Noregs miljø- og biovitskaplege universitet

Master's Thesis 2020 30ECTS

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Faculty of Biosciences
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INFLUENCE OF THE ANIMAL FEED BINDERS ON OPTIMAL NUTRITIONAL AND PHYSICAL QUALITIES OF THE ANIMAL FEED PELLETS AND FEED PRODUCTION CAPACITY- A LITERATURE REVIEW

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Feed Manufacturing Technology

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Master of Science in Feed Manufacturing Technology

Submission date: August 17th, 2020

Acknowledgement

To God Almighty be the glory for sustaining me throughout this journey.

I sincerely express my gratitude to my supervisor Dr. Dejan Dragan Miladinovic for his support and guidance in writing this thesis. Many thanks to my study advisor, Stine Telneset for being helpful during this period.

I would like to thank my husband, Damilola Bello for his understanding and support. I appreciate my parents for believing in me. I am grateful to Mr. and Mrs. Soneye for their love and their moral support. To my amazing siblings and friends, you are the best gift to me. I love you all.

Olatomiwa Ayoola
17th August, 2020

Abstract

Binders are binding/firming agents that develop solid bridges through chemical reaction to make strong interparticle bonding. They are used to strengthen pellets, improve pellets integrity, durability and stability, reduce nutrient leaching and prevent fragmentation and abrasion of pellets during handling, transportation and storage. Binders like lignosulfonate, bentonite and sepiolite enhance pellet strength and durability by acting as a filler to fill in pore spaces between particles. Some have adhesive forces that help to glue and consolidate particles. Binders such as starch and protein improve pellet strength and durability through chemical reaction by changing the nature of feed mix after undergoing heat, moisture and heat treatment during the pelleting process. Besides improving physical pellet properties, some binders can enhance animal's growth and digestibility. Supplementing binders in feed are distinct for different animal species diets. Therefore, selection of binder in feed is based on its suitability for a specific animal species

Key words: Binders, Durability, Stability, Lignosulfonate, Bentonite, Sepiolite, Agar, Pelleting.

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Abbreviations

CaLS	Calcium lignosulfonate
PPQ	Physical pellet quality
%	Percentage
DMR	Dry Matter Rentention
DM	Dry Matter
ms-1	Metre per second
mm	Millimeter
°C	Degree Celsius
l/d	length to diameter
PDI	Pellet Durability Index
HM	High methoxyl
LM	Low methoxyl

Fig	Figure
hrs	Hours
min	Minute
CMC	Carboxymethylcellulose
Ca2+	Calcium
AME	Apparent Metabolizable Energy
CP	Crude Protein
CU	Copper

1.0 INTRODUCTION

Feed production involves controlled processes to produce high-quality feed for stimulating and enhancing animal functionality. Hence, the animal feed industry is continually searching for strategies to improve feed processing techniques in order to produce quality and economical feed. A major feed processing technique that needs consistent improvement is pelleting.

Pelleting is a thermal process used in producing animal feed. The purpose of pelleting is to maintain homogeneity by agglomeration/compaction of feed particles through mechanical and thermal process (Thomas and Van der Poel, 1996; Abdollahi *et al*., 2013). Compaction of particles is stimulated through mechanical forces and bonding forces between interparticle. Compaction starts by rearranging particles at low pressure followed by elastic and plastic deformation of particles when pressure is increased. This leads to particles interlocking, which results in the densification of biomass, i.e. pellet (Tabil, 1998). Compaction of feed particles materials into pellets minimize costs and challenges faced with ground feed during handling, transportation, and storage (Kaliyan and Morey, 2009).

The advantages of pelleting include high bulk density, better flow properties, reduction in generating dust and fines (Thomas and Van der Poel, 1996). Pellet with bad qualities easily disintegrates causing feed wastage and increasing production cost thus, it is essential to produce pellets with excellent qualities. Factors such as steam conditioning, conditioner residence time/temperature, type of feed ingredients, feed formulation, influence the production of high quality and stable pellets (Lim and Cuzon, 1994; Thomas and Van der Poel, 1996; Tabil,1998; Briggs *et al*., 1999). Controlling these factors during manufacturing processes produce pellets with superior pellet quality (Tabil, 1998).

Sometimes, putting these processing factors in place are insufficient to manufacture high pellet quality; therefore, the inclusion of binding agent is employed. Binders are binding/firming agents that develop solid bridges through chemical reaction to make strong interparticle bonding (Paolucci *et al*., 2012). Solid bridges are formed by high pressure through diffusion, chemical reaction, crystallization, hardening of binders after cooling and solidification of melted particles after cooling /drying (Thomas and Van der Poel, 1996; Tabil and Sokhansanj, 1996; Kaliyan and Morey, 2009).

Binders are used to strengthen pellets, improve pellets integrity, durability and stability. They also reduce nutrient leaching and prevent fragmentation and abrasion of pellets during handling, transportation and storage (Acar, 1991; Penaflorida and Golez, 1996; Tumuluru *et al*., 2016; Attar et al., 2018).

Lim and Cuzon (1994) classified binders as natural, modified or synthetic. Natural binders such as starch and protein increase the nutritional value of feed and are naturally found in feed ingredients(Paolucci *et al*., 2012). Synthetic binders, on the other hand, are produced artificially and do not necessarily improve the nutritional value of feed examples include Urea-formaldehyde, Na or Ca bentonite. Modified binders include polysaccharides like carboxymethylcellulose (CMC), alginate, agar, carrageenan, guar gum (galactomannan), gelatin, pectin and lignosulfonate (Lim and Cuzon,1994). Modified binder like gelatin provide nutritional value in animal feed (Paolucci *et al*., 2012).

Binders like lignosulfonate, bentonite and sepiolite enhance pellet strength and durability by acting as a filler to fill in pore spaces between particles (Yalcin *et al.*, 2017a; Ouyang *et al.*, 2006). Some like have adhesive forces that help to glue and consolidate particles. Binders like starch and protein improve pellet strength and durability through chemical reaction by changing the nature of feed mix after undergoing heat, moisture and heat treatment during the pelleting process (Lim and Cuzon, 1994).
In conclusion, acceptability of binders in feed production is hinged on its binding capacity, inclusion level, interference with growth and digestibility, availability and cost.

The purpose of this review is to discuss the effect and benefits of various pellet binders on pellet quality. Ways to maximize these benefits to produce the best pellet quality will be analysed.

2.0 LITERATURE REVIEW

2.1 Pelleting process

The pelleting process involves several phases in manufacturing animal feed. It starts with receiving the raw materials, grinding or particle size reduction, proportioning or batching, mixing, heating or thermal treatment (or pellet shaping), packaging, storing and ends with loading (Abdollahi *et al*., 2013).

2.1.1 *Grinding*

After receiving raw materials, they are ground to smaller particles either by hammer or roller mill before mixing. Grinding is done mainly for cereal grain. The purpose of grinding is to increase surface area for nutrient digestibility, improve homogeneity and facilitate further processing (Behnke, 1996). Afterwards, the ground feed ingredients are proportioned and mixed with other feed ingredients to blend the nutrients uniformly. They are further subjected to thermal treatment by steam conditioning in the conditioner.

2.1.2 *Steam conditioning*

Steam conditioning is the most crucial factor in pelleting. It is a thermomechanical process that involves adding heat and steam to mixed feed ingredient under constant shear or pressure (Svihus, 2018). The aim of conditioning is to pre heat and moisten the feed mix into a state that will facilitate further processing. The addition of moisture using steam improves pellet quality(Skoch *et al*., 1981). Steam has the ability to provide proper balance of heat and moisture needed for optimization of conditioning process(Svihus, 2018) The quality of conditioning process depends on the mix particle size, steam quality and quantity, initial moisture and temperature content of the mix, and the retention time in the conditioner for the interaction of feed and mash (Yasothia, 2018; Svihus 2018). Steam quality is the amount of steam in the vapor phase. High quality steam has more energy to increase feed mash temperature than low quality steam (Gilpin *et al.*, 2002) For ideal conditioning, dry saturated steam is used as it contains less moisture and maximizes the relationship between feed temperature and moisture percentage (Kenny and Rollins, 2007). According to Kenny and Rollins (2007), dry saturated steam increases mash temperature by 16°C for every 1% added moisture. During conditioning, a temperature of 75-80^{o}C is usually attained (Svihus, 2018) an conditioning process occurs between 20-25s (Kaliyan and Morey, 2009) . Steam conditioning aids the release and activation of natural binders, natural lubricants and artificial binders in feed as a result, pellet quality is improved(Kaliyan and Morey, 2009). Steam alters starch and protein structure resulting in starch gelatinization and protein plasticization. Both starch gelatinization and protein plasticization contributes to feed particles binding property thereby, promoting production of quality pellets (Behnke, 1994)

2.1.3 *Pelleting*

Following steam conditioning is pelleting. Pelleting is the most common processing method to shape feeds. Pellet is a cylinder of feed with varying length and width produced by pressing the feed through a thick metal plate containing hole called die (Svihus, 2018). Conditioned feed flows into the pellet chamber and is forced through the die. The pressure exerted by the rolls in the pellet chamber combined with the temperature will result in chemical changes that will cause the feed particles to glue together called pellets(Svihus, 2018).

2.1.4 *Cooling and Drying*

Pellets come out of the pellet mill die with a temperature from 80 to 90^{o}C and 15–17% moisture. This is unsuitable for storage thus, the pellets need to be cooled or dried to 8^{o}C temperature and 10–12 % moisture content (Abdollahi *et al*., 2013). Cooling is achieved by passing a stream of air through a bed of hot pellets in a vertical or horizontal cooler. Cooling occurs by the evaporation of water from excess moisture and by contact with the air. The warmer the air the more moisture will be evaporated from the pellets. The residence time of pellet in the cooler should be taken into consideration to avoid redundant pellets. Cooling for too long time is detrimental to the pellets as the pellets may become too hard and lose its nutritional value (California pellet mill, 2012). However, the time is relative depending on the warmness of the steam of air passed through the pellet.

Lastly, pellets are packaged, stored and transported to various locations.

2.2 Factors affecting pellet quality

Pellets undergo stress and pressure during production and post-production process such as handling, transportation and storage (Thomas and Van der Poel, 1996); It causes pellet disintegration (generation of dust and fines), fragmentation and abrasion. To optimize pellet production, it is imperative to produce good physical quality pellets with high nutritional value that can withstand stress and the rigors of handling, transportation and storage (Briggs *et al*., 1999; Kaliyan and Morey, 2009). Pellet quality includes the nutritional and physical quality.

Pellet nutritional quality is evaluated by how pellet improve growth, digestibility and health of animals while pellet physical quality (PPQ) is evaluated by how hard or durable a pellet is. It includes hardness and durability. However, it varies according to animal species. For birds, pellets physical properties such as durability and hardness are necessary for enhancing their performance (Thomas and Van der Poel, 1996; Abdollahi *et al.,* 2013). Aquatic animals mostly require additional pellet characteristics such as flowability, sinking velocity/floatability, water absorption capacity and water stability (Kaliyan and Morey, 2009, Abdollahi, 2011; Khater *et al*., 2014). The three main parameters used in measuring PPQ are:

Hardness: is the maximum force required to resist/withstand crushing without cracking or breaking (Kaliyan and Morey, 2009). Kahl device can be used in measuring hardness (Thomas and Van der Poel, 1996).

Durability: is the ability of pellets to remain intact after subjection to load and force during transportation, handling and storage (Thomas and Van der Poel, 1996). The tumbling can, Holmen tester, and Ligno tester can be used for measuring durability (Kaliyan and Morey, 2009). It measures the amount of intact pellets remaining after subjection to loads and pressure.

Water stability: is the ability of pellets to retain its physical integrity when immersed in water for a specific time (Obaldo *et al*., 2002). High water stability means minimum disintegration and nutrient leaching.

Factors such as steam conditioning, conditioner residence time/temperature, type of feed ingredients, feed composition and formulation, influence the production of high quality and stable pellets. Also, pelleting equipment, die geometry, die speed, rate of production affects pellet quality (Lim and Cuzon, 1994; Thomas and Van der Poel, 1996; Tabil and Sokhansanj, 1996; Briggs *et al*., 1999). Additionally, post-production conditions such as cooling, drying and storage conditions affect the strength and durability of pellets (Kaliyan and Morey, 2009). Controlling these factors during manufacturing processes increase production efficiency and pellet quality (Tabil and Sokhansanj, 1996).

2.2.1 *Particle size*

Fine and medium particle size grinds increase pellet durability due to high reactive surface area (Tabil and Sokhansanj,1996). Reducing particle size increases particle surface area; Due to the large surface area, fine particles are able to absorb more moisture than large particle therefore they experience better conditioning (Kaliyan and Morey, 2009). Franke and Rey (2006) suggested using 0.5–0.7 mm particle size for good pellet durability. Particles ground larger than 1-1.5mm may be unsuitable for pellet production (Franke and Rey, 2006).

2.2.2 *Feed formulation*

Different ingredients have distinct characteristics that affect feed processing. These characteristics influence the amount of moisture, pressure or heat to be applied to produce during processing. Fiber has stiff and elastic characteristics that makes bonding between particles difficult (Thomas *et al*. 1998). Inclusion of fat/oil in feed negatively affects pellet durability (Angulo *et al*., 1996; Cavalcanti, 2004). Fat increases lubrication between the feed particles and the pellet die-wall. As a result, die friction and pressure is decrease thereby reducing pellet durability (Kaliyan and Morey, 2009). A study by Briggs *et al*. (1999) suggested that using more than 5.6% of oil content prior to pelleting does not affect pellet quality depending on the amount of protein and conditioner residence time. Briggs *et al*. (1999) further explained that increasing the protein content increased the pellet durability but increasing the oil content above 5.6 % decreased pellet quality. This is congruent with Cavalcanti and Behnke (2005) report about the negative impact of fat on pellet durability, probably based on reduced compression forces and increased flowability of compacted materials within the die hole. Also, the influence of protein on pellet quality depends on the source of the protein and properties of protein and heat denaturation (Cavalcanti and Behnke, 2005).

2.2.3 *Steam conditioning*

Steam conditioning increased feed production rate by 64% and increased pellet durability index (PDI) by 26%. Steam also decreased energy usage in the pelleting machine (Skoch *et al*. 1981) . Abdollahi (2011) reported improved pellet durability and hardness through steam conditioning. Steam conditioning at a specific temperature(50-70^{o}C) and moisture content causes starch gelatinization and protein denaturation thereby improving pellet quality (Abdollahi *et al.*, 2012). To achieve optimum pelleting, Tabil and Sokhansanj (1996) suggested using a conditioning temperature less than 92^{o}C and 1.5 to 2.5% of moisture

2.2.4 *Moisture addition*

Pellet durability can also be improved by moisture addition as suggested by (Abdollahi *et al*., 2013). Moisture addition during mixing and conditioning aids pellet binding by Van der Waal’s forces (Tabil and Sokhansanj, 1996). Water causes recrystallization between interparticle molecules by penetrating the surface particles of soluble material. As a result, pellet durability is improved. Abdollahi *et al*. (2012) observed increased PDI from 56.5% to 67.2% when 2.4% moisture was added to feed conditioned at 60 °C .

2.2.5 *Die size*

Increase in the length to diameter (l/d) increases pellet durability. The larger the die length to diameter (l/d) ratio, the better the pellet durability(Heffner and Pfost,1973). Increasing die l/d ratio from 5 to 9 increased the durability of alfalfa pellets from 50 to 80% (Hill and Pulkinen, 1988). Smaller die with 6.1mm diameter produced pellets with better durability compared to large die with 7.5mm diameter (Tabil and Sokhansanj, 1996. However, smaller die are unable to handle diets with moisture content above 10%. According to Thomas *et al*. (1997) die speed depends on the pellet size. Thomas *et al*. (1997) recommended high die speed (about 10 ms^{-1}) for small pellets with 3–6-mm diameter, and low die speed (about 6–7ms^{-1}) for large pellets.

Controlling these parameters are sometimes inadequate to produce pellets with the best properties. Thus, binding agents are introduced.

2.3 Binders

Binders are binding/firming agents used for improving pellet quality (Tiamuyi and Solomon, 2012). They are used to strengthen pellets, improve pellets integrity, durability and stability. Also, binders prevent pellets fragmentation and abrasion during handling, transportation and to reduce the specific energy consumption during processing (Acar *et al*., 1991; Penaflorida and Golez, 1996; Tumuluru *et al*., 2016; Attar *et al*., 2018).

Binders can either be liquid, e.g. molasses (Thomas and Van der Poel, 1996) or solid that forms bridges to make strong interparticle bonding (Paolucci *et al*., 2012). Solid bridges are formed by high pressure through diffusion, chemical reaction, crystallization, hardening of binders after cooling and solidification of melted particles after cooling /drying (Thomas and Van der Poel, 1996; Tabil and Sokhansanj, 1996; Kaliyan and Morey, 2009).

Different binders have distinct properties that qualify their usage in producing feed for various animal species. Generally, its viscous properties enable their usage in feed production. Binders are usually added in powder form or as liquids. When added, its ability to disperse and react with other raw material is paramount. Dispersion of a binder depends on binder viscosity and applied shear rate during processing. High shear rate and low viscosity result in a homogenous dispersion while high viscosity and low shear rate result in a heterogeneous mixture (Mort, 2005).

Conventionally, applying binders in liquid form requires using a spray. A typical example of the spraying mechanism is top- spray(Pusapati and Rao, 2014). Top spray as the name implies is termed according to the position of the spray gun. Using top spray fluids helps to prevent segregation of fines, improve flow and contribute to homogeneous distribution of all components (Pusapati and Rao, 2014). In a top-spray fluid, the spray coverage relative to the mass in the mixer should be taken into consideration for homogenous dispersion. Effective binder coverage entails proper mixing and low contact angle between the binder and other ingredients. The distribution of binders on the surface of other ingredients determines the reaction rates as reactions occur at the surface interface between the binder and other ingredients (Mort, 2005). Binders act as a filler by filling in the pore space between particles or function as an adhesive consolidating or gluing materials by reducing pore spaces (DeSilva and Anderson, 1995).

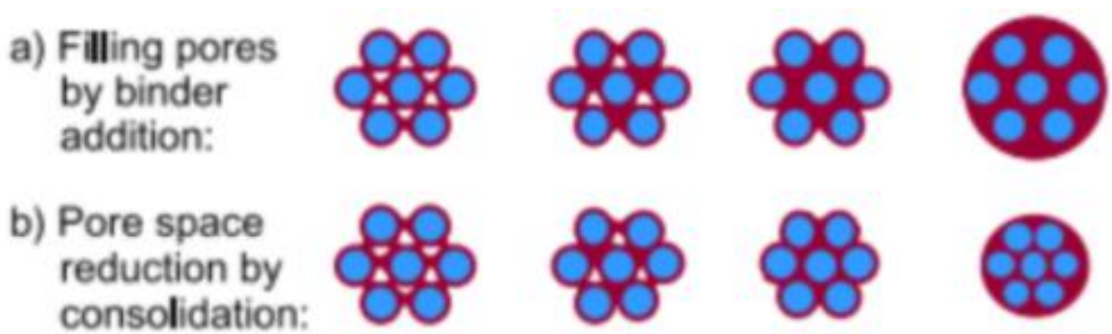

Figure 1: Binder loading in liquid bridge structure (Mort, 2005)

Lim and Cuzon (1994) classified binders as natural, modified and synthetic. Natural binders such as starch and protein increase the nutritional value of feed and are naturally found in feed ingredient

(Paolucci *et al.*, 2012). Modified binders include polysaccharides like carboxymethyl cellulose (CMC), alginate, and lignosulfonate. Synthetic binders, on the other hand, are produced artificially and do not necessarily improve the nutritional value of feed examples include Urea-formaldehyde, Na or Ca bentonite (Lim and Cuzon 1994)

Binders like lignosulfonate, bentonite and sepiolite enhance pellet strength and durability by acting as a filler to fill in pore spaces between particles (Ouyang *et al.*, 2006; Yalcin *et al*., 2017a). Some have adhesive forces that help to glue and consolidate particles. Binders like starch and protein improve pellet strength and durability through chemical reaction by changing the nature of feed mix after undergoing heat, moisture and heat treatment during the pelleting process (Lim and Cuzon, 1994).

Pellet quality is enhanced by binders through binding mechanisms and forces that bond the particles together. The binding forces are classified as (i) solid bridges are formed by high pressure through diffusion, chemical reaction, crystallization, hardening of binders, e.g. molasses after cooling, solidification of melted particles after cooling /drying (ii) Intermolecular attractive forces (hydrogen bridges, and van der Waals' forces, electrostatic, and magnetic forces) between solid particles (iii) Interlocking bonds caused by folding and plying of fibers and bulky materials during compression, (iv) adhesive and cohesive forces between particles caused by the presence of viscous binders, and (v) interfacial and capillary forces due to the presence of liquids (Thomas and Van der Poel, 1996; Tabil and Sokhansanj, 1996; Kaliyan and Morey, 2009).

Selection of binders are based on their binding properties and how they affect the nutritional properties of feed. Fundamentally, for proper optimization and activation of pellet binder, steam conditioning is vital to provide heat and moisture. (Kaliyan and Morey, 2009).

2.4. Feed binder market

Binders are used to reduce pellet fines and dust so as to prevent wastage. To reduce production cost, cost, binders are added to pelleting process to prevent this loses. According to marketsandmarkets.com(2020), by the end of 2020, the estimated value for global feed binder market is expected to be USD 4.5 billion and it is predicted to increase annually by 3% to USD 5.1 billion by 2025. Feed producers are more apprised of the benefits of binders; based on this, their usage is expected to rise. Guar gum, corn starch, agar, carrageenan, and gelatin are effective binders but are very costly to include in the feed. Lignosulfonate and clay are less expensive and can be included at low concentrations. Lignosulfonate seems to be the fastest growing binder in the market and the poultry sector is also projected to dominate the market. The rise in the global poultry production has contributed to its growth in the feed binder market. Globally, based on the demand for feed binders, the Asia pacific region is projected to increase the market growth (marketsandmarkets.com, 2020). Table 1 comprises names of binder manufacturers, the type of binder produced and the inclusion level as seen on the companies' websites.

Product	Binder/Inclusion level	Company/Manufacturer	Source
PellTech®	Lignin/ 0.25- 0.75%	Borregaard	www.borregaard.com
Ameri-Bond 2X®	Lignosulphonate/0.5%	Borregaard	www.borregaard.com
LignoBond DD®	Lignosulphonate/0.5-1.0%	Borregaard	www.borregaard.com
NOVAXAN ™	Xanthan Gum	ADM (Archer Daniels Midland Company)	www.adm.com
Protamylasse™	Starch and Sugar	Avebe	www.avebe.com
VEGIGEL®	Agar	Gelita	www.gelita.com
Pro-Bind plus	Gelatine/ 0.25% - 0.5%	Darling Ingredients (Sonac)	www.sonac.biz
KELFLO®	Carrageenan	CP Kelco Inc.	www.cpkelco.com
GENU®	Pectin	CP Kelco Inc.	www.cpkelco.com

KELFLO®	Xanthan Gum	CP Kelco Inc	www.cpkelco.com
Pell-Tuff®	Lignosulfonate/0.2-0.5%	Cra-vac Industries INC	cravac.com
Protein Plus®	Gelatine	Cra-vac Industries INC	cravac.com
Sepifeed®	Sepiolite/1.0-2.0%	Sepiolsa	www.sepiolsa.com
Akucell® Cellulose Gum	carboxymethylcellulose	Nouryon	www.nouryon.com
WALOCEL™ CRT	Sodium Carboxymethylcellulose/1.0-2.0%	Dupont	www.dupont.com
Hydrocolloids	Carrageenan,Pectin, Xanthan gum	Cargill	www.cargill.com

Table 1: Names of binder manufacturers, the type of binder produced and the inclusion level

2.5 Types of binders

2.5.1 *Starch*

Starch acts as a binding agent in feed processing (Wood, 1987; Thomas *et al*., 1998). Starch granules consist of branched (amylopectin) and unbranched (amylose) molecular structure joined by hydrogen bonding(Svihus *et al*., 2005). Upon heating at above 80◦C in the presence of adequate water, the physicochemical properties of starch are altered, thereby influencing starch functionality (Collado and Corke, 2003; Svihus *et al*., 2005). The alteration of the physicochemical properties of starch in the presence of heat and adequate moisture under high-shear and high-pressure conditions is termed Gelatinization. Gelatinization reaction leads to the formation of starch cross-linking with the other biomass components (Tumuluru *et al*., 2016). The ability of starch to form gel is the basis of its use as a binding agent.

At a specific temperature 55-70° C (Christianson *et al*., 1981) during heating in the presence of moisture, the kinetic energy gained by the starch molecules causes the breakdown of the intermolecular hydrogen bonding of the starch granule. The granule swells rapidly with time as a result of solvation of the amorphous regions, loss of the crystalline order and water diffusion inside the granular structure. Starch paste is formed during swelling of the granules when there is continuous leaching out of the linear amylose molecules. Cooling of the starch paste will result in a strong gel when it thickens due to the formation of hydrogen bonds (Whistler and Daniel, 2000; Collado and Corke, 2003).Due to their unique properties of forming gel, starch is widely applied as thickeners, stabilizers and texture enhancers in the food industry (Tabil *et al*., 1997; Collado and Corke, 2003). Apart from improving the feed nutritional value, starch acts as natural binders and are vital in producing quality pellets in the feed industry (Kannadhason *et al*., 2009; Tiamuyi and Solomon, 2012).

Tiamuyi and Solomon (2012) reported that using starch as a binder, increased pellet durability values due to the gelatinization of starch. Starch from various sources has different functional properties. It is therefore essential to understand how various starch sources affect pellet qualities. Researchers (Wood, 1987; Dominy *et al*., 2004; Solomon *et al*., 2011), have demonstrated that wheat possesses excellent binding properties for manufacturing pellets with good physical quality. Generally, wheat flour is an excellent natural binder (Dominy *et al*., 2004). Perhaps, it may be due to their low crude fibre level and gluten protein (Solomon *et al*., 2011, Tiamuyi and Solomon 2012). Tiamuyi and Solomon (2012), screened various grain cereals by testing their influence on pellet physical properties. It was discovered that diets made with wheat starch produce the best pellet quality with minimum dust and high water stability. Pellets produced from wheat starch exhibited superior pellet quality, water stability and pellet disintegration compared to other grain starches.

Compared with other grain cereals like rice starch, guinea-corn starch, wheat starch and maize starch, pellets produced with millet starch had bad qualities due to its weak binding properties (Tiamuyi and Solomon, 2012). However, Solomon *et al*. (2011) observed that combining millet starch with yeast (Saccharomyces cerevisae) can increase pellet floatability for 30 mins when immersed in water. Also, tapioca flour can be used as a binding agent in producing pellets with water stability of less than 8hrs. Ali (1988), reported that utilizing 28.5% level of tapioca flour as a binder in prawn feed pellets improved water stability due to its binding capacity.

Using cassava and corn starch have also shown to moderately increase pellet durability and enhance water stability for 50 mins when immersed in water (Solomon *et al*., 2011). The binding effect of cassava starch have also been reported in the production of pharmaceutical tablets (Chitedze *et al*., 2012). A study by Orire *et al*. (2010) found that using 5% level yam starch as binder for fish feed minimize dust level, improved pellet qualities and water stability. He observed that inclusion level at 20% yields less dust but did not increase the pellet quality. Probably, due to high levels of starching the pellets agglutinate as a result of over binding (Orire *et al*., 2010).

Finally, Tiamuyi and Solomon (2012) stated the benefits of using starch as binders which include affordability and availability in various plant sources, thereby reducing feed cost thus, contributing to pellet nutritional content.

2.5.2 *Protein*

Protein is a macromolecule consisting of linear chains of amino acids arranged in a three dimensional shape. It is made up of primary, secondary, tertiary and quaternary level of structure(Pollock, 2007). Protein will plasticize under heat and act as a binder thereby improving pellet durability (Winowiski, 1988; Briggs *et al*., 1999).During feed pelleting, protein undergoes denaturation that weakens its chemical bonds and as a result forms complex bonds/protein network due to the high temperature, moisture and pressure (Wood, 1987; Thomas *et al*. 1998; Hayta and Alpaslan, 2001). Heating feedstuffs alters protein structure and may cause destruction of three-dimensional structure of proteins, leading to new covalent-bond formations such as disulfide bridges (Svihus and Zimonja, 2011). Denaturation process starts through reversible breakage of hydrogen and van der Waal bonds followed by irreversible changes due to formation of covalent -bond formations such as disulfide bridge (Weijers and Van't Riet 1992). Denaturation of proteins during processing induces the binding functionality of protein (Svihus and Zimonja, 2011).

The degree of protein denaturation is affected by heat, temperature, moisture content, residence time and pH. The functional properties of protein are also affected by these factors (Thomas *et al.*, 1998; Zarkadas and Wiseman, 2005; Svihus and Zimonja, 2011) as well as protein sources and properties. (Cavalcanti and Behnke, 2005). Heat processing is vital by destroying heat-labile anti nutritional substances, thus improving digestibility of both protein sources. However, excess heat can be detrimental as they cause destruction or alteration of amino acids and reduce amino acid availability/ protein nutritional quality (Papadopoulos, 1989). Thermal damage of proteins is avoided by controlling time, temperature, moisture content while processing.

Protein is widely used in the food and beverage industry due to their properties such as water holding capacity, solubility, gelation, cohesion, and binding abilities (Briggs *et al*., 1999). Proteins play a significant role in pellet binding because it exerts adhesive forces useful in binding feed particulates (Thomas *et al*., 1998; Moradi *et al*., 2019)

Sørensen (2012) observed that proteins in native or undenatured state have better binding properties than heated or denatured proteins when used in feed formulations. Native proteins have a higher solubility than denatured proteins, and solubility of main feed constituents appears to be an important factor for the quality of the final product. Heat treated proteins are already unfolded and form less soluble aggregates (Sørensen, 2012).

Formulations containing raw soya protein and pre-gelatinized tapioca starch exhibited superior pellet durability whereas, and those containing denatured soya protein and native tapioca starch have inferior pellet durability. Pellets prepared from native starch and denatured soya-bean meal had low durability and hardness due to their low binding capacity. It means that formulations containing raw protein irrespective of the presence pre-gelatinized starch are harder than those containing denatured protein (Wood, 1987).

Wheat is recognized as a raw material which exhibits good binding properties for manufacturing pellets with good physical quality. These binding properties are due to the hydration and presence of the gluten (Wood, 1987). According to McKee (1988), wheat gluten enhances water pellet stability. The biochemical and rheological properties of most wheat products are determined by gluten protein (Hayta and Alpaslan, 2001). The use of wheat gluten(10g/kg) and wheat 200g/kg are beneficial for increasing physical pellet quality, while improving the performance of broilers such as improved weight gain. 20g/kg wheat gluten inclusion resulted in greater pellet durability index and pellet hardness in both starter and finisher diets but the weight gain and feed intake (FI) were not affected. High inclusion rate of wheat gluten (20 g/kg) may have accounted for lack of influence on weight gain FI and feed per gain, probably due to pellet agglutination (Argüello-Guevara and Molina-Poveda, 2013; Moradi *et al*., 2019).

Wheat gluten-based diets decreased pellet water stability when compared to guar gum and PolyMethylCarbamide (PMC). However, increasing pelleting temperature from 70-90^{0}C increases pellet water stability by 1.5%. It was suggested that increasing pelleting temperature reduces leaching and disintegration of wheat gluten-based pellets diets. Probably, increase in temperature leads to more starch gelatinization and also enhanced formation of ingredient-binder matrix (Ali *et al*., 2010).

Combining wheat gluten with other binders may enhance its binding properties to improve water stability. Pellet diets produced with 50g/kg of wheat gluten and alginate maintained water stability after 3hrs immersion in water. It prevented high levels of dry matter loss after 60min water immersion. Thus, diets produced with 50g/kg of wheat gluten and sodium alginate showed superior water stability, water absorption rate (Ali *et al*., 2010) and low disintegration after 3h water immersion(Argüello-Guevara and Molina-Poveda, 2013). Also, adding defatted soy to diets enhanced the physical quality by increasing hardness and durability (Søresen *et al*., 2009).

Generally, increasing protein content increased the pellet durability (Briggs *et al*., 1999).

2.5.3 *Lignosulfonates*

Lignin is a highly branched aromatic biopolymer extracted from the cell walls of wood where it contains up to 30%. It is the world's second most abundant organic molecule (Flatt and Schober, 2012; Macfarlane *et al*., 2014). It makes cell walls rigid and gives resistance to wood, preventing it from bending due to external forces. Due to their adhesive properties, lignin molecules have strong binding activity which are negatively affected by very high moisture content (Tumuluru *et al*., 2016).

Lignosulfonates are lignin products obtained as by-product from sulfite pulping of wood (Acar *et al*., 1991; Tabil *et al*., 1997; Flatt and Schober, 2012; Macfarlane *et al*., 2014). They are sulfonate salts containing magnesium, calcium, sodium made from lignin of sulfite pulp-mill liquors at different pH levels (Tabil *et al*., 1997; Aro and Fatehi, 2017). Lignosulfonates are commercially available as sodium and calcium (Elumalai and Pan, 2011; Calvo-flores *et al*., 2015). Sodium lignosulfonates usually have a lower viscosity compared to calcium lignosulfonates; this is because sodium has a stronger electrokinetic repulsive force which increases repulsion thereby reducing viscosity (Madad *et al*., 2011). Sulfonation of lignin causes the bonds between lignin-lignin and lignin-polysaccharides to break thus, reducing the molecular weight of the lignin. Due to this process, lignosulfonates are anionically charged and are water soluble (Flatt and Schober, 2012; Aro and Fatehi, 2017). Lignosulfonates anion charge exert electrostatic repulsion thereby, enhancing it's application as plasticizers or water reducers to improve concrete quality (Huang *et al*., 2018).

Lignosulfonates are highly branched macromolecules composed of propylphenol side chains connected irregularly by ether or C–C bonds attached to aromatic rings (Fig. 2) (Flatt and Schober, 2012). During pelleting process, the application of pressure increase interparticle contact thus, promoting interparticle attraction between close particles through weak van der Waals forces (Rumpf, 1962). Particle deformation caused by the application of pressure results in smaller particles filling the voids between larger particles, this may contribute to mechanical interlocking between close particles (Strydom *et al*., 2018). Thus, improving pellet durability.

Due to their unique properties, lignosulfonates have a vast range of applications and are used as binders, emulsifiers and dispersants in the feed and construction industry. (Macfarlane *et al*., 2014; Aro and Fatehi, 2017). They are non- hazardous; thus, lignosulfonates are suitable for use as binders in animal feed (Acar *et al*., 1991; Macfarlane *et al*., 2014).

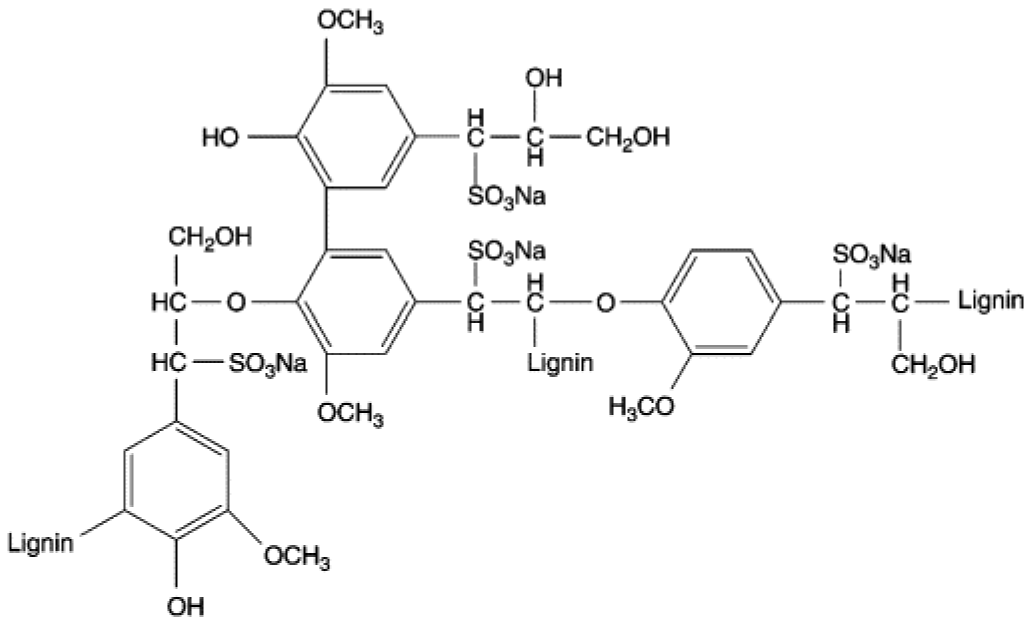

Figure 2: Structure of a lignosulfonate molecule (Flatt and Schober, 2012)

Lignosulfonate is often used as binder in pelleting animal feeds. Inclusion of calcium lignosulfonate (CaLS) in broiler's diet increased pellet durability index (Corey *et al*., 2014). Also, Acar *et al*. (1991), investigated the effects of CaLS on pellet quality and observed improved duraability when CaLS was used as a binder.

0.5% CaLS enhanced pellet quality with different levels of fat and have shown to increase the physical pellet quality with high levels (3%) of Soybean oil compared to (1.5%) low levels of oil (Abadi *et al*., 2019). In addition, Corey *et al*. (2014), demonstrated that pellets manufactured with 0.5% CaLS and diet containing 3% mixer added fat optimized digesta viscosity, improved pellet quality and true amino acid digestibility. However, when CaLS was used with diets containing calcium fat powder it showed no significant improvement in the physical quality of the feed pellet (Abadi *et al*., 2019). Broilers fed diets manufactured with CaLS increased feed consumption and live weight gain (Corey *et al*., 2014; Acar *et al*., 1991). CaLS inclusion to broilers diet increased feed conversion ratio (Acar *et al*., 1991). Conversely, Corey *et al*. (2014) reported decreased feed conversion ration when CaLS inclusive diets were fed to the birds. The difference is probably due to variable feed formulation used in manufacturing the bird's diets.

Overall, CaLS independently reduced energy use of the pellet mill when used in the extruder (Corey *et al*., 2014).

2.5.4 *Clay minerals*

Clays are naturally occuring fine-grained minerals containing hydrous aluminium phyllosilicates that imparts plasticity when wet and harden upon drying (Guggenheim and Martin, 1995). Clays like bentonite and sepiolite are used as binders in producing animal feed (Tabil, 1998).

2.5.4a *Bentonite*

Bentonite is an aluminium phyllosilicate clay principally composed of montmorillonite as the mineral constituent (Tabil *et al*.,1997; Moosavi, 2017). Also, bentonite is a smectite clay minerals, which contributes greatly to the properties of bentonites, especially swelling (Xie *et al*., 2004). Bentonites have excellent rheological and absorbent properties. In addition, bentonite has excellent plasticity and lubricity, high dry bonding strength, high shear and compressive strength, good impermeability and low compressibility property. Their high swelling capacity contributes to its ability to form gel-like masses in the presence of moisture (Al-Ani and Sarapää, 2008). Bentonite expands when water is added due to hydration/ adsorption of interlayer cations(Na^+ and Ca^{2+}) (Reisch, 2000). After expanding, they disperse in water and form a thin adsorption layer to coat the surface of particles like a gel contributing to its effectiveness as a binder (Kawatra and Ripke, 2001). Bentonite acts a filler and reduce porous space in feed pellets (Thomas *et al.*, 1998). Based on these unique properties, bentonite is used as a binder in iron ore and feed industry (Christidis and Scott, 1996).

Inclusion of sodium bentonite in feed formulation improves Pellet Durability Index (PDI) and pellet hardness. (Moradi *et al*., 2019). A study by Attar *et al*. (2018) showed that 2-min steam conditioning of a diet containing 15 g/kg sodium bentonite increased PDI and hardness. Diets containing 15 g/kg processed sodium bentonite (PSB) and conditioned for 2 minutes significantly increased PDI and hardness. Abdollahi (2011) observed improved pellet durability and hardness through steam conditioning. According to Attar *et al*. (2018), the moisture quantity and time in the conditioner may have increased starch gelatinization thereby ameliorating pellet quality. The ability of sodium bentonite to improve pellet hardness depends on the inclusion rate, pellet diameter and length (Moradi *et al*., 2019). Based on this, Moradi *et al*. (2019), suggested that increasing pellet lengths and dosage of sodium bentonite to 20 g/kg sufficiently prevent how high amount of oil negatively influence pellet hardness.

Hence, using high quantities of oil in commercial feed production requires a higher inclusion rate of bentonite to improve pellet quality(Attar *et al*., 2018). Also, adding 2% of bentonite to diets containing high levels of fat is ineffective to alter PDI but with low levels of fat (1.5 %), it improved pellet quality (Abadi *et al*., 2019). Pellet durability was not affected by addition of bentonite to formulations which contained 0 or 9% added fat, but it improved pellet durability at fat inclusion levels of 3% and 6% (Salmon, 1985).

2.5.4b *Sepiolite/Palygorskite*

Sepiolite is a hydrated magnesium silicate (Si12Mg8O30(OH2)4(OH)4) belonging to the group of phyllosilicates (Parisini *et al*., 1999; Ouhida *et al*., 2000; Yalçına *et al*., 2017). Structurally, sepiolite are made of two parallel layers of silicon tetrahedra connected with a layer of magnesium octahedra. Both palygorskite and sepiolite are hydrated magnesium aluminium silicates. Sepiolite has higher magnesium content than palygorskite and has a slightly larger unit cell size. Palygorskite and sepiolite are both thin elongate chain type structures. The elongate structures are immobile and non-swelling when dissolved in water resulting in formation of a random network capable of trapping liquid and providing excellent thickening, suspending, and gelling properties (Al-Ani and Sarapää, 2008). These clays are stable at high temperatures, unaffected by electrolytes thereby retaining their viscosity Both palygorskite and sepiolite are used as a binder for pelleted animal feed (Al-Ani and Sarapää, 2008). Naturally, both palygorskite (Al-Ani and Sarapää, 2008) and sepiolite are a feed additive used as a binder or lubricant (Parisini *et al*., 1999; Yalçına *et al*., 2017) as a result of its physical and chemical properties (Ouhida *et al*., 2000).

Incorporation of sepiolite as a pellet binder in rabbit and broiler feeds increases pellet durability. Sepiolite is used as a pellet binder to improve durability, especially in high fat diets (Angulo *et al*., 1995). Adding sepiolite to broilers starter diet with 25g/kg of added fat improves pellet durability. Although, inclusion to diets containing high levels of fat (50g/kg) did not minimize the negative influence of fat pellet quality. Using a higher amount of sepiolite with diets containing high levels of fat reduced the negative effect of fat on pellet quality (Angulo *et al*., 1996). 20 g/kg of sepiolite products can be used to produce feeds for all animal species as it helps in feed component hydrolysis (Parisini *et al*.,1999) .

2.5.5 *Agar*

Agar is a hydrocolloid composing two galactose-based polymers, agarose and agaropectin (Fig. 3) (Stringer, 2005; Carballeira and Sinisterra, 2009). Agarose has the greatest gelling capacity compared to agaropectin. Primarily, agar is obtained from the cell wall of red algae Gelidium and Gracilaria as an amorphous and translucent product (Fabbrocini *et al*., 2012) consisting repeating units of l-galactose and 3,6-anhydro-l-galactose with low degrees of sulfonic groups. (Carballeira and Sinisterra, 2009). It is insoluble in cold water but solubilizes in hot water at 40°C and forms gel at a temperature lower than its melting point (~38°C). (Stringer, 2005; Carballeira and Sinisterra, 2009; Fabbrocini *et al*., 2012). Dissolving agar powder in boiling water and then cooled to room temperature, forms a reversible elastic and turbid gel network (Labropoulos *et al*., 2001).

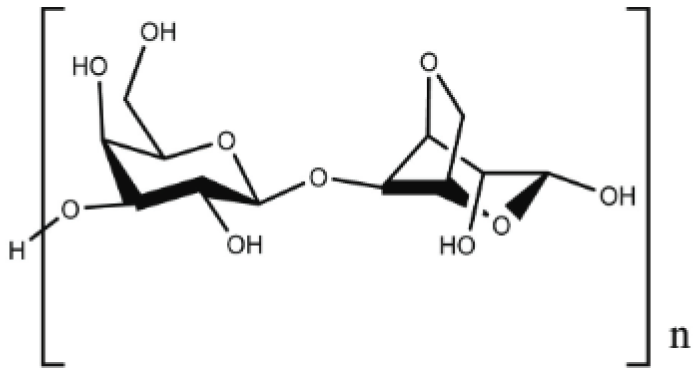

Figure 3: Chemical structure of agar (Shahidi and Rahman, 2018)

Due to its unique properties as a clarifying, thickening and gelling agent, it is applied in the feed, food, pharmaceutical and cosmetic industry. Agar is used as a food/feed binder due to its structure, rheological behavior and stability.

Agar as a food binder in algae-based diets generates firm pellets. Fabbrocini *et al*. (2012) found that pellets containing 3% agar maintained water stability up to six days without affecting nutrient absorption in the sea urchins. Agar is recommended as a binder where the water stability of the feed pellets is required beyond 8 hours (Ali, 1988). Fabbrocini *et al*. (2012) study indicated that agar limited nutrient leaching in algae-based diets for sea urchins. This is attributed to its insoluble property.

In contrast, when Argüello-Guevara and Molina-Poveda (2013) evaluated the effect of six different binding agents (agar, sodium alginate, cassava starch, gelatin, wheat gluten and kelp meal in 30g/kg and 50g/kg concentration. Agar diets presented more disintegration and decreased water stability at both concentration. Also, agar performed poorly with pellet stability and durability when compared to Carrageenan and CMC (Ruscoe *et al*., 2005).

The discrepancies in these studies might be as a result of different factors in manufacturing the pellets and feed formulations.

2.5.6 *Carboxymethylcellulose*

Carboxymethylcellulose (CMC) is an anionic, water soluble, cellulose derivatives with carboxymethyl groups. Structurally, the carboxymethyl groups connected to hydroxyl groups of the glucopyranose monomers forms the cellulose polymer (Paolucci *et al*., 2012).

CMC hydrates rapidly due to its ability to absorb water (Thomas *et al.*, 1998). Its ability to dissolve in water at any temperature depends on the polymerization rate, substitution rate and how evenly the substitution is distributed. Hence, increase in the rate of polymerization and decrease in the substitution rate and uniformity enhances water solubility of CMC (Ergun *et al*., 2016) The rate of polymerization, concentration, ionic strength and pH affects viscosity of CMC (Paolucci *et al*., 2012; Ergun *et al*., 2016). Thus, as polymerization rate increases, the viscosity increases with increase in concentration.

Also, at high concentration, CMC forms a thermoreversible gel. In addition, increasing ionic strength and decreasing pH causes viscosity to reduce (Paolucci *et al*., 2012). CMC is an organic binder used in the iron ore, food and feed industry (Ergun *et al*., 2016; Van der Merwe and Garbers-Craig, 2017). Using attenuated total reflectance infrared spectra (ATR-FTIR) and light microscopy (LM) to analyze the binding mechanism of CMC, it was observed that compaction of particulates develops ionic attraction or electrostatic forces between the CMC and particulates leading to high cohesion strength of the pellets (Thomas *et al.*, 1998; Si *et al*., 2016). When CMC is dissolved in water, hydrogen bonds are formed due to the reaction between electric dipole from water molecule and OH groups on the CMC. Also, strong bonds are formed at the interface of the solid particles and CMC. Electrostatic bond, hydrogen bond and the strong bond increases inter-particle bonding. As a result, pellets with better product quality are produced (Si *et al*., 2016).

Adding CMC solution to compression process of cotton stalks and wheat straw significantly increases pellet quality. However, when it was added to rape straw it decreased the pellet quality probably because rape straw contains lots of extractives (Si *et al*., 2016). These extractives contain

40- 45 % oil (Von Der Haar *et al*., 2014) that have high amount of long fatty acid chain which prevents binder viscous effects. It might also be due to the oleo-phobic properties of CMC which reduces the adhesive force and van der Waals force between particles resulting in low bonding effect and leading to weak pellet quality. It is therefore not advisable for CMC to be used as a binder for pelleting materials rich in extractives (Si *et al*., 2016).

Ruscoe *et al*. (2005) observed that Shrimp diets bound with carrageenan and CMC retained significantly more dry matter than diets bound with agar and gelatin. Thereby, supporting that diets containing CMC solution improves pellet quality and prevents nutrient leaching.

2.5.7 *Guar gum*

Guar gum is a water soluble macromolecule obtained from the endosperm of guar beans seed (Cyamoposis tetrugonobbus). Guar gum is a galactomannan polysaccharide consisting of ~-~,4-D-mannose with galactose side chain (Fig. 4). Guar gum can hydrate in cold or hot water and the hydroxyl (-OH) groups forms a strong hydrogen bond liable for its viscous property even at low concentration. (Storebakken,1985; Paolucci *et al*., 2012). The presence of the hydroxyl group is responsible for the hydrogen bonding activity (Mudgil *et al*., 2004). Substituting the hydroxyl groups in guar gum with hydroxypropyl may prevent intermolecular arrangement thus, hydrogen bonds stability is decreased (Cheng and Prud'homme, 2002). Viscosity and hydration rate of guar gum is affected by temperature, pH, particle size, concentration (Mudgil *et al*., 2014). Hydration rate reduces when dissolved salt and other binding agent(sucrose) is present in guar gum solution (Bemiller and Whistler, 1993). Based on its non-ionic and uncharged behaviour, guar gum solution is stable over a wide range of pH(1.0-10.5). Higher temperature gives better viscosity. For maximum viscosities, Mudgil *et al*. (2014) suggested using temperature range of 25–40 °C.
Due to its viscous nature, it is beneficial as a thickener and stabilizer in the feed, food, pharmaceutical and cosmetics industry.

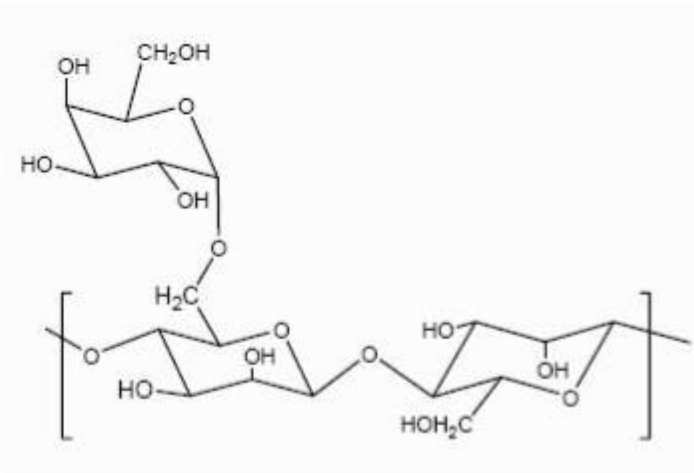

Figure 4: Chemical structure of guar gum (Manjanna, 2010)

Guar gum as a binder in processing shrimp feed pellets showed average values of stability(Ali *et al*., 2005; Ali *et al*., 2010). Dominy *et al*. (2004) observed guar gum inefficacy to produce pellets with good water stability. However, increasing pelleting temperature reduces leaching and disintegration of pellets leading to a 9% decrease in water turbidity of pellets made with guar gum(Ali *et al*., 2005; Ali *et al*., 2010).   Hence, water stability of guar gum bound diets maybe increased by increasing pelleting temperature. Caltagirone *et al*.,(1992) also suggested increasing guar gum concentration to improve its stability. When used in a pellet mill for processing shrimp feed pellets, guar gum is able to absorb high moisture content which is suitable for feed processing and contributes to better pellet quality. (Ali *et al*., 2005; Ali *et al*., 2010). The water stability of guar-gum bound diets can also be increased by combining guar gum with starch.

Guar gum combined with various starch sources showed good water stability and reduced leaching and disintegration. The viscous property of gums increases starch granule swelling during gelatinization thereby improving starch viscosity. For instance, wheat starch viscosity increases by adding low content of polysaccharide gums (Christianson *et al*., 1981). Also, using 2% guar gum with maida flour/wheat flour in feed production immensely improves water stability of pellets. However, utilizing more than 2% level of guar gum in feed had no effect on water stability. (Ali *et al*., 2005).

2.5.8 *Gelatin*

Gelatin is a protein obtained by partial hydrolysis of collagen. Collagen is a protein component derived from the bone, skin, tendon and connective tissue of animals (Pope, 1992). Two types of gelatin are classified based on the manufacturing process. They are known as Type A gelatin with isoelectric point at pH 8–9 extracted from acidic hydrolysis of pork skin. On the other hand, Type B gelatin with isoelectric point at pH 4–5 is extracted from alkaline hydrolysis of bones and animal skin (Paolucci *et al*., 2012; Gómez-Guillén *et al*., 2011). Type A improves the blend viscoelasticity while Type B increases the gel strength. The viscosity of gelatin depends on the type of gelatin, concentration, temperature, and time.

Gelatin is a digestible protein composed of amino acids(except tryptophan) and it is soluble in water (Gómez-Guillén *et al*., 2011; Paolucci *et al*., 2012). Gelatin is solubilized by soaking in cold water and stirring under heat until it reaches 35°C, it is then allowed to cool after heating. This interaction leads to the formation of gel (Djagny *et al*., 2001). Due to exposed polar regions, gelatin in aqueous food process promotes the formation of hydrogen bond with water. As gelatin binds with water, it swells and absorbs water. It can then be dispersed in hot water and with other ingredients. High concentration of gelatin increases the rate of gelation, thereby increasing the gel strength (McWilliams, 2001)

The gel strength, viscosity, setting behaviour and melting point of gelatin depend on their molecular weight distribution and the amino acid composition, the imino acids (proline and hydroxyproline). The imino acids are essential in the renaturation of gelatin crystals during gelling. As a result, high gel strength and melting point of gelatin is attributed to high levels of amino acids (Johnston-Banks, 1990).

Gelatin is a hydrocolloid used as an emulsifier, foaming, gelling, thickening or stabilizing agent. Based on these properties, gelatin is used in the food industry and pharmaceuticals. Its application in the feed industry is majorly because of its gel forming ability. (Gómez-Guillén *et al*., 2011; Paolucci *et al*., 2012).

Eric De Muylder *et al*. (2008) recognized that gelatin-based binders are a good alternative to gluten and urea formaldehyde in producing stable pellets. Also, a combination of gelatin with tapioca starch produces hard pellets with good pellet quality properties (Eric de Muylder *et al*. 2008). Using high levels of gelatin in feed production is ineffective and results in pellets with poor quality. Therefore, carefully selecting the right amount for feed formulation is important (Ali, 1988).

2.5.9 *Alginate*

Alginate is salt of alginic acid obtained from the cell wall of brown seaweed. It is available as a matrix of calcium, magnesium, and sodium salt (Sharmeen *et al*., 2019; Pereira and Cotas, 2020). Alginate is an anionic polymer linked with 1,4 D-mannuronic and L-guluronic acid (Fig. 5) (Storebrakken, 1985; Lee and Mooney, 2012).

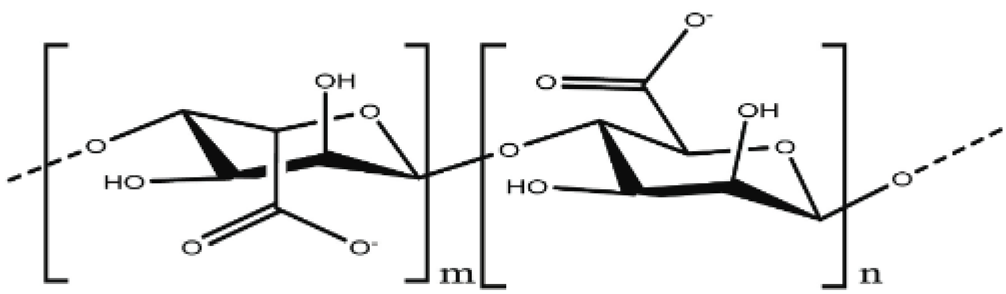

Figure 5: Chemical structure of alginate (Shahidi and Rahman, 2018)

The presence of bipolar ions, -OH and -COOH groups of the molecules contribute to its ability to form gels and are responsible for its unique properties. Also, alginate has a high water absorption rate (Storebakken, 1985; Tariverdian *et al*., 2019). Alginate exhibit high viscosity at low concentration.The viscosity of alginate is affected by molecular weight, concentration, temperature, pH and calcium ion (McHugh, 1987). The presence of Ca^{2+} in alginate solution increases viscosity. Gel formation is achieved by ionic cross linking with cation or with acid precipitation. Alginate reacts with many di- and trivalent cations such as $Ca^{2+}$to form gels (Ching *et al*., 2017). Alginate is used as gelling agents, thickeners and stabilizers in the food, pharmaceutical, and cosmetic industries (Pereira and Cotas, 2020).

By investigating the effect of 50g/kg sodium alginate and 50g/kg wheat gluten or kelp meal independently on the quality of shrimp feed pellet, sodium alginate showed the best water stability performance, water absorption and protein leaching after 180- min immersion (Argüello-Guevara and Molina-Poveda, 2013). It also retained 88% of dry matter (DM) after 60min of immersion and 83% of DM after 180min immersion in water. Thus, it has the ability to maintain pellet integrity for a long period of time (Argüello-Guevara and Molina-Poveda, 2013). In agreement, Ali (1988) suggested using sodium alginate to produce pellets with water stability beyond 8hrs.

Ruscoe *et al*. (2005) tested how various binders and moisture content affect pellet stability of freshwater crayfish diet. It was observed that pelleted alginate diet was significantly more stable than the pelleted carrageenan diet in both moist and dry feed. However, pelleted dry alginate diets were more stable than pelleted moist alginate diets. Generally, dried diets containing (10% moisture) retained more dry matter than moist diets containing (50% moisture). It is possible that the drying causes more gelatinization of starches resulting in better binding properties. Additionally, moisture present in a moist diet allows fast re-hydration while re-hydration occurs slowly in a dry diet due to less moisture hence increases dry matter retention(DMR). Alginate showed good binding properties compared to carrageenan when used to produce fresh crayfish feed (Ruscoe *et al*., 2005).

Compared with polysaccharides like pectin and chitosan, alginate binders performed poorly in freshwater crayfish diets. The diet water stability was analyzed using low angle laser light scattering technique to monitor the diameter of released particles within 24hrs of water immersion. Alginate based diets released particles with a small diameter causing them to disintegrate more than other binder-based diets (Volpe *et al*., 2012). It is probably because other binders used in this experiment had high binding properties when used in crayfish feed compared to Alginate.

2.6.0 *Pectin*

It is a natural polymer of D- galacturonic acid that contains methyl ester groups and occur as structural materials in plants (Fig. 6). Pectin is a complex polysaccharides present in most plant pectins (Rollin and De Vries, 1990). Classification of pectin is based on the degree of esterification(Gawkowska *et al*., 2018). High-methoxyl (HM) pectins have over 50% of their carboxyl groups esterified with methanol while esterification of carboxyl groups in low-methoxyl (LM) pectins is between 5- 50% (May, 1990; Baron *et al*., 2016). Viscosity and gelling ability of pectin is influenced by source and method of extraction (Gawkowska *et al*., 2018). In HM pectin, the reaction of hydrogen bonds and hydrophobic interactions between pectin molecules in the presence of sugars and acids result in the formation of thermo irreversible gel formation. In LM pectin, gel is formed when Ca2+ ions create ionic linkage between two different carboxyl group thus forming thermo-reversible gel (Thakur *et al*.,1997). Commercial pectin is obtained from citrus peel or from apple pomace due to the good gelling properties of pectin from this source (Rollin and De Vries, 1990; Thakur *et al*.,1997).

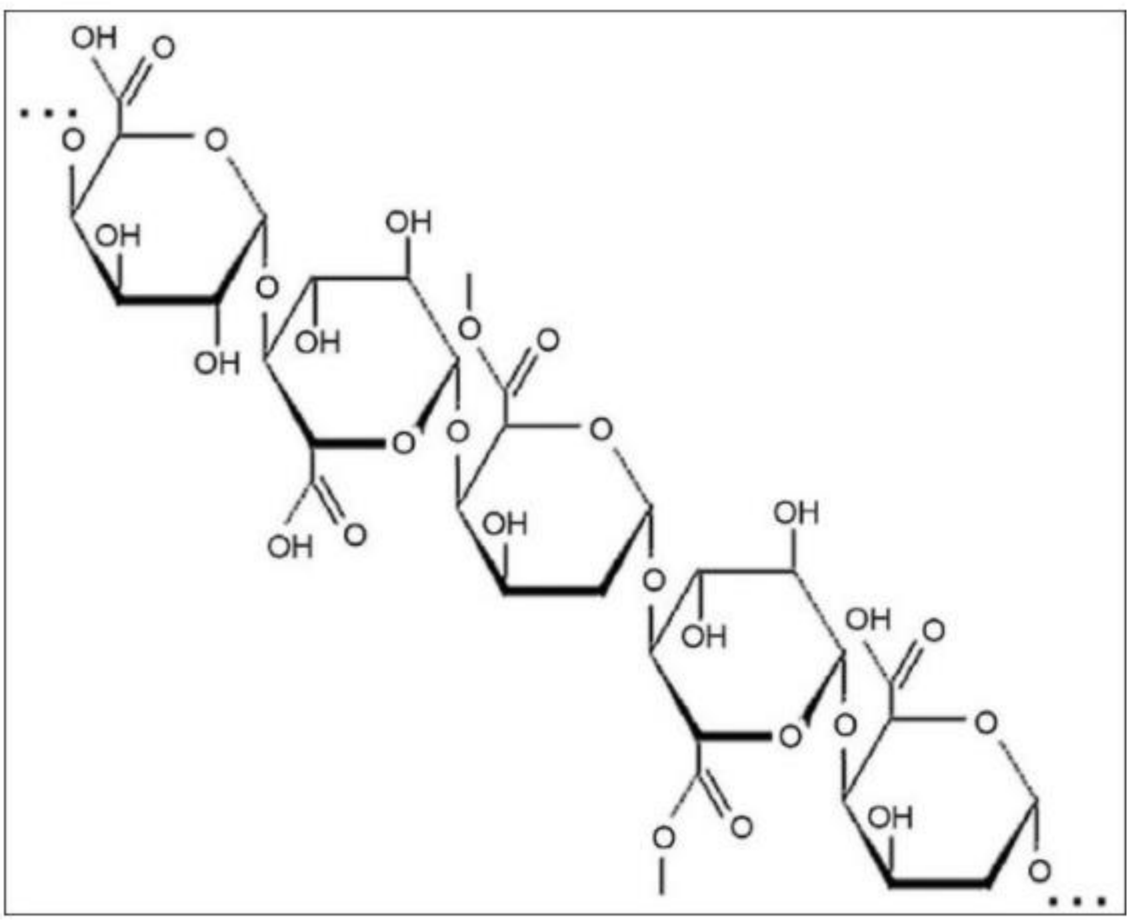

Figure 6: Chemical structure of pectin (Shendge *et al*., 2014)

The properties of pectin to form gel is influenced by the degree of esterification/methylation, pH, presence of other solutes, molecular size, number and arrangement of side chains, and molecule charge density (Thakur *et al*.,1997). It is able to form gel in the presence of Ca^{2+}, sugar or acids at low pH values and gel strength depends on Ca^{2+}concentration, temperature and acidity (Paolucci *et al*., 2012; Thakur *et al*.,1997). The viscosity of pectin solutions and gel formation depend on their solubility.(Gawkowska *et al*., 2018). Pectin solubility increases when the degree of methylation increases but decreases when polymer size increases (Sila *et al*., 2009). High concentration increased viscosity but viscosity decreased when temperature increased. High pectin concentration may reduce intermolecular distances and increase intermolecular interactions such as hydrogen bonding. As temperature increases the molecules kinetic energy of molecules increases as a result, intermolecular distances also increase and viscosity declines (Kar and Arslan, 1999). Its application in the food and feed industry is based on the gelling property.

Producing pellets with pectin by cold extrusion improves pellet water stability and acts as energy source to enhance growth rates and weight gain in farmed crayfish (Volpe *et al*., 2012).Thus, pectin can be employed for producing good quality pellets mainly for crayfish feed.

2.6.1 *Carrageenan*

Carrageenan is a group of sulfated galactan derived from red seaweeds extracted by water or aqueous alkali. It contains 15 to 40% ester-sulfate and it’s formed by galactose and 3,6 -anhydrogalactose copolymers and are alternately connected by α-1,3 and β-1,4-glycosidic linkage (Fig. 7) (Therkelsen, 1993; Necas and Bartosikova, 2013).

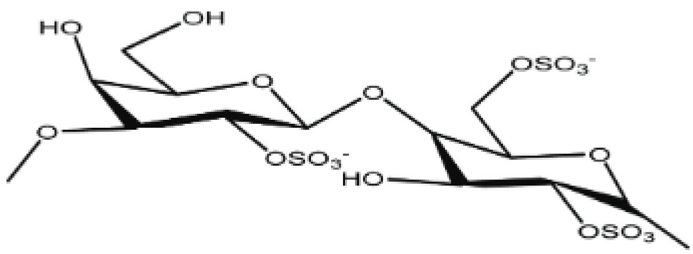

Figure 7: Chemical structure of carrageenan (Shahidi and Rahman, 2018)

Carrageenan is classified into various types such as kappa, iota, lambda. The physical properties of these carrageenans are based on its solubility in potassium chloride. Kappa and iota carrageenans are able to form gel in the presence of potassium or calcium ions while lambda carrageenan is not capable (Stanley, 2011). Commercially, carrageenan is chiefly available as sodium potassium and calcium salts (Therkelsen, 1993; Paolucci *et al*., 2012).
Carrageenan is a hydrocolloid that is water soluble and has a gelling and viscous property. It contains 15 to 40% ester sulphate content (Therkelsen, 1993; Paolucci *et al*., 2012). The gel strength depends on the amount of ester sulfate. High content of ester sulfate reduces its solubility and temperature as a result, gel strength is reduced. Also, viscosity is increased by high concentration and reduced by temperature (Paolucci *et al*., 2012; Necas and Bartosikova, 2013). At high temperatures and low pH below its functionality is reduced. Application of carrageenan depends mainly on their rheological properties (Therkelsen, 1993).

Ruscoe *et al*. (2005) observed that shrimp diets bound with carrageenan increased dry matter retention than diets bound with agar and gelatin. Also, carrageenan acts as a binder and an energy source when used in shrimp diet thereby improving water stability and the shrimp growth. Compared with binders like CMC, carrageenan produced pellets with the best quality property.

3.0 Effect of binders on growth and digestibility

Understanding how binders affect animal growth and digestibility is important in formulating feed. Low concentration may affect the physical pellet quality while high concentration may cause a reduction in diet/nutrient digestibility.

3.0.1 *Poultry*

Poultry birds need quality pellets that contribute to nutrient availability to improve growth and digestibility. Hence, binders that hinders nutrient availability may be detrimental to poultry growth and digestibility. Therefore, it is necessary to know how binders work in a broiler's diet to influence growth and digestibility.

Acar *et al*. (1991) investigated the effect of CaLS bound pellets on broilers diets and found that CaLS does not affect the Crude Protein(CP), Apparent Metabolizable Energy (AME) and amino acid content of the diet. On the other hand, augmenting broiler diets with 1 or 2 g/kg of montmorillonite (a bentonite mineral) loaded with Copper (Cu) promotes broilers growth performance through ion exchange with Cu2þ. Additionally, it enhanced intestinal morphology and increases enzyme activities in intestinal mucosa and digesta. Sepiolite reduces digesta viscosity and increases digesta retention time thereby, promoting enzymes activity (Ouhida *et al*., 2000). Consequently, increasing digestion and absorption feed nutrients in broilers, as a result, feed efficiency and broilers body weight are improved (Ma and Guo, 2008).

Conditioning time and pellet binder may contribute to nutrient availability for villi development thereby, improving nutrient absorption. As a result, broilers growth performance is enhanced (Attar *et al*., 2018). Based on Attar *et al*. (2018) study, 2 min conditioning of 7.5 or 15 g/kg sodium bentonite bound diet, improved nutrient retention of broilers and influenced broilers growth performance. In addition, adding 2% sepiolite into broiler diets improved growth performances and feed efficiency (Ayed *et al*., 2011).

3.0.2 *Farmed aquatic organisms*

Addition of binder aids pellet quality, stability and retains nutrients for easy ingestion. Nutrients accessibility by farmed aquatic organisms is key to improving growth and digestibility. Some binders promote nutrient accessibility because there is a balance between water absorption and nutrient retention. Binders that have moderate water absorption level will soften pellets (Argüello-Guevara and Molina-Poveda, 2013) for easy access to nutrients without much nutrient leaching. Other binders may hinder nutrient accessibility because they form very hard pellets that retain nutrients through gel matrix formation (Dominy *et al*., 2004). Hence, it is essential to know how binder influences growth and digestibility of different aquatic organisms.

Pectin fed crayfish exhibited high enzyme (amylase) activity in the intestine resulting in better weight gain and growth rate of crayfish. In farmed crayfish *(Cherax albidus)*, pectin facilitated growth improvement by acting as a supplementary energy source (Volpe *et al*., 2012).

Alginate seems to improve growth performance in sea bass larvae(*Dicentrarchus la*brax) (Person Le Ruyet *et al.,* 1993) and farmed crayfish (*Cherax albidus)* (Volpe *et al.,* 2008; Coccia *et al*., 2010). However, octopus fed with 1% alginate-bound diet showed negative effects on their growth and weight. This is because digestion of alginate is limited in octopus due to lack of amylase enzyme (Aguila *et al*., 2007) that helps with digestion and nutrient absorption of diets (Rosas *et al*., 2008).Moreover, alginate has shown to reduce growth and digestibility in barramundi (*Lates calcifer*) (Partridge & Southgate, 1999), lobster juveniles (Simon, 2009) and shrimp diets (Argüello-Guevara and Molina-Poveda, 2013). According to Argüello-Guevara and Molina-Poveda (2013) alginate bound diets prevent loss of amino acids and other attractants in the diet that might decrease feed intake especially for shrimp that are chemoreceptors. In agreement, Morales *et al*. (1993) observed that using sodium alginate as binders in rainbow trout diet did not influence feed intake.

In a similar phenomenon, alginate and guar gum reduce the feed intake and apparent digestibility of crude protein and lipid in rainbow trout (Storebakken, 1985). Guar gum is able to retain essential nutrients in diets due to gel matrix formation (Dominy *et al*., 2004). This sometimes makes it difficult for the fish to access essential nutrients in the diet thereby reducing digestibility.

To improve growth and digestibility, we can combine alginate and guar gum with other binders like wheat gluten. Independently, wheat gluten can improve growth and digestibility (Argüello-Guevara and Molina-Poveda, 2013) because it increases the nutritional value of diets. For instance, using 50g/kg of sodium alginate and wheat gluten in the shrimp diet increased feed conversion ratio thereby enhancing growth rate and digestibility (Argüello-Guevara and Molina-Poveda, 2013). In the same way, combining guar gum, wheat gluten and vegetable wax resulted in better feed conversion ratio, weight gain, growth rate thus improving shrimp performance (Dominy *et al*., 2004).

In lobster juveniles (*Jasus edwardsii*), gelatine enhanced digestibility at 7-8% inclusion level (Simon, 2009) by promoting nutrient absorption (Rosas *et al*., 2008). Although agar decreased diets digestibility in lobster juveniles (Simon, 2009), it significantly increased weight in juvenile shrimp (*Palaemonetes varians* and *Palaemon elegans*) (Palma *et al*., 2008) and growth in farmed crayfish (Volpe *et al*., 2008; Coccia *et al.*, 2010).
Using CMC as binders enhanced digestibility in lobster juveniles (Jasus edwardsii) (Simon, 2009). On the contrary, in fingerling Japanese flounder, CMC inclusive diets resulted in inferior weight gain, feed efficiency, protein digestibility, protein and energy retention compared to diets containing starch or wheat gluten. CMC increased diets viscosity and decreased proteolytic enzymes' activities leading to poor growth performance (Yamamoto and Akiyama, 1995).

Overall, adding clay minerals (silica, cellulose or a natural zeolite) in European sea bass juveniles diets does not influence protein digestibility, growth and feed ingestion (Dias *et al*., 1998).

4.0 Discussion

Various binders have different effects on growth and digestibility of different animal species. They also have limited inclusion levels for optimal pellet quality and functions in different species. For instance, exceeding or limiting the optimal inclusion level could affect digestibility in crab feed. High amount of binders could increase pellet hardness to an extent that it is difficult for the crab to access the pellet nutrients thus decreasing digestibility. Crab’s feed made with 10% bread flour increased the level of crude protein digestibility while that of crude fat was reduced (Catacutan, 2017). As explained by Catacutan (2017), it’s possible that 10% bread flour is not sufficient enough to bind the crude fat sources compared with protein sources, thus leading to leaching of fat components in the feed. Also, Orire *et al*. (2010) found that using 5%

level Yam starch as a binder for fish feed minimized dust level, improved pellet qualities, water stability and hardness. It was observed that inclusion level at 20% yields less dust but did not increase the pellet quality. Probably, high levels of starching the pellets agglutinate as a result of overbinding (Orire *et al.*, 2010). Consequently, knowing the binder type and inclusion level appropriate for different animal species is paramount in selecting binders.

Natural binders like wheat flour add nutritional value to diets but it is required in high levels (200g/kg) to give adequate pellet quality and stability. Nonetheless, while pellets produced might have moderate hardness and durability, its stability is usually low compared to other types of binder. Hence, it is essential to add a modified or synthetic binder to a natural binder when used to produce pellets with high stability.

4.1 ***Lignosulfonate***

In turkey/poultry diet, incorporating 0.5 % lignosulfonate binder improved pellet quality (Abadi *et al*., 2019) and enhanced amino acid digestibility from 4-7%. A possible explanation is that adding lignosulfonate as pellet binder in diet had no effect on conditioner electrical energy usage but reduced pellet mill electrical energy use and hot pellet temperature (Wamsley and Moritz, 2013; Corey *et al*., 2014; Miladinovic and Salas, 2014). Generally, high conditioning temperature is not necessary to activate lignosulfonate binding potential (Cecilia, 2008). Based on this, heat-labile nutrients can be preserved.
Furthermore, 0.5 % lignosulfonate inclusion into diets made with finely ground barley decreased power consumption but increased power consumption for coarse ground barley. Nonetheless, at a higher inclusion level of 0.65%, the power consumption for both particle sizes increased (Miladinovic and Salas, 2014). Lignosulfonate(LS) affinity for water and ability to dissolve readily (Cecilia, 2008) causes it to bind with water molecules thus reducing water activity, this reduces the lubricating effect of the bound-water molecules thereby increasing power consumption. To minimize power consumption, more water contents can be added (Miladinovic and Salas, 2014). Calcium Lignosulfonate (CaLS) improves pellet quality by acting as a filler of feed particles pores. It becomes liquid during steam conditioning and hardens upon drying. As a result, pellet quality is ameliorated. Another reason is that CaLS functions as a dispersing agent

and maintains feed particles' rheological properties during pellet extrusion (Ouyang *et al.*, 2006). Lignosulfonate also reduces fats' negative impact on pellet quality (Cecilia, 2008; Abadi *et al*., 2019)

4.2 *Clay minerals*

In the cattle feed diet, adding 1-1.5% sepiolite as a binder improved physical pellet quality. It improves pellet durability and lowers energy consumption in dairy cattle feed and fattening cattle feed. At 1.5% inclusion level, sepiolite increased moisture content after conditioning and improved the feed's lubricating effect thus, reducing energy consumption. Although, the moisture content is relative to the amount of sepiolite added (Yalcin *et al*., 2019).

Incorporating sepiolite reduces pellet production time in fattening cattle feed production. But the pellet production time was the same in dairy cattle feed. Perhaps, the ingredients and chemical composition of diets contribute to the difference in production time (Yalcin *et al*., 2017b). In addition, incorporating 1% sepiolite in broiler starter diets reduced pellet production time and enhanced pellet durability index (Galán, 1996; Durna *et al.,* 2016; Yalcin *et al*., 2018). However, in layers diets, the pellet production time was not affected but energy consumption was decreased (Yalcin *et al*., 2018). It is probably because the broiler diet and layers diet have different feed formulation and chemical composition. Sepiolite improves pellet durability by acting as a filler and decreasing the porous space in the pelleted feed (Yalcin *et al*., 2017a). In addition, it is essential in improving pellet quality with high fat and fiber levels (Angulo *et al*., 1995).

Similarly, pellets made with 1% palygorskite (a clay mineral with similar physical properties to sepiolite) improved pellet quality and growth performance of broilers(Pappas *et al*., 2010; Zhang *et al*., 2017). Sepiolite and palygorskite absorb polar liquid and form gel during the pelleting process thus, improving pellet quality. The improvement in pellet quality is caused by the increase of solid-solid bonding interaction (Pappas *et al*., 2010; Zhang *et al*., 2017; Yalcin *et al*., 2017a).

Bentonite also gave better pellet quality (Moradi *et al.*, 2019) and decreased pellet press energy consumption by acting as a lubricant in the die hole (Thomas *et al*.,1998). The quantity of bentonite and sepiolite used in producing pellets is usually relative to the quantity of oil in the diets (Attar *et* *al*., 2018; Moradi *et al.*, 2019). A 2% inclusion level of bentonite is recommended in producing broilers feed (Moradi *et al.*, 2019).

Overall, clay minerals have sorptive and rheological properties enabling improvement in pellet quality (Galan, 1996; Liu, 2007; Zhang *et al*., 2017).

4.3 *Agar*

Polysaccharides such as agar, alginate, pectin, gelatin, carrageenan and guar gum are suitable as a binder for aquaculture diet. They form hydrogels and have the ability to entrap nutrients in a three-dimensional network thus, improving feed hardness and stability (Paolucci *et al*., 2015; Volpe *et al*., 2015). Agar-bound diets with 2% concentration have high stability in water, low water absorption and nutrient leaching rate (Paolucci *et al*., 2015). Fabbrocini *et al*. (2012) found that pellets containing 3% agar maintained water stability up to six days without affecting nutrient absorption in the sea urchins. Agar is recommended as a binder where the water stability of the feed pellets is required beyond 8 hours (Ali, 1988). Fabbrocini *et al*. (2012) indicated that agar limited nutrient leaching in algae-based diets for sea urchins.

Due to their gelling properties, three-dimensional networks are obtained that are strongly agglutinated thus, absorption of water and nutrient leaching is minimized (Paolucci *et al*., 2015). This property might also limit digestibility when fed with agar bound diets. Simon (2009) observed that algal carbohydrates (i.e., agar and alginate) decreased diets digestibility in lobster juveniles. Also, Ruscoe *et al*. (2005) and Argüello-Guevara and Molina-Poveda (2013) observed that agar-based diets produce pellets with high disintegration level compared to other binding agents like carrageenan, CMC, alginate and gelatin.

4.4 *Pectin*

Coccia *et al*. (2010) noted that the presence of polysaccharides in crayfish diets ameliorated crayfish growth. Coccia *et al.* (2010) studied the effects of four polysaccharides (alginate, agar, chitosan and pectin) as binders in producing pellets for crayfish. It was observed that pectin and chitosan bound pellets showed the greatest stability in water up to 24hrs. Volpe *et al*. (2008), also affirmed that pectin added at 2.5 % concentration is a good binder for producing feed pellets for crayfish. In producing feed pellets with superb water-stable qualities for crayfish, pectin performed absolutely well compared to agar and alginate (Volpe *et al*., 2008).Thus, pectin is a binder recommended for manufacturing feed pellets for both adult and juvenile crayfish Cherax albidus, due to its gelling capacity and ability to boost growth and weight gain in crayfish (Volpe *et al*., 2008; Coccia *et al*., 2010; Volpe *et al*., 2012). Pectin bound pellets of 0.5% concentration showed strong binding capacity due to the smooth and regular distribution of nutrients inside the polymer (Volpe *et al*., 2015). Pellets from low esterification of apple pectin have great water stability and low nutrient leaching during 24 h of water immersion. Based on this, it has the capacity to promote crayfish growth when used as dietary ingredients (Volpe *et al*., 2015). Pectin is also used to promote pig's nutrition and health due to its prebiotic, antimicrobial and antiviral property (Wiese, 2019)

4.5 *Gelatin*

Gelatin-based binders make firm pellets and also improve pellets nutritional value because they contain protein and are easily digestible. At 3% and 5% concentration, gelatin produces stable feeds that are intact after 216 h immersion in seawater (Pearce *et al*., 2002). Gelatin at 4% concentration also created stable urchin feed after 48 h immersion in seawater (Caltagirone *et al*., 1992). However at concentrations below 3%, feed stability may decline but it is still suitable to use (Partridge and Southgate, 1999; Pearce *et al*., 2002). Stability of feed made with gelatin can be affected by concentration in the feed, source, purity level, and water temperature used in making the feed (Pearce *et al*., 2002). At 2% concentration, gelatin-based diet enhanced nutrient absorption, amino acid catabolism and promoted enzyme activity thereby increasing Octopus growth (Rosas *et al*., 2008). Compared to carrageenan based diets, gelatin-based diet also enhanced growth and survival rate in fish (Liu *et al*., 2008). Using gelatin as binders enhanced apparent digestibility in lobster juveniles (Simon, 2009). In barramundi larvae, 2-3% gelatin is very effective for producing a firm micro bound diet (Partridge and Southgate, 1999). Although, Rosas *et al*. (2008) suggested 5 to 7% of gelatin is suitable for use in formulating diet for *Octopus maya*. Ali (1988) however noted that using high levels of gelatin in feed production is ineffective and results in pellets with poor quality. Therefore, carefully selecting the right amount for feed formulation is important.

4.6 *Guar gum*

Guar gum produced pellets with moderate water stability when applied as binders in shrimp feeds (Ali *et al*., 2010). Water stability of guar gum pellets can be increased by increasing the temperature and concentration. At 2.5% concentration, the growth rate and feed conversion of fish fed guar gum-bound diets were better compared to the control due to feed consistency. Large concentrations may decrease both growth and feed conversion (Storebakken, 1985). Storebakken, (1985) observed that both alginate and guar gum reduce the feed intake and apparent digestibility of crude protein and lipid in rainbow trout. Guar gum forms gel matrix that retains essential nutrients; this sometimes makes it difficult for the fish to access essential nutrients in the diet thereby reducing digestibility(Morris *et al*., 1981; Dominy *et al.*, 2004).

4.7 *Carrageenan*

5 % carrageenan bound diet improved water stability after 60 min immersion in water. Fish fed with carrageenan-wheat flour diet gave better growth rate and feed efficiency. Carrageenan-bound diet is able to enhance water stability even with high lipid contents. (Hashim and Saat, 1992). Also, carrageenan bound diet improved water stability and shrimp growth (Ruscoe *et al*., 2005). Carrageenan at 2–3% inclusion is a suitable binder in weaning diets for Barramundi larvae, *Lates calcarifer* (Partridge and Southgate, 1999). Although carrageenan is suitable for producing stable feeds, Liu *et al*. (2008) observed poor growth and survival rate when fish (postlarval tongue sole) were fed with carrageenan bound diets. Similarly, European sea bass and white sturgeon larvae experienced deteriorated growth when fed with carrageenan bound diet (Person Le Ruyet *et al*., 1993; Gawlicka *et al*., 1996). The poor growth and survival rate is probably because the polymer matrix formed during gelat minimizes the use of nutrients in carrageenan bound diet.

4.8 *Alginate*

Alginate is also a suitable binder in producing aquaculture feed. According to Pearce *et al*. (2002) sodium alginate is more effective at higher concentration. Akiyama *et al*. (1997) showed that using 30 % concentration of sodium alginate in sea urchin feed ameliorated its growth rate. Conversely, fish fed with 2% sodium alginate bound feed improved growth and survival rate compared with carrageenan, CMS, and gelatin (Liu *et al*., 2008). Also, shrimp fed 5% sodium alginate bound diet showed the best water stability performance, water absorption and protein leaching after 180- min immersion (Argüello-Guevara and Molina-Poveda, 2013). Besides, in postlarval tongue sole diet, 2% sodium alginate bound feed had better stability. However, for crayfish diets, compared to binding agents like pectin and chitosan, alginate disintegrated faster when submerged in water. Although, Pearce *et al*. (2002) suggested using high concentrations of sodium alginate, nonetheless, usage may depend on the animal species.

4.9 *Carboxymethylcellulose*

2% sodium carboxymethylcellulose bound diet improved the stability but did not enhance the growth and survival rate of postlarval tongue sole. (Liu *et al*., 2008). Similarly, in fingerling Japanese flounder, CMC inclusive diets resulted in inferior weight gain, *feed* efficiency, protein digestibility, protein and energy retention. The reason is that CMC increases diets viscosity and decreased proteolytic enzymes' activities leading to poor growth performance (Yamamoto and Akiyama, 1995). However, using CMC as binders enhanced apparent digestibility in lobster juveniles (Simon, 2009) and improved pellet quality in shrimp feed (Ruscoe *et al*., 2005).

Finally, combination of binders have shown to improve pellet water stability, growth and digestibility. Independently, some binders like guar gum may hinder growth and digestibility in some animals. A combination with other binders can improve the ability of guar gum to positively affect growth and digestibity. Won *et al*. (2018) reported that a mixture of 10% of dietary guar gum and 5% xanthan gum and 5% carrageenan may improve growth in juvenile sea cucumber. Also, pellets produced with wheat flour and 2% of guar gum improved water stability due to the presence of gluten which improves their binding properties (Ali *et al*., 2005). Catacutan (2017) observed that combination of glutinous rice starch (7%), carrageenan (3%), carboxymethylcellulose (CMC) (3%) and a synthetic binder(1%) improved pellet water stability in mud crabs diet. 5% inclusion level of carrageenan bound diet increased the apparent digestibility coefficient of Crude Protein and crude fat. Also, the combination of carrageenan and CMC increased Crude protein digestibility (Catacutan, 2017).

Table 2: summarizes the benefits of binders for different species

Binders	Inclusion level(%)	Species	Effect on Growth	Effect on Digestibility	Effect on Stability	Effect on PPQ
Lignosulfonate	0.5%	Poultry	-	Positive	-	Positive (Corey *et al.*, 2014)
Sepiolite	1-1.5%	Poultry Cattle	Positive (Ayed *et al.*, 2008; Attar et al., 2018	Positive (Attar *et al.*, 2018)	-	Positive Angulo *et al.*,1995; Angulo *et al.*, 1996).
Bentonite	1.5-2%	Poultry	-	-	-	Positive Moradi *et al.*, 2019; Abdollahi *et al.*, 2011

Agar	2-3%	Sea Urchins (Fabbrocini *et al*. 2012)	-	-	Positive	
Agar		Lobster juveniles		Negative (Simon, 2009)		
Agar	2%	Shrimp	Positive (Palma *et al*.,2008)		Negative (Ruscoe *et al*., 2005).	
Agar		Crayfish (Volpe *et al*., 2 008; Coccia *et al*., 2010).	Positive			
Pectin	0.5 - 2.5%	Crayfish(Volpe *et al*., 2008; Coccia *et al*., 2010; Volpe *et al*., 2012)	Positive	-	Positive	
Gelatin	2- 5 %	Lobster Juveniles (Simon, 2009)	-	Positive	-	
Gelatin		Octopus (Rosas *et al*., 2008 Postlarval tongue sole. (Liu *et al*., 200	Positive			

Guar gum	2- 2.5 %	Rainbow trout (Storebakken, 1985)	-	Negative (Rainbow trout)	-	.
	2-2.5%	Shrimp (Ali *et al.*, 2010)	-	-	Average (Shrimp)	-
Carrageenan	2-5%	Shrimp (Ruscoe *et al.*,2005)	Positive	-	Positive	-
Carrageenan	2-5%	European sea bass, White sturgeon larvae (Person Le Ruyet *et al.*, 1993; Gawlicka *et al.*, 1996) Postlarval tongue sole. (Liu *et al.*, 2008	Negative	-	-	-
Alginate	2-30%	Shrimp (Argüello-Guevara and Molina-Poveda, 2013)	Negative Argüello-Guevara and Molina-Poveda, 2013	Negative (Argüello-Guevara and Molina-Poveda, 2013	Positive	-
Alginate		Sea bass larvae (*Dicentrarchus labrax*) (Person	Positive	-	-	-

		Le Ruyet *et al.*, 1993). Farmed crayfish Volpe *et al.*, 2008; Coccia et al., 2010)				
Alginate		Crayfish (Ruscoe *et al.*, 2005	-	-	Positive	-
Alginate		Barramundi (*Lates calcifer*) (Partridge & Southgate, 1999), Lobster juveniles (Simon, 2009). Octopus (Rosas *et al*., 2008)	Negative	Negative	-	-
Alginate		Postlarval tongue sole. (Liu *et al*., 2008)	Positive	-	Positive	-
Alginate		Rainbow trout (Storebakken, (1985)	-	Negative	-	-
Carboxymethylcellulose		Shrimp (Ruscoe *et al.*,2005)	-	-	Positive	-

Carboxymethylcellulose		Lobster juveniles (Simon,2009)	-	Positive	-	-
Carboxymethylcellulose		Fingerling Japanese flounder, (Yamamoto and Akiyama, 1995)	Negative	Negative		
Carboxymethylcellulose	2%	Postlarval tongue sole (Liu *et al*., 2008).	Negative	-	Positive	-

Table 2: Benefits of binders for different species

*PPQ:Physical pellet quality, -: no data to support this

5.0 CONCLUSION

Pellets with binders have better quality than pellets without binders. Binders influence pellet quality due to their viscous properties. Besides improving physical pellet properties, some binders can enhance animal's growth and digestibility. Supplementing binders in feed are distinct for different animal species diets. Therefore, selection of binder in feed is based on its suitability for specific animal species.

There are limited articles or old articles on some animal species like tilapia and rainbow trout. Based on this, more research has to be carried out to ascertain the binder suitable for these fish.

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Sepiolsa www.sepiolsa.com

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