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A descriptive study of the physical quality of commercial broiler pellets across the world

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Feed Manufacturing Technology

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Ying Wang

Abstract

This thesis work intends to give a general insight into commercial broiler pellets' physical quality and discuss the differences from a scientific point of view. The samples were delivered to the Norwegian University of Life Sciences by Aviagen customers located in twelve countries. Afterwards, the pellet size (length and diameter) and pellet physical quality indexes, including pellet durability, pellet hardness, dry matter content, fine percentage, and particle size distribution, were then measured. Major findings between pellet size and pellet qualities are: 1) Nutritionists should discuss the impacts of grinding on pellet quality in line with grain types and particle sizes. Similar to common sense, roller mill grinding gave more homogeneous results than hammer mill grinding. 2) The influence of raw materials on pellet quality varied with the ratio of protein, starch, and fibre within grains. In general, pellets made with wheat showed better physical quality values than pellets made with maize. 3) Whole wheat addition (post-pelleting) is a popular way to increase pellet broiler diets' structure and reduce the production cost. 4) Pellet length showed relatively strong non-causal linear relations with pellet hardness values ($r=0.47$) and fine production ($r=-0.40$). 5) The strong correlation between pellet hardness and pellet durability ($r=0.75$) was spotted. Even though the correlations shown in this study are exclusive for received samples, these findings could still be used as an indicator for later research. Future works intend to study the interactions between pellet quality and pellet texture are encouraged.

Keywords

commercial broiler pellets, physical quality, pellet size, particle size distribution

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Abbreviations

AVE	Average
CV	Coefficient of Variance
DM	Dry Matter
F	Fine
HM	Hammer Mill
K.H	Kahl Hardness
ND	Nutrient Density
NL	the Netherlands
NWW	No Whole Wheat
PDI	Pellet Durability Index
PSD	Particle Size Distribution
RM	Roller Mill
RM	Raw Material
RSA	the Republic of South Africa
SBM	Soybean Meal
SD/σ	Standard Deviation
SFM	Sunflower Meal
TA.H	Texture Analyser Hardness
UK	the United Kingdom
WW	Whole Wheat

1. Introduction

The feed section takes up to 60-70% of the production costs in commercial broiler industries, with pellets being a popular feed form. To increase the profit for farmers and merchandisers, it seems promising through decreasing the feed cost and optimising the growth performance of broilers. Feed costs mainly consist of expenses on raw materials and processing technologies. Since two complementary principles (the least-cost programme and the ideal protein concept) dominate the selection and proportioning of raw materials economically and nutritionally (Abdollahi, M. et al., 2013), there is little margin for extra optimisations. On the other hand, there are few universal guidelines on the manufacturing technologies relating to broiler feed. Hence, modifying the pelleting process to improve the pellet physical quality and feed efficiency seems feasible. To achieve this, a deep and thorough understanding of how different processing methods can influence different physical qualities is necessary (Cutlip et al., 2008). Relevant mechanisms have been illustrated by Behnke (1994), Behnke (2001), Briggs et al. (1999), Miladinovic and Svihus (2005), Muramatsu et al. (2015), Thomas and van der Poel (1996), Thomas et al. (1997), and Winowiski (1995). These literatures are general studies for all animal species, and some even referred to biomass. For broiler chickens, sufficient studies regarding the influence of different feed forms (e.g., Abdollahi et al. (2018a), Almeida et al. (2018), Amerah et al. (2007a), Attia et al. (2014), Massuquetto et al. (2018)), nutrient densities (like Abdollahi et al. (2018b), Hamungalu et al. (2020), and Massuquetto et al. (2020)), raw materials (e.g., Amerah and Ravindran (2008), and Singh and Ravindran (2015)) on growth performance can be found. However, minimal numbers of studies were conducted focussed on the physical quality of pelleted broiler feed and the following performance of broilers (Bouvarel et al. (2009), Abdollahi, M. et al. (2013), Abdollahi and Ravindran (2013), Abdollahi, M. R. et al. (2013b)). Besides, studies focused on interactions between pellet size or particle size and pellet physical quality are scarce, leading to studies of Lowe (2005) and Wood (1987). Therefore, scientific experiments are required to quantitatively measure the extent to which pellet textures (including size and particle distribution) would influence pellet quality, broiler growth performance, and digestive tract development.

The present thesis reviewed how pelleting process would affect the final quality and texture of pellets. Some relevant studies about the performance of broilers fed pellets with different quality levels and textures were included. Experiments on received broiler pellet feed samples analysed their physical quality values, then compared them with recommended values of previous studies. Since restricted information about feed formulations and processing settings of received samples were provided, the results only showed existing relations among received samples, not potential trends. Therefore, they need to be viewed critically.

2. Description of the pelleting process

The most popular hydrothermal treatment used in commercial broiler pellets is the steam-conditioning pelleting practice. In a feed manufacturing factory, the pelleting line usually consists of storage silos, dosing systems, milling machines, mixing machines, a pre-conditioner, a pellet press, a cooling-and/or a drying machine. Besides, different types of conveyors are installed to transport materials between apparatus.

Raw materials are delivered to the feed manufacturing factory either by trucks or ships. The sampling and the quality control process will be performed right after the ingredients have arrived. Then, materials are sent to different silos outside the factory for storage.

Before pelleting, ingredients that require size reduction are released and weighed by the dosing system then sent to grinding machines. Raw ingredients that are pre-ground can be used directly upon mixing. Materials are ground into desired sizes based on the type of feed that is producing. The most popular grinder used in feed factories is the hammer mill due to its high capacity and efficiency and relatively homogenised final particle size distribution (Thomas & van der Poel, 1996). Aside from the hammer mill, the roller mill, the disc mill, the multicracker, and the pin mill can be used. As Svihus (2006) indicated in his paper, in practice, grains used in broiler diets are commonly ground by a hammer mill with a 3 to 4 mm-diameter die. Ground ingredients are sent to corresponding silos inside the factory and stored there until usage. According to the feed formulation, required mash ingredients are further dosed onto the underneath weighing panel and transported to the mixer. Micro-ingredients like vitamins and minerals can either be added to the mixer manually or by the dosing system. Liquid ingredients can be added through the mixer, the pre-conditioner, pellet-press into the feed mash, or through vacuum coating after pelleting. A high percentage of fat/oil is usually added separately in the mixing process and after pelleting during the vacuum coating process since a high fat/oil content during pelleting will badly influence pellet quality. A pressure pump is used to help homogenously spraying liquid materials to the feed mash during mixing through nozzles. After proper mixing, feed mash will be released through the under-hopper of the mixer and further transported to the pre-conditioner.

There are two types of conditioning-pelleting used in animal feed productions. The first one is a hot-conditioning pelleting. Hot steam is ejected into the pre-conditioner to increase the temperature of the feed mash and the machine aside from increasing the moisture content of the feed mash. The other one is a cold-conditioning pelleting. Instead of hot steam, water can be added here to increase the moisture content of mashed ingredients if needed.

Moreover, the energy required to heat materials and the machine is generated from mechanical frictions between feed particles. In the conditioner, feed mixtures are mixed by the rotating paddles installed on the central shaft and moved towards the outlet. The angle of paddles can be adjusted to control the retention time of feed. After properly mixed, feed materials will enter the pellet press. The rotating shaft located in the centre of the pellet press will send materials to the pellet zone. The pellet zone consists of a ring die with cylindrical perforations, stationary rolls, and stationary knives. The rolls push materials into the cylindrical holes in the die, where friction, pressure, and temperature further build-up and induce necessary chemical reactions to form pellets. Svihus (2006) reported that the temperature in the pellet press could reach 80 – 90 ℃. Then, newly formed pellets will be cut by knives mounted outside the ring die once they reached a certain length. Furthermore, the length of pellets can be influenced by feeder rate, the number of knives, and the rotating speed of the pellet die. Afterwards, hot pellets will be transported to a dryer and a cooler.

Room temperature air is continuously sent into the cooler to take away the extra heat and moisture inside the pellets. In commercial feed industries, the time for cooling is limited. Too rapid cooling would dry up the outer layer but leave the core moist, leaving concerns for moulding, self-ignition, and breakage. While too slow cooling would not be economically efficient. After the cooling process, when the temperature of pellets is lowered to around room temperature, extra drying can be used if the moisture content of pellets is higher than 13%.

3. Introduction to pellet physical quality

3.1. Definition of physical quality

The physical quality of pellets numerically described their abilities to withstand attrition (Abdollahi, M. R. et al., 2013a; Thomas & van der Poel, 1996). Attrition includes fragmentation and abrasion. Fragmentation is the breakage of intact pellets into smaller sizes, and abrasion refers to the production of fines on the sensitive surfaces of pellets. Based on the different types of forces that pellets encountered during handling and transportation, it can be assumed that fragmentation mostly happens during storage (static forces) and handling (impact forces), whereas abrasion mainly happens during transport.

3.2. Different physical quality indicators

3.2.1. Pellet durability

According to Thomas and van der Poel (1996), pellet durability defines to what extent pellets can withstand attrition during transportation. Furthermore, the pellet durability index (PDI) is used as a quantitative way to express the percentage of fines generated from original pellets (calculated by weight) (Thomas & van der Poel, 1996). It is also possible to compare PDI tested under the same procedures between different pellets.

Thomas and van der Poel (1996) summarized different types of devices used to test pellet durability. The first durability tester was invented in 1963 by the name Pfost Tumbling Can, focusing on testing the abrasion of pellets under mechanical forces. Furthermore, the Holmen durability tester was created twenty-one years later, focusing on measuring the abrasion and fragmentation during pneumatic forces. These two devices are still used in today's feed industry.

The pellet durability of received broiler pellet samples in this study was measured using the Holmen durability tester. It generates pneumatic airflows to mimic the vibration pellets would encounter during practical handling and transportation. Pellet attrition can happen when pellets hit the metal sieve surfaces and hit each other due to the air movement inside the perforated testing chamber. Thomas and van der Poel (1996) confirmed that agitating dust-free pellets in the Holmen durability tester resulted in a mixture of fragments and fines. Moreover, a later study conducted by Salas-Bringas et al. (2007) mentioned that the Holmen tester could not automatically separate broken pellets from dust as the perforations are of the same size.

Detrimental influence of a high percentage of fines includes feed refusal of birds, complaints from farmers, unbalanced nutrients inclusions, and respiratory system diseases in broilers and personnel. These would reduce the beneficial effects of feeding pellets to birds, hence a high chance to reduce their growth performances. Therefore, it is essential to optimise the physical quality to reduce economic losses and possibly improve the growth performance of broilers.

3.2.2. Pellet hardness

The term hardness refers to the maximum strength required to break or crush a pellet at one time (Thomas & van der Poel, 1996). External forces responsible for pellet breakages are mainly the compression force and the impact force (Thomas & van der Poel, 1996). The compression force is a kind of static force that accumulates during the storage of layers of pellets. Moreover, the impact force is a dynamic force that pellets may encounter during handling and transportation.

Thomas and van der Poel (1996) presented five different devices intended to test pellet hardness were introduced, including the Kahl tester, the Schleuniger testing apparatus, the Pendulum, the Universal Tension and Compression apparatus, and the Kramer shear press. Moreover, these machines focus on studying different breakage mechanisms. For example, the Kahl tester measures the static force, while others measure the dynamic force. Among the four devices measuring the dynamic force needed to break a pellet, the Pendulum apparatus is the only one that measures the impact, while other machines measure the compression.

The pellet hardness values of received broiler pellet samples were measured with the Kahl Manual tester and the Tinius Olsen Texture Analyser. The Tinius Olsen Texture analyser shares the same operation principle with the Universal Tension and Compression apparatus. The Kahl Manual Hardness is the most used device for testing pellets hardness. Because it is relatively cheap compared to the devices mentioned above, and it is easy to carry and operate. The Kahl tester uses a spring (either 2.5 mm or 3.5 mm in diameter) to add the static pressure applied on the inserted pellet. The maximum strength used to break the pellet can be read from the scale in kg. The alternative apparatus (the Tinius Olsen Texture Analyser) uses a movable flat panel to add the compression force applied on the sample pellet. The speed and the sensitivity of the movable panel are controlled through accompanied computer software. The force (N) used by the moving panel is recorded as a function of time and stored automatically as a line chart. Besides, the Tinius Olsen Texture Analyse can also measure the tensile strength (Salas-Bringas et al., 2007; Thomas & van der Poel, 1996). The measuring process takes a much longer time comparing to that of the Kahl hardness tester. Besides, only trained personnel have permission to operate the Texture Analyser. These two aspects make this type of device less appealing (Salas-Bringas et al., 2007).

3.2.3. Particle size distribution

Since feed pellets are agglomerates of ground raw materials, the characteristics of intact pellets and those of the composing particles should be considered. To describe the texture of intact pellets and composing particles, scientific terms macrostructure and microstructure are used, respectively (Svihus, 2006).

3.2.3.1. The macrostructure

As Svihus (2006) illustrated, the pellet macrostructure mainly affects the feed intake and the feeding behaviour of broilers. Portella et al. (1988) also mentioned that birds would selectively eat pellets most suitable for their beaks, and typically, this preference for size increased as they grew. As both mentioned by Abdollahi and Ravindran (2013) and Cutlip et al. (2008), feeding suitable pellets size to broilers is beneficial for boosting their growth performance.

The dry sieving process can measure the particle size distribution of mash diets and the macrostructure of pelleted or crumbled diets. The dry sieving is performed using a set of sieves with different perforation sizes. Furthermore, the particle size distribution is calculated as the ratio of feed that remained on each sieve to the total weight of feed tested (usually 100 g). Besides, mathematical calculations, like the geometric mean diameter (GMD) and the geometric standard deviation (GSD), can also be used to make comparisons. In this study, the purpose of the dry sieving process is to give a detailed description of the distribution of particles in pelleted diets.

After ingestion, pellets will lose their macrostructure soon after being moisturized and kneaded in the crop (Engberg et al., 2002; Nir et al., 1995). Then, the microstructure of pellets becomes more prominent and starts to insert effects on the digestive tract and digestion process itself.

3.2.3.2. The microstructure

The microstructures within diets will affect gizzard development (Amerah & Ravindran, 2008) and that of the lower digestive tract (Amerah et al., 2007b; Portella et al., 1988). The microstructure may also influence digestion efficacy through varying contact surface areas with digestive enzymes (Melo-Durán et al., 2020). Controversial statements have been made about how microstructure would affect pellet durability. Similar to the dry sieving process, the wet sieving is modified to test the particle size distribution of agglomerated animal diets and evaluate the effect of relevant processing treatments (Lyu et al., 2020). In general, the wet sieving process shares the same principle as the dry sieving process but more complicate and time-consuming (Lyu et al., 2020). Pellets need to be fully dissolved in water to perform the test. Several benefits of the wet sieving process are pointed out by Lyu et al. (2020), including mimicking the digestion process in the digestive tract and improve the accuracy of particle size distribution results for preventing clog of particles with running water.

4. Effect of pelleting on broiler performance

Early in the 19th century, Patton et al. (1937) demonstrated that broilers fed pelleted diets showed higher average daily weight gains, higher feed intakes, and lower feed conversion ratios than broilers fed mashed diets. Similar results were discovered by later studies like Engberg et al. (2002) and Abdollahi, M. R. et al. (2013a). One of many explanations for this improved growth performance in broiler chickens fed a pelleted diet is that they spend less time on eating, hence less energy expenditure on maintenance (Abdollahi, M. R. et al., 2013a), which agreed with the previous study of Nir et al. (1994). Feeding broilers with pellets reduced feed selection and feed wastage, and less dust production also improved the health of their respiratory systems (Abdollahi, M. R. et al., 2013a; Behnke, 2001).

However, pelleting treatment is not a perfect solution for all problems. Huang et al. (2006) spotted a significant reduction in the gizzard size in birds fed pelleted diets compared to birds fed mash diets and inferred that a lack of structural components (coarse particles) could not stimulate gizzard development. This statement agreed with previous research conducted by Engberg et al. (2002). Liermann et al. (2020) later found the same results in broilers fed finely ground pellets and expanded pellets. The underdeveloped gizzard would induce broilers overeating in broilers, hence leading to proventriculus dilatation problems (Liermann et al., 2020). Besides, studies of Amerah et al. (2007b) and Amerah et al. (2009) further discovered doubled gizzard sizes when large particles or structural components were fed to birds. Apart from influencing the gizzard size, feeding would also affect the content pH in stomachs and intestines. Both Engberg et al. (2002) and Huang et al. (2006) found that broilers fed on pelleted diets had a higher gizzard content pH than broilers fed on mashed diets. In addition, Engberg et al. (2002) found that birds fed pellets had a lower intestinal pH, which would have fewer stimulations on the pancreas. Hence, reducing the pancreas size and the pancreatic bicarbonate secretion into the small intestine. All these would influence the digestion and absorption of nutrients in the small intestine and further affect the growth performance of birds.

5. Justification

Very systematic and completed illustrations of how different factors influenced pellet physical quality was illustrated by Thomas and van der Poel (1996), Thomas et al. (1997), and Behnke (2001). Moreover, most papers discussed pellet physical quality under a well-designed experimental situation. Therefore, this thesis work is dedicated to studying the physical quality of commercial broiler pellets and discussing the potential interactions between different pellet features that existed in industrial products from a scientific point of view.

6. Material and methods

6.1. Feed samples

In total, fifty-eight broiler pellet samples were sent to the Norwegian University of Life Sciences, Ås, Norway, to perform physical quality tests. Samples were collected either from feed mill or farm silo by Aviagen customers, then sent to Aviagen personnel who further delivered them to the university. Relevant sample information was provided by Aviagen personnel, either gathered from customers or by visual inspections. Table 1 shows the most valuable backgrounds of samples. Information about the exact percentage of cereals grains used in samples was not provided. Details about the grinding process, like the size of the die and the particle size of ground materials, were also unknown. Besides, there was no clarification about the amount of whole wheat added to the pellets. Samples were stored inside the cooler (4 ℃) in the IHA building soon after arrival and were only taken out for testing and photographing at the university's feed lab in the IHA building.

Table 1. The production country, raw material, and grinding method of pellets were shown below. And the whole wheat addition was marked by yes or no.

Sample No.	Country	Raw Material[1]	Grinding Method[2]	Whole Wheat Yes/No[3]
1	Italy	Maize/Wheat/SBM[4]	Hammer Mill + Disc	No
2	Italy	Maize/Wheat/SBM	Hammer Mill + Disc	No
3	Italy	Maize/Wheat/SBM	Hammer or Roller Mill, depends on raw materials	Yes
4	Italy	Maize/Wheat/SBM	Hammer Mill	No
5	Italy	Maize/Wheat/SBM[5]	Hammer Mill	No
6	Italy	Maize/SBM	Roller Mill	No
7	Spain	Wheat/Maize/SBM[6]	Hammer Mill	No
8	Spain	Maize/SBM	Hammer Mill	No
9	Spain	Wheat/Maize/SBM	Hammer Mill	Yes
10	Spain	Wheat/Maize/SBM	Hammer Mill	Yes

1 "Raw material" stands for the major cereal and protein sources used in the pellets.
2 The milling methods of feed ingredients provided by sample producers.
3 Visual judgement of whole wheat particles among pellets.
4 Maize/wheat/SBM - maize and soybean meal (SBM) are the main cereal and protein sources, wheat might be up to 25% inclusion.
5 Maize/SBM or wheat/SBM - the main cereal and protein sources.
6 Wheat/maize/SBM - wheat and SBM are the main cereal and protein sources, maize inclusion might be up to 25%

Sample No.	Country	Raw Material[1]	Grinding Method[2]	Whole Wheat Yes/No[3]
11	Spain	Wheat/SBM	Hammer Mill	No
12	France	Wheat/SBM	Hammer Mill	No
13	France	Wheat/SBM	Roller Mill	No
14	France	Wheat/SBM	Roller Mill	No
15	France	Wheat/SBM	Roller Mill	No
16	France	Wheat/SBM	Hammer Mill	No
17	France	Wheat/SBM	Hammer Mill	No
18	NL	Wheat/SBM	Hammer Mill	No
19	NL	Wheat/SBM	Hammer Mill	No
20	NL	Wheat/SBM	Hammer Mill	No
21	NL	Wheat/SBM	Hammer / Roller Mill	No
22	NL	Wheat/SBM	Hammer Mill	No
23	NL	Wheat/SBM	Hammer Mill	No
24	NL	Wheat/SBM	Hammer Mill	No
25	Germany	Wheat/SBM	Hammer Mill	Yes
26	Germany	Wheat/SBM	Hammer Mill	No
27	Serbia	Maize/SBM	Hammer Mill	No
28	Serbia	Maize/SBM	Hammer Mill	No
29	Serbia	Maize/SBM	Hammer Mill	No
30	Finland	Wheat/SBM	Hammer Mill	No
31	Finland	Wheat/SBM	Hammer Mill	No
32	Finland	Wheat/SBM	Hammer Mill	No
33	Finland	Wheat/SBM	Multicracker	No
34	Finland	Wheat/SBM	Multicracker	No
35	Czech Rep[1]	Wheat/SBM	Roller Mill	No
36	Czech Rep	Wheat/SBM	Roller Mill	No
37	Czech Rep	Wheat/SBM	Roller Mill	No
38	Hungary	Wheat/Maize/SBM	Hammer Mill	No
39	Hungary	Wheat/Maize/SBM	Hammer Mill	Yes
40	UK	Wheat/SBM	Hammer Mill	Yes
41	UK	Wheat/SBM	Hammer Mill	Yes
42	UK	Wheat/SBM	Hammer Mill	No
43	UK	Wheat/SBM	Hammer Mill	Yes
44	UK	Wheat/SBM	Hammer Mill	Yes
45	UK	Wheat/SBM	Roller Mill	Yes
46	UK	Wheat/SBM	Hammer Mill	Yes
47	UK	Wheat/SBM	Hammer Mill	Yes
48	UK	Wheat/SBM	Hammer Mill	No
49	UK	Wheat/SBM	Hammer Mill	No
50	UK	Wheat/SBM	Hammer Mill	No
51	Brazil	Maize/SBM	Hammer Mill	No
52	Brazil	Maize/SBM	Hammer Mill	No
53	NL	Wheat/Maize/SBM	Hammer Mill	No
54	NL	Wheat/Maize/SBM	Hammer Mill	No

1 The Czech Republic.

Sample No.	Country	Raw Material[1]	Grinding Method[2]	Whole Wheat Yes/No[3]
55	RSA[1]	Maize/SFM/SBM[2]	Hammer Mill	No
56	RSA	Maize/SFM/SBM	Hammer Mill	No
57	RSA	Maize/SFM/SBM	Hammer Mill	No
58	RSA	Maize/SFM/SBM	Hammer Mill	No

6.2. Description of photography procedure

Pictures of all samples were taken over two consecutive hours (from 5.30 p.m. to 7.30 p.m.) on the same table inside the feed lab. For each sample, two to three tablespoons of random pellets were scooped out of the bag then placed on the blank A4 paper above the ruler used as a size indicator. The same mobile phone was used as a hand-held camera. Therefore, the position of the camera was not constant during shooting. Hence, pictures were cropped into similar sizes for better presentation. Furthermore, the sample number was labelled in the top right corner of the picture. Since the yellow light from the bulb in the room shadowed the original colour of feed pellets, the visual presentation might be biased.

6.3. Description of physical quality measurements

Steps performed during the pellet hardness tests, the pellet durability tests, the dry-and wet sieving processes, and the determination of fine content and dry matter content are explained in the following content.

6.3.1. Preparation of dust-free pellets

Samples were weighed out from the sample bag using a sample divider and a balance (Weighing GF-3000 Analytical Balance, A&D INSTRUMENTS LTD). Then those pellets were subjected to 1.5 mm amplitude sieving with the Analytical sieve shaker AS 200 Control (RETSCH GmbH & Co. KG, Haan, Germany) on a 2.0 mm sieve (RETSCH GmbH & Co. KG, Haan, Germany) for 1 min. Afterwards, pellets that remained on the 2.0 mm sieve were ready for other physical quality tests.

1 the Republic of South Africa.
2 Maize/SFM/SBM - maize is the main cereal source, the inclusion of sunflower meal (SFM) is higher than 15% together with SBM providing large ratio of protein to the diet.

6.3.2. Pellet durability tests

The durability index of pellets was measured using the New Holmen Automatic Pellet Tester NHP 200 (Holmen Chemical Ltd., Borregaard Group, Norsolk, UK). 100 g of dust-free pellets were subjected to the pneumatic force within the Holmen tester for 80 s. Furthermore, fragments were blown out through the 2.5 mm mesh pre-installed around the testing chamber (Figure 1). The pellet durability index (PDI) was calculated automatically and shown on the black and white screen. The formula used for calculating the PDI is listed below *Eq.1*. One sample (No. 52) did not show any pellet durability index when tested with the Holmen durability tester due to poor pellet quality.

$$PDI\ (\%) = \frac{the\ weight\ of\ fragments\ returned}{the\ weight\ of\ original\ samples} * 100\% \qquad (1)$$

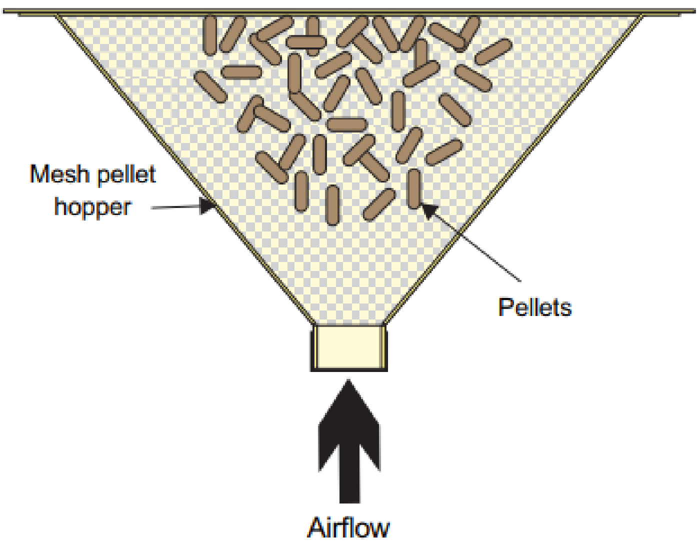


Figure 1. A demonstration figure of the working zone within the Holmen durability testers.

6.3.3. Pellet hardness tests

6.3.3.1. the Kahl hardness tester (Amandus Kahl Gmbh Co.)

For each sample, around thirty pellets were randomly picked from the sample bag and placed in descending order by length (Figure 2). Then, the middle fifteen pellets, plus the longest and the shortest ones, were chosen for further hardness tests. The length and diameter of all seventeen pellets were measured before the hardness test with an electronic calliper (Würth

Group Int., type 0-150 mm). The testing procedures followed the user-guidance flyer for the Kahl tester and the measuring steps by Thomas (1996). Figure 3 shows the functional region of a Kahl hardness tester. The force needed to break the pellet was read on the scale in kilograms (kg). Later, the average hardness value of those fifteen pellets was used to represent that of the sample.

Figure 2. A presentation of how pellets were lined up before the hardness tests.

Figure 3. A schematic figure of the functional zone of a Kahl hardness tester (Inspired by Lowe (2005)).

6.3.3.2. the Texture analyser (Tinius Olsen, H5KT, Salfords, England)

The Texture Analyser, which shares the same working principle as the Universal compression test device mentioned by Thomas and van der Poel (1996), was used as an alternative device to evaluate hardness values. Pellets that have a diameter close to the average diameter of the sample were selected for further tests. The testing procedures were conducted under the instructions of the relevant technician. The pellet was placed horizontally on the flat lower panel before conducting the measuring procedure. The force used to break it was recorded automatically in Newton (N) as the upper panel began to drop (Figure 4). For each sample, the same procedures were repeated fifteen times. However, only nineteen samples were tested using the Texture Analyser due to unexpected malfunctioning.

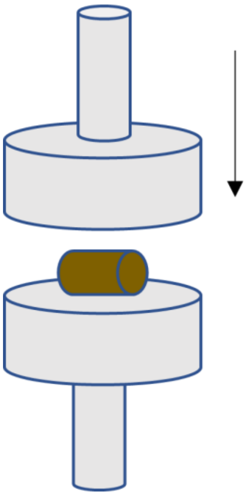


Figure 4. A schematic presentation of the functional zone of the Texture Analyser device. The downward arrow indicated the moving direction for the upper panel.

6.3.4. Fine percentage measurements

Randomly took 100 g of pellets from the sample bag with the help of a sample divider, then gently placed them on the sieve set. The sieve set consisted of an empty 2.0 mm sieve (Retsch, GmbH & Co. KG, Haan, Germany) and a clean bottom with known bare weight. Later, the sieve set was subjected to 1.5 mm amplitude vibration for 1 min. The collector with particles inside was weighed again to calculate the fine percentage (*Eq.2*).

$$Fine\ (\%) = \frac{the\ weight\ of\ fines\ (g)}{the\ total\ weight\ of\ sample\ (g)} * 100\% \qquad (2)$$

6.3.5. Dry matter content measurements

The dry matter content (DM%) was calculated directly by measuring the moisture content (*Eq. 4*). The moisture content test was carried out in the following sequences. For each sample, approximately 50 g of randomly taken pellets were ground into small particles using a mortar and a pestle (Figure 5). Then, the ground pellets were moved evenly into two pre-weighed empty metal trays. Trays with materials inside were weighed again before they were stored inside the oven (WTC binder FD-53, Tuttlingen, Germany) for overnight drying at 104 ℃. Afterwards, the two trays were weighed again to calculate the moisture of that sample (*Eq. 3*).

Figure 5. The mortar and the pestle used to grind pellets were shown on the left side. And the metal tray with ground materials was presented on the right side.

$$Moisture\ \% = \frac{the\ weight\ of\ metal\ tray\ after\ drying\ (g) - the\ weight\ of\ empty\ metal\ tray (g)}{the\ sample\ weight\ put\ onto\ the\ metal\ tray\ (g)} \quad (3)$$

$$DM\ \% = 100 - Moisture\ \% \quad (4)$$

6.3.6. The particle size distribution measurements

6.3.6.1. Description of the dry sieving steps

Figure 6. A presentation of the dry sieving assembly.

Pre-weighed empty sieves with a diameter of 3.5 mm, 2.8 mm, 2.0 mm, 1.6 mm, 1.0 mm, 0.5 mm, 0.2 mm, 0.1 mm, and a collector were stacked into one set with decreasing diameter values from top to bottom. Then the sieve set was placed on the Analytical sieve shaker AS 200 Control (Retsch, GmbH & Co. KG, Haan, Germany) set at 1.2 mm amplitude for 1 min (Figure 6). Exactly 100 g of pellets were weighed out using a sample divider and poured onto the top sieve. After sieving, sieves with materials inside were weighed again to calculate the weight of samples that remained. Unfortunately, sample No.28 did not perform the dry sieving test as the amount left was inadequate (< 100 g).

6.3.6.2. Description of the wet sieving steps

For the wet sieving process, the same set of sieves used in the dry sieving process was used again, but each with a rubber band (0.8 mm diameter) tightened around the bottom edge to prevent water overflow. Moreover, a collector with a water outlet was used as the bottom for the set of sieves during vibration on the Analytical sieve shaker AS 200 Control (Retsch, GmbH & Co. KG, Haan, Germany). Besides, 100 g of dust-free pellets (pre-sieved on a 2.0 mm sieve) were soaked in a beaker with 500 ml water for 2 hours, stirred now and then to help pellets dissolve. Afterwards, the watery mixture was poured on the top sieve and covered using a lid with a water inlet (Figure 7).

The wet sieving process was conducted as described by Miladinovic (2009). First, sieves were tightly locked on the shaker. Then the wet sieving was performed at 1.2 mm amplitude following the "3-1-3-1-3" order. The "3" stands for three minutes of sieving with water running through the sieves, and "1" stands for one minute of sieving with still water in the bottom two sieves. After sieving, sieves (without rubber bands) were placed separately in the oven (WTC binder FD-53, Tuttlingen, Germany) for overnight drying at 104 ℃. Dried sieves were weighed again to calculate the materials that remained.

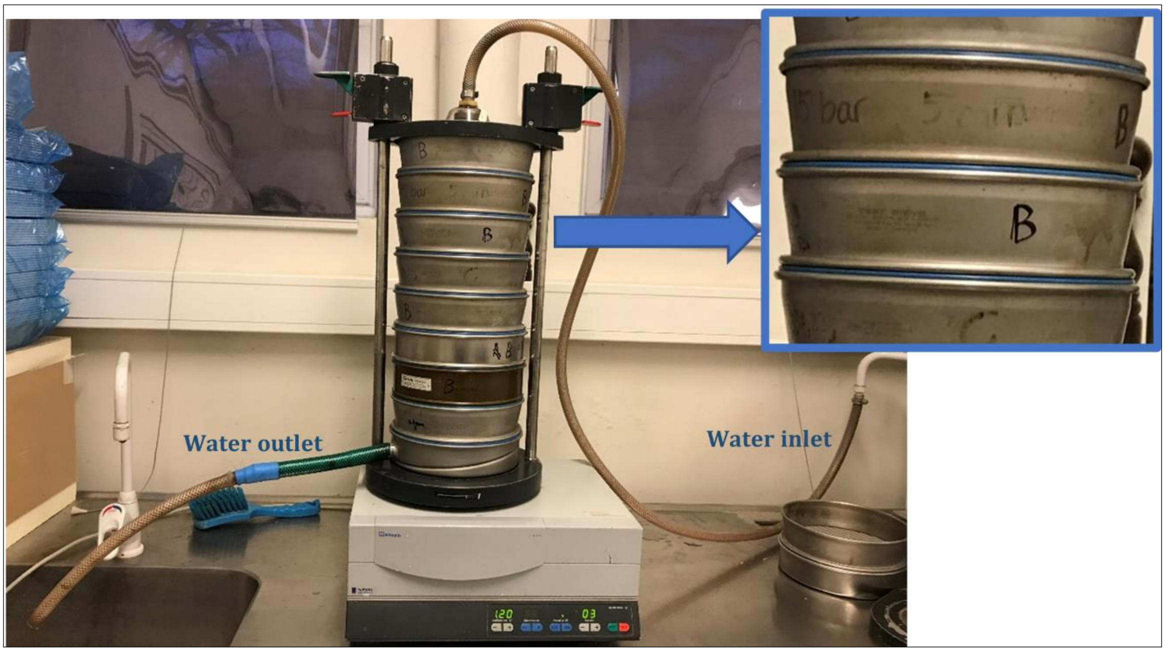


Figure 7. A presentation of the wet sieving assembly.

6.4. Statistical analysis

The measured pellet physical quality results were recorded in Excel and analysed. The standard deviation (SD) was used to show variations around the mean. Furthermore, the coefficient of variation (CV) was applied to make comparisons between different treatments. The Pearson correlation coefficient was calculated to understand whether there is a statistical relationship between different data sets or not. Besides, the mathematical relationship between two or more variables was exhibited using a scatter chart with a linear regression equation shown.

7. Results

7.1. Overview of pellet quality and size results

The average value, minimum and maximum value, the standard deviation (SD), and the coefficient of variance (CV) for each physical quality test were presented in Table 2. Pellet length and pellet diameter values showed moderate distributions around their mean values, respectively. Among all the CV%, the DM% showed the closest distributions around its mean value, while fine% varied largely around its mean value. The CVs of pellet hardness and pellet durability to their respective mean value were acceptable. Even though the average fine percentage was only 7.51%, large variations existed as the CV was 130.70%. The dry matter content of samples showed the smallest variations around the mean value. The particle size distribution resulted from the dry sieving process with pellet samples, and the wet sieving process with dissolved pellet particles, were presented in Figure 8.

Table 2. The average value, the standard deviation (SD), and the coefficient of variance (CV) of all fifty-eight samples. The minimum and the maximum value found in the average values of included samples for each physical quality index were also shown.

	Length (mm)	diameter (mm)	Hardness[1]		PDI[2] (%)	Fine%	DM%
			the Kahl (kg)	the Texture Analyser (N)			
Average	6.19	3.46	4.5	42.5424	69.81	7.51	88.73
Minimum	2.64	2.45	1.9	14.1952	2.00	0.19	83.67
Maximum	9.52	4.70	8.6	77.8329	96.10	52.38	92.20
SD	1.19	0.42	1.4	18.17	21.20	9.81	1.38
CV (%)	19.15	12.25	31.7	42.71	30.37	130.70	1.56

1 The hardness results tested by the Kahl tester included fifty-eight samples, while that by the Texture Analyser device included nineteen samples.
2 Fifty-seven samples were analysed for their pellet durability values.

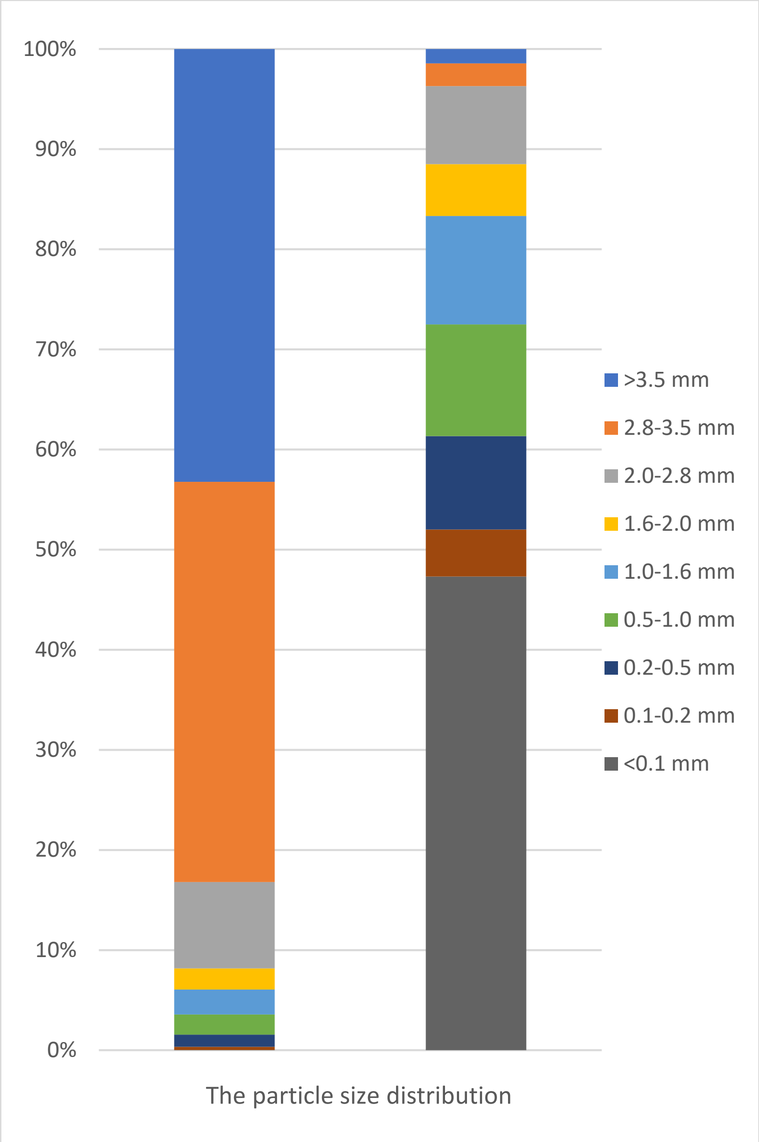


Figure 8. The PSD results of the dry sieving process consisting of fifty-seven samples (left bar) and the wet sieving process including fifty-eight samples (right bar).

Since different countries have different standards and regulations on broiler feed production, it might be interesting to show and compare the physical quality results of received samples among countries (Table 3). For pellet hardness, samples produced in Brazil and Germany had the lowest and highest values, 2.90 and 7.11 kg, respectively. For durability, the smallest average PDI was spotted in samples made in Italy (48.11%), while the biggest one was found in samples from Germany (94.70%). The highest average fine% was seen in the samples produced in Brazil (27.36%), and the lowest value was of samples made in Hungary (0.56%). Overall, samples produced in different countries all have high DM content values. Numerically, French samples had the lowest DM% (87.38%), and Hungarian samples had the highest DM%, 92.18%. Lastly, the pellet length values ranged from the smallest of 5.47mm to the largest 6.94

mm, in samples from Finland and Germany, respectively. Samples from Germany also had the smallest diameter value, 3.05 mm, while samples from Brazil had the biggest diameter value, 4.45 mm.

Table 3. The average valueand the coefficient of variation (CV) of the Kahl hardness, the pellet durability index, the fine percentage, the dry matter content, the pellet length and diameter of all samples grouped by production countries[1,2].

Countries	the Kahl hardness		Pellet Durability Index		Fine percentage		Dry Matter content		Pellet length		Pellet diameter	
	average (kg)	CV (%)	average (%)	CV (%)	average (%)	CV (%)	average (%)	CV (%)	average (mm)	CV (%)	average (mm)	CV (%)
Brazil (2)	2.90	47.63	52.80	-	27.36	129.29	89.09	2.23	6.00	4.89	4.45	8.06
Finland (5)	6.30	36.80	85.81	9.03	7.76	78.55	88.89	0.87	5.47	46.48	3.50	3.93
France (6)	4.08	13.60	70.14	12.19	10.01	120.88	87.38	2.26	6.18	7.52	3.63	1.85
Germany (2)	7.11	7.56	94.70	2.09	3.78	122.26	88.29	0.02	6.94	10.01	3.05	0.25
Hungary (2)	5.27	11.68	82.90	6.48	0.56	93.67	92.18	0.03	6.92	8.72	3.46	7.03
Italy (6)	3.27	18.31	48.11	36.90	7.00	84.25	88.78	0.70	6.41	8.50	3.34	15.53
RSA (4)	4.71	27.81	65.93	25.99	2.74	101.61	90.38	0.70	6.23	12.18	4.13	1.54
Serbia (3)	3.61	20.51	51.90	46.86	6.19	72.33	88.40	1.22	6.03	14.15	3.79	13.10
Spain (5)	3.51	22.56	61.99	16.49	4.57	78.89	88.60	1.03	6.40	13.35	3.16	17.61
The Czech Republic (3)	5.50	21.62	84.68	9.73	5.58	45.74	89.55	0.34	6.32	6.60	3.40	1.27
The NL (9)	4.43	28.78	65.16	51.32	7.16	116.46	88.81	1.23	6.00	31.14	3.20	7.93
The UK (11)	4.46	16.69	78.45	19.76	8.86	131.10	88.04	1.15	6.23	16.48	3.36	6.94

1 The blue coloured cell represents the lowest value within each column; and the green coloured cell represents the highest value within each column.
2 The countries were listed in alphabetic sequence.

Figure 9 and Figure 10 exhibited the particle size distributions of the pellets and the dissolved pellet particles, respectively, of samples from different countries. The countries were listed in alphabetic sequence.

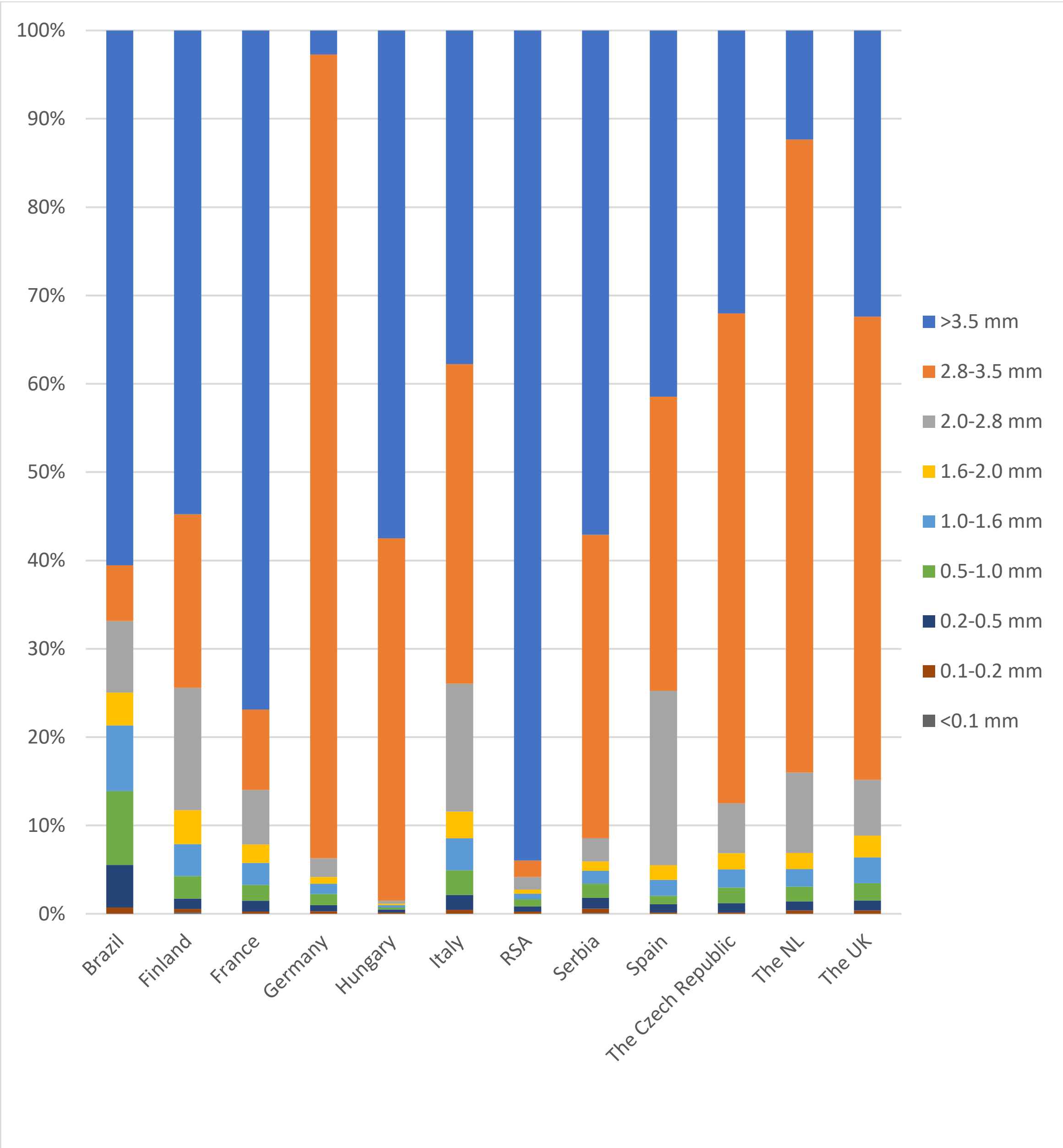


Figure 9. The average particle size distribution of the dry sieving tests of different production countries[1,2].

1 The countries were listed in random sequence.
2 One sample from Serbia did not have enough pellets left to perform the dry sieving. Therefore, dry sieving results of the other fifty-seven samples were shown country wise.

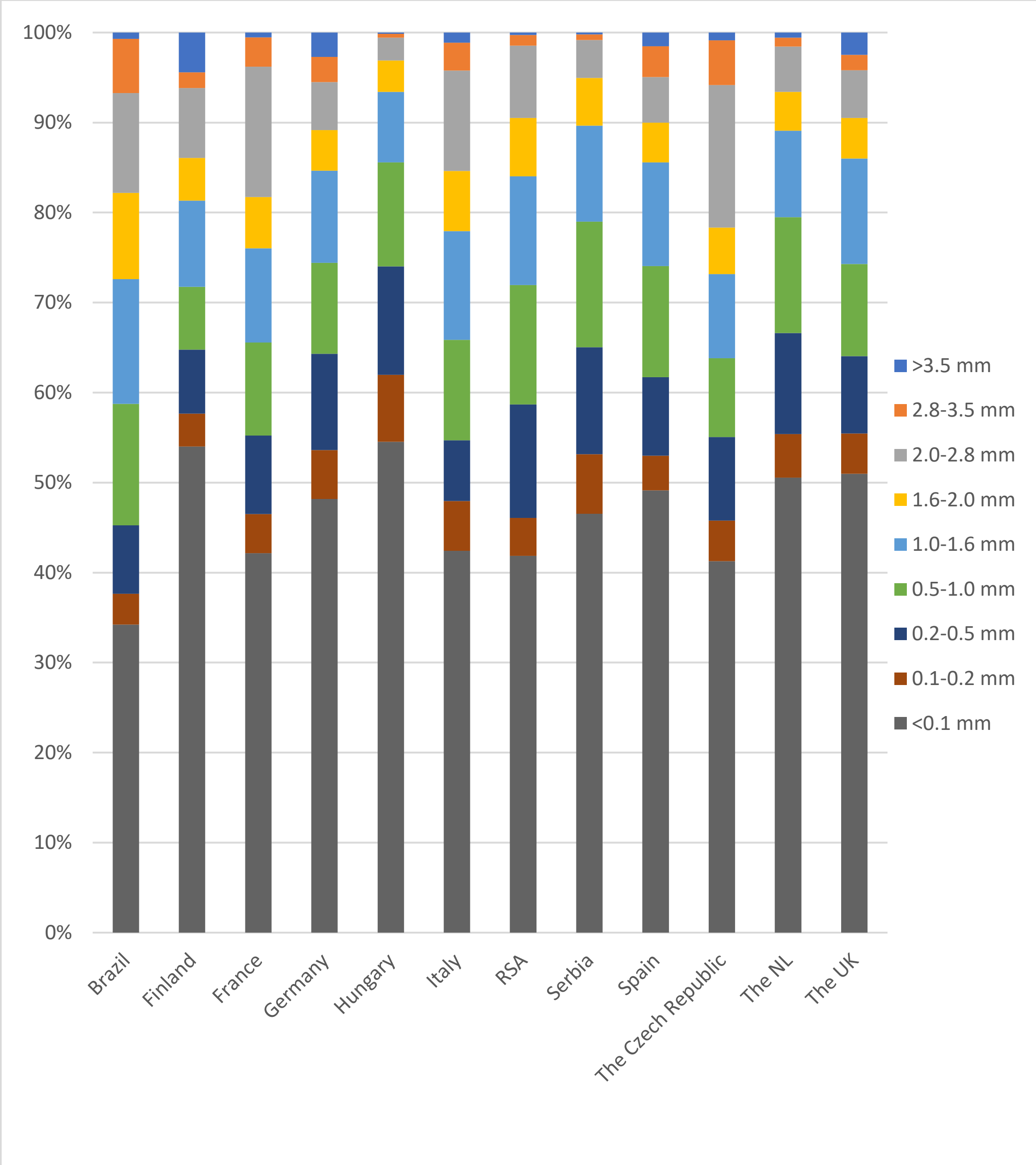


Figure 10. The average particle size distribution from the wet sieving tests of different production countries[12].

7.2. Influence of raw material on pellet quality and size

Based on the raw material information regarding the primary and secondary cereal/protein sources, samples were divided into five different groups with the number of inclusion addressed in the brackets: wheat/SBM (35), maize/SBM (7), maize/SFM/SBM (4), maize/wheat/SBM (5), wheat/maize/SBM (7).

1 The countries were listed in alphabetic sequence.
2 The wet sieving results of all fifty-eight samples.

It appears that pellets with higher inclusions of wheat showed higher average hardness values in comparison to pellets with higher percentages of maize (Table 4). Besides, maize/SFM/SBM samples showed a higher hardness value than maize/SBM samples.

Table 4. The average pellet hardness values of samples grouped by their main raw material compositions. The number of included samples in each group was indicated in the brackets.

	Pellet hardness						
	the Kahl tester (kg)					the Texture Analyser (N)	
	Wheat/SBM (35)	Maize/SBM (7)	Maize/SFM/SBM (4)	Maize/Wheat/SBM (5)	Wheat/Maize/SBM (7)	Wheat/SBM (15)	Maize/SBM (4)
Average	4.89	3.16	4.71	3.31	4.34	45.46	31.59
CV (%)	30.17	26.75	27.81	19.95	19.07	36.26	71.50

Generally, pellets made with higher wheat inclusion showed better pellet durability results compared to pellets made with higher maize inclusion (Table 5). Samples formulated with maize/SFM/SBM showed a better durability index than maize/SBM pellets.

Table 5. The average pellet durability index of samples grouped by their main raw material compositions. The number of included samples in each raw material group was indicated in the brackets.

	PDI (%)				
	Wheat/SBM (35)	Maize/SBM (6)	Maize/SFM/SBM (4)	Maize/Wheat/SBM (5)	Wheat/Maize/SBM (7)
Average	75.46	51.91	65.93	46.92	75.49
CV (%)	28.03	29.81	25.99	41.73	10.85

As shown in Table 6, no consistent patterns exist among the fine percentage and dry matter content related to the main raw material compositions. Besides, the pellet length and diameter values did not show any corresponding changes regarding the primary and secondary raw material compositions (Table 7).

Table 6. The average fine percentage and the average dry matter content of samples grouped by their main raw material compositions. The number of included samples in each raw group was indicated in the brackets.

	Fine (%)					Dry Matter (%)				
	Wheat/SBM (35)	Maize/SBM (7)	Maize/SFM/SBM (4)	Maize/Wheat/SBM (5)	Wheat/Maize/SBM (7)	Wheat/SBM (35)	Maize/SBM (7)	Maize/SFM/SBM (4)	Maize/Wheat/SBM (5)	Wheat/Maize/SBM (7)
Average	7.04	12.69	2.74	6.69	7.95	88.38	88.59	90.38	88.58	89.82
CV (%)	122.37	140.14	101.61	97.79	123.34	1.46	1.50	0.70	0.51	1.83

Table 7. The average pellet length and diameter values of samples grouped by their main raw material compositions. The number of included samples in each group was indicated in the brackets.

	Pellet Length (mm)					Pellet Diameter (mm)				
	Wheat /SBM (35)	Maize/ SBM (7)	Maize/S FM/SBM (4)	Maize/Wh eat/SBM (5)	Wheat/Mai ze/SBM (7)	Wheat /SBM (35)	Maize/ SBM (7)	Maize/SFM /SBM (4)	Maize/ Wheat /SBM (5)	Wheat/ Maize/S BM (7)
Average	6.26	6.05	6.23	6.51	5.72	3.34	3.91	4.13	3.32	3.34
CV (%)	20.62	8.68	12.18	8.40	28.93	8.08	13.01	1.54	17.40	12.31

There are no apparent relationships between the primary and secondary raw materials used in the diet and the particle size distribution of pellets (Figure 11).

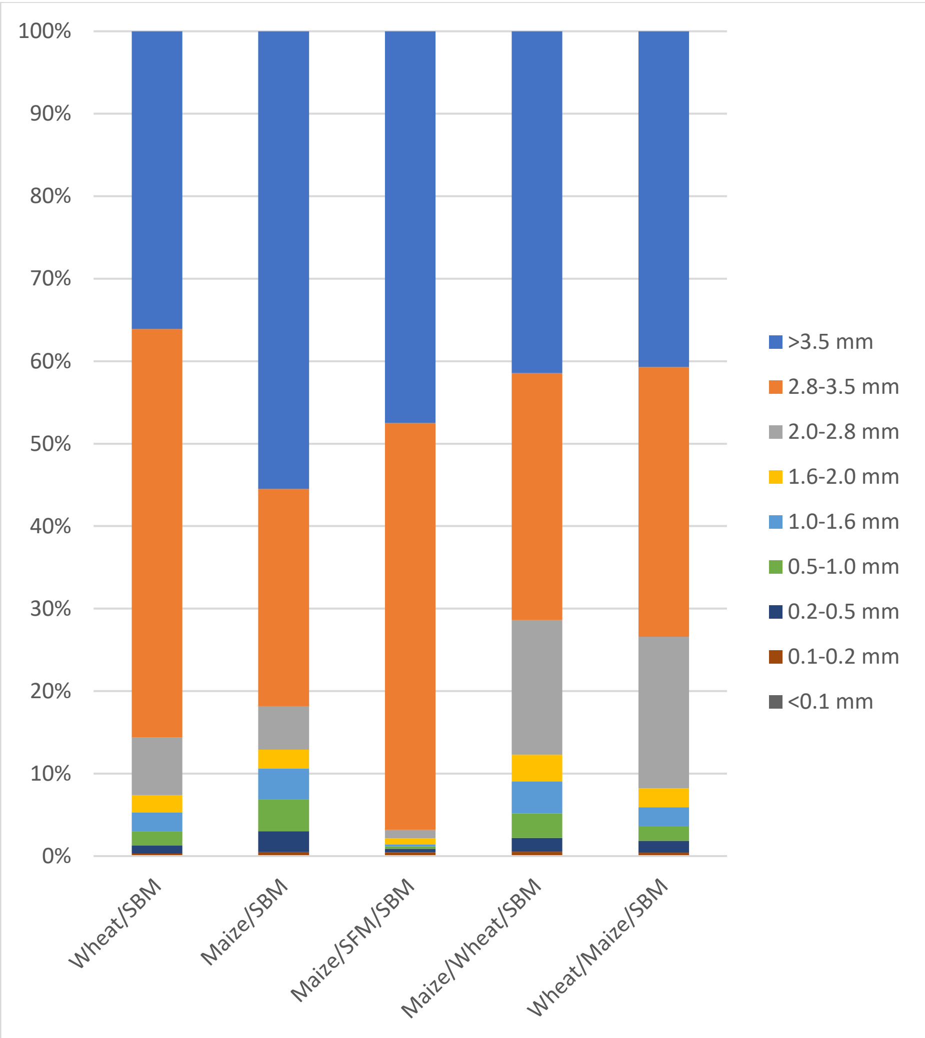


Figure 11. The particle size distribution results from the dry sieving process of different raw material groups as indicated below the bars[1].

1 The number of samples analysed in each of the five groups (from left to right) was thirty-five, six, four, five and seven.

The wet sieving results better presented the particle size distribution within pellets than the dry sieving results. As shown in Figure 12, broiler pellets made with wheat had higher amounts of small particles (<0.1 mm) than the ones made mainly with maize. Moreover, the pellets contained wheat had a higher percentage of particles larger than 2.8 mm than the pellets that contained none.

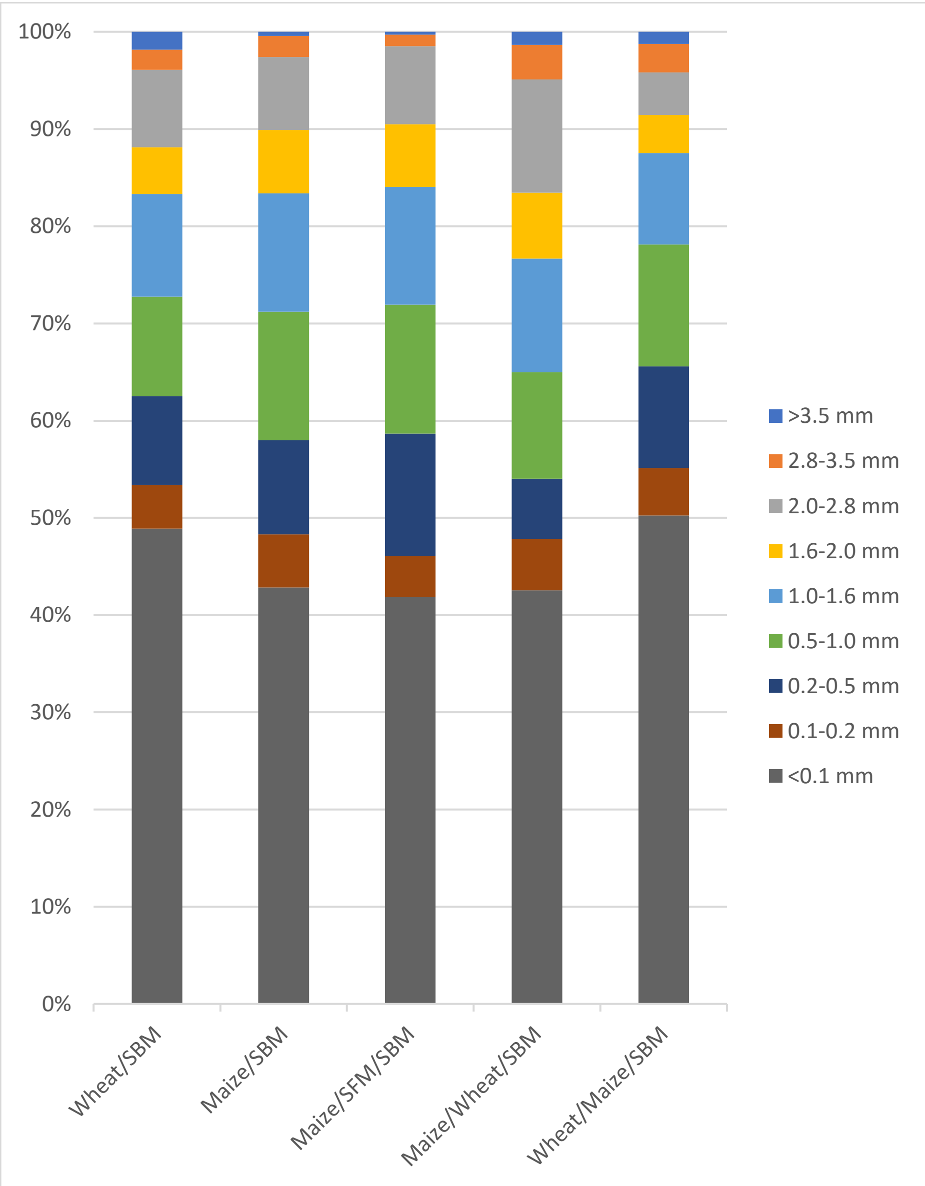


Figure 12. The particle size distribution results from the wet sieving process for different raw material groups as indicated below the bars[1].

1 The number of samples analysed in each of the five groups (from left to right) is thirty-five, seven, four, five and seven.

7.3. Influence of grinding on pellet quality and size

The physical quality results of received samples were divided into different groups based on the grinding method applied during production. Forty-four samples used hammer milling (HM), eight used roller milling (RM), two used multicracker, and the last four had mixed milling systems. Therefore, only the HM and the RM ground samples were analysed for their physical quality and texture results. Furthermore, others were excluded due to the unclarity in grinding methods and the limitation in sample numbers.

As shown in Table 8, pellets ground by RM and HM showed similar average hardness values when tested with the Kahl tester. The hardness results measured with the Texture Analyser showed a slightly higher average value for pellets ground by RM than HM. Pellets ground with RM had better average durability than that of pellets milled by HM. For the ratio of fines generated, RM pellets showed a higher average value compared to HM pellets. Besides, there was no difference between the dry matter content of pellets milled by different two methods. Furthermore, the length and diameter values of pellets seem not influenced by the grinding method applied (Table 9).

Table 8. The average value and the coefficient of variance (CV%) for different pellet physical quality indexes were presented. The samples were grouped by their respective grinding methods-Hammer Milling (HM) and Roller Milling (RM), and the number of analysed samples was indicated in the following brackets.

	Pellet hardness				PDI (%)		Fine (%)		DM (%)	
	Kahl tester (kg)		Texture Analyser (N)							
	RM (8)	HM (44)	RM (4)	HM (14)	RM (8)	HM (43)	RM (8)	HM (44)	RM (8)	HM (44)
Average	4.39	4.48	42.84	39.94	75.70	69.82	9.88	7.01	88.15	88.82
CV (%)	27.81	31.01	19.83	45.99	18.79	30.64	102.20	145.21	2.33	1.47

Table 9. The average length and diameter values of pellet samples separated into RM and HM groups. And the number of included samples was mentioned in the brackets.

	Pellet Length (mm)		Pellet Diameter (mm)	
	RM (8)	HM (44)	RM (8)	HM (44)
Average	6.16	6.15	3.47	3.51
CV (%)	6.52	17.67	4.51	12.74

The particle size distribution results for pellets (dry sieving results) and dissolved pellet particles (wet sieving results) are showed in Figure 13 and Figure 14, respectively. RM pellets and HM pellets had identical particle distribution results tested with the dry sieving process. On the other hand, results from wet sieving showed that RM pellets have a higher ratio of particles ranging from 1.6 mm to 3.5 mm, and a lesser ratio of particles smaller than 1.6 mm (especially <0.1 mm) than HM pellets.

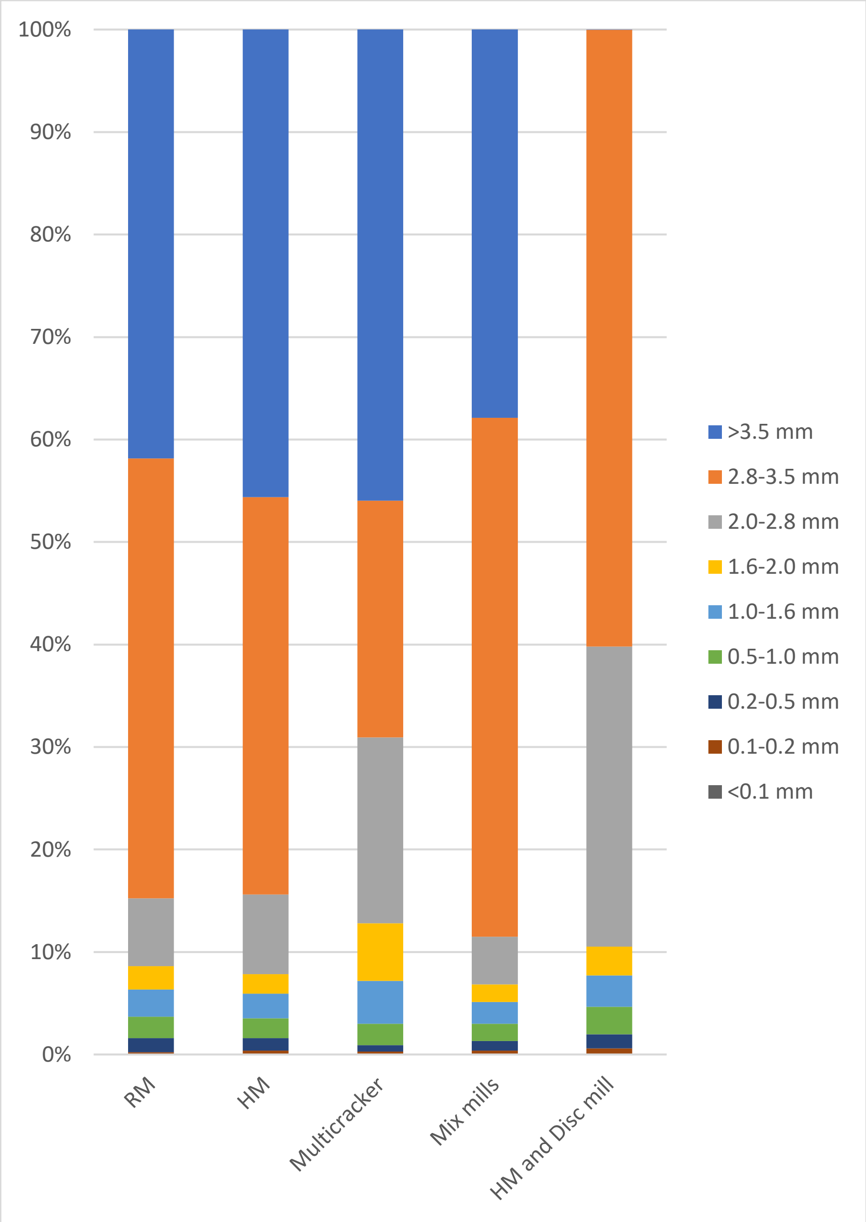


Figure 13. The average particle size distribution of the dry sieving results grouped by different grinding methods[1].

1 The number of samples included in each group was listed as the following: RM-eight, HM-forty-three, Multicracker-two, Mix mills-two, HM-and-Disc mill-two.

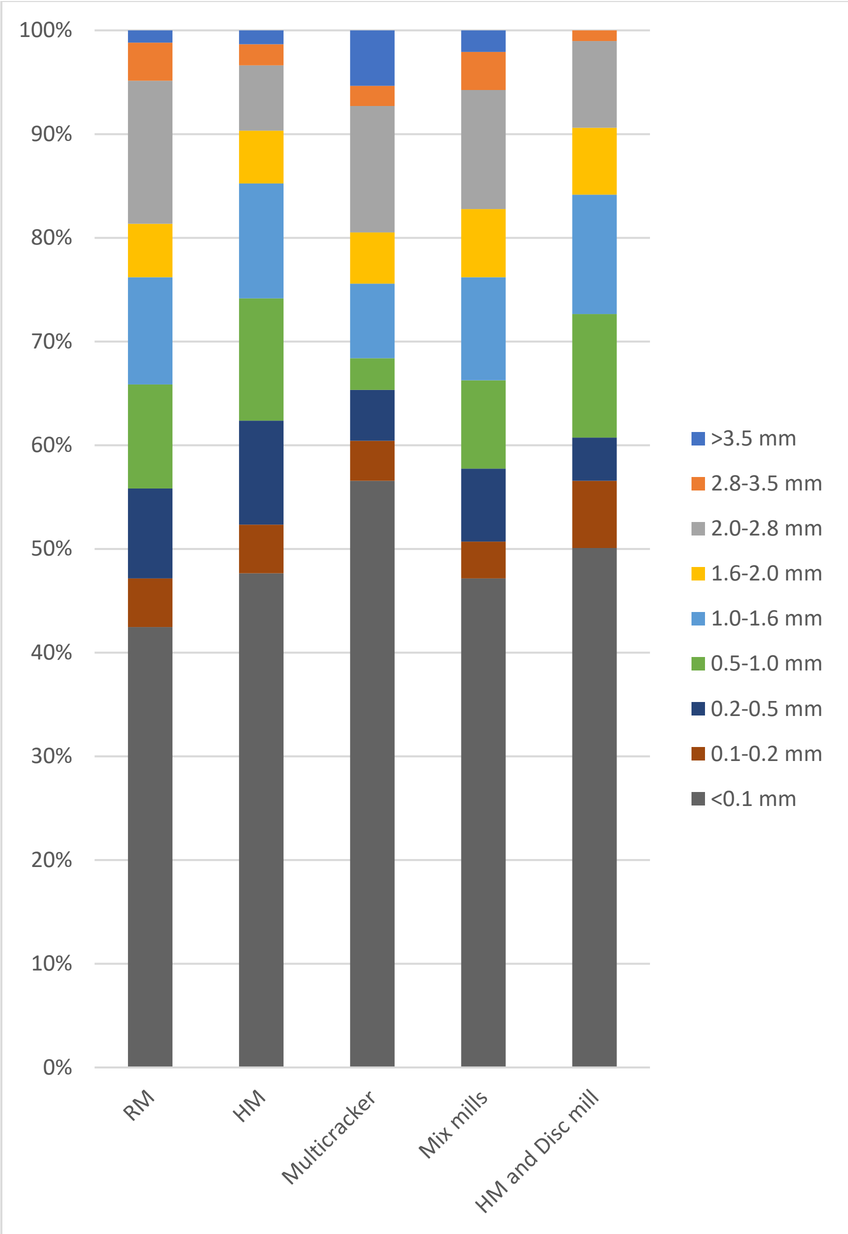


Figure 14. The average particle size distribution of the wet sieving results grouped by different grinding methods[1].

7.4. Influence of whole wheat on pellet quality and size

In this part, physical quality and pellet size results were divided based on whether samples had whole wheat addition or not, forming whole wheat (WW) and no whole wheat (NWW) groups. As shown in Moreover, WW samples had a slightly bigger average length and a smaller average diameter value than NWW samples (Table 11).

1 The number of samples included in each group was listed as the following: RM-eight, HM-forty-four, Multicracker-two, Mix mills-two, HM-and-Disc mill-two.

Table 10, the average hardness values tested with the Kahl tester, and the Texture Analyser showed controversial results. The average hardness value for the WW group was slightly higher than that for the NWW group. Furthermore, WW pellets showed higher PDI than NWW pellets. However, the average hardness values tested by the Texture Analyser showed controversial results. It seems that WW pellets were more durable than NWW pellets. Besides, NWW pellets contained a higher percentage of fines than WW pellets. Both groups had similar dry matter percentages. Moreover, WW samples had a slightly bigger average length and a smaller average diameter value than NWW samples (Table 11).

Table 10. The average value and the coefficient of variance (CV) for different pellet physical quality indexes. The samples were separated into having whole wheat addition (WW) and no whole wheat addition (NWW). And the number of analysed samples was indicated in the following brackets.

	the Kahl hardness (kg)		the Texture Analyser hardness (N)		PDI (%)		Fine (%)		DM (%)	
	WW (12)	NWW (46)	WW (7)	NWW (12)	WW (12)	NWW (45)	WW (12)	NWW (46)	WW (12)	NWW (46)
Average	4.56	4.44	40.09	43.97	77.83	67.68	5.13	8.12	88.40	88.82
CV (%)	20.91	34.27	21.52	50.53	16.98	33.24	73.30	132.88	1.74	1.51

Table 11. The average length and diameter values for samples with and without whole wheat addition. The number of samples included was indicated in the brackets.

	Pellet Length (mm)		Pellet Diameter (mm)	
	WW (12)	NWW (46)	WW (12)	NWW (46)
Average	6.51	6.11	3.37	3.49
CV (%)	10.39	20.93	11.01	12.54

According to the dry sieving results shown in Figure 15, WW pellets had a higher percentage of particles larger than 2.0 mm than NWW pellets. The same tendency existed in the particle size distribution resulted from the wet sieving test (Figure 16).

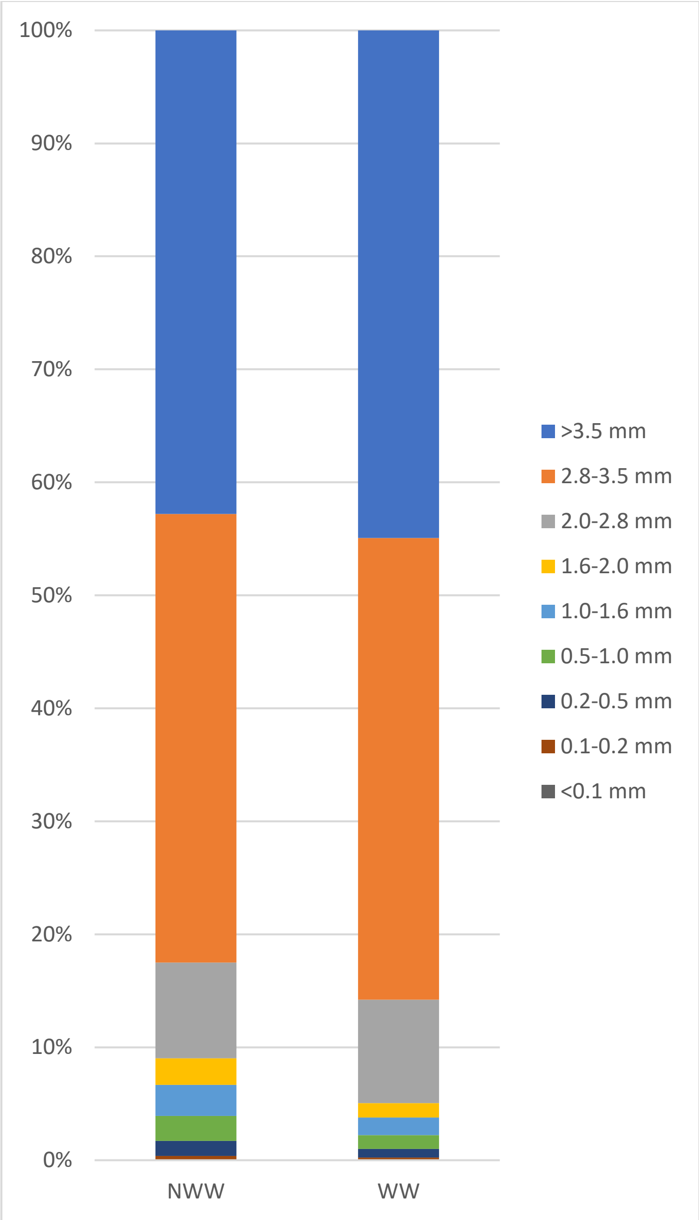


Figure 15. The average particle size distribution of the dry sieving process for samples without whole wheat addition (NWW) or with (WW)[1].

1 There were forty-five samples belonged to the NWW group and twelve samples belonged to the WW group.

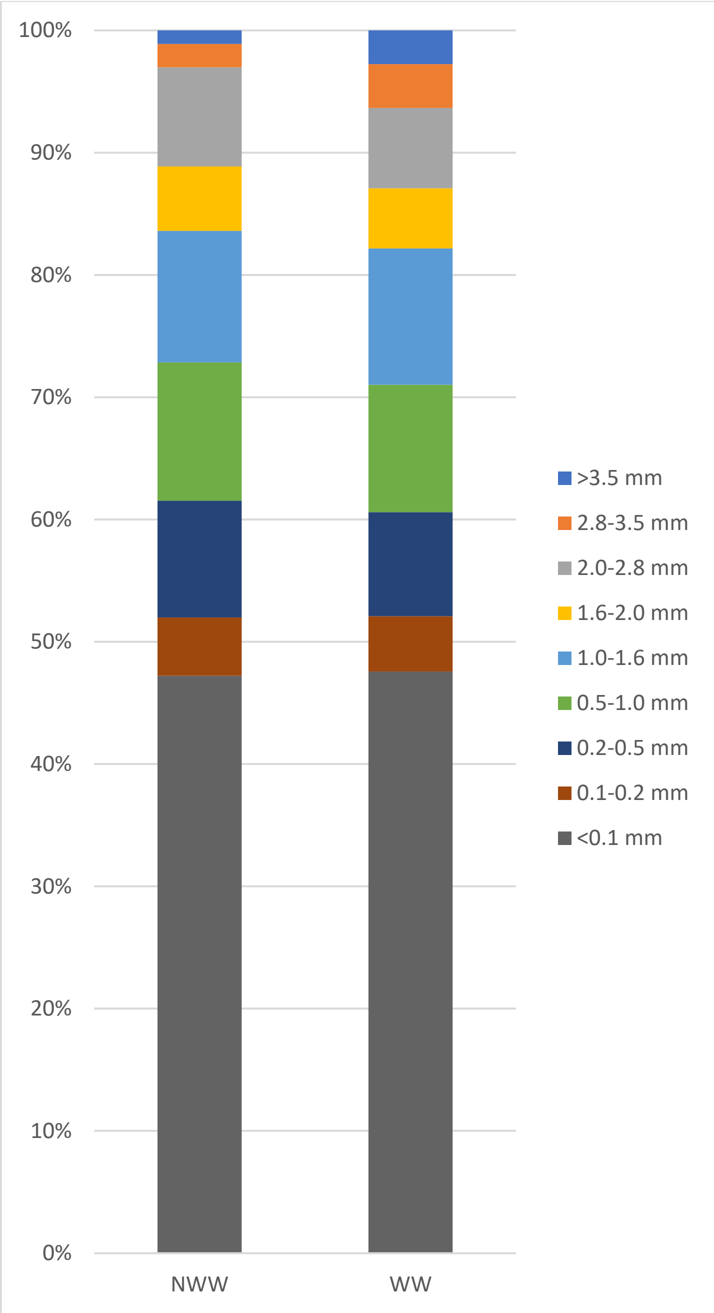


Figure 16. The average particle size distribution resulted from the wet sieving process and divided into no whole wheat addition (NWW) and whole wheat addition (WW)[1]*.*

7.5. Influence of pellet size on physical quality values

The Pearson correlation coefficients showed that pellet length had a fairly strong positive linear relationship (r=0.47) with pellet hardness and a fairly strong negative correlation (r=-0.40) with

1 There were forty-six samples belonged to the NWW group and twelve samples belonged to the WW group.

the fine percentage. Aside from these, only week and very week correlations were found (Table 12).

Table 12. The Pearson correlation coefficients between pellet size and other four pellet quality features were listed in this table. And the number of samples included was indicated in the brackets.

	Pellet Length	Pellet Diameter
Pellet Hardness (58)	0.47	-0.04
Pellet Durability (57)	0.26	0.07
Fine Percentage (58)	-0.40	0.20
Dry Matter Content (58)	-0.12	0.20

The following scatter charts further exhibited how well pellet hardness and pellet length fitted into a linear regression line (Figure 17 and Figure 18) and how the fine percentage values were in samples with increasing pellet length values (Figure 19).

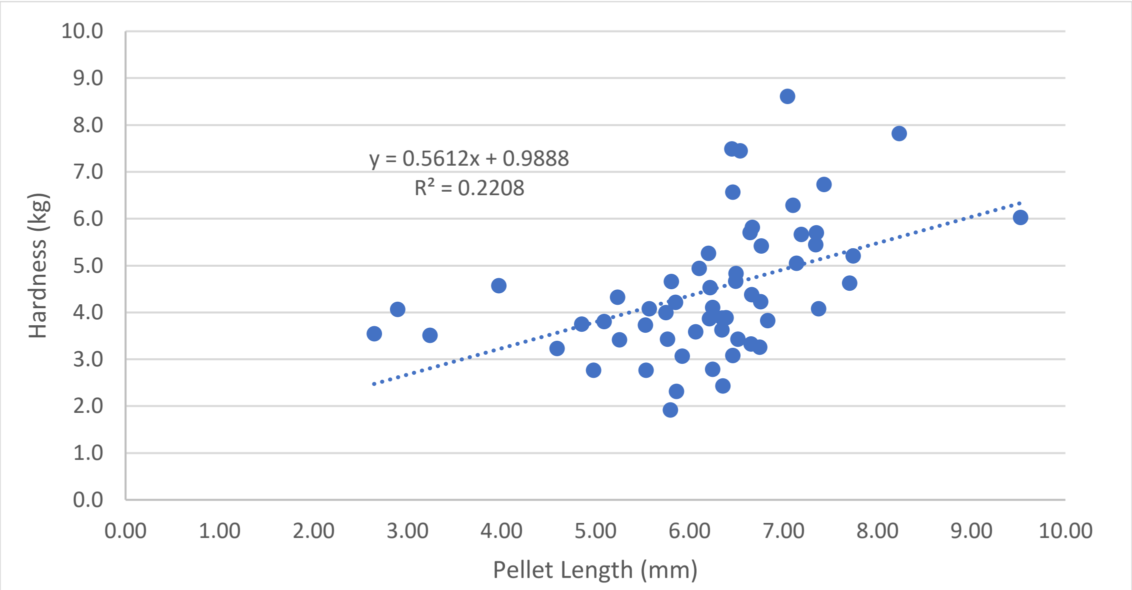


Figure 17. The relationship between pellet length values and their hardness values measured with the Kahl tester[1].

1 Fifty-eight samples were included to analyse the relationship between the pellet length and the hardness index.

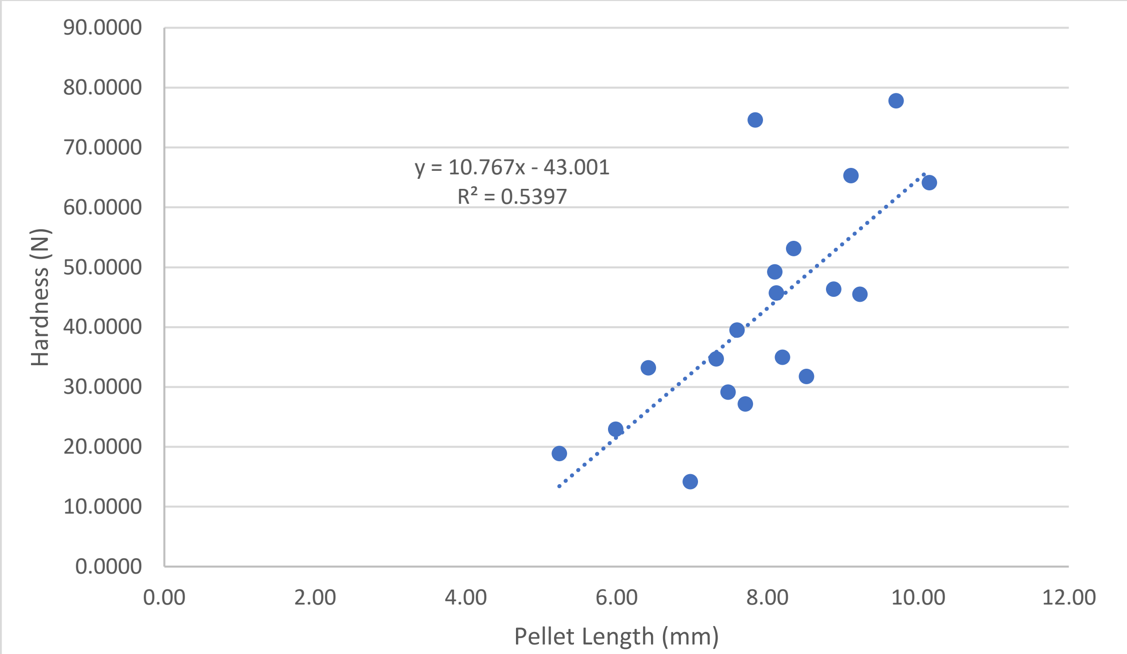


Figure 18. The relationship between pellet length values and corresponding hardness results tested byt the Texture Analyser device[1].

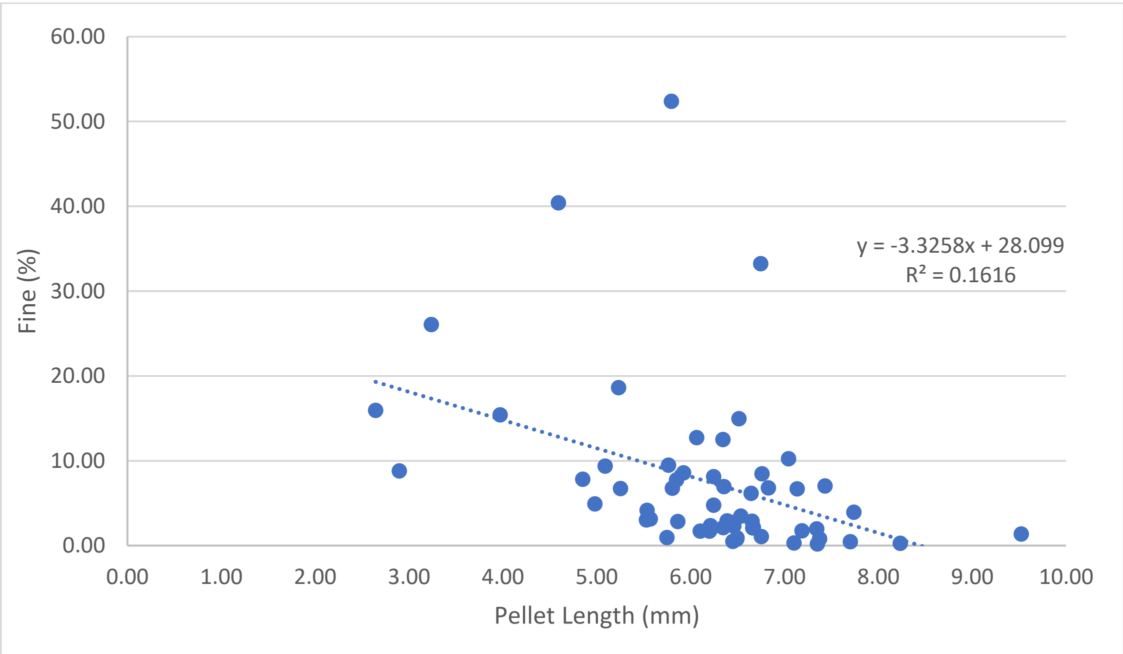


Figure 19. The relationship between the pellet length values and respective fineness results of fifty-eight samples.

7.6. Influence of particle size within pellets on physical quality and

1 Only nineteen samples had their hardness measure by the Texture Analyser, therefore, were included.

pellet size

The Pearson correlation coefficients between particle size distribution of dissolved sample pellets and relevant pellet texture and quality values were concluded in Table 13. The pellet diameter had a fairly strong positive relationship with particles ranged between 1.6 and 2.0 mm and a fairly strong negative relation with particles smaller than 0.1 mm. Particles larger than 3.5 mm had weak positive relations with both pellet hardness values and durability values. Furthermore, the fine percentage was slightly positively influenced by particles ranging from 2.0 to 3.5 mm. Besides, no other strong correlations were found.

Table 13. The Pearson correlation coefficients between the particle size distribution and pellet length, pellet diameter, pellet hardness, pellet durability, and fine percentage were listed in this table. The number of involved samples was addressed in the following brackets.

	Particle size distribution								
	>3.5 mm	2.8-3.5 mm	2.0-2.8 mm	1.6-2.0 mm	1.0-1.6 mm	0.5-1.0 mm	0.2-0.5 mm	0.1-0.2 mm	<0.1 mm
Pellet Length (58)	0.16	-0.01	-0.01	0.13	0.10	-0.04	-0.10	-0.04	-0.03
Pellet Diameter (58)	-0.12	0.15	0.26	0.40	0.24	0.11	0.12	-0.13	-0.44
Pellet Hardness (58)	0.38	-0.15	-0.16	-0.09	-0.20	-0.21	0.05	-0.08	0.23
Pellet Durability (57)	0.29	0.03	-0.05	-0.13	-0.17	-0.25	0.01	-0.15	0.16
Fine Percentage (58)	-0.05	0.37	0.26	0.11	-0.02	-0.17	-0.18	-0.22	-0.15

7.7. Interactions between different pellet quality indexes

The Pearson correlations between different physical quality indicators showed two relatively strong relationships. There was a strong positive correlation between pellet hardness and durability values (r=0.75) and a fairly strong negative relation between the hardness results and the fine percentage results (r=-0.38).

Table 14. The Pearson correlation coefficients between different pellet quality indexes were listed in this table, and the number of analysed samples was indicated in the brackets.

	Pellet Hardness	Pellet Durability	Fine Percentage	Dry Matter Content
Pellet Hardness (58)	1.00			
Pellet Durability (57)	0.75	1.00		
Fine Percentage (58)	-0.38	-0.18	1.00	
Dry Matter Content (58)	0.07	-0.02	-0.08	1.00

It was clear that pellet durability values increased with increasing hardness values but with different gradients. As shown in Figure 20, the correlation coefficient between pellet durability values and the pellet hardness smaller than 5.5 kg was 0.81, indicating a very strong relationship. When the hardness values reached over 5.5 kg, the correlation coefficient between these two physical quality indicators dropped to 0.49.

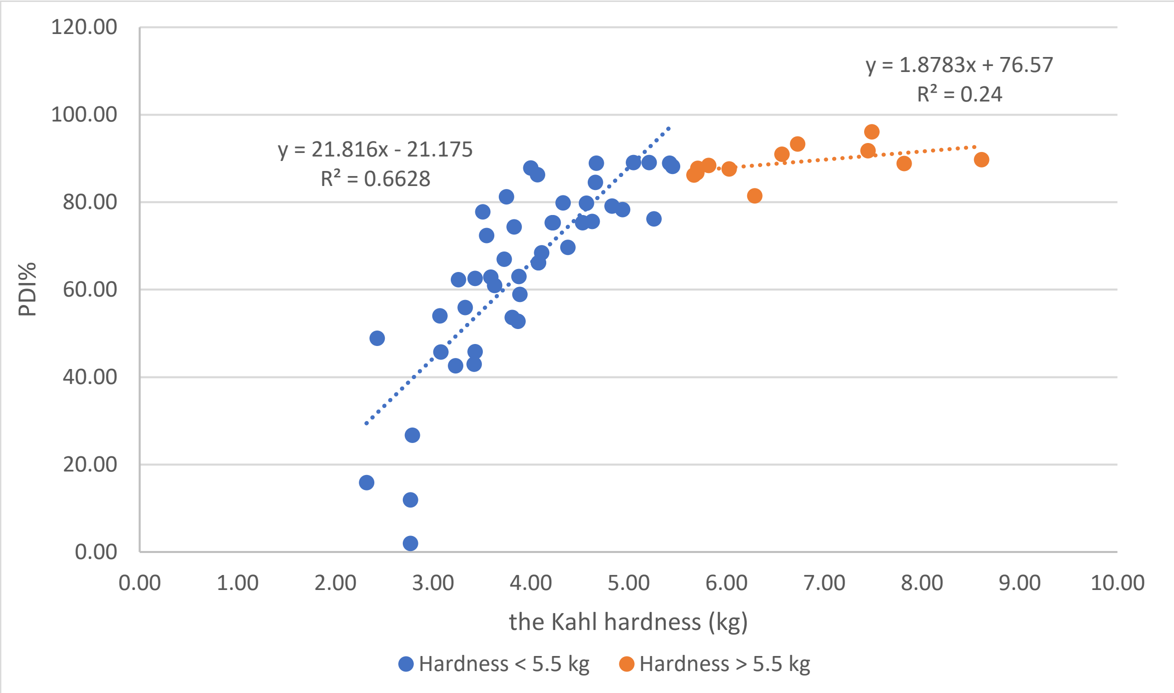


Figure 20. The scatter chart of PDI results and corresponding hardness results tested using the Kahl tester was shown. And the data was divided into two groups regarding the point where pellet hardness value was 5.5 kg[1].

7.8. Comparisons between the two measurements for hardness

The Pearson correlation coefficient between the hardness values tested by the two devices was 0.83, indicating a very strong positive correlation (Figure 21). Since no causal relationship existed between these two methods, this high correlation coefficient meant it was feasible to test pellet hardness with different devices but still showing a similar overall trend.

1 In total fifty-seven samples were included in this analysis.

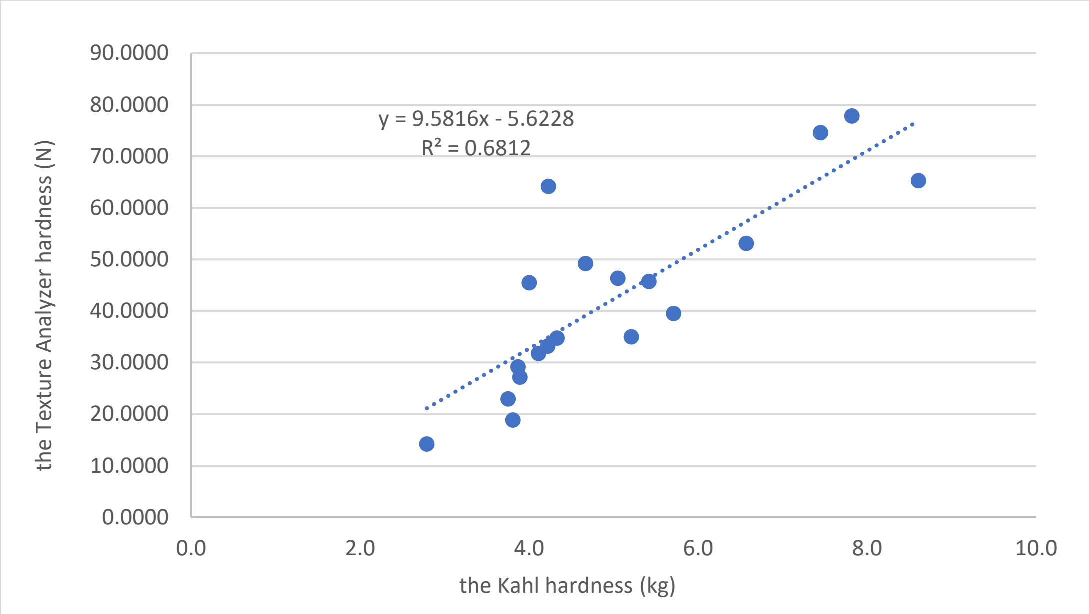


Figure 21. The scatter chart showed the relateion between the pellet hardness results tested by the Kahl tester and the Texture Analyser device. In total, nineteen samples were included.

8. Discussion

8.1. Comprehensive understanding of broiler pellets

Based on common senses, the pellet durability and hardness values of received samples suggested that pellets produced in Germany had the best physical quality compared to other samples. Numerical variations existed among pellet size values. Different pellet physical quality features of received samples are reasonable since samples were produced in various countries and aimed for different feeding phases. Lemons et al. (2019) concluded that it is difficult to find an optimum particle size of broiler feed since different strains have different beak capacity which regulates their feeding behaviour the most.

Pellet hardness is an important pellet quality index since it is enormously related to the pellet selection issue (Thomas & van der Poel, 1996) and ingestion speed issue (Mohammadi Ghasem Abadi et al., 2019) of broilers. In the experiment performed by Parsons et al. (2006) where soft (added 2.5% water during pelleting) and hard (added 0.2% of commercial binder) pellets were produced and fed to broilers from 3 to 6 weeks old. Results showed that broilers fed hard pellets had higher live weight gain and better feed efficiency than broilers fed soft pellets. Later research found that the short-term preference for hard pellets was reinforced when hard pellets were related to high energy density vs soft pellets with low energy density (Bouvarel et al., 2009).

The grinding process directly influences the particle size distribution of raw materials and indirectly affects the pellet durability and hardness values through particle sizes. The average PDI of received samples showed a higher value in RM pellets compared to HM pellets. This result is in accordance with the findings of Vukmirović et al. (2017), where the authors reported that RM pellets showed better pellet durability values than HM pellets. According to Nir et al. (1995), RM generated fewer fines during milling and gave a more uniform particle size distribution than HM, which could explain the better durability values found in RM pellets. Besides the differences between different milling machines, the settings during grinding are also important.

Controversial statements have been made about how particle size (microstructure) would affect pellet quality. One theory is that the ratio of coarse particles in the pellet negatively relates to the quality (durability and hardness) of pellets. Miladinovic (2013) illustrated that coarse ground wheat using an HM negatively influenced pellet durability and hardness, whereas finely ground wheat formed harder and more durable pellets. Similar conclusions on coarse grinding adversely influenced pellet durability and hardness were mentioned by Nir et al. (1995), Behnke (1994), Angulo et al. (1996), Svihus et al. (2004), Amerah et al. (2008), and Lyu et al. (2020). Besides, Mohammadi Ghasem Abadi et al. (2019) found that pellets with all feed ingredients ground by a 6 mm-screen (HM) showed lower durability values than 2 mm-screen, 36.9% and 42.7%, respectively. While for pellet hardness, these two sizes did not show significant influence. Theoretical explanations given by Behnke (2001) stated that fine grinding increased the surface area of particles, thus easier for moisture and heat penetration during pelleting, hence, the formation of firmer pellets against abrasion. As later supplemented by Svihus et al. (2004), coarse particles created weak points within pellets, and coarse particles had a lower starch gelatinisation degree than small particles. However, Reece et al. (1986) found pellets with coarse ground corn (9.53 mm-screen HM) showed numerically higher durability values ($P>0.05$) than with finely ground corn (3.18 mm-screen HM and 6.35 mm-screen HM). Moreover, da Silva et al. (2018) proved that coarse particles increased the PDI numerically in all three feeding phases (starter, grower, and finisher) but only statistically significant ($P<0.05$) in the finisher phase (81.10% vs 73,87% for coarse and fine grinding, respectively). The fine particles and coarse particles were achieved by grinding materials through a screen of 5.0 mm and 6.5 mm to achieve particles of 650 µm and 850 µm, respectively. Then, the pellet durability was tested with a Pfost tumbling Can and then sieved on a 3.0 mm sieve. Despite the controversial results of grinding on pellet quality, economically, fine grinding requires more energy and might reduce the production rate in feed factories (Amerah et al., 2007a). Therefore, in practice, the effect of improved pellet quality still needs to be balanced with the costs during feed production and the benefits from the growth performance of birds.

However, it is impossible to relate the differences among particle size distributions of dissolved pellets exclusively to the effects of different grinding methods due to the size reduction during pelleting (Amerah et al., 2007b). Melo-Durán et al. (2020) compared the wet sieving results of ground mash and pellets. They found out that pelleting process reduced the relative proportion of particles larger than 1.0 mm and increased the ratio of particles smaller than 0.5 mm. However, the tested particle distribution results of dissolved pellets can be used as a good indicator for estimating their influence on the gastrointestinal tract of broilers. It has been proved that pellets will dissolve in the crop almost immediately after consumption (Engberg et al., 2002; Nir et al., 1995). Engberg et al. (2002) found dissolved particles tended to flow directly into the duodenum and jejunum, bypassing the gizzard. However, the authors did not indicate a specific particle size. An earlier study by (Moore, 1999) found that particles had an average of 0.5 mm-length and 0.25 mm-width left the gizzard. Later research conducted by Rodrigues and Choct (2018) confirmed that particles smaller than 0.1 mm flowed directly into the lower digestive tract. Based on this finding, on average, 47.30% of the particles (<0.1 mm) within received samples would flow directly into the small intestine region and bypassing the gizzard of broilers.

On the other hand, the lack of coarse particles in the diet would impair the stimulation for a proper developed gizzard and proventriculus region (Amerah et al., 2007b; Hamungalu et al., 2020; Svihus et al., 2010). As mentioned in previous texts, the underdeveloped gizzard might induce proventriculus dilatation (Liermann et al., 2020). Hence, reduce the secretion of gastric juice (mainly HCl) in the proventriculus (Amerah et al., 2008; Engberg et al., 2002; Hamungalu et al., 2020). Considering the average particle size distribution resulted from dissolved pellet samples showed that about 60% of the particles (<0.5 mm) would not stimulate the proper development of the gizzard and proventriculus region.

8.2. Effects of raw materials

On average, received samples that contained a higher percentage of wheat showed higher hardness values and higher PDIs than samples containing low or no wheat. Behnke (1994) mentioned that replacing corn/sorghum with hard winter wheat significantly improved the pellet durability in both diets resulted from one unpublished experiment. However, Amerah et al. (2008) found higher pellet durability values in pellets made with corn than with wheat. These controversial results are understandable as the specific features of used cereals vary, such as the protein and fibre content, the pre-treatment applied. As illustrated by Camire et al. (1990), the hardness of wheat had a significantly ($P<0.001$) positive relationship with pellet durability. According to Wood (1987), the state of protein and starch in raw materials affected the pellet quality greatly. The author discovered that pellets contained raw SBM, and pre-gelatinised tapioca starch had the highest PDI compared to pellets contained denatured SBM and native starch. Behnke (2001) also stated that increasing the protein content of pellets would improve their durability index.

Among all the received samples, only the four samples made in the Republic of South Africa additional used SFM. Strictly limited numbers of studies were designed to explore the effect of SFM on pellet quality as SFM is mainly used as a cheap protein substitute for other protein-rich ingredients. Čolović et al. (2015) compared the pellet durability and hardness values of five diets composed of varying percentages of corn, SFM and SBM. Results showed that pellet hardness increased with increasing protein content in the diet. However, the fibre content would negatively influence the positive effect of protein as the hardness value of corn pellets excessed one of the SFM pellets containing higher fibre content (Čolović et al., 2015). Similar to pellet hardness, the PDI also increased with increasing protein content, but the negative influence of fibre was covered by the positive effect of starch and protein (Čolović et al., 2015). To conclude, the effect of raw materials on pellet durability and hardness should be considered as the fibre, starch, and protein contained within.

8.3. Effects of whole wheat addition

The particle size distribution of dissolved pellets exhibited that pellets containing wheat had a higher ratio of particles smaller than 0.1 mm and a higher ratio of particles larger than 2.8 mm compared to other samples that contained low or no wheat. The reason pellets with wheat showed quantitatively more particles larger than 2.8 mm could be due to whole wheat addition. The intact wheat grains could also explain why spotted in WW samples had a higher PDI value.

Limited research studied the influence of whole wheat addition on pellet quality since whole wheat is normally used as a structural component in pelleted diets or used to dilute the nutrient density for broilers. Advantages like increased gizzard weight have been reported after feeding broilers with whole wheat added post-pelleting (Amerah & Ravindran, 2008; Hetland et al., 2002; Svihus et al., 2002). Besides, the addition of whole wheat reduced the production cost of broilers (Hetland et al., 2002; Ravindran et al., 2006). Ravindran et al. (2006) even concluded that the economic benefits of whole wheat addition were maintained up to a 200 g addition or replacement of ground wheat per kg of feed.

8.4. Impacts of pellet size on pellet physical quality

A relatively strong positive correlation existed between the pellet length and the pellet hardness ($r=0.47$). Abdollahi and Ravindran (2013) reported a similar finding, showing that increasing the pellet length alone from 3 mm to 5 and even 7 mm significantly ($P<0.001$) enhanced the pellet hardness. The other fairly strong relationship found was between the fine percentage and the length of pellets ($r=-0.40$). Cerrate et al. (2009) indicated that the fine percentage (particles < 2.0 mm) decreased from 17% in 3.17 mm-diameter pellets to 4% in 1.59 mm-diameter pellets (maize/SBM based).

Unlike other very weak relations found in the present study, previous research found interesting results. Aside from the increased hardness values from elongated pellets, Abdollahi and Ravindran (2013) also found significant ($P<0.001$) improvements in pellet durability values. Wood (1987) reported a very strong linear positive correlation ($r=0.89$) between the pellet length and pellet durability values. However, this connection between pellet length and pellet quality is also not causal. Theoretically, one explanation of improved PDI by increased length given by Lowe (2005) was that the increased pellet length reduced the sensitive surface area of pellets for a certain weight of pellets. Hence, reduce fine production and numerically improve the PDI. This theory also explained the adverse effect of pellet length on fine generations. Besides, Miladinovic (2013) mentioned that pellets with larger diameter values tended to have a higher moisture content. Opposite to the Pearson correlation coefficients found in the present study, Miladinovic (2013) reported that pellet diameter had a positive relationship with pellet hardness values and a negative relationship with pellet durability. The negative relationship between diameter and durability was supported by Thomas and van der Poel (1996), that 6 mm-diameter pellets were more breakable than 3 mm-diameter pellets. Besides, the experimental study performed by Abdollahi, M. et al. (2013) showed a significant ($P<0.001$)

interaction between pellet length and pellet diameter on pellet durability and hardness values. The authors found improvements in durability and hardness values were greater with 3 mm-diameter pellets than 4.76 mm-diameter pellets when pellet length was improved from 3 mm to 6 mm.

8.5. Interactions between different physical quality indexes

Similar to the strong positive relationship (r=0.75) found between pellet hardness and pellet durability of received samples, a similar result was reported by Wood (1987), who found a very strong linear relationship between pellet hardness and pellet durability values (r=0.94). The very high correlation coefficient found by Wood (1987) could be due to having designed experiments and pellets, unlike the uncertainty and heterogeneity of received samples. Abdollahi and Ravindran (2013) suggested that the improved hardness values in longer pellets reduced the fine generation, which was also spotted in the present study as having a weak correlation (r=-0.38) between pellet hardness values and fine percentages. Besides, similar to the very weak relations between the dry matter content of pellets and other physical quality features found in this study, Miladinovic (2013) reported that the dry matter content did not influence pellet durability values. However, a controversial statement was mentioned by Lyu et al. (2020) that low moisture content will make pellets more subjected to breakage without providing any relevant experimental results.

9. Conclusion

The present thesis examined the size and physical quality of commercial broiler pellets produced worldwide and discussed these results with previous literature findings. Major conclusions are: 1) Nutritionists should discuss the impacts of grinding on pellet quality in line with grain types and particle sizes. Similar to common sense, roller mill grinding gave more homogeneous results than hammer mill grinding. 2) The influence of raw materials on pellet quality varied with the ratio of protein, starch, and fibre within grains. In general, pellets made with wheat showed better physical quality values than pellets made with maize. 3) Whole wheat addition (post-pelleting) is a popular way to increase pellet broiler diets' structure and reduce the production cost. 4) Pellet length showed relatively strong non-causal linear relations with pellet hardness values (r=0.47) and fine production (r=-0.40). 5) The strong correlation between pellet hardness and pellet durability (r=0.75) was spotted, and a fairly strong negative relation (r=-0.38) between pellet hardness and the fine percentage was spotted. However, due to the large variations and uncertainties of received samples, the results mentioned in this study need to be interpreted critically.

After all, the beneficial effects of processing on physical quality indexes need to be compared with the cost of production and the economic interest from broiler growth performance. Therefore, further studies focus on the interactions between different physical quality indicators are preferable. Moreover, trials designed to study the influence of different pellet features on broiler growth performance are encouraged to find a solution for optimising the economic balance between production cost and growth performance gains in commercial broiler farming.

10. References

Abdollahi, M., Ravindran, V., Wester, T., Ravindran, G. & Thomas, D. (2013). The effect of manipulation of pellet size (diameter and length) on pellet quality and performance, apparent metabolisable energy and ileal nutrient digestibility in broilers fed maize-based diets. *Animal Production Science*, 53 (2): 114-120.

Abdollahi, M. R. & Ravindran, V. (2013). Influence of pellet length on pellet quality and performance of broiler starters. *Journal of Applied Poultry Research*, 22 (3): 516-522. doi: https://doi.org/10.3382/japr.2013-00736.

Abdollahi, M. R., Ravindran, V. & Svihus, B. (2013a). Pelleting of broiler diets: An overview with emphasis on pellet quality and nutritional value. *Animal Feed Science and Technology*, 179: 1–23. doi: 10.1016/j.anifeedsci.2012.10.011.

Abdollahi, M. R., Ravindran, V., Wester, T. J., Ravindran, G. & Thomas, D. V. (2013b). Influence of pellet diameter and length on the quality of pellets and performance, nutrient utilisation and digestive tract development of broilers fed on wheat-based diets. *British Poultry Science*: 1-9. doi: 10.1080/00071668.2013.780285.

Abdollahi, M. R., Zaefarian, F. & Ravindran, V. (2018a). Feed intake response of broilers: Impact of feed processing. *Animal Feed Science and Technology*, 237: 154-165. doi: https://doi.org/10.1016/j.anifeedsci.2018.01.013.

Abdollahi, M. R., Zaefarian, F., Ravindran, V. & Selle, P. H. (2018b). The interactive influence of dietary nutrient density and feed form on the performance of broiler chickens. *Animal Feed Science and Technology*, 239: 33-43. doi: https://doi.org/10.1016/j.anifeedsci.2018.03.005.

Almeida, E. A., Silva, F. H. A., Crowe, T. G., Macari, M. & Furlan, R. L. (2018). Influence of rearing temperature and feed format in the development of the pendulous crop in broilers. *Poultry Science*, 97 (10): 3556-3563. doi: https://doi.org/10.3382/ps/pey221.

Amerah, A., Ravindran, V., Lentle, R. & Thomas, D. (2007a). Feed particle size: Implications on the digestion and performance of poultry. *World's Poultry Science Journal*, 63 (3): 439-455.

Amerah, A., Ravindran, V., Lentle, R. & Thomas, D. (2007b). Influence of feed particle size and feed form on the performance, energy utilization, digestive tract development, and digesta parameters of broiler starters. *Poultry Science*, 86 (12): 2615-2623.

Amerah, A. & Ravindran, V. (2008). Influence of method of whole-wheat feeding on the performance, digestive tract development and carcass traits of broiler chickens. *Animal Feed Science and Technology*, 147 (4): 326-339.

Amerah, A., Ravindran, V., Lentle, R. & Thomas, D. (2008). Influence of feed particle size on the performance, energy utilization, digestive tract development, and digesta parameters of broiler starters fed wheat-and corn-based diets. *Poultry science*, 87 (11): 2320-2328.

Amerah, A., Ravindran, V. & Lentle, R. (2009). Influence of insoluble fibre and whole wheat inclusion on the performance, digestive tract development and ileal microbiota profile of broiler chickens. *British poultry science*, 50 (3): 366-375.

Angulo, E., Brufau, J. & Esteve-Garcia, E. (1996). Effect of a sepiolite product on pellet durability in pig diets differing in particle size and in broiler starter and finisher diets. *Animal Feed Science and Technology*, 63 (1): 25-34. doi: https://doi.org/10.1016/S0377-8401(96)01036-X.

Attia, Y., El-Tahawy, W., El-Hamid, A., Nizza, A., Bovera, F., Al-Harthi, M. & El-Kelawy, M. (2014). Effect of feed form, pellet diameter and enzymes supplementation on growth performance and nutrient digestibility of broiler during days 21-37 of age. Archiv Tierzucht 57 (2014), 57, 34, 1-11. doi: 10.7482/0003-9438-57-034. *Archiv fur Tierzucht*, 57: 1-11. doi: 10.7482/0003-9438-57-034.

Behnke, K. C. (1994). *Factors affecting pellet quality*: Maryland Nutrition Conference. Dept of Poultry Science and animal Science ….

Behnke, K. C. (2001). Factors influencing pellet quality. *Feed Tech*, 5 (4): 19-22.

Bouvarel, I., Chagneau, A.-M., Lecuelle, S., Lescoat, P., Ferreira, G., Duvaux-Ponter, C. & Leterrier, C. (2009). Feed composition and hardness interact in preference and intake in chickens. *Applied Animal Behaviour Science*, 118 (1): 62-68. doi: https://doi.org/10.1016/j.applanim.2009.01.008.

Briggs, J. L., Maier, D. E., Watkins, B. A. & Behnke, K. C. (1999). Effect of ingredients and processing parameters on pellet quality. *Poultry Science*, 78 (10): 1464-1471. doi: https://doi.org/10.1093/ps/78.10.1464.

Camire, M. E., Camire, A. & Krumhar, K. (1990). Chemical and nutritional changes in foods during extrusion. *Critical Reviews in Food Science & Nutrition*, 29 (1): 35-57.

Cerrate, S., Wang, Z., Coto, C., Yan, F. & Waldroup, P. (2009). Effect of pellet diameter in broiler starter diets on subsequent performance. *Journal of Applied Poultry Research*, 18 (3): 590-597.

Čolović, R. R., Pezo, L. L., Vukmirović, Đ. M., Čolović, D. S., Bera, O. J., Banjac, V. V. & Lević, J. D. (2015). Effects of sunflower meal quality on the technical parameters of the pelleting process and pellet quality. *Biosystems Engineering*, 140: 98-105. doi: 10.1016/j.biosystemseng.2015.09.010.

Cutlip, S. E., Hott, J. M., Buchanan, N. P., Rack, A. L., Latshaw, J. D. & Moritz, J. S. (2008). The Effect of Steam-Conditioning Practices on Pellet Quality and Growing Broiler Nutritional Value. *Journal of Applied Poultry Research*, 17 (2): 249-261. doi: https://doi.org/10.3382/japr.2007-00081.

da Silva, P. G., Oliveira, L. M. S., de Oliveira, N. R., de Moura Júnior, F. A., Silva, M. R. S., Cordeiro, D. A., Minafra, C. S. & Dos Santos, F. R. (2018). Effects of processing, particle size and moisturizing of sorghum-based feeds on pellet quality and broiler production. *Asian-Australasian journal of animal sciences*, 31 (1): 98-105. doi: 10.5713/ajas.17.0473.

Engberg, R., Hedemann, M. & Jensen, B. (2002). The influence of grinding and pelleting of feed on the microbial composition and activity in the digestive tract of broiler chickens. *British poultry science*, 43 (4): 569-579.

Hamungalu, O., Zaefarian, F., Abdollahi, M. R. & Ravindran, V. (2020). Performance response of broilers to feeding pelleted diets is influenced by dietary nutrient density. *Animal Feed Science and Technology*, 268: 114613. doi: https://doi.org/10.1016/j.anifeedsci.2020.114613.

Hetland, H., Svihus, B. & Olaisen, V. (2002). Effect of feeding whole cereals on performance, starch digestibility and duodenal particle size distribution in broiler chickens. *British poultry science*, 43 (3): 416-423.

Huang, D., Li, D., Xing, J., Ma, Y., Li, Z. & Lv, S. (2006). Effects of feed particle size and feed form on survival of Salmonella typhimurium in the alimentary tract and cecal S. typhimurium reduction in growing broilers. *Poultry Science*, 85 (5): 831-836.

Lemons, M., McDaniel, C., Moritz, J. & Wamsley, K. G. S. (2019). Interactive Effects of High or Low Feed Form and Phase of Feeding on Performance of Ross x Ross 708 Male Broilers Throughout a 46 d Growout. *Journal of Applied Poultry Research*, 28 (3): 616-630. doi: https://doi.org/10.3382/japr/pfz012.

Liermann, W., Frahm, J., Berk, A., Böschen, V. & Dänicke, S. (2020). Fine Grinding or Expanding as Pre-treatment for Pelleting in Processing Diets Varying in Dietary Rapeseed Expeller Proportions: Investigations on Performance, Visceral Organs, and Immunological Traits of Broilers. *Frontiers in Veterinary Science*, 7: 762.

Lowe, R. (2005). Judging pellet stability as part of pellet quality. *AFMA Matrix (South Africa)*.

Lyu, F., Thomas, M., Hendriks, W. H. & van der Poel, A. F. B. (2020). Size reduction in feed technology and methods for determining, expressing and predicting particle size: A review. *Animal Feed Science and Technology*, 261: 114347. doi: https://doi.org/10.1016/j.anifeedsci.2019.114347.

Massuquetto, A., Durau, J. F., Schramm, V. G., Netto, M. V. T., Krabbe, E. L. & Maiorka, A. (2018). Influence of feed form and conditioning time on pellet quality, performance and ileal nutrient digestibility in broilers. *Journal of Applied Poultry Research*, 27 (1): 51-58. doi: https://doi.org/10.3382/japr/pfx039.

Massuquetto, A., Panisson, J. C., Schramm, V. G., Surek, D., Krabbe, E. L. & Maiorka, A. (2020). Effects of feed form and energy levels on growth performance, carcass yield and nutrient digestibility in broilers. *Animal*, 14 (6): 1139-1146. doi: https://doi.org/10.1017/S1751731119003331.

Melo-Durán, D., Pérez, J. F., González-Ortiz, G., Sala, R., Villagómez-Estrada, S., Bedford, M. R., Graham, H. & Solà-Oriol, D. (2020). Influence of Particle Size and Xylanase in Corn-Soybean Pelleted Diets on Performance, Nutrient Utilization, Microbiota and Short-Chain Fatty Acid Production in Young Broilers. *Animals*, 10 (10): 1904.

Miladinovic, D. & Svihus, B. (2005). Optimising press settings contributes to better pellet quality. *Feed Tech*, 9 (5): 15-17.

Miladinovic, D. (2009). Wet Sieving procedure on a “Retsch AS 200 Control” for feed manufactured pellets or feed compound (Procedure Manual). *Fôrtek-Norwegian University of Life Science (UMB), Ås, Norway*.

Miladinovic, D. (2013). Strenght and Durability of Feed Pellets Influenced by Different Particle Size Distribution, Pellet Volume and Dehydration Techniques. *Annual Transactions of the Nordic Rheology Society*, vol. 21.

Mohammadi Ghasem Abadi, M. H., Moravej, H., Shivazad, M., Karimi Torshizi, M. A. & Kim, W. K. (2019). Effects of feed form and particle size, and pellet binder on performance, digestive tract parameters, intestinal morphology, and cecal microflora populations in broilers. *Poultry Science*, 98 (3): 1432-1440. doi: https://doi.org/10.3382/ps/pey488.

Moore, S. (1999). Food breakdown in an avian herbivore: who needs teeth? *Australian Journal of Zoology*, 47 (6): 625-632.

Muramatsu, K., Massuquetto, A., Dahlke, F. & Maiorka, A. (2015). Factors that Affect Pellet Quality: A Review. *Journal of Agricultural Science and Technology*, 5: 717-722. doi: 10.17265/2161-6256/2015.09.002.

Nir, I., Twina, Y., Grossman, E. & Nitsan, Z. (1994). Quantitative effects of pelleting on performance, gastrointestinal tract and behaviour of meat-type chickens. *British Poultry Science*, 35 (4): 589-602.

Nir, I., Hillel, R., Ptichi, I. & Shefet, G. (1995). Effect of particle size on performance.: 3. Grinding pelleting interactions. *Poultry science*, 74 (5): 771-783.

Parsons, A. S., Buchanan, N. P., Blemings, K. P., Wilson, M. E. & Moritz, J. S. (2006). Effect of Corn Particle Size and Pellet Texture on Broiler Performance in the Growing Phase. *Journal of Applied Poultry Research*, 15 (2): 245-255. doi: https://doi.org/10.1093/japr/15.2.245.

Patton, J., Buskirk, H. & Rauls, L. (1937). A study of the relative merits of pellets and mash poultry feeds. *Veterinary Medicine*, 32: 423-427.

Portella, F., Caston, L. & LEESON, S. (1988). Apparent feed particle size preference by broilers. *Canadian Journal of Animal Science*, 68 (3): 923-930.

Ravindran, V., Wu, Y. B., Thomas, D. & Morel, P. (2006). Influence of whole wheat feeding on the development of gastrointestinal tract and performance of broiler chickens. *Australian Journal of Agricultural Research - AUST J AGR RES*, 57. doi: 10.1071/AR05098.

Reece, F. N., Lott, B. D. & Deaton, J. W. (1986). The Effects of Hammer Mill Screen Size on Ground Corn Particle Size, Pellet Durability, and Broiler Performance. *Poultry Science*, 65 (7): 1257-1261. doi: 10.3382/ps.0651257.

Rodrigues, I. & Choct, M. (2018). The foregut and its manipulation via feeding practices in the chicken. *Poultry science*, 97 (9): 3188-3206.

Salas-Bringas, C., Plassen, L., Lekang, O. & Schuller, R. (2007). Measuring physical quality of pelleted feed by texture profile analysis, a new pellet tester and comparisons to other common measurement devices. *ANNUAL TRANSACTIONS-NORDIC RHEOLOGY SOCIETY*, 15: 149.

Singh, Y. & Ravindran, V. (2015). Influence of method of wheat inclusion and pellet diameter on performance, nutrient utilisation, digestive tract measurements and carcass characteristics of broilers. *Animal Production Science*, 55 (4): 474. doi: 10.1071/an13489.

Svihus, B., Hetland, H., Choct, M. & Sundby, F. (2002). Passage rate through the anterior digestive tract of broiler chickens fed on diets with ground and whole wheat. *British poultry science*, 43 (5): 662-668.

Svihus, B., Kløvstad, K. H., Perez, V., Zimonja, O., Sahlström, S., Schüller, R. B., Jeksrud, W. K. & Prestløkken, E. (2004). Physical and nutritional effects of pelleting of broiler chicken diets made from wheat ground to different coarsenesses by the use of roller mill and hammer mill. *Animal Feed Science and Technology*, 117 (3): 281-293. doi: https://doi.org/10.1016/j.anifeedsci.2004.08.009.

Svihus, B. (2006). The role of feed processing on gastrointestinal function and health in poultry. *Avian gut function in health and disease*, 28: 183-194.

Svihus, B., Sacranie, A., Denstadli, V. & Choct, M. (2010). Nutrient utilization and functionality of the anterior digestive tract caused by intermittent feeding and inclusion of whole wheat in diets for broiler chickens. *Poultry science*, 89 (12): 2617-2625.

Thomas, M. & van der Poel, A. F. B. (1996). Physical quality of pelleted animal feed 1. Criteria for pellet quality. *Animal Feed Science and Technology*, 61 (1): 89-112. doi: https://doi.org/10.1016/0377-8401(96)00949-2.

Thomas, M., van Zuilichem, D. J. & van der Poel, A. F. B. (1997). Physical quality of pelleted animal feed. 2. contribution of processes and its conditions. *Animal Feed Science and Technology*, 64 (2): 173-192. doi: https://doi.org/10.1016/S0377-8401(96)01058-9.

Vukmirović, D., Fišteš, A., Lević, J., Čolović, R., Rakić, D., Brlek, T. & Banjac, V. (2017). Possibilities for preservation of coarse particles in pelleting process to improve feed quality characteristics. *Journal of Animal Physiology and Animal Nutrition*, 101 (5): 857-867. doi: https://doi.org/10.1111/jpn.12489.

Winowiski, T. S. (1995). *Pellet quality in animal feeds*: American Soybean Association.

Wood, J. F. (1987). The functional properties of feed raw materials and their effect on the production and quality of feed pellets. *Animal Feed Science and Technology*, 18 (1): 1-17. doi: https://doi.org/10.1016/0377-8401(87)90025-3.

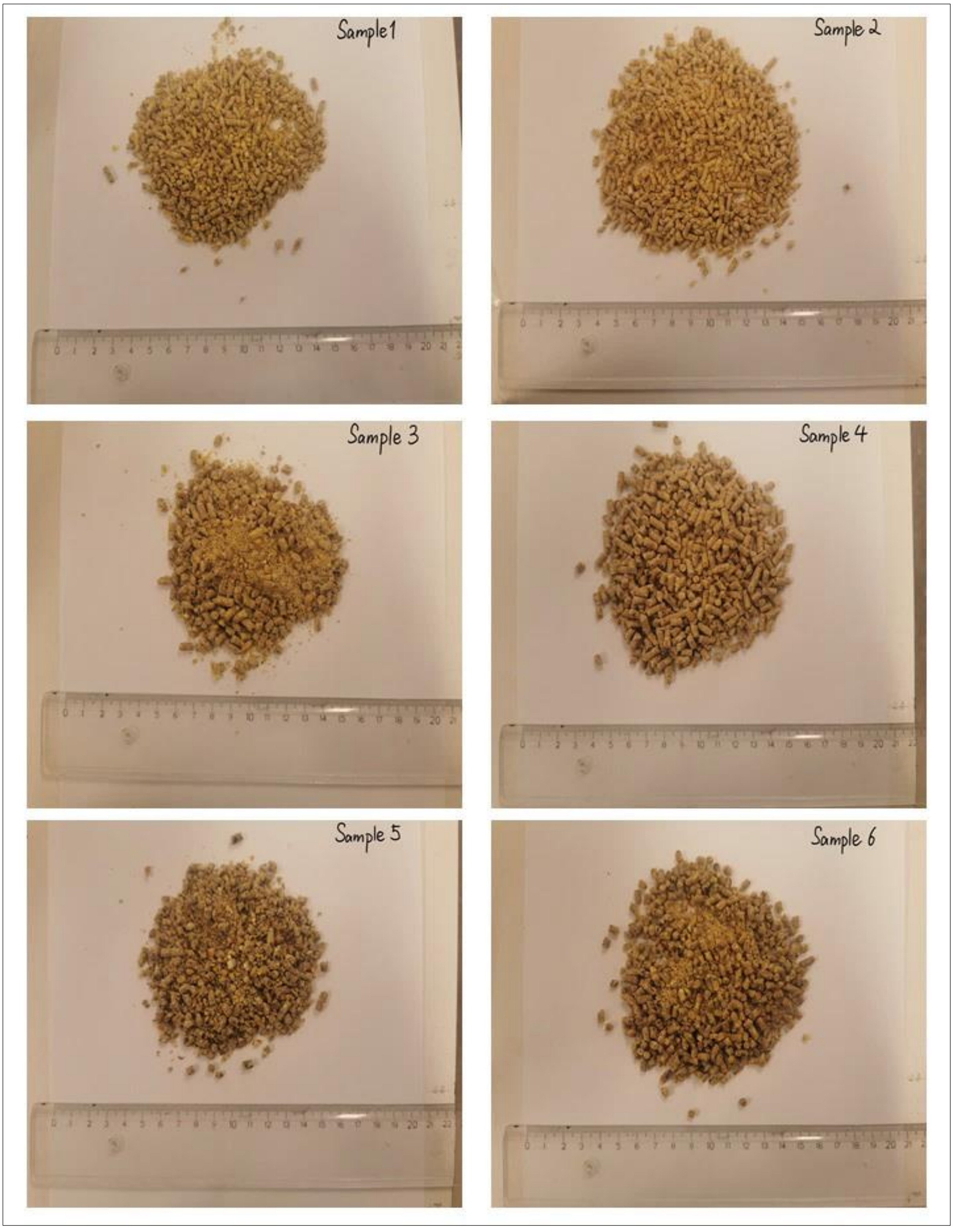
11. Appendixes

Appendix A: Background information for samples

Sample No.	Customer Name	Country	Date of Sampling	Sample Source	*Phase details*	Raw Material	*Grinding Method*	Whole Wheat Yes/No
1	Amadori (Veggy feed) - NO OGM	Italy	30/11/2020	Feed Mill	*10-21 days*	Maize/Wheat/SBM	*Hammer Mill + Disc*	No
2	Amadori (conventional) - OGM	Italy	01/12/2020	Feed Mill	*10-21 days*	Maize/Wheat/SBM	*Hammer Mill + Disc*	No
3	Fileni	Italy	04/12/2020	Feed Mill	*22-33 days*	Maize/Wheat/SBM	*Hammer or Roller Mill, depends on raw materials*	Yes
4	Martini	Italy	30/11/2020	Feed Mill	*21-30 days*	Maize/Wheat/SBM	*Hammer Mill*	No
5	AIA/La Pellegrina	Italy	10/12/2020	Feed Mill	*24-33 days*	Maize/Wheat/SBM	*Hammer Mill*	No
6	Leocata Mangimi SPA/AVISP from Sicily	Italy	03/12/2020	Feed Mill	*22-36 days*	Maize/SBM	*Roller Mill*	No
7	Uvesa	Spain	11/12/2020	Feed Mill	*15-28 days*	Wheat/Maize/SBM	*Hammer Mill*	No
8	Guissona	Spain	10/12/2020	Feed Mill	*21-31 days*	Maize/SBM	*Hammer Mill*	No
9	Crusvi	Spain	11/12/2020	Feed Mill	*21-30 days*	Wheat/Maize/SBM	*Hammer Mill*	Yes
10	Padesa	Spain	14/12/2020	Farm silo	*11-21 days*	Wheat/Maize/SBM	*Hammer Mill*	Yes
11	Inasur	Spain	10/12/2020	Feed Mill	*14-24 days*	Wheat/SBM	*Hammer Mill*	No
12	Gouessant	France	02/12/2020	Farm silo	*28-38 days*	Wheat/SBM	*Hammer Mill*	No
13	Sanders 1	France	04/12/2020	Farm silo	*20-30 days*	Wheat/SBM	*Roller Mill*	No
14	Sanders 2	France	04/12/2020	Farm silo	*30-40 days*	Wheat/SBM	*Roller Mill*	No
15	Sanders 3	France	17/12/2020	Farm silo	*20-30 days*	Wheat/SBM	*Roller Mill*	No
16	Nutrea Languidic	France	11/12/2020	Farm silo	*28-42 days*	Wheat/SBM	*Hammer Mill*	No
17	Nutrea Plouaguat	France	11/12/2020	Farm silo	*28-42 days*	Wheat/SBM	*Hammer Mill*	No
18	De Heus	NL	07/01/2021	Feed Mill	*19-28 days*	Wheat/SBM	*Hammer Mill*	No
19	De Hoop	NL	06/01/2021	Feed Mill	*15-28 days*	Wheat/SBM	*Hammer Mill*	No
20	Agrifirm - phase 2	NL	12/01/2021	Feed Mill	*8-16 days*	Wheat/SBM	*Hammer Mill*	No
21	Agrifirm - phase 3	NL	11/01/2021	Feed Mill	*16-24 days*	Wheat/SBM	*Hammer / Roller Mill*	No
22	De Heus - Spelderholt	NL	01/12/2020	Farm silo	*11-20 days*	Wheat/SBM	*Hammer Mill*	No
23	RDS Control	NL	01/12/2020	Farm silo	*11-20 days*	Wheat/SBM	*Hammer Mill*	No
24	RDS Sustainable	NL	01/12/2020	Farm silo	*11-20 days*	Wheat/SBM	*Hammer Mill*	No
25	Teepker Rothkotter	Germany	18/12/2020	Farm silo	*11-20 days*	Wheat/SBM	*Hammer Mill*	Yes
26	Teepker Aviagen	Germany	18/12/2020	Farm silo	*11-20 days*	Wheat/SBM	*Hammer Mill*	No
27	Chick Prom	Serbia	09/12/2020	Feed Mill	*10-24 days*	Maize/SBM	*Hammer Mill*	No

Sample No.	Customer Name	Country	Date of Sampling	Sample Source	***Phase details***	Raw Material	***Grinding Method***	Whole Wheat Yes/No
28	TENEN	Serbia	15/12/2020	Feed Mill	*14-30 days*	Maize/SBM	*Hammer Mill*	No
29	HRANA PRODUKT	Serbia	26/12/2020	Feed Mill	*15-30 days*	Maize/SBM	*Hammer Mill*	No
30	Hankkija Oy	Finland	26/10/2020	Feed Mill	*10-18 days*	Wheat/SBM	*Hammer Mill*	No
31	Hankkija Oy	Finland	05/11/2020	Feed Mill	*18-32 dsys*	Wheat/SBM	*Hammer Mill*	No
32	Saterehu Oy	Finland	30/11/2020	Farm silo	*1-14 days*	Wheat/SBM	*Hammer Mill*	No
33	Atria-Chick Oy/ A-Rehu Oy	Finland	01/12/2020	Feed Mill	*1-7/8 days*	Wheat/SBM	*Multicracker*	No
34	Atria-Chick Oy/ A-Rehu Oy	Finland	01/12/2020	Feed Mill	*17-32days*	Wheat/SBM	*Multicracker*	No
35	De Heus CZ	Czech Rep	08/12/2020	Feed Mill	*11-20 days*	Wheat/SBM	*Roller Mill*	No
36	A Feed	Czech Rep	07/12/2020	Feed Mill	*10-15 days*	Wheat/SBM	*Roller Mill*	No
37	A Feed	Czech Rep	07/12/2020	Feed Mill	*16-21 days*	Wheat/SBM	*Roller Mill*	No
38	Napsugar-trade	Hungary	29/11/2020	Feed Mill	*not given*	Wheat/Maize/SBM	*Hammer Mill*	No
39	Bona Farm	Hungary	28/11/2020	Feed Mill	*not given*	Wheat/Maize/SBM	*Hammer Mill*	Yes
40	Moy Park Nirl 1 (NW 1)	UK	01/12/2020	Feed Mill	*12-22 days*	Wheat/SBM	*Hammer Mill*	Yes
41	Moy Park Nirl 2 (NW 2)	UK	01/12/2020	Feed Mill	*12-22 days*	Wheat/SBM	*Hammer Mill*	Yes
42	Moy Park JE Porter (NW 3)	UK	02/12/2020	Feed Mill	*12-22 days*	Wheat/SBM	*Hammer Mill*	No
43	Moy Park Ashbourne Bin 8	UK	09/12/2020	Feed Mill	*12-22 days*	Wheat/SBM	*Hammer Mill*	Yes
44	Moy Park Ashbourne Bin 15	UK	08/12/2020	Feed Mill	*12-22 days*	Wheat/SBM	*Hammer Mill*	Yes
45	ABN Flixborough	UK	15/12/2020	Feed Mill	*15-23 days*	Wheat/SBM	*Roller Mill*	Yes
46	ABN Bury	UK	20/12/2020	Feed Mill	*15-23 days*	Wheat/SBM	*Hammer Mill*	Yes
47	ABN Langwathby	UK	17/12/2020	Feed Mill	*15-23 days*	Wheat/SBM	*Hammer Mill*	Yes
48	Avi Ped Diet 3 (finisher)	UK	08/12/2020	Farm silo	*26-45 days*	Wheat/SBM	*Hammer Mill*	No
49	Avi Ped Diet 1 (Starter)	UK	09/11/2020	Farm silo	*0-11days*	Wheat/SBM	*Hammer Mill*	No
50	Avi Ped Diet 2 (Grower)	UK	07/12/2020	Farm silo	*12-25 days*	Wheat/SBM	*Hammer Mill*	No
51	Bello Alimentos LTDA	Brazil	11/12/2020	Feed Mill	*12-28 days*	Maize/SBM	*Hammer Mill*	No
52	Granja Regina	Brazil	09/12/2020	Feed Mill	*16-24 days*	Maize/SBM	*Hammer Mill*	No
53	Coppens	NL	14/01/2021	Feed Mill	*0-10 days*	Wheat/Maize/SBM	*Hammer Mill*	No
54	Coppens	NL	14/01/2021	Feed Mill	*10-21 days*	Wheat/Maize/SBM	*Hammer Mill*	No
55	Astral A	RSA	07/12/2020	Feed Mill	*18-26 days*	Maize/SFM/SBM	*Hammer Mill*	No
56	Astral B	RSA	09/12/2020	Feed Mill	*18-26 days*	Maize/SFM/SBM	*Hammer Mill*	No
57	Astral C	RSA	08/12/2020	Feed Mill	*18-26 days*	Maize/SFM/SBM	*Hammer Mill*	No
58	Astral D	RSA	08/12/2020	Feed Mill	*18-26 days*	Maize/SFM/SBM	*Hammer Mill*	No

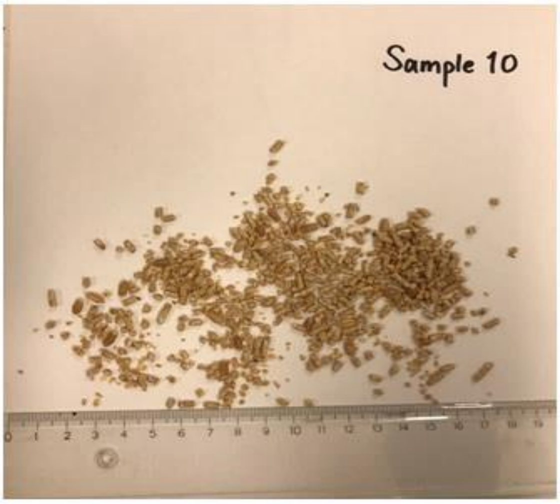
Appendix B: Visual presentations of the feed samples




Sample 7


Sample 8


Sample 9


Sample 10


Sample 11


Sample 12


Sample 13

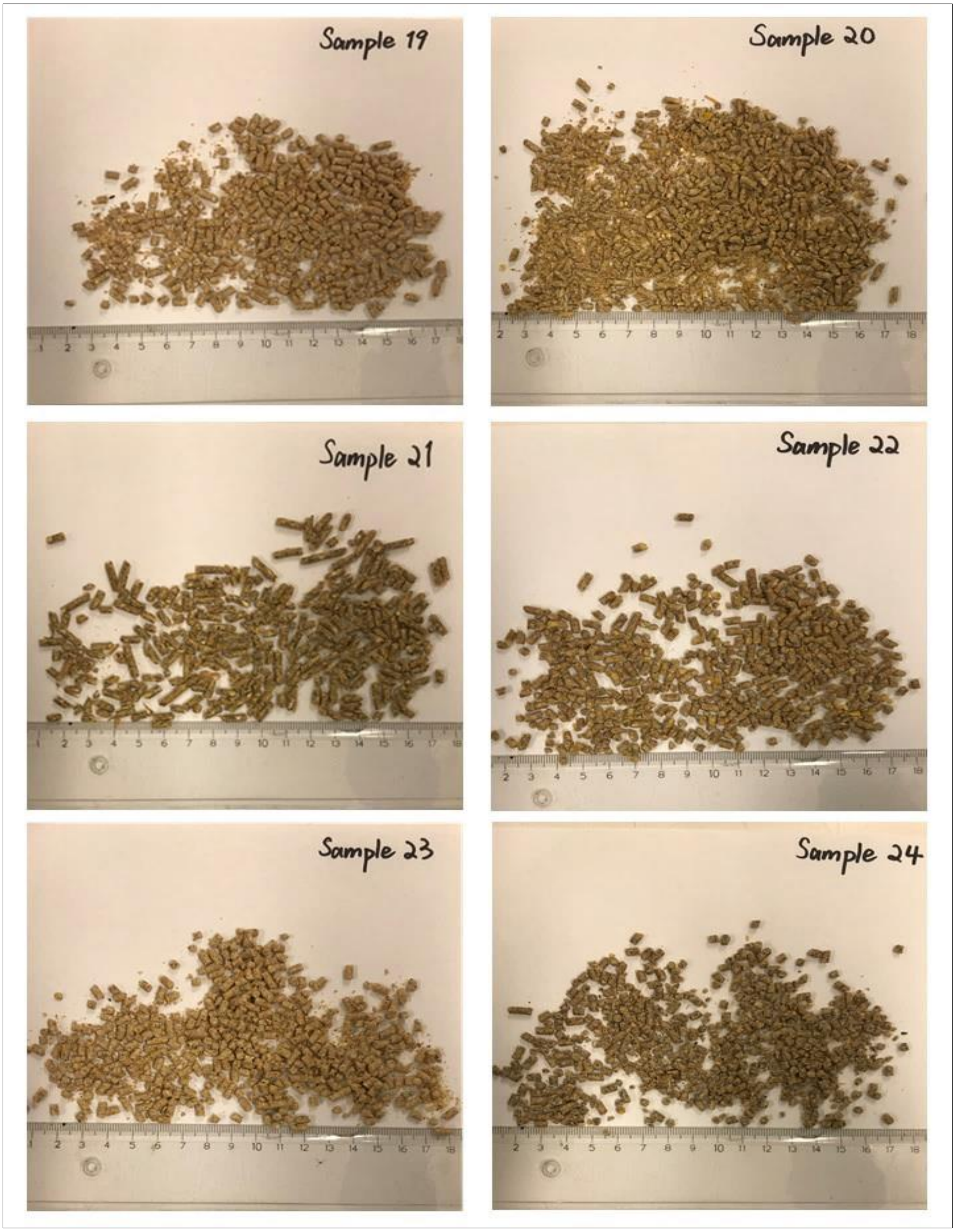
Sample 14

Sample 15

Sample16

Sample 17

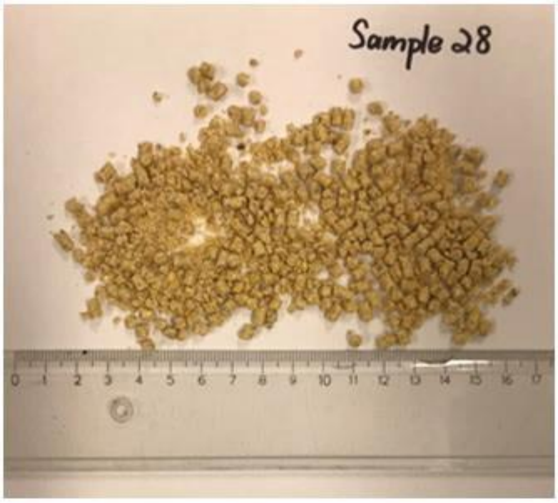
Sample 18


Sample 19
Sample 20
Sample 21
Sample 22
Sample 23
Sample 24


Sample 25


Sample 26


Sample 27


Sample 28


Sample 29


Sample 30


Sample 31

Sample 32

Sample 33

Sample 34

Sample 35

Sample 36


Sample 37

Sample 38

Sample 39

Sample 40

Sample 41

Sample 42


Sample 43

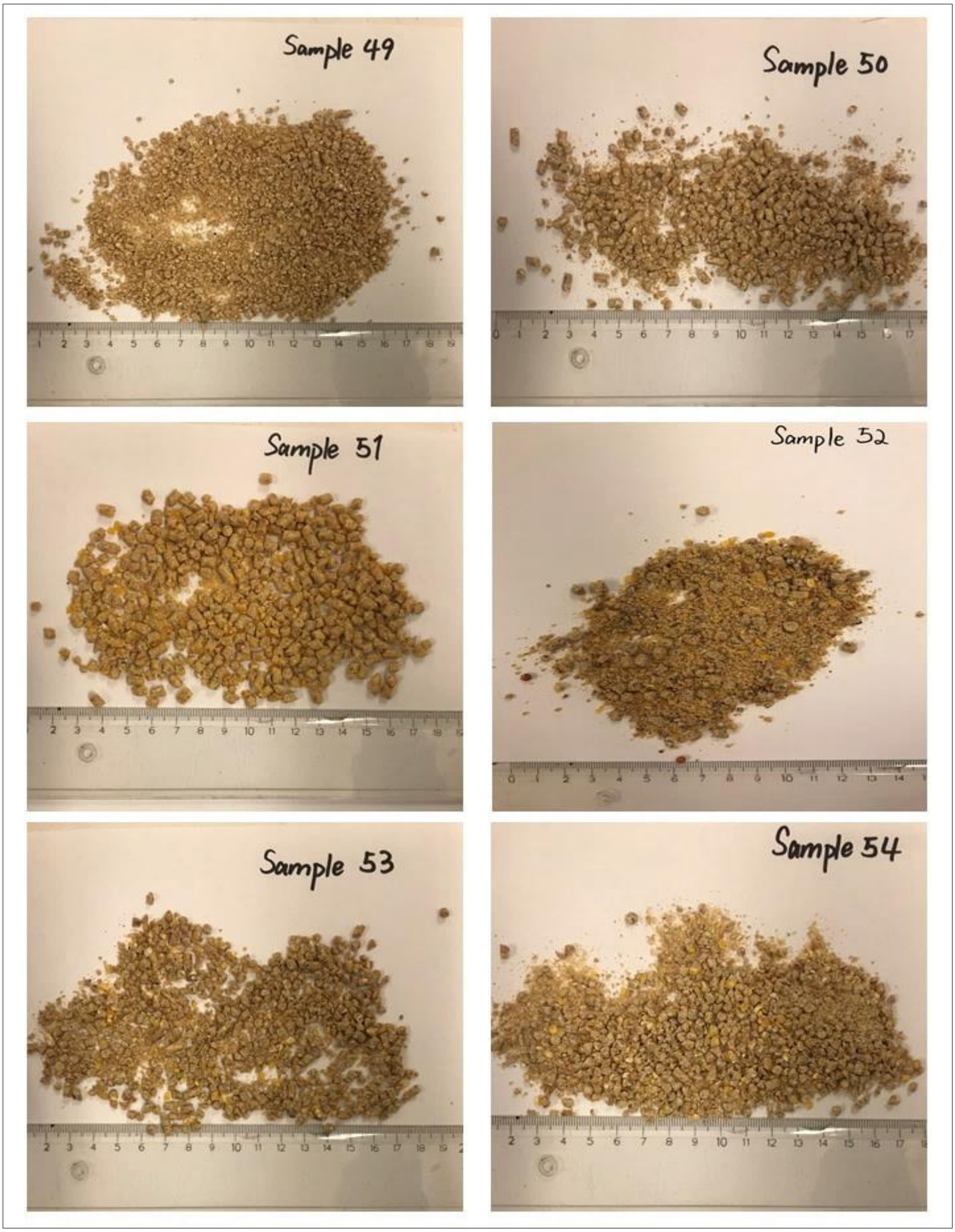

Sample 44

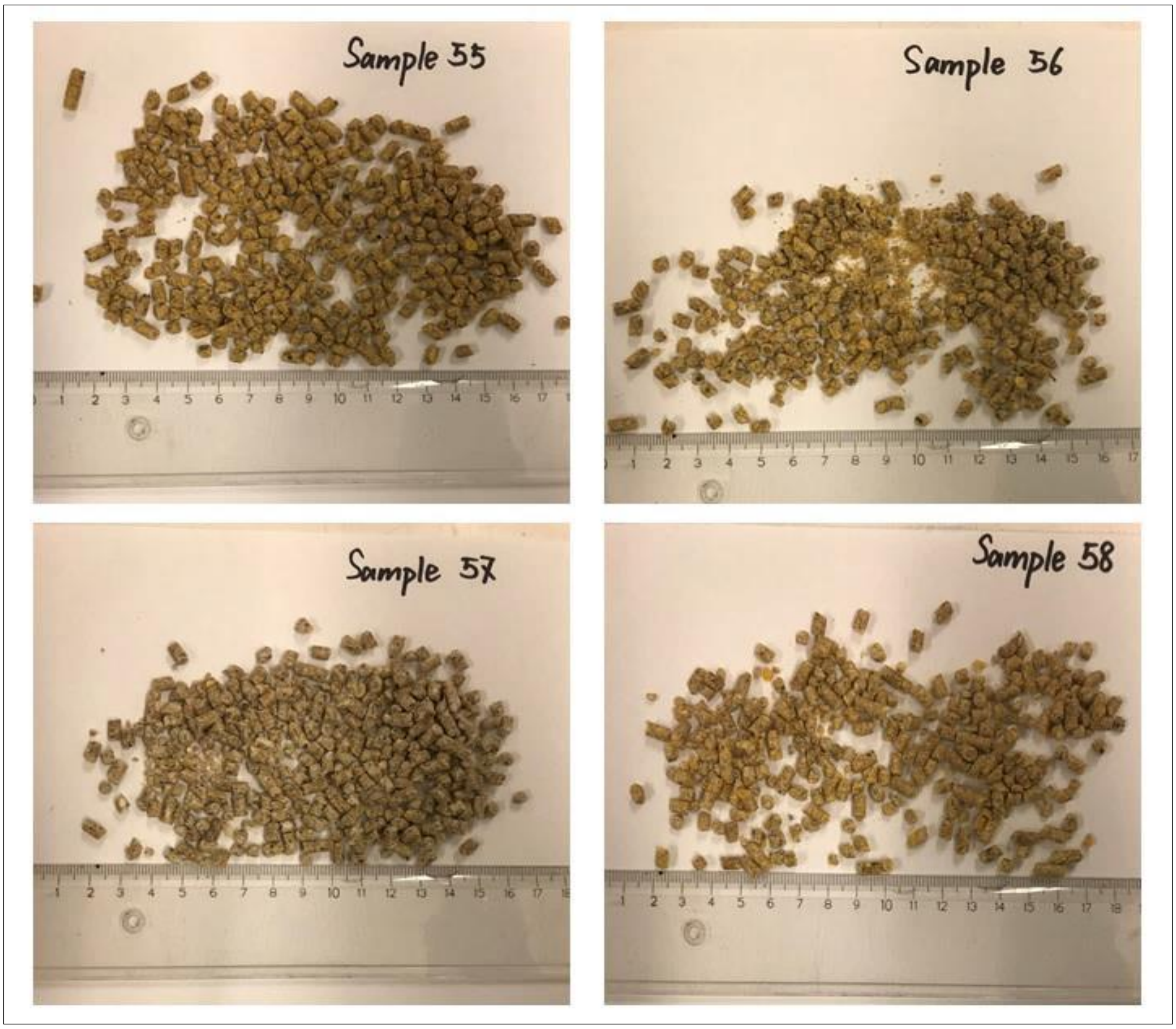

Sample 45


Sample 46


Sample 47


Sample 48


Sample 49
Sample 50
Sample 51
Sample 52
Sample 53
Sample 54


Sample 55
Sample 56
Sample 57
Sample 58

Appendix C: Raw data section 1

Hardness, PDI, Fine percentage, DM

Sample Nr.	AVE.L	AVE.D	AVE.K.H (kg)	K.H σ	K.H CV	AVE.TA.H (N)	TA.H σ	TA.H CV	PDI%	F%	DM%
1	6.51	2.73	3.43	1.00	29.20				45.80	14.96	88.33
2	5.86	2.67	2.32	0.61	26.08				15.90	2.86	88.37
3	6.34	3.73	3.63	0.87	24.01				60.95	12.52	89.39
4	7.37	3.60	4.08	0.65	16.02				66.20	0.79	88.41
5	6.46	3.89	3.08	0.75	24.33				45.75	2.31	88.42
6	5.92	3.40	3.07	1.11	35.97				54.05	8.58	89.75
7	7.70	3.57	4.63	0.74	16.00				75.60	0.46	89.29
8	6.35	3.71	2.43	0.45	18.42				48.90	6.97	87.04
9	5.53	3.38	3.73	0.72	19.23				66.95	3.04	89.14
10	5.77	2.45	3.43	0.52	15.10				62.55	9.50	88.62
11	6.65	2.70	3.33	0.64	19.13				55.95	2.90	88.92
12	5.57	3.69	4.08	0.89	21.87				66.15	3.15	89.59
13	6.75	3.71	3.26	0.94	28.82				62.30	33.25	83.67
14	5.81	3.53	4.66	0.83	17.86				84.55	6.77	87.71
15	6.06	3.66	3.59	0.57	15.83				62.85	12.74	88.08
16	6.22	3.60	4.53	0.61	13.40				75.35	2.02	87.29
17	6.66	3.60	4.38	0.90	20.46				69.65	2.10	87.93
18	7.19	3.27	5.67	1.37	24.21				86.20	1.75	89.03
19	6.67	3.25	5.82	1.16	19.87				88.45	2.16	88.35
20	6.83	2.70	3.83	0.64	16.58				74.35	6.81	87.02
21	9.52	3.04	6.03	0.67	11.06				87.65	1.39	87.80
22	6.10	3.14	4.94	0.98	19.77				78.35	1.73	90.72
23	4.98	3.16	2.77	0.65	23.37				11.90	4.94	89.36
24	5.54	3.20	2.77	0.51	18.46				2.00	4.19	89.69
25	7.43	3.05	6.73	1.28	19.05				93.30	7.05	88.30
26	6.45	3.06	7.49	1.66	22.09				96.10	0.51	88.27
27	6.25	3.31	2.79	0.81	28.97	14.1952	5.94	41.88	26.75	8.12	87.23
28	5.09	3.75	3.81	0.65	17.14	18.8738	10.73	56.87	53.65	9.38	89.35
29	6.75	4.30	4.23	0.64	15.08	64.1538	37.67	58.72	75.30	1.07	88.62
30	6.54	3.66	7.45	1.48	19.80	74.5999	33.39	44.75	91.75	3.50	88.96
31	7.04	3.56	8.61	1.50	17.40	65.2992	26.26	40.21	89.75	10.27	88.00
32	2.90	3.48	4.07	0.95	23.45				86.30	8.80	88.19
33	2.64	3.29	3.55	1.09	30.70				72.40	15.96	89.63
34	8.23	3.51	7.82	1.33	16.97	77.8329	41.29	53.05	88.85	0.28	89.65
35	6.46	3.35	6.57	1.49	22.70	53.1239	13.39	25.20	90.95	2.78	89.34
36	5.85	3.42	4.22	0.84	19.89	33.2114	16.76	50.46	75.35	7.77	89.90
37	6.65	3.43	5.71	1.27	22.28	39.5172	18.70	47.33	87.75	6.18	89.40
38	7.35	3.29	5.70	0.96	16.80				86.70	0.19	92.16
39	6.50	3.63	4.83	1.20	24.87				79.10	0.93	92.20
40	6.76	3.72	5.42	0.68	12.48	45.7075	22.68	49.61	88.95	8.48	88.35

Sample Nr.	AVE.L	AVE.D	AVE.K.H (kg)	K.H σ	K.H CV	AVE.TA.H (N)	TA.H σ	TA.H CV	PDI%	F%	DM%
41	7.14	3.79	5.05	1.05	20.81	46.3673	21.45	46.25	89.05	6.71	89.20
42	7.34	2.98	5.45	1.27	23.29				88.20	1.99	88.73
43	6.39	3.43	3.89	0.62	15.83	27.1493	14.08	51.84	58.90	2.92	87.54
44	6.25	3.39	4.11	0.69	16.73	31.7516	15.91	50.12	68.45	4.78	87.63
45	5.75	3.24	4.00	1.06	26.51	45.4965	20.44	44.93	87.80	0.97	87.33
46	6.49	3.17	4.67	1.50	32.01	49.2118	16.99	34.52	88.90	0.77	86.68
47	7.74	3.41	5.21	0.94	18.05	34.9760	17.26	49.34	89.05	3.94	86.45
48	5.23	3.27	4.33	1.07	24.81	34.7216	13.55	39.02	79.85	18.64	88.13
49	4.59	3.32	3.23	0.66	20.36				42.60	40.42	89.67
50	4.85	3.25	3.75	0.76	20.21	22.9694	11.49	50.02	81.25	7.82	88.71
51	6.21	4.20	3.87	1.52	39.14	29.1477	13.21	45.32	52.80	2.35	87.68
52	5.80	4.70	1.92	0.53	27.50				-	52.38	90.49
53	3.97	3.54	4.57	0.64	14.06				79.75	15.44	88.32
54	3.24	3.54	3.51	0.58	16.56				77.80	26.07	89.00
55	6.35	4.17	3.88	0.64	16.54				63.05	2.15	90.95
56	5.25	4.04	3.42	0.92	26.89				43.00	6.75	90.56
57	6.20	4.18	5.26	1.29	24.62				76.20	1.73	90.51
58	7.10	4.13	6.29	1.90	30.25				81.45	0.33	89.48
Average	6.19	3.46	4.46			42.5424			69.81	7.51	88.73
SD	1.19	0.42	1.42			18.17			21.20	9.81	1.38
CV%	19.15	12.25	31.72			42.71			30.37	130.70	1.56
Min	2.64	2.45	1.92			14.1952			2.00	0.19	83.67
Max	9.52	4.70	8.61			77.8329			96.10	52.38	92.20

Appendix D: Raw data section 2

The dry sieving results (%)

Sample Nr.	>3.5 mm	2.8-3.5 mm	2.0-2.8 mm	1.6-2.0 mm	1.0-1.6 mm	0.5-1.0 mm	0.2-0.5 mm	0.1-0.2 mm	<0.1 mm
1	0.02	54.78	26.01	4.66	5.37	4.96	2.37	0.84	0.03
2	0.02	64.94	32.24	0.90	0.72	0.42	0.33	0.32	0.00
3	67.12	11.64	8.34	3.18	3.72	3.01	1.84	0.72	0.01
4	91.02	6.07	1.06	0.26	0.32	0.31	0.90	0.00	0.00
5	48.34	11.86	13.63	7.14	9.25	6.10	2.93	0.70	0.00
6	19.42	67.33	5.26	1.87	2.32	1.91	1.81	0.01	0.00
7	94.60	2.85	0.71	0.28	0.37	0.33	0.81	0.03	0.00
8	78.10	9.44	5.04	2.05	2.54	1.29	1.21	0.32	0.00
9	32.31	59.94	4.61	1.10	0.93	0.46	0.70	0.00	0.00
10	2.21	10.58	75.51	3.97	4.05	2.08	1.16	0.33	0.02
11	0.04	83.55	12.94	0.79	1.08	0.74	0.71	0.09	0.00
12	83.11	9.99	3.01	0.84	1.54	0.74	0.76	0.19	0.00
13	53.31	8.43	16.05	6.23	7.14	5.04	3.07	0.54	0.00
14	77.78	13.18	2.39	0.86	1.55	2.05	1.60	0.34	0.02
15	67.22	10.46	10.96	3.62	3.75	2.11	1.29	0.37	0.01
16	88.44	8.04	1.66	0.32	0.41	0.50	0.44	0.03	0.00
17	90.88	4.43	2.78	0.72	0.63	0.29	0.14	0.00	0.00
18	32.00	62.35	2.82	0.73	0.90	0.54	0.29	0.12	0.00
19	8.41	89.14	0.96	0.32	0.53	0.42	0.01	0.00	0.00
20	0.19	68.87	23.22	1.88	2.18	1.83	1.10	0.30	0.01
21	8.38	89.21	0.92	0.29	0.47	0.37	0.03	0.01	0.00
22	2.54	94.24	1.86	0.56	0.36	0.18	0.03	0.05	0.00
23	9.57	82.43	2.15	1.06	1.77	1.54	0.69	0.30	0.01
24	8.97	83.81	2.44	1.10	1.42	1.07	0.56	0.26	0.00
25	4.21	83.90	3.61	1.40	2.18	2.39	1.37	0.50	0.00
26	1.22	97.46	0.63	0.12	0.16	0.11	0.02	0.05	0.00
27	21.92	66.94	3.06	1.49	2.06	2.24	1.45	0.55	0.10
28	-	-	-	-	-	-	-	-	-
29	92.06	1.67	2.13	0.66	0.85	0.94	0.99	0.47	0.05
30	87.93	3.63	1.20	0.81	2.17	2.67	1.23	0.24	0.04
31	82.13	5.04	4.35	1.54	2.26	2.44	1.35	0.40	0.12
32	11.43	43.41	27.26	5.69	5.12	3.57	2.01	0.79	0.52
33	2.28	37.81	34.55	10.99	8.30	4.13	1.26	0.40	0.12
34	89.59	8.34	1.72	0.24	0.09	0.01	0.03	0.01	0.01
35	21.93	72.57	2.50	1.03	1.15	0.55	0.13	0.05	0.00
36	40.30	45.16	7.06	1.76	1.96	1.70	1.55	0.29	0.00
37	33.71	48.30	7.41	2.60	3.07	3.03	1.52	0.10	0.00
38	22.19	77.50	0.04	0.04	0.06	0.12	0.03	0.04	0.00
39	92.72	4.55	0.64	0.27	0.46	0.37	0.61	0.26	0.02
40	90.29	3.14	1.49	0.92	1.56	1.56	0.62	0.15	0.01

Sample Nr.	>3.5 mm	2.8-3.5 mm	2.0-2.8 mm	1.6-2.0 mm	1.0-1.6 mm	0.5-1.0 mm	0.2-0.5 mm	0.1-0.2 mm	<0.1 mm
41	85.81	3.67	2.20	1.50	2.70	2.45	1.20	0.26	0.00
42	0.32	95.18	1.63	0.52	0.98	0.81	0.31	0.09	0.00
43	52.3	41.8	3.01	0.8	0.88	0.53	0.35	0.19	0.01
44	41.25	49.81	5.09	0.84	1	0.99	0.63	0.18	0.00
45	20.39	77.33	1.06	0.27	0.33	0.18	0.07	0.05	0.00
46	9.87	88.42	1.07	0.1	0.14	0.12	0.08	0.06	0.01
47	39.52	54.76	3.02	0.92	0.71	0.46	0.36	0.12	0.00
48	6.99	67.69	6.62	3.17	5.48	5.06	3.62	1.02	0.07
49	1.18	16.35	38.04	15.75	15.5	7.83	3.7	1.40	0.07
50	7.64	77.85	5.96	2.19	2.56	1.77	1.26	0.52	0.05
51	91.78	4.53	2.96	0.14	0.21	0.12	0.05	0.05	0.01
52	29.22	8.06	13.2	7.3	14.65	16.63	9.53	1.39	0.00
53	27.67	35.83	20.77	4.05	4.05	4.15	2.53	0.76	0.00
54	12.95	37.15	26.3	6.41	6.16	4.94	3.98	1.56	0.02
55	96.9	0.67	0.21	0.14	0.42	0.91	0.6	0.08	0.00
56	86.71	3.46	2.91	1.09	1.7	1.91	1.51	0.54	0.00
57	93.96	2.32	1.91	0.53	0.42	0.31	0.26	0.21	0.00
58	98	1.02	0.59	0.06	0.01	0.04	0.09	0.13	0.00
Average	43.16	39.87	8.61	2.11	2.50	1.99	1.21	0.33	0.02

Appendix E: Raw data section 3

The wet sieving results (%)

Sample Nr.	>3.5 mm	2.8-3.5 mm	2.0-2.8 mm	1.6-2.0 mm	1.0-1.6 mm	0.5-1.0 mm	0.2-0.5 mm	0.1-0.2 mm	<0.1 mm
1	0.00	1.89	14.36	8.29	11.12	10.53	8.33	4.90	40.59
2	0.00	0.17	2.39	4.62	11.87	13.33	0.00	8.08	59.58
3	3.62	6.82	17.27	6.98	8.85	7.74	5.95	3.71	39.07
4	0.01	0.19	4.71	6.75	14.99	14.01	11.05	6.55	41.73
5	3.03	8.70	19.65	7.15	11.61	9.19	5.71	3.26	31.69
6	0.13	0.82	8.61	6.23	14.08	12.07	9.52	6.68	41.86
7	0.23	0.71	5.10	4.80	10.69	12.07	9.20	2.62	54.56
8	0.81	0.48	9.09	4.17	11.63	11.64	7.28	5.08	49.82
9	3.38	6.76	4.05	4.17	10.35	11.52	8.91	3.32	47.54
10	3.12	8.60	3.44	3.23	10.30	11.87	7.79	4.37	47.27
11	0.09	0.55	3.73	5.58	14.60	14.62	10.54	3.85	46.45
12	0.13	1.23	10.59	6.37	11.56	10.90	9.01	5.62	44.58
13	0.77	5.32	23.11	6.41	10.60	9.13	8.13	3.60	32.92
14	0.07	1.03	8.47	5.39	10.04	12.15	8.36	5.02	49.47
15	0.63	5.86	18.95	4.23	10.17	9.67	8.93	3.89	37.68
16	1.28	4.02	12.50	4.76	9.88	9.95	8.71	4.24	44.66
17	0.27	2.11	13.39	6.94	10.50	10.26	9.19	3.65	43.70
18	2.65	2.94	8.43	5.34	6.61	9.38	8.00	6.15	50.50
19	0.04	0.48	5.24	4.57	10.97	12.26	10.53	5.75	50.15
20	0.13	0.43	6.21	4.23	9.54	11.61	9.59	2.76	55.50
21	0.57	0.51	5.68	6.19	11.01	9.31	8.14	3.33	55.27
22	0.04	0.75	2.59	4.33	10.45	15.91	12.31	5.31	48.31
23	0.00	0.10	1.51	3.98	11.06	13.40	14.33	6.45	49.20
24	0.00	0.04	2.69	1.84	8.03	14.95	14.61	5.17	52.67
25	5.31	5.40	7.35	4.10	9.39	7.92	10.11	5.44	44.98
26	0.09	0.21	3.30	4.93	11.09	12.27	11.29	5.45	51.37
27	0.42	1.25	6.24	6.13	9.63	11.06	9.54	4.72	51.00
28	0.18	0.54	2.64	5.89	11.13	15.71	13.78	7.88	42.27
29	0.01	0.09	3.76	3.90	11.26	15.03	12.38	7.18	46.38
30	2.81	1.35	7.33	5.03	12.86	10.16	5.72	2.67	52.08
31	8.56	3.38	5.50	6.40	10.50	6.73	6.87	3.63	48.43
32	0.01	0.06	1.71	2.44	10.21	11.79	13.13	4.33	56.33
33	4.36	1.81	14.72	6.87	8.42	3.85	5.69	3.36	50.93
34	6.34	2.09	9.66	2.98	5.95	2.32	4.10	4.37	62.20
35	0.26	0.41	3.82	6.18	10.19	12.29	11.92	6.00	48.94
36	0.73	6.77	20.72	4.28	9.89	6.94	4.87	5.07	40.73
37	1.57	7.77	22.93	5.07	7.96	7.03	11.11	2.47	34.10
38	0.00	0.13	1.09	3.56	8.70	14.91	13.11	6.74	51.76
39	0.28	0.76	3.93	3.41	6.98	8.23	10.95	8.13	57.34
40	1.57	0.57	2.69	5.09	14.12	13.15	9.16	3.88	49.76

Sample Nr.	>3.5 mm	2.8-3.5 mm	2.0-2.8 mm	1.6-2.0 mm	1.0-1.6 mm	0.5-1.0 mm	0.2-0.5 mm	0.1-0.2 mm	<0.1 mm
41	1.54	0.67	2.87	4.56	15.85	14.42	8.35	3.66	48.09
42	9.04	0.14	1.95	2.16	10.89	11.04	12.80	5.79	46.19
43	4.63	4.54	10.43	7.53	12.12	11.44	7.70	3.34	38.27
44	1.97	3.86	10.34	7.07	13.28	6.09	8.51	4.77	44.10
45	5.26	1.33	3.93	3.27	9.99	10.78	6.67	4.73	54.04
46	2.33	3.42	9.23	4.77	10.33	8.84	9.59	4.72	46.76
47	0.10	0.31	3.25	4.79	12.35	12.92	8.45	4.38	53.45
48	0.51	2.08	5.14	4.91	8.71	4.56	6.72	5.16	62.22
49	0.24	0.86	4.31	3.29	11.65	10.85	7.73	3.80	57.26
50	0.16	0.86	4.09	2.50	9.29	8.81	8.63	5.11	60.55
51	0.23	1.58	10.19	10.96	15.63	17.30	8.35	3.26	32.51
52	1.17	10.50	12.00	8.19	12.06	9.73	6.83	3.56	35.97
53	0.95	1.36	5.55	4.28	10.82	16.06	11.32	5.81	43.84
54	0.84	2.15	7.54	3.82	8.07	13.09	12.05	2.95	49.49
55	0.05	0.36	4.52	5.38	13.40	15.18	14.75	6.07	40.29
56	0.21	0.82	12.13	6.52	13.89	12.67	11.23	3.38	39.15
57	0.72	2.49	9.06	7.35	10.59	9.94	12.74	6.31	40.80
58	0.17	1.03	6.41	6.63	10.49	15.29	11.62	1.16	47.21
Average	1.44	2.27	7.79	5.19	10.83	11.14	9.34	4.70	47.30

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