. Any variation for example change in temperature, moisture, screw speed, pressure, time along with extruded material chemical composition and structure can easily influence the nutritional value, digestibility of feed or feed ingredients and performance of the poultry bird. To attain maximum results from the extrusion processing techniques all conditioned should be maintained at optimum levels.

Introduction

Feed cost contributes a large proportion of the total cost in commercial poultry bird production (Khattak et al., 2006). In feed production to gain maximum production from the chicken, not only ingredients contributes the higher amount of the total cost but feed processing also contribute a huge cost (Beuković et al., 2010; Gracia et al., 2010; Wu and Ravindran, 2004). Feed processing techniques have both positive and negative effect on digestibility and animal performance which affect the profitability of production (Al-Marzooqi and Wiseman, 2009; Buchanan et al., 2010; Liu et al., 2013). To improve the nutritional value of the ingredients and feed different processing techniques are being used (Liu et al., 2013). In recent years the extrusion technique is extensively used in feed of animals, because this technology has numerous advantages, including the possibility of wide application, high productivity, energy efficiency and high quality of the resulting product(Brenes, Viveros, Centeno, Arija, & Marzo, 2008; Moritz et al., 2005). Extrusion may increase digestibility of starch by starch gelatinization, melting, fragmentation, destruction of antinutritional factor and making starch easily accessible to digestive enzymes (Abd El-Khalek & Janssens, 2010; Dust et al., 2004; Lankhorst, Tran, Havenaar, Hendriks, & van der Poel, 2007; Liu et al., 2013; Ljokjel, Sorensen, Storebakken, & Skrede, 2004; Murray et al., 2001). Extrusion may alsobe able to increase digestibilityvalue of proteins, amino acids and nitrogen (Al-Marzooqi & Wiseman, 2009; Cheftel, 1979; Sagum & Arcot, 2000). Extrusion process influences protein digestibility by denaturation of protein, modification of side chains of amino acids and denaturing of antinutritional factor. Denaturation of protein leads to increased digestibility (Cheftel, 1979).

It is not always seen that extrusion increase the digestibility of starch and protein. Some time it has no effect or may reduce the protein and starch digestibility of the feed ingredients or feed (G. H. Chiang, 1983; Dahlin & Lorenz, 1993; Hurrell & Carpenter, 1981; Ljokjel, Harstad, & Skrede, 2000; Mahasukhonthachat, Sopade, & Gidley, 2010; Plavnik & Sklan, 1995; Saalia & Phillips, 2011; Skrede & Krogdahl, 1985).Extrusion cooking may be defined as a short time high-temperature process in which moistened, starchy and/or proteiniousfood or food materials are plasticized and cooked in a tube with the help of moisture, temperature, pressure and mechanical shear. Any variation in this process for example change in temperature, moisture (Wood, 1987) screw speed(M. Bhattacharya & Hanna, 1985; B. Y. Chiang & Johnson, 1977)pressure, time along with extruded material chemical composition and structure(Becker, Hill, & Mitchell, 2001; Colonna & Mercier, 1985; Lin, Hsieh, & Huff, 1997) can easily influence the digestibility of feed or feed ingredients. So, to achievebetterresults from the extrusion process optimum conditions should be maintained.

Gelatinization of starch, structural changes in protein and amino acid, denaturation of anti-nutritional factors along with sterilization of ingredients are the main features of extrusion process which leads to the better digestibility, intake, feed conversion ratio and production in poultry birds. Many researchers have reported positive effect of extrusion on the performance of the chicken(Amornthewaphat, Lerdsuwan, & Attamangkune, 2005; Marsman et al., 1997; Moritz et al., 2005; Nageswara and Reddy, 2004). They attributed better performance to improvedgelatinization, intake, digestibility, removal of anti-nutritional factors and good quality of extruded feed or ingredients. However, sometimes extruded food/ingredients have no effect or have adverse effect on performance of the chicken(Ljubojević, N. Milošević, S. Bjedov, & V. Stanaćev, 2011; Naber & Touchbur.Sp, 1969; Sloan, Bowen, & Waldroup, 1971). These results were associated to different extrusion condition and chemical composition of the ingredients which influence the performance of the poultry. This review is based on some question like what is extrusion. Is there any positive or negative effect on the ingredients/feed nutritive value due to extrusion? How poultry bird responds when fed extruded feed/ingredients?

What is extrusion?

Extrusion process is short time high-temperature process in which moistened, starchy and/or proteinious food or food materials are plasticized and cooked in a tube with the help of moisture, temperature, pressure and mechanical shear. This process results in molecular transformation and chemical reactions within the processed feed or ingredients. This processing technology has positive impact as compared to other heat treatment because of mechanical shearing. These mechanical shearing treatments break covalent bond in biopolymers, disrupt complex structure, and mix thefood/ingredients. (Bjorck, Asp, Birkhed, & Lundquist, 1984) in their studies reported that break covalent bond in biopolymers, disrupt complex structure, and mixing of food/ingredients by mechanical shearing treatment facilitate change in the functional properties of food/ingredients and or texturize them.Furthermore, the extrusion process has also positive impact in term of denaturing of harmful enzymes, inactivation of anti-nutritional factors (tannin, phytate, trypsin inhibitor, haemagglutanin) and also sterilize the final product of extrusion(Bhandari, D'Arcy, & Young, 2001; Carvalho & Mitchell, 2000).This extrusion process is used in many different places and having different application and extensively used in food and feed industry(Amornthewaphat et al., 2005; Eastman, Orthoefer, & Solorio, 2001; Liu et al., 2013). Due to increased application of the extrusion, physic-chemical, function, and nutritional effects of extrusion process are considered to be of high importance. The destruction of anti-nutritional factors, reduction of the losses of nutrient along with increasing digestibility of the starch and protein are considers the bases of extrusion process. It has also been reported by different investigators that extrusion process have both positive and negative effects on food or feed ingredients/mixture nutritional quality under different extruder conditions (temperature, feed moisture, screw speed and screw configuration) and raw-material characteristics (composition, particle size).

Starch

Starchesare polysaccharides made of basic unit of glucose which are linked together and form long chains. Amylose and amylopectin are the two types of starch molecule. In most natural starch Amylose (linear) is average 20-30% of the starch. It is not true for all kind of starch for example Waxy corn starch contains only amylopectin (branched). There are also examples of other starches which only contain amylose.Presence of these two kinds within the grains give them specific properties during cooking process and leads a major role in gel formation process. The contribution of amylose and amylopectin in gel formation gives viscosity to the cooked material.Plant stores energy in the form of starch like rice wheat corn and other grain. These grains are the store house of energy for plants. Rice, wheat and corn are the major sources of starch in poultry feed. It is not easy for mono-gastric species including poultry to digest the grain starch easily. A lot of studies indicate that extrusion process have significant effect on the starch digestibility in the mono-gastric animals.

Factor affecting Gelatinization

Moisture Content

Higher level of moisture in the feed, food or ingredients of feed/food results in higher degree of gelatinization when combined with higher temperature. That is the reason; increasing moisture content leads to higher degree of hydrolysis (Hakulin, Linko, Linko, Seiler, & Seibel, 1983). (Wood, 1987) observed in his studies that higher moisture content (30-50%) leads to efficient gelatinization. Furthermore, limited amount of water or solvent in the substrate required higher heat for complete gelatinization(Sun, W. Yang, T. Siebenmorgen, A. Stelwagen, & Cnossen, 2002). At the same time other researcher (S. Bhattacharya, Das, & Bose, 1988; Lin et al., 1997)also reported that increase water content reduce the gelatinization of products during the process of extrusion. (Lund, 1981) indicated that, usually, water to starch ratio 1.5:1 is required for complete gelatinization, and water to starch ratio 0.3:1 may be required for beginning of gelatinization process.

Amylose to Amylopectin Ratio

Amylose and amylopectin quantity within the cereals grains affect the gelatinization process. Cereals are more resistant to gelatinization with high amylose content during the extrusion processing as compared to cereals having the moderate to high content of amylopectin. Starches which are high in amylopectin are easy to swell as compare to starch rich in amylose, amylose containing starch during extrusion loss order within the granules, followed by its destruction(Colonna & Mercier, 1985). There is also opposite finding about this study that higher temperature is required for high and low amylopectin starch barley as compare mid-range barely.

Lipids

In cereals internal lipid have been shown there effect on starch granules swelling and gelatinization properties. Increasing and decreasing the fat content effect the starch gelatinization in extrudates. (Lin et al., 1997)reported significantly decreased starch gelatinization in extrudates when fat content were increased in the byproduct. In this study the decreased gelatinization was might be due to the presence of starch-lipid interaction. (Mira, Persson, & Villwock, 2007) reported starch–lipid interactions decrease starch swelling capacity. Many other scientists also reported that starch-lipid interaction decrease solubility and granule disruption (Bhatnagar & Hanna, 1994b; Galloway, Biliaderis, & Stanley, 1989; Ghiasi, Varrianomarston, & Hoseney, 1982). The amylo-lipid complex within starch granules restricts the penetration of the water(Becker et al., 2001). (Hoover & Manuel, 1996) reported Amylose-lipid interaction and crystallite reorientation in normal maize, waxy maize, dullwaxy maize and amylomaize V starches by applying heat moisture treatment. Amylose-lipid formation depends upon the material starch and lipid. Monoglycerides and free fatty acids are more susceptible to make these kinds of complexes as compare to triglycerides (Bhatnagar & Hanna, 1994a).

Processing/Screw Speed

Processing time and screw speed of the extruder have also major effect on the gelatinization of the extrudate.(Jain, D.Mridula, & Neharika, 2013)reported that screw speed alters the physical characteristics of the extrudates. (Basediya, Pandey, Shrivastava, Khan, & Nema, 2013)reported that during extrusion process speed ofextruder influence the nutritional quality of the extrudates. Decrease starch gelatinization has been reported by researcher(B. Y. Chiang & Johnson, 1977) by increasing the speed of screw during processing. They concluded that the reduced starch gelatinization was due to less cooking time caused by enhanced screw speed whichdecreased retention time of the sample in the extruder. Changes of screw speed resulted in changes of products temperature and variation in the temperature may be able to influence the starch gelatinization. Similar results have been reported by (Lin et al., 1997) during study. They reported changes instarch gelatinization caused by variation of temperature due to screw speed.As described earlier during extrusion process screw speed is also one of the factorsaffectingnutritional value of substrate(Basediya et al., 2013). The screw produces the shear force which is also one of the reasons to change the nutritional value of extrudates(Marsman, Gruppen, & Vanderpoel, 1993). Normally, shear forces are varied by changing the screw speed. However, by changing the screw speed the residence time is largely affected.

Granule size

Granule size has effecton gelatinization of starch during extrusion process.Larger the granule sizes, easier is to gelatinize and the smaller granule size takes long time to get gelatinized. (Chiotelli & Le Meste, 2002; Peng, Gao, Abdel-Aal, Hucl, & Chibbar, 1999)reported that large starch granules within the endosperm have a higher gelatinizationcapacity than small granules and hence reflectgreater crystallinity of large granuleas compare to small starch granules. The process of extrusion reduces particle size and changes the crystalline structure of the starch which makes starch more available for digestive enzymes (Goelema, Smits, Vaessen, & Wemmers, 1999; Thomas, Huijnen, van Vliet, van Zuilichem, & van der Poel, 1999).

Effect of extrusion processing on digestibility of poultry

Starch structure of cereals is an important factor for digestion of starch and is therefore considered as key factor to determine the quality of starch in feed. Starch digestion is also affected by other factor like animal related factors. Animal related factor are breed, age, sex, feed intake and passage rate of feed in gastrointestinal tract of the animal. Hence the starch digestibility of gastrointestinal tract in poultry depends upon a lot of factors including amylose and amylopectin ratio. Extrusion process is also one of major factors affecting digestibility of starch by its gelatinization. (Nayak, Berrios, & Tang, 2014)reported that extrusion process is involved in the gelatinization process. Other researchers(Lankhorst et al., 2007) also reported that the quality of carbohydrate can be modified by thermo-mechanical treatment through gelatinization or shift towards the resistant starch (Dust et al., 2004). In excess water condition, less systematic amorphous regions of starch disrupted firstly, which allows the water to join free hydroxyl group of the starch granules. The effect of moisture on starch may be due to its new crystallization or recrystallization or due to perfection ofstarch granules crystallization regions. High temperature and moisture extrusion results in greatergelatinization and significant rise in *in-vitro* starchdigestibility(Ljokjel et al., 2004; Murray et al., 2001; Zimonja and Svihus, 2009) and *in-vivo* starch digestibility (Nalle et al., 2013; Zimonja and Svihus, 2009). (Nalle et al., 2013) reported enhanced apparent illeal starch digestibility in their experiment. The digestibility of the starch due to extrusion is increased due to gelatinization and by making starch more liable to enzyme degradation. Glennie (1987) explained more starch susceptibility to enzyme degradation after extrusion process due to increased water solubility indices, reduced amylose content and molecular weight of starch during the extrusion process. Zimonja and Svihus (2009) reported increased starch susceptibility for enzymatic breakdown in the higher gelatinization degree of the starch. Abd El-Khalek and Janssens (2010) also reported similar finding that extrusion of corn showed an increase digestibility of starch because of accessibility of digestive enzymes to starch. Water or moisture content is always considered primary part of the extrusion process. Some studies have reported that extrusion without water can also improve the digestibility of the raw starches (Al-Marzooqi and Wiseman, 2009; Liu et al., 2013). Improvement in digestibility of raw starches during extrusion process without water might be due to granular disorganization (as evidenced by X-ray diffraction patterns) and changes in crystallinity (Al-Marzooqi and Wiseman, 2009). Improved starch gelatinization and digestibility has also been reported by (Liu et al., 2013) in dry extrusion.

Extrusion process is not always considered to increase the digestibilty of the ingridients (Davis and Arnold, 1995; Nalle et al., 2013). Although it is considered more benficial method to increase the digestibility of the starch but it is not true in every situation. Some time it has no effect or negative effect on the digestibility of the ingridients or feed. Plavnik and Sklan (1995) have found no differences in starch apparent digestibility of extruded diet in broiler. Dahlin and Lorenz (1993) reported lower carbohydrate digestibility in high tannin sorghum extruded at low-moistures (15g/kg) and low-temperatures (80–100 ◦C). Mahasukhonthachat et al. (2010) reported starch decreased rate that was due to increasing extrusion moisture from 250 to 400 g/Kg. For maximum benefits from the extrusion process, in case of digestibility, the extrusion condition should be standardized. It is necessary to standardize the temperature and moisture during the extrusion process because fluctuation in the temperature may be able to affect the gelatinization process of starch. Retrogradation of starch is also an important factor in the process of gelatinization. This process occurs when gelatinized starch internal molecule re-associate. Retrogradation process occurs more quickly in the amylose based starch while the process of retrogradation is known to be low in amylopectin based starch and need more time (Lii et al., 2004). It is generally described that in mono gastric animal retrograded starch is resistant to digestion (Eerlingen et al., 1994). This process mainly depends upon the concentration of the water (Zeleznak and Hoseney, 1986). To obtain maximum benefits from extruded diet/ingredients water concentration should be maintained at standard level.

As described earlier extrusion process may can increases the digestibility of the starch and proteins. A lot of reasercher have reported positive effect on digestibility of protein by extrusion process (Ahmed et al., 2014; Al-Marzooqi and Wiseman, 2009; Arija et al., 2006; Lichovnikova et al., 2004; Marsman et al., 1997; Nalle et al., 2013). It should be kept in mind boht possibilities of increasing and decreasing digestibiltiy can happen after the extrusion process. These possiblities mainly depends upon the processing conditiones, chemical compostion and other factors. Processing pattren especailly heat processing of food influences protein digestibility bydenaturation of protein which increase protein digestibility. Heat processing alsomodifiyside chains of amino acids which delay the action of digestive enzymes. Al-Marzooqi and Wiseman (2009) reported infuenced amino acid digestibility in growing poultry birds fed ingredients extruded at high processing temperatures. Significantly higher apparent ileal crude protein (CP) digestibility. Marsman et al. (1997) was reported in broiler fed extruded soybean meal. Improved ileal digestibility of CP and amino acids in chicken has also been reported by Arija et al. (2006) when broiler chicken were fed diet containing extruded kidney bean. Extrued diets in laying hen also increased total tract apparent digestibility (TTAD) of essential amino acids and nitrogen retention (Lichovnikova et al., 2004). Ahmed et al. (2014) reported increased apparent ileal digestibility of CP and some of AA such as Asp, Glu, Ser, Thr and Trp when fed extruded canola meal to the chicken. Nalle et al. (2013) reported reduced trypsin inhibitor activity of peas following extrusion process. Similarly, Mariscal-Landin et al. (2002) reported that reducedtrypsin inhibitor actvityin rawand extruded Friléne peas which were supposed to increase protein and amino aciddigestibilities.Similar results have been reported by other workers (Hancock et al., 1992; Hancock and Bramel-Cox, 1991). As already discussed that heat treatment can also increase the digestibility of the amino acid. This theory is supported by Fernandezfigares et al. (1995) experiments. They reoported increased digestibility of amino acid in growing broilerfed heat treated (autoclaving) vetch and bitter vetch meals. Fapojuwo et al. (1987) also reported 59% increased digestibility (0.449 versus 0.714) when dry extrusion temperature of sorghum increased from 50 to 200◦C.

Extrusion process is not always considered to have beneficial effect on the digestibilty of the ingridients (Davis and Arnold, 1995). This process may have no or negative effect on the bioavailability and digestibility of the protein, amino acid and nitrogen of the ingridients/feeds. The variation in the digestibility may be attributed due to a lot of factor like fluctuation in the processing condtioned, chemical composition of the indgirdients and machinary used. Nalle et al. (2013) reported that extrusion had no effect on apparent ileal protein digestibility.

Heat processing have negative effect of the bioavailability of the amino acids in feed stuff (Parsons et al., 1992). Over heating of feed stuff can decrease protein solubility and may also can destroy certain amino acids (Araba and Dale, 1990). Negative effect of high extrusion temprature has also been reported by Vanderpoel et al. (1992). These effects can reduce the digestibility of protein and amino acid. Skrede and Krogdahl (1985) reported reduced total tract digestibility of all amino acids due to heat treatment of soybean meal by autoclaving at 135°C for 30 minutes. Similar results on the protein and amino acid digestibility results has been repoted by Ljokjel et al. (2000) and Ljokjel et al. (2004). Similar findings were also observed for amino acid digestibility with increased heat treatment, mainly for lysine (Martinez Amezcue and Parsons, 2007). Some time processing techniques have no effect on the digestibility of the protein.

Nalle et al. (2013) reported extrusion process of Peas (*Pisum sativum* L.) did not change apparent ileal protein digestibilty. Saalia and Phillips (2011) reported similar results about *in-vitro* protein digestibility and fluorodinitrobenzene (FDNB)-available lysine between extruded and non-extruded peanut meal. One of the most important amino acid is lysine, which is mostly condsidered first limiting amino acid in creal based animal feed, is very susceptible to heat treatment and can easily react with free sugar cause Milard reaction. Due to this milard reaction the availability of the lysine reduced so the digestibilty of the feed is reduced.

Effect of extrusion processing on performance of poultry

Extruder conditions along with compositon of ingridients and feed may influences starch gelatinisation at vairous level which may cause differences in growth performance of the poultry. Different studies described different effect of extrusion on the perfornamce of the poultry (Amornthewaphat et al., 2005; Ljubojević et al., 2011; Nageswara et al., 2004; Sloan et al., 1971). Extrusion of corn meal has significantly affected the improvement of production performance of broiler chickens. Moritz et al. (2005) observed that extrusion process of corn led to an increase in body weight of broiler chickens, aged 0 to 3 weeks. Furthermore, Marsman et al. (1997) reported improved growth performance of the broilers fed extruded SBM. Conditioning time can change the degree of geletinization of starch. So,degree of geletinization can affect the growth rate and body weight of the poultry. Abd El-Khalek and Janssens (2010) reported different degree of geletiniztion affect the body weight and growth rate in pigon.

Extrusion process may also have no effect on the performance of the poultry (Nageswara et al., 2004). Sloan et al. (1971) reported that extrusion have no effect on weight gain and feed effeciency ratio in broilers. Similar observations were made by Naber and Touchbur.Sp (1969). Nageswara et al. (2004) also reportedno benefical effect on performance of layer by using different processing techniques on maize-soy or maize soy-palm kernal diets including extrusion cooking or expander extrusion except extrusion processing of the maize soy diet which only improved feed utilisation efficiency. Similarly, Ljubojević et al. (2011) reported similar production for both extruded and control feed and concluded there was no expectation that the extrusion process had major positive effects.

It is considered that extrusion have positive effect on the performance of the chicken but there are also some studies which reported negative effect of extrusion on the performance of chicken. Amornthewaphat et al. (2005) observed that extruded crushed corn has a negative effect on performance of broilers. Similar results on growth performance of broilers have also been reported by Zhuge et al. (1990) when fed diet having sorghum that was wet-extruded 130/135◦C prior to incorporation into broiler diets.

Moisture content of diets may also influence feed intake (Moritz et al., 2001) and thus can influence the digestibility and performance of the poultry bird. One explanation for the variation in results may that these differences are due to different types of extruders (wet or dry, with one or two extractors) and different condition during the extrusion process, such as temperature, humidity, pressure, etc. (Hongtrakul et al., 1998). Table References (Alonso et al., 2000; Camire et al., 1990).

On the basis of the reviw, although extruion technique seems to have more benfits on nutritient digestibility and performance in poutlry but extrusion porcess effect on nutrient digestibility and performance of poultry is in-consistent. The unequivocal performance of poultry and nutrient digestibility was mainly due to variationsin processing techniques and extrusion conditions. To obtain maximun nutrient digestibility and performance of the poultry processing techniques and extrusion conditions should be maintained at standard levels.

Extrusion effect on Digestibility and Performance in Poultry: SUMMARY

Author	Process	Reasults			
		Geletinization	Digestibility of Starch	Digestibility Protein,Nitrogen, amino acids	Performance
Sloan et al., 1971	Extrusion	X	X	X	↔Performance
Cheftel, 1979	Extrusion	X	X	↑Protein	X
Hurrell and Carpenter, 1981	Extrusion	X	X	↓Amino Acid	X
Chiang, 1983	Extrusion	X	X	↓Amino Acid	X
Skrede and Krogdahl, 1985	Extrusion	X	X	↓Protein, Amino Acid	X
Fapojuwo et al., 1987	Extrusion	X	X	↑Protein	X
Bhattacharya et al., 1988	Extrusion	↓Geletinization	X	X	X
Zhuge et al., 1990	Extrusion	X	X	X	↓Performance
Camire et al., 1990	Extrusion	X	↑Digestibility	X	X
Hancock and Bramel-Cox, 1991	Extrusion	X	X	↑Nitrogen	X
Hancock et al.,1992	Extrusion	X	X	↑Nitrogen	X
Dahlin and Lorenz, 1993	Extrusion	X	↓Digestibility	X	X
Plavnik and Sklan, 1995	Extrusion	X	↔Digestibility	X	X
Marsman et al., 1997	Extrusion	X	X	↑CP,Amino Acid	↑Performance
Ljokjel et al., 2000	Extrusion	X	X	↓Protein, Amino Acid	X
Alonso et al., 2000	Extrusion	X	↑Digestibility	X	X
Murray et al., 2001	Extrusion	↑Geletinization	X	X	X
Sun et al., 2002	Extrusion	↑Geletinization	X	X	X
Lichovnikova et al., 2004	Extrusion	X	X	↑Amino Acid	X
Dust et al., 2004	Extrusion	↑Geletinization	X	X	X
Nageswara et al., 2004	Extrusion	X	X	X	↔Performance
Ljokjel et al., 2004	Extrusion	↑Geletinization	X	X	X
Amornthewaphat et al., 2005	Extrusion	X	X	X	↓Performance
Moritz et al., 2005	Extrusion	X	X	X	↑Performance
Milošević et al., 2006	Extrusion	X	X	X	↑Performance
Arija et al., 2006	Extrusion	X	X	↑CP,Amino Acid	X
Martinez Amezcua and Parsons, 2007	Extrusion	X	X	↓Amino Acid	X
Zimonja and Svihus, 2009	Extrusion	↑Geletinization	↑Digestibility	X	X
Marzooq and Wiseman 2009	Extrusion	↑Geletinization	X	X	X
Mahasukhonthachat et al., 2010	Extrusion	X	↓Digestibility	X	X
El-Khalek and Jamssens, 2010	Extrusion	X	↑Digestibility	X	X
Ljubojević et al., 2011	Extrusion	X	X	X	↔Performance
Liu et al., 2013	Extrusion	X	↑Digestibility	X	X

↓ Represents decreasing trend
↑ Represents Increasing trend
↔ Represents no effect

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