Natural Energy of Briquette, Definitions, Benefits and Technologies

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ABSTRACT

As the third largest energy resource after coal and oil, biomass used to catch the highest demand for energy till mid-19th century. Different resources of biomass like tea waste, straws of colza, wheat straw and waste paper, olive refuse, cotton stalks have been utilized to be transformed to briquettes or as a binder for lignite. By-products from the wood industry like sawdust or cutter dust can be used as the biomass to be possessed as pellets. Briquetting of biomass can be acted out via mixing it with some type of binder (roll and char briquetting, pelleting) or through direct compacting (piston press technology and screw technology). Briquetting, some characteristics of the materials are optimized yielding a denser, more usage convenient product and of course with a higher heating value which is an indicative of higher energy content in the feed material lignin acts as a binder and in higher temperatures, it softens and helps the binding process. Lignin which exists in the biomass acts as glue and improves the binding features of the biomass. Crystalline micro fibrils are formed by cellulose and are surrounded by amorphous cellulose inside plant cells. Compression and high temperature of the process causes plasticity of protein and starch, turning them to binders which contribute to the solidity of the produced pellet. The results indicated that the mechanical properties of the briquettes improved with increasing mill scale ratio in the mixture, whereas the reduction percentages decreased with decreasing temperatures. The processes involved in transforming biomass into fuel product are pyrolysis, gasification and densification.

KEYWORD

Briquetting- Pellet production- biomass- binder- energy.

INTRODUCTION

In fact that natural resources of energy is diminishing on one hand and the increasing demand and need for them on the other hand, stimulated a movement toward substituting the existing limited underground resources which incurred huge costs to extract and refine with some accessible eco-friendly product via a low-cost production process of producing some innovative carbonaceous materials, introduced later on as biomass in the industry [1]. Considering the history of demand for biomass fuels, wood consumption rate rose 2% per annum between 1974 and 1994 [2]. Renewability and low-cost production process of biomass fuels grabbed high demands for domestic cooking, industrial process heating, electrical power generation etc [3]. The processes involved in transforming biomass into fuel product are pyrolysis, gasification and densification; densification refers to a pre-treating process of losing the bulky biomass materials whereby they are transformed into the appropriate form for further treatment in the combustion equipment. Modifications are also carried out on the material for transport and storage convenience [4]. The latest process known as briquetting technology grabbed the utmost attention [3]. In the process of briquetting external compressive forces are applied rather than binding agents to aggregate the particles and compact them. The higher the pressing force is, the higher the density and stickability between the particles [5]. The outcome of this process has come to be known as briquette with comparative advantages of greater volumetric energy density, easy storage/transportation over the previous products. Each country considers its own biomass resources and thus varieties and quantities of biomass differ in various geographical areas due to their distinguished climate, flora and agriculture [3]. As the third largest energy resource after coal and oil [6], biomass used to catch the highest demand for energy till mid-19th century. Later due to the emergence of a higher tendency toward fossil fuels, demand for biomass decreased considerably, though it still supplies about 1250 million tones oil equivalent ( MTOE) and meets around 14% of the global annual demands for energy [7].

Researches indicate different resources of biomass like tea waste [8], straws of colza [9], wheat straw and waste paper [10], olive refuse [11], cotton stalks [12] have been utilized...
to be transformed to briquettes or as a binder for lignite [13, 14,15]. By-products from the wood industry like cutter shaving can be also used to produce another type of biomass fuels known as pellets.

**DENSIFICATION**

Densification refers to a pretreating process of loosening the bulky biomass materials whereby they are transformed into the appropriate form for further treatment in the combustion equipment [4]. Biomass densification processes can be categorized as balling, pelleting, extruding and briquetting that Bailer, pelletizer, screw press, piston press or roller press utilized to carry out. For solid fuel applications, two binderless high pressure compaction technologies of pelleting and briquetting are used which are carried out by a piston press or a screw press. This technique has got the utmost attention by developing countries during the recent years [16].

One of the main causes of less usage as a source of energy of agricultural and forestry residues were own Inconveniences; however this has been overcome by densification and reshaping of the residues [16].

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Tabil and Sokhansanj [17] explored the compression characteristics of alfalfa pellets; Ndiema et al., [18] studied the influence of die pressure on relaxation characteristics of briquetted biomass ; Adapa et al., [19] explained pelleting fractionated alfalfa products; Li and Liu [20] worked on the high-pressure densification of wood residues for fuel; Mani et al., [21] investigated the compaction characteristics of lignocellulosic biomass using an Instron ; and Tumuluru et al., [22] studied the impact of pelleting process variables upon the quality attributes of wheat distiller’s dried grains with soluble.

** PARTICLE SIZE AND SIZE REDUCTION **

The particle size is smaller, the compression process is easier, alternatively, create a larger surface for the binding. Grinding operation could be done by means of a hammer mill. For some wastes such as wood, straw may require chopping before hammer mill [23, 20, 24].

** PELLET PRODUCTION **

By-products from the wood industry like sawdust or cutter dust can be used as the biomass to be possessed as pellets. Sawdust is usually comprised of about 50 %water .In the first stage, the raw materials are sieved to get rid of stone or coarse sand and metals. In the second stage, the raw materials grind into suitable size in a different mill. In the third stage, the raw materials are preheated up to more than 90 %dryness. In the last stage, the dry materials are compressed. When the wood materials are compressed, the temperature will rise and lignin will be released working as a glue to stick the material together [25, 26].

** BRIQUETTING OF BIOMASS **

Through briquetting, some characteristics of the materials are optimized yielding a denser, more usage convenient product and of course with a higher heating value this is an indicative of higher energy content [27]. Agricultural and forestry residues are a case in point. Due to their uneven bulky sizes they were rarely used as bio-fuels. These troubles have been overcome via densifying the residues into compressed standard shapes. As the merits of the process one can cite the increased caloric content of the material per unit, yielding a uniform shape of output with a well-defined quality, the convenience of usage of the product in terms of handling, transportation and storage, optimized combustion which contributes to a higher efficiency, lower emission and less ashes. All the above mentioned characteristic reduces the amount of investment needed for furnaces and purification equipment whereby contributed to the cost efficiency of the operation process of the industry [28].

Briquetting of biomass can be acted out via mixing it with some type of binder (roll and char briquetting, pelleting) or through direct compacting (piston press technology and screw technology). The sticky characteristics of the thermally softened lignin contribute to the strength of the briquettes produced out of lignocellulosic input. The binderless press-agglomeration of residual lignocellulosic biomass has been investigated and the findings indicate that not only the properties of the input material itself but also the pressure, temperature and velocity of the compaction process as well as moisture presence and dispersal of particle size effects the output of the press agglomeration [29].

A briquette is a cylinder of organic matter, which has been compressed and at least has a diameter of 25 mm .If the diameter is smaller they are called pellets .Pellets normally have a diameter of 6 to 12mm [30]. Butler and McCollly [31] observed that the density of chopped alfalfa hay pellets was correspondent to the natural logarithm of the applied pressure and found that increasing pressure significantly increased the density. Yaman et al. [11] recommended that the selection of briquetting pressure should be such that it influences the mechanical strength by increasing the plastic deformation . However, fractures may occur in the briquette above an optimum briquetting pressure, because of sudden dilatation [11]. For a given die size and storage condition, there is a maximum die pressure beyond which no significant gain in cohesion (bonding) of the briquette can be achieved [18]. High pressures and temperatures during densification may develop solid bridges by a diffusion of molecules from one particle to another at the points of contact, which increases density . Li and Liu [32] observed that compression of oak sawdust at pressure application rates varying from 0.24 to 5.0 MPa/s had a significant effect on the dry density of the product. Demirbas et al., [33] observed in their research on the compaction of biomass waste materials like waste paper, that increasing the pressure from 300 MPa to 800 MPa on
biomass with ~7% moisture content at first increased the density sharply, from 0.182 g/mL to 0.325 g/mL, and then the densities increased slightly to 0.405 g/mL.

**Mechanisms of bonding of grinds during densification of biomass**

In order to yield a densified biomass in a good quality there are some process variables that should be observed in densification like, die diameter, die temperature, pressure used to compress the particles, binder involvement or lack of it, and biomass drying.

Tabil and Sokhansanj [17, 34] in their study indicate that the compaction of the biomass particles during pelletization process can occur as a result of elastic and plastic deformation of the fragments under higher pressure. They cite two important factors to be observed in pelletization process including the ability of the grinds to shape pellets of good mechanical strength, and the ability of the process to optimize density. The former has to do with substantial behaviour of bonding or interlocking mechanisms which yield a better densified biomass. Figure 1 illustrates the deformation mechanisms of the grinds during compression.

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**Chemical composition**

The chemical content of the biomass, which comprises components like cellulose, hemicelluloses, Lignocellulosic, protein, starch, lignin, crude fiber, fat, and ash, influences the densification process. Compression and high temperature of the process causes plasticity of protein and starch, turning them to binders which contribute to the solidity of the produced pellet [43].

**Lignin**

In the feed material lignin acts as a binder and in higher temperatures, it softens and helps the binding process. Bradford and Levi [44] found that the auto-adhesive action of thermally softened, non-crystalline wood polymers was like that of mastic which had a small internal strength by its own. At first, when the non-crystalline wood polymers acted as an adhesive between crystalline zones pellet durability increased. However, above a threshold “excessive mastic” between crystallites the strength and durability of the pellets declined. Lignin which exists in the biomass acts as glue and improves the binding features of the biomass. High temperatures and pressures, which are observable during densification processes, make the lignin soften and improve the binding ability of the biomass. The low thermosetting properties and low melting point (~140°C) helps lignin to take an active part in the binding phenomena [45].

**Cellulose**

Crystalline micro fibrils are formed by cellulose and are surrounded by amorphous cellulose inside plantcells [46]. The hemicelluloses and lignin form an amorphous matrix that reinforces the cellulose micro fibrils. Hydrogen bonding occurring between the glucose monomers produces the structural integrity of the cellulose [47]. Zanderson et al. [48] in their paper about hot pressing of wood material concluded that the binding strength of wood based products mainly depends on the conversion of cellulose to an amorphous state.

In hot condition protein plasticizes and acts as a binder. It helps increase the strength of the densified products [49, 43]. During feed pelleting, the combination of heat, moisture, and shear effects result in protein denaturation, which induces the binding functionality of protein [50, 51]. Proteins such as wheat [50, 52] rye and barley [53], and soybean meal [52], which are derived from cereal grains and have dough-forming capabilities help improve the pellet durability. Cavalcanti [52] reported that protein derived from corn [i.e., corn gluten meal] had negative effect on pellet durability. In wood [50] observed higher pellet hardness and durability when adding raw protein than denatured protein. Starch (raw or pregelatinized) which has...
been pelleted with raw protein had a minor effect on pellet durability. The average Holmen pellet durability for rations containing 40 %raw starch and 60 %raw protein was 85%, while this amount was 96%, for rations containing 40 % pregelatinized starch, 60 %raw protein, this amount was 96%.

**LIGNOCELLULOSIC BIOMASS**

Due to the low density of residual lignocellulosic biomass, it is of restricted application. The output of the first and second timber transformation industry features 20 to 30% in density of all the provided input. Briquetting of biomass as mentioned before pertains the densification process whereby the handling properties of the biomass as well as its volumetric caloric value are manipulated in order to provide a uniform, usage convenient fuel or input for further modification. Lignocellulosic biomass requires a complex process of the kind and thus no coherent theory can be given [54]. The technologies utilized in binderless briquetting processes are of two types of screw and piston-pressed technology based machines. Under screw pressed technology, the biomass is constantly squeezed out by a screw through a taper die, which also transfers external heat in to reduce friction. Through piston-press technology, the biomass is punched and propelled (conforming to impact or hydraulic technology respectively), into a die by a reciprocating ram or piston by exercising high pressure in both cases which is effective in raising the temperature of the biomass and consequently having the component lignin of the biomass be fluidized and act as a binder [54].

Among the aforementioned technologies the hydraulic presses are seen to have advantages over the others due to such properties as ease of use, low maintenance, low consumption and applicability for densifying low-quality residues like cotton, paper, wet sawdust, etc. However it has some defects as low product density, friability and production. The issue has been investigated in a study carried out by Granda et al., [54] to improve the quality of hydraulic pressed densified output via increasing density and friability/abrasion resistance.

Experimental design is needed to systematize the estimation of the experiments necessary to develop a model. The obtained model is expected to correlate quality variables (density and friability) and the effective factors [55, 56, 57, 58] (pressure, temperature, moisture content, input particle size distribution, and compaction velocity and die diameter) in order to improve output quality in terms of higher density and friability [29].

**STARCH**

Many researchers have acknowledged that during densification of starch rich biomass using an extrusion process such as pelleting the presence of heat and moisture gelatinizes the starch and lead to a better binding [51]. In this process starch acts as a binder [50, 51]. It is noticeable that the native starch shows less binding ability compared to the gelatinized starch. In the presence of heat and moisture, gelatinization of starch occurs. Starch gelatinization is improved by mechanical shearing during the densification process. To study corn starch gelatinization, Stevens [59] and Cavalcant [52] used a differential scanning calorimeter (DSC) device. They found that starch gelatinization occurred in two ways; i) hydration and swelling of starch granules and disruption of the crystalline structure because of the effect of temperature and moisture; and ii) disruption of starch granules by shear friction when the feed mash expelled through the pellet die. The pellet durability increases with the increase in the percentage of starch gelatinization [60].

**FAT**

Existence of fat (whether animal based or vegetable based) in feed results in lower pellet durability [61, 52, 43, 62, 63]. The reason is that fat acts like a lubricant between the feed particles, and between the feed, and also the pellet-mill die wall. Because of low friction in the die, pressure in the die declines and leads to pellets with lower durability. As fat has a hydrophobic nature, when it is added to the feed, it inhibits the binding properties of the water-soluble components in the feed such as starch, protein, and fiber [51]. When there is no added fat, sometimes the (natural) fat in the cell wall may come out of the cell and act as a binding component between particles and form solid bridges. It can have a positive effect on pellet durability [51]. For reaching to maximum pellet quality, fat addition before pelleting should not exceed 1.5% [52]. According to Briggs et al., [43], the oil content should not exceed 5.6 % in rations formulated using high-oil corn and soybean meal. Cavalcanti [52] studied the binding application of starch, protein, and fat in 13 different model feeds obtained by mixing different percentages of corn, soybean meal, and soybean oil. He concluded that the level of fat inclusion beyond 6.5 % is harmful for pellet durability. Moreover, high levels of fat (>6.5%) affected the binding functionality of starch and protein. He also found that the fat content factor was the most important factor determining the pellet durability.

Adding binder was necessary to significantly improve the pellet durability of high fat rations; however, when the added fat content was 3 or 6 % in a turkey ration, pellet durability increased by about two to three percentage points. When the added fat level of feed is 40 g/kg, the average pellet durability was 86.5 % without sepiolite and 93.6 % with sepiolite.

**BINDERS (ADDITIVES)**

Binder is added to glue particle (coal). Not needing to soften the lignin makes a low pressure and temperature requirement. Finding a suitable binder which is cheap, no hygroscopic and non-abrasive is difficult. Also, ash content of the binder should be low; not to affect the heating value [23].

A binder (additive) is a liquid or solid that causes forming a bridge, film, matrix, or a chemical reaction to make strong inter-particle bonding. Steam conditioning or preheating is necessary to provide heat and moisture to activate the
inherent or added binders. Selection of binders depends on cost and environmental friendliness of the binders [17, 64]. In some European countries, addition of binders is banned [65]. In Austria, biological additives rich in starch content (e.g., maize and rye flour) of only 2 % [66] studied the effect of adding 1 to 2 percent calcium lignosulfonate to four types of turkey and poultry rations. It leads to the durability of 90 to 97% for pellet.

Salmon [67] reported that when the added fat content was no or 9% adding sodium betonies (2.5%) did not improve the pellet durability.

Payne [68] found that hardness of dairy feed pellets (measured after 24 h of making) was 166 N with lignosulfonate (2.5%), and 131.4 N without lignosulfonate (i.e., because of addition of 2.5 % lignosulfonate, 27 % increase in strength was observed). Angulo et al., [69] used sepiolite, hydrated magnesium silicate clay, as a binder at rate of 20 g/kg of feed to increase the durability of feed pellets made from the diet of pig grower, sow, or rabbit (with high levels of fat content). They concluded that when the added fat level of feed is 5 g/kg the average durability of pellets was 95.8 %without sepiolite and 96.8 %with sepiolite.

BINDERLESS DENSIFICATION

Binderless densification is possible only with decayed and composed biomass. Raw materials which had been unused residues have been accumulated and composed over previous year's mountains of waste bagasse. Fresh biomass can also be briquetted after pretreatment (aerobic and/or anaerobic fermentation after size reduction, if necessary). The process requires high pressure which results in two problems: a) High electricity energy consumption in driving motor with 13.9 – 16.6% of the total production cost and b) High wear rate of machine parts [23].

TECHNIQUES

According to operating condition it could be classified into two categories: I) Hot and high pressure densification. II) Cold and low pressure densification. Also, we can categorize them according to mode of operation; 1. Batch densification 2. Continuous densification. The most important densification process is the hot and high pressure continuous process [42, 30, 70] considering the type of equipment used; densification can be categorized into four main categories: 1. piston press densification; 2. Screw press densification; 3. Roll press densification; and 4. Pelletizing. A briquette is a cylinder of organic matter, which has been compressed and at least has a diameter of 25 mm. If the diameter is smaller they are called pellets. Pellets normally have a diameter of 6 to 12 mm [30].

PISTON PRESS DENSIFICATION/BRIQUETTING

A reciprocating piston forces the raw materials falling from the feed hopper into a tapered die. Then, the material is heated to 150-300 °C [42, 30, and 71].
wastes was equivalent to that of subbituminous coal, and can be co-fired with coal in power plant [32].

**Screw press densification or extruder**

In a screw press, the biomass is extruded continuously through a heated tapered die. The quality of the extruded logs and the production processes of a screw press are superior compared to piston press technology. However, compared to the wear of parts of a piston press, like the ram and die, screw press parts need more maintenance. The central hole in the densified logs produced by a screw press helps to achieve uniform and efficient combustion, and helps to carbonize the material more quickly due to better heat transfer. Many researchers have studied the densification of woody and lignocellulosic biomass using a screw press, pellet mill and briquette press [23, 42]. In the screw press, the raw material from feed hopper is conveyed and compressed by a screw. These presses produce denser and stronger briquettes compared with piston press. There are basically three types of screw presses: 1) conical screw press 2) screw press with heated die 3) extruder [23].

1. **Conical screw press**

Produce denser and stronger briquettes compared to piston presses. A rotating die head extrudes the material through a perforated matrix to produce briquettes of diameter of 2.5 cm. A knife cuts the dandified product to a specified length [23, 32].

Briquetting of biomass can be done through various techniques. The application of an experimental design technique and the later statistical analysis of the results are presented, applied to a laboratory hydraulic press densification process of lignocellulosic biomass. The most appropriate experiment type is determined for a first set of experiments; calculating, among other things: minimum number of tests to carry out to obtain binding conclusions, most influential factors, and search paths to improve fuel quality. Another experiment type is determined for a second set of experiments, taking account of the most influential factors [1, 3] pressure, temperature and moisture content, and also the number of tests to carry out considering the improvement of density and friability. Finally, an approximation study of the best product allows conclusions to be reached on product behaviour beyond the experimental design range factors [54].

2. **Screw press with heated die**

In screw presses, material is fed continuously into a screw, which forces the material into a cylindrical die. This die is often heated to raise the temperature to the point where lignin flows.

**Extruder**

The purpose of using an extruder performing compaction is to bring the smaller particles closer. Therefore, the forces acting between the particles go stronger and provide more strength to the densified material. During screw extrusion, the biomass material moves from the feed port through the barrel and compacts against a die with the help of a pressure made by rotating screw. This process causes friction from the shearing of biomass. The effects of some factors, including internal and external friction heat and high rotational speeds (~600 rpm) of the screw, increase the temperature of the biomass increases. When this heated biomass is forced through the extrusion die, it forms briquettes or pellets with the required shape. If the die is tapered the biomass becomes more compacted and if the heat produced within the system is not enough for the material to reach a pseudo plastic state for smooth extrusion, we can provide extra heat to the extruders from outside the system using band or tape heaters [74].
The advantages of screw press densification are:
1) The output is continuous and its size is uniform, it shows an easy ignition and combustion.
2) There is a concentric hole in the briquette that helps combustion.
3) The machine runs very smoothly without any shock load.
4) The machine is lighter than the piston press.

The disadvantages of screw press densification are:
1) The parts and the oil used in it are free from dust or raw material contamination. Wear of the screw and die is the main problem.
2) The power requirement of the machine is higher than the piston press.

Roll press densification

The principle of pressure and agglomeration is the base of densification of biomass using a roller press. In this process pressure is applied between two counter rotating rollers. When the granular biomass is forced through the gap between the two rollers, it rotates with the rolls and is pressed in small dies or pockets. Design parameters, have a major role in the quality of the biomass, the diameter of the rollers, minimum gap size, roll force, and shape of the die. Roller presses are composed of two parallel cylinders of the same diameter that rotate on horizontal axes in opposite directions. The rotation of the rollers make the feed be drawn in from one side and ejected from the other side in the densified form. A small gap separates the two rollers. This separation can be adjusted considering biomass type and physical characteristics like particle size, moisture content, and additional binder. The final shape of the densified biomass depends on the type of die used.

Pelletizing press

It is composed of a matrix and a roller. The pressure between them makes frictional heating and forces the material to move through the perforations in the matrix plate. The extruded pallets are cut off at a specified length using a knife. These are normally 5-15 mm in diameter and have a length bellow 30 mm. Capacity of these presses ranges from slightly below 1 ton/h to about 30 ton/h.

The disk matrix press is composed of a die in the form of a plane disk and rollers. The ring matrix press consists of a die in the form of a ring and rollers.

The most standard pellet machines are roller presses which have a circular die and cog-wheel pellet principle. The operating principles of a roller press with a circular die and a cog-wheel pellet principle are shown in Figure 10. These machines initially were developed for the production of animal feedstuffs. They extrude small pellets of diameter 10-30 mm through a die with many holes. The extruding mechanism is an eccentric roller that moves inside the large cylindrical or conical die. Its throughput performance depends on various factors. The most important of these factors is the fineness of the pressed materials. Furthermore, the size of the die and its holes plays a major role. With the cog-wheel pellet principle, the pressed materials are pre-compressed, and then pressed and formed in the press canals in the roller coat. The press canals have different cross sections, such as cylindrical, plate-type or wavy. Nendel et al., [78] proposed a high-pressure compression process for compressing the uncut stalks especially straw. The principle of the stamp press process presented in Figure 11 were used in this project. The main force of compression works axially. The stalks are pre-compressed by a two-stage band press. Clauss [24] noted that after the dosage step, the stalks were pressed in a press cylinder under pressure up to 200 MPa without any additional binding materials. Through this process the stalks were compressed to a ratio of about 80:1. The density of the
processed briquette was about 0.9 kg/m³, depending on the processed material.

Fig. 9. the principle of the high pressure piston press [24]

Energy required for densification

Energy input forms a sizable fraction of densified biomass production cost. Biomass densification systems need energy for the two main processes usually involved; –fuel preparation, drying and size reduction, for example, rice husk obtained from the mills can be normally densified without drying and needs no size reduction. In contrast, if the raw material needs both size reduction and drying, the necessary energy for fuel preparation may be significant.

–the densification process itself [23].

Discussion and Conclusion

Accordingly, the mechanism of densification which compacted biomass attains self bonding. It is claimed that in high pressure, pectin and other low molecular substances are squeezed out of the plant cells and act as binding agents for the particles. Lignin softens between 130-190°C and shift below 100 °C under the plasticizing influence of water. It is believed that the softened lignin acts as internal glue during densification. However, it is not universally accepted. Some researcher argues that self bonding may be partly because of adhesive degradation products of hemicelluloses [23].

The properties of the solids that are important to densification are flow ability and cohesiveness, Particle size, Surface forces, Adhesiveness, Hardness, Particle size distribution [23 and 32].

Many methods and procedures have been tested and examined for determination of particle density of pellets and briquettes. Round robin trials were organized involving five European laboratories, which measured the particle densities of 15 pellet and five briquette types. The test included stereo metric methods, methods which works with the principle of liquid displacement (hydrostatic and buoyancy) applying different procedures and one method based on solid displacement.

The results for both pellets and briquettes, showed that the application of a method based on either liquid or solid displacement (only tested on pellet samples) result in improved reproducibility compared to a stereo metric method. For both, pellets and briquettes, the variability of measurements strongly depends on the fuel type itself. For briquettes, the three methods tested based on liquid displacement illustrated similar results. A coating of the samples with paraffin did not improve the repeatability and the reproducibility.

When the buoyancy method was applied using a wetting agent to reduce surface tensions without sample coating, determinations with pellets was the most reliable method. This method gave the best values for repeatability and reproducibility. Therefore, less replication are required to reach a special accuracy level. For wood pellets, the method based on solid displacement gave better values of repeatability; however, this instrument was tested at only one laboratory [79].

The compression strength of densified biomass depended on the temperature at which densification is carried out. Maximum strength is achieved at a temperature around 220 °C [23].

It was also found that at a given applied pressure, higher density of the product was obtained at higher temperature. It has been reported that for pellets produced in a laboratory scale device in the temperature range 130°C to 170 °C strength and moisture stability will increase by increasing press temperature [23].

About the quality of the pellets made from agricultural biomass, pressure plays an important role. Butler and McColly [31] observed that the density of chopped alfalfa hay pellets was correspondent to the natural logarithm of the applied pressure and found that increasing pressure significantly increased the density. Yaman et al. [14] recommended that the selection of briquetting pressure should be such that it influences the mechanical strength by increasing the plastic deformation. However, above an optimum briquetting pressure, fractures may occur in the briquette because of sudden dilation [11]. For a given die size and storage condition, there is a maximum die pressure beyond which no significant gain in cohesion (bonding) of the briquette can be achieved [18]. High pressures and temperatures during densification may develop solid bridges by a diffusion of molecules from one particle to another at the points of contact, which increases density. Li and Liu [20] observed that compression of oak sawdust at pressure application rates varying from 0.24 to 5.0 MPa/s had a significant effect on the dry density of the product. Demirbas et al. [33] in their article about the compaction of biomass waste materials like waste paper, observed that increasing the pressure from 300 MPa to 800 MPa on biomass with ~7 % moisture content at first increased the density sharply, from 0.182 g/mL to 0.325 g/mL, and then the densities increased slightly to 0.405 g/mL [33].

Moisture content has an important role as it facilitates heat transfer and too high moisture makes steam formation and could lead to explosion. So the Suitable moisture content could be of 8-12 (68%).

Drying depends on factors like initial moisture content, particle size, types of densified, throughput [23].
According to relevant content, if the particle size becomes fine, the compaction process is easy and it should be less than 25% of the densified product, so fine particles give a larger surface area for bonding [24].

If the strength and durability values of pellets do not correspond to the quality standards or marketing requirements, additives are added to the feed which are in the range of 0.5 to 5% (by weight) to increase the pellet quality or to minimize the pellet quality variations [17]. Up to now, more than 50 organic and inorganic binders have been used for densification [80]. Binders which are usually used in the animal feed industry are lignosulfonate (by-product from pulp and paper industries), bentonite (clay mineral), modified cellulose binders (e.g., sodium carboxymethyl cellulose), molasses, starches, and proteins [68, 81, and 17]. Addition of bentonite (2.4 % by weight) improved the durability of feed pellets about six percent [82]. In some European countries, addition of binders is banned [65]. In Austria, biological additives rich in starch content (e.g., maize and rye flour) of only 2 % [66] studied the effect of adding 1 to 2 percent calcium lignosulfonate to four types of turkey and poultry rations. It leads to the durability of 90 to 97% for pellet. He found that adding binder was necessary to significantly improve the pellet durability of high fat rations. Post and Young [82] found that addition of bentonite (2.4 %by weight) improved the durability of feed pellets about six percent. Salmon [67] reported that when the added fat content was 0 or 9%, adding sodium bentonite (2.5%) did not improve the pellet durability. However, when the added fat content was 3 or 6 % a turkey ration, pellet durability increased by about two to three percentage points. Payne [68] found that hardness of dairy feed pellets (measured after 24 h of making) was 166 N with lignosulfonate (2.5%), and 131.4 N without lignosulfonate (i.e., because of addition of 2.5 % lignosulfonate, 27 %increase in strength was observed). Angulo et al., [69] used sepiolite, hydrated magnesium silicate clay, as a binder at rate of 20 g/kg of feed to increase the durability of feed pellets made from the diet of pig grower, sow, or rabbit (with high levels of fat content). They concluded that the average durability of pellets when the added fat level of feed is 5 g/kg was 95.8 % without sepiolite and 96.8 % with sepiolite. When the added fat level of feed is 40 g/kg, the average pellet durability was 86.5 % without sepiolite and 93.6 % with sepiolite. Another research by Dobie [83] showed that without the application of a good bonding agent, grass hay could not be formed into good quality cubes. Cubes produced from blue panic grass, Timothy grass, range hay, Pangola grass, and Congo grass without a binder showed durability of 15 to 44 %. In contrast, by adding 5.0 to 10 % (by weight) of a liquid binder (containing ammonium lignin sulfate, wood sugars, 2.4 %nitrogen in the form of ammonia, and 50 % water), durability of cubes increased to 93-97 %. Addition of about 5 % (by weight) of the same liquid binder to bagasse pith increased the durability of the cubes from 88.8 to 99.3% (by weight) are allowed for wood pellet production [65].

Choosing Binder

Raw Material Preheating reduces the wear and energy consumption because it softens the raw material before it is compacted also work and pressure of compression could be reduced by a factor of two by preheating to 200-225 °C before densification. In case of sawdust some researchers show that preheating increases the screw life from 17 hours to 44 hours. Two-piece Screw and Hard facing of Screws could increase the life of the screw [23].

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