Iranica Journal of Energy & Environment

Journal Homepage: www.ijee.net

IJEE an official peer review journal of Babol Noshirvani University of Technology, ISSN:2079-2115

Preparation and Characterization of Fuel Pellets from Corn Cob and Wheat Dust with Binder

S. A. El-Sayed* and M. Khairy

Mechanical Power Engineering Dept., Zagazig University, Al-Sahrkia, Egypt

P A P E R I N F O

Paper history:
Received 28 June, 2016
Accepted in revised form 20 August 2016

Keywords:
Corn Cob
Wheat Dust
Pellets
Mechanical Properties
Combustion Characteristics

A B S T R A C T

This study concentrates on pelletization of powdered corn cob and wheat dust with 40% Epoxy binder. Two cylindrical pellets of different sizes and a new hexagonal one were investigated in this work. By densification process, the bulk density increased 8-10 times, having its maximum value fora hexagonal shape (new shape). It was found that the compressive resistance, the water resistance and the impact resistance of the pellets were in general higher for pellets produced at higher pressure. It was found that due to the binder and pelletization, the fuel quality was enhanced compared to the raw biomass as: the moisture content decreased, both fixed carbon and carbon contents increased, ash content reduced, oxygen content decreased and higher heating value (H.H.V) increased. Scanning Electron Microscopy was used to identify the binding mechanism of biomass dust particles in pellets. Pelletization process had improved combustion characteristics compared to raw biomass as: high combustion temperature ranges [T_onset becomes lower and T_offset becomes higher], maximum weight loss rates decreased and reduced residues which leads to a higher combustion efficiency. The analysis of ash yields of combustion process was investigated. It was found that the fouling index (FI) and slagging index (SI) tendency of wheat dust pellets are higher than that of corn cob pellets.

***doi**: 10.5829/idosi.ijee.2017.08.01.13*

INTRODUCTION

Biomass products of high energy potential involve agricultural residues, which are biological forms of renewable energy. Corn cob and wheat dust are regarded as being the most important of such residues because these products have an excellent energy potential andalso represent a major by-product in various countries. In Egypt, a large amount of corn cob is produced annually and no effective methods are being used for its utilization. The accumulation of the waste causes a significant environmental disposal problem represented in the fermentation of such wastes, their degradation products, psychological hazards and other related health issue which raise the burden on the national economy [1]. Corn cob is an important by-product of the sweet corn processing industry in Egypt, where they signifyabout 15% of total corn production.The quantity of corncobs produced was approximated to be about 54,424 tons in 2008 (corresponding to data obtainedfrom the Directorate of Agriculture, Egypt). Worldwide, these huge amounts are either used as animal feeds or are coming back to the harvested field [2]**.** Corn cob, a residue of the maize crop, is a lignocellulosic biomass material which contains high amounts of natural constituents and energy. Corn cobs exist as individual pieces with similar sizes and shapes. It could be utilized without briquetting/pelleting for most of the applications such as industrial scale heating. For applications needing high quality feedstock such as warming, corn cobs may need to be pelleted. The pellets produced from corn cobs have a tendency of water absorption due to the high porosity of corn cob particles. In Egypt, a large amount of wheat dust is produced annually.The husk of the grain, separated when milling white flour. The more that the grain is handled, the most dust is produced. The moredust produced in a confined space, the greater the chance of exceeding the lower explosive limit of the dust. The more thelower explosive limit is exceeded, the greater the likelihood of an explosion. Open burning in the field is generally the most frequentway of its disposal. Even so,

* Corresponding author: Saai A. El-Sayed
E-mail: shamad53@hotmail.com

Please cite this article as: S. A. El-Sayed and M. Khairy, 2017. Preparation and Characterization of Fuel Pellets from Corn Cob and Wheat Dust with Binder, Iranica Journal of Energy and Environment 8 (1): 71-87.

biomassis actually a source of alternative energy, replacing with fossil energy and thus decreasing a greenhouse gases emissions while treating local polluting of the environment problems from open burning [3, 4]. Even now, the use of corn cob and wheat dust for energy production facea significant problem in terms of the cost and logistics of collecting, transporting, storage and handling, especially because of the its low density. The bulk density of crushed corn cob is around 356.72 kg/m^3, while it is roughly 111 kg/m^3 for wheat dust [5]. Densification of biomass directly into durable pellets is an effective solution to these problems where the bulk density of biomasses elevated 8-10 times [6]. There are three phases during densification of biomass. Within the first phase, particles rearrange themselves,to create a closely packed mass where almost all of the particles retain their properties and the energy is dissipated due to inter-particle and particle-to-wall friction. In the next phase, the particles are forced against each other and undergo plastic and elastic deformation, which increases the inter-particle contact significantly; particles become bonded through van der Waal's electrostatic forces. In the 3rd phase, a significant reduction in volume at higher pressure results in the density of the pellet achieving the true density of the component ingredients [7].

Upon densification, several agricultural biomass materials, especially those from straw and Stover, create a poorly produced pellets or compacts which are more often dusty, difficult to handle and costly to produce. The best quality compacts can be produced by the control of the production procedures and biomass physical and chemical characteristics. Biomass grinds fluctuate in their response to the compression forces during pelleting as biomass differ broadly in its chemical composition [8, 9]. The different components include moisture content , fixed carbon contentand ash content; varianceis a result of factors including varying harvest times and techniques, climate conditions, plant genetics and soil composition [10]. To a great extent, the quality of manufactured compacts depends on the physical forces that bond the particles together[11]. To produce and manufacture good quality products that can with stand numerous forces during transportation and handling, it is important to estimate suitable and dependent quality parameters (density and durability) with respect to various independent variables (moisture content and grind size) [12]. Many researchers have found that the optimum moisture content for densification of biomass is different for each individual feedstock and operating condition. The optimum feedstock moisture content of several biomass feedstocks has been investigated by numerous researchers. Base on literature [13] increasing in moisture content from 10 to 15 % (w.b.) increased the corn Stover briquette durability from 62 to 84% at 150 MPa pressure. Generally, moisture contents of 11–12% (wb) is used for wheat- and corn-based feed pelleting [14]. According to literature **[6],** production of high quality pellets is possible only if the moisture content of the feed is between 8 and 12% (wb). Moisture contents above or below this range would lead to lower quality pellets. As given in literature **[15]** for both corn Stover and switch grass, the bulk density of compacts decreased with an increase of moisture content from 7 to 15% and 9 to 20%, respectively. In addition, they concluded that grinds at a moisture content of 10% (wb) produced good quality compacts. Based on other investigator [16] at lower loads, the compact density was higher at 15% (wb), stable pellets can be formed by a range of moisture between 8 and 12 % (wb) depending on the biomass in question. As a general rule, the higher the moisture content, the lower the density of the pellet. The moisture content of feeding material, when optimal, serves as a binding agent, facilitates heat transfer, and aids in the thermal softening and self-bonding of individual particles in the pellet. Any further increase in moisture content beyond the optimal range would reduce the inter-particle forces by increasing the contact area of the particles [17, 18]. The physical properties of biomass pellets also depend on pelleting process variables such as biomass particle size, die thickness, die geometry (length-to-diameter ratio), die speed, temperature, applied pressure, and hold time [19-23]. The effectiveness of a densification process to create strong and durable bonding in densified products such as pellets can be determined by testing the strength (i.e., compressive resistance, impact resistance, and water resistance) of the densified products [24]**.** These tests can indicate the maximum force/stress that the densified products can withstand, and the amount of fines produced during handling, transportation, and storage.Compression strength (or crushing resistance or hardness) is the maximum crushing load a pellet can with stand before cracking or breaking [21]**.**

The proximate and ultimate values have an effect on quality parameters, e.g. the HHV of the biomass pellets [25]. HHV is really a measure of the chemical energy bound in a feedstock; this energy is released during combustion [25]. HHV is considered the single most important property of solid biofuels; it's important for the design and operation of both small- and large-scale boilers to ensure biomass optimization in energy production, as well as for the design of storage facilities [10, 11, 25]. Storage capacity of pellet central heating systems should be sufficient to store 1–1.5 times the annual fuel demand; pellets with a lower HHV will require a greater amount of space to meet this demand [10]. Particle size, along with moisture content, is one of the most significant factors affecting overall pellet quality. Finer particle sizes generally correspond with greater pellet strength and durability as larger particles serve as fissure points [26]. Fine particles readily absorb moisture than large particles, and therefore, undergo a

higher degree of conditioning. Also, large particles are fissure points that cause cracks and fractures in compacts**.** Additives or binders may be added to improve the pellet's mechanical properties, i.e. increase density and strength, improve the pelletizing process (through put) or improve of moisture resistance [27]. Additional reasons for additive addition is to enhance the combustion properties i.e. ash melting point, slagging and corrosion. Choice of binders generally depends on cost and environmental friendliness of the binders. Pelleting and Briquetting are high pressure compaction processes, whichyields construction of solid bridges due to particles mechanical interlocking, their diffusion at high pressure and temperature and change of chemical composition in biomass such as protein, starch, and lignin [28, 29]. During pelleting, the pressure and temperature developed in the die can also help to plasticize protein and starch, and soften the lignin. Thermogravimetric analysis (TGA) is used to determine the composition of materials (proximate analysis) and study thermal pyrolysis of biomass fuels and kinetic parameters determination [30]Potentially,TGA kinetic data offer a mechanistic insight into the thermal break down, and can be extrapolated to be representative of high heating rate situations faced in industry [31]The advantage of TGA analysis is that it gives a rapid estimation of fuel values such as the ignition (T_{IG}), peak (Tm), and burn out temperatures (T_B). Ash related operational problems, like slag and deposit creation in combustion devices and also fine particle emissions, are major concerns in biomass combustion that decreases the overall performance and may prevent an extension of the biomass resource base for heat and power production. The phenomenon of fouling is described in general terms by [32], and specifically for grate boilers by [33, 34]. The mechanisms of slag formation in grate boilers are not covered to the same extent in the literary works, but [35] depict the present understanding. The distribution and change of alkali metal substances within the burner and boiler during biomass burning determines to a huge extent the type of operational problem and degree of severity. Deposit formation on heat transfer surfaces and formation of fine particle emissions is mainly influenced by the release of alkali species. Suppressing the release, i.e. capturing alkali metals in the bottom ash as non-volatile compounds, is thus one way to control fouling and emissions. However, a drawback of capturing alkali metals in the bottom ash during fixed bed combustion is an increased risk of slagging due to the potential formation of sticky ash melts [35, 36]. Controlling both slag and deposit formations during biomass combustion requires a fundamental understanding about ash transformation, especially when the fuel resource base is extended towards new ash rich assortments and biomass mixtures for co-combustion situations.

The objectives of this paper are (1) to investigate the physical properties (moisture content, particle size distribution, bulk density) of corn cob and wheat dust, (2) to investigate the effects of compression on biomass particle structure, (3) to study the effect of pelleting process variables (die size and compressive load) on bulk density, unit density, impact resistance, water resistance and durability of the biomass pellets, (4) to study the effect of pelleting on combustion characteristics and ash analysis of the produced biomass pellets will be investigated.The focus on this particular raw material was due to the high potentials of Egypt.

MATERIAL AND METHODS

Characterization of the raw materials

Corn cob and wheat dust samples were collected from local farms in Al-harkia Governate in Egypt. We choose these local farms, because of fertile soils in the Nile Delta, high concentration of sunlight, slight diseases and pests, warm weather and good irrigation systems. Nile water is the major source of irrigation water in Egypt and there is no efficient rainfall in this area. In Egypt, mineral fertilizers, particularly nitrogen, phosphate and potash are being used to an increasing extent in the cultivation. The types of pesticides that used in the farms are Dicamba, Diflufemican, Glyphosate, Prochloraz and Propiconazole.The corn cob was harvested in October 2014, and the wheat was harvested in May 2014. The materials were sundried for 3 days, stored in plastic bags and kept in a room temperature for two months in the laboratory. The size reduction of the cut pieces has been done in two stages. In the first stage of milling, the samples were grinded in a grain milling machine and converted into small, elongated pieces like a needle shape powder with size about 1 cm. These small, elongated pieces were got in the second stage of the milling to produce fine powders which are used in this work.The second stage of the milling machine has cutting teeth (CT) and grinding screen (GS) with small opening holes as shown in **Fig. 1**. The hammer mill has 3 hammer knives, single phase electric motor of 1.84 kW, 220 V, and 1450 rpm.

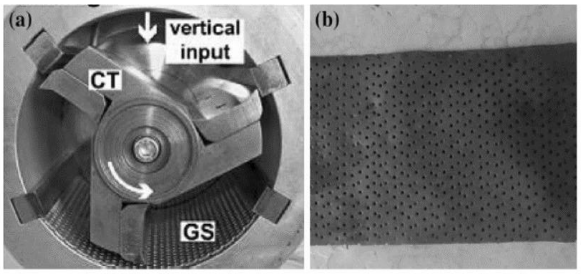


Figure 1. The cutting mill machine used in the second stage of milling, b the GS

Binder

As the fact that biomass havea tendency to resist the compressive force and spring back when it is released, binders may be needed to reduce its springiness and maintain highest bulk density. Epoxy 1092 has been used as a binder in the densification process, that its composition shown in Fig. 2. Part A consists of an epoxy resin Araldite PY 1092-1 (100 part by weight) and Part B is the epoxy curing agent, sometimes called hardener HY 1092 (50 part by weight). It's produced by Huntsman advanced materials, specialty chemicals (Egypt) S.A.E. Viscosity of epoxy (A and B) is 0.4 Pa.s at 25 ^{o}C, density (g/cm^3) at 25 ^{o}C: 1.15 for Part A and 1.0 for Part B, static flexural strength = 60. 33MPa, static flexural modulus = 2.118 GPa, Vol. Shrinkage =4-5% and failure strain = 4.16 % [37]**.** The advantages of epoxy 1092 are: excellent mechanical properties,thermal stabilities, and low cost, excellent chemical resistance [sulfuric resistance 10%, hydrochloric acid 10%, ammonia 10% and caustic soda 30%], very good processing properties, will not crystallize, low viscosity of the system which facilitates it's manual application, allowing for the impregnation of porous surfaces, thereby increasing the cohesion of the superficial layers, low shrinkage and long working life. The quantity of binder selected must provide, the final product its required strength, so that it is able to withstand handling, transportation and storage, and for the safety of those manufacturing the pellet it should be non-toxic. On the other hand, the effect of the binder and the amount present on a pellet combustion, the emissions given off when it burns and the residue left after combustion, also need to be considered carefully.

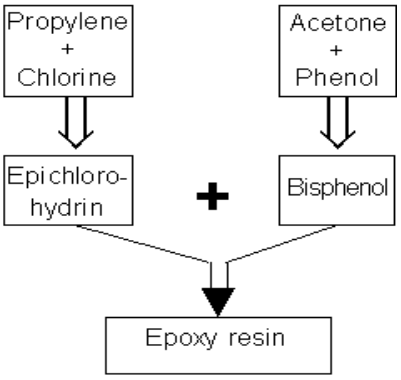


Figure 2. The composition of Epoxy

Fuel characterization

The Ultimate analysis involves the evaluation of important chemical elements that make up the biomass, namely carbon, hydrogen, oxygen, nitrogen and sulfur. The ultimate analyses of the corn cob and wheat dust were performed by using a (CHNOS elemental analyzer, Model Vario EL III) to measure carbon, hydrogen, nitrogen and sulfur contents. Oxygen content was then calculated by difference. This analysis helps to identify the quantity of air required for complete combustion, the volume and composition of combustion gases and heat of combustion of biomass which depends primarily on its carbon and hydrogen content. The proximate analysis is a standardized procedure that attempts to quantify some key physical characteristics of biomass, which have an effect on its combustion characteristics. It does this by considering biomass to be made up of four main components: moisture content, volatile matter, ash and fixed carbon.The moisture content is a measure of the amount of water in the fuel by ASTM D 4442-07 [38]**.** The dried samples were then heated in a muffle furnace in to determine ash contents as stated in ASTM Standard E 1755-01 for biomass. Volatile Matter (VM) and Fixed Carbon (FC) were determined using thermogravimetric (TG) analysis. The higher heating value of the materials was done using (Barr oxygen bomb calorimeter, Model 1341EE Plain Oxygen Bomb Calorimeter).The calorific value is an important value in determining the amount of energy contained in a set volume of biomass.

Thermogravimetric analysis

Thermo gravimetric analysis (TGA), the most useful and quick technique for evaluating combustion characteristics of solid fuel, was carried out on a thermogravimetric analyzer (Shimadzu TGA-50). All experiments were conducted at atmospheric pressure, the temperature range is from 0^{o}C temperature to1000°C and a heating rate of (30) Kmin^{-1}under a nitrogen flow rate of 30 ml/min. Limited by the size of the sample pan, the pellet was broken into small parts using a razor blade manually and a small mass approximately 14.37 mg for corn cobpellets, 3.324mg for crushed corn cob, 13.56mg for wheat dust pellets and 2.153mg for raw wheat dust. The calorific value (or heating value) is the standard measure of the energy content of a fuel.

Particle size analysis

It has been observed that the particle size of biomass feedstock (especially for non-fibrous type biomass) has a large influence on the stability of the final pellet formed.Prior to densification experiments, the geometric mean particle diameter (d_{gw}), and geometric standard deviation of particle diameter (S_{gw}) of ground agricultural straw samples were determined using ASAE Standard S319. Mechanical sieving is the most common, cheap and simple technique used for deducing the particle-size distribution of powdered materials. The standard procedure that followed when sieving a dry sample using the mechanical sieving technique is the American Society for Testing and Materials (ASTM) C 136 [39], the American Association and State Highway and Transportation Officials (AASHTO) T 27 [40] and ASTM D 422—Standard Test Method for Particle-Size Analysis of Soils. A sieving test was performed on a 100 g sample of the aggregate in a laboratory. A typical sieve

analysis involves a nested column of sieves with wire mesh cloth (screen) was utilized. After the shaking was completed the stack was removed from the shaker and carefully weighted, and the mass of each sieve was recorded with its retained powder. In addition, the mass of the bottom pan with its retained fine powder was weighted and recorded. These steps were repeated until the end point criteria were met (the mass of the test sieves didn't change by more than 5 % of the previous mass on that sieve). This was achieved during this work by observing the change in mass in each sieve in the tested three samples. The total losses should not exceed 2 % of the mass of the original tested sample according to the standard which is achieved in the present work. The proper sieving time is the smallest amount of time in which the particle-size distribution does not change significantly. In this work, sieving analysis is repeated three times with a fresh sample and continuing the mechanical agitation for 15, 20 and 25 min. It is noted that the mass retained on a certain sieve is almost the same in the three times, so the proper sieving time has taken the shortest time (i.e. 15 min). Sieving analysis has been done using available sieves (1.8, 1.6, 1.25, 1, 0.85, 0.8, 0.5, 0.3, 0.25, 0.2, 0.15 mm) in the lab. The resulted data form the sieving analysis was used to determine mass retained, mass passed, totals mass and cumulative retained masses and their percentages.

Pellet preparation

In order to form pellets from an agricultural residue, the structure of the material needs to broken down to give a random distribution of unconnected fibers, before it can be reformed into pellets. Corn cob and wheat dust are difficult to breakdown down by fermentation, or take a long time, so these materials need to be agglomerated with the addition of a binder [41]. The residuals have to be in good mixing with 40% binder (Epoxy 1092) in this study and then puts this charge in mold and compressed it by hydraulic pressing unit with different pressures [10, 12, 15 bars]. This single pelleting unit was used by others [11, 42] as shown in Fig. 3**.** This unit included hydraulic pump and a plunger connected to the upper moving crosshead of the hydraulic pressing unit which provided the load necessary to compress the biomass samples. Molds and plungers were manufactured to form the pellets as shown in Figs. 4a and 4b. Cylindrical molds (of different dimensions) 42 mm long and 18, 10 mm in diameter (D1, D2) respectively, and hexagonal die with side length = 6 mm and 42 mm long (D3). Pellets have in general a cylindrical shape and are about 6-25 mm in diameter and 3-50 mm in length Alakangas, E. In: New European pellet standards. The dies were slip fit into a stainless steel base with a hole matching the outer diameter of the die. This steel base supported the whole assembly and allowed the plunger to move straight down with no lateral movement during the compression process. This gave stability and allowed the plunger to move straight down with no lateral movement. The plunger was attached to the upper moving crosshead of the testing machine. After compression of the pellet and attaining the pre-set load, the plunger was stopped and held in position for at least one minute for the relaxation.

Figure 3: Single pelleting unit

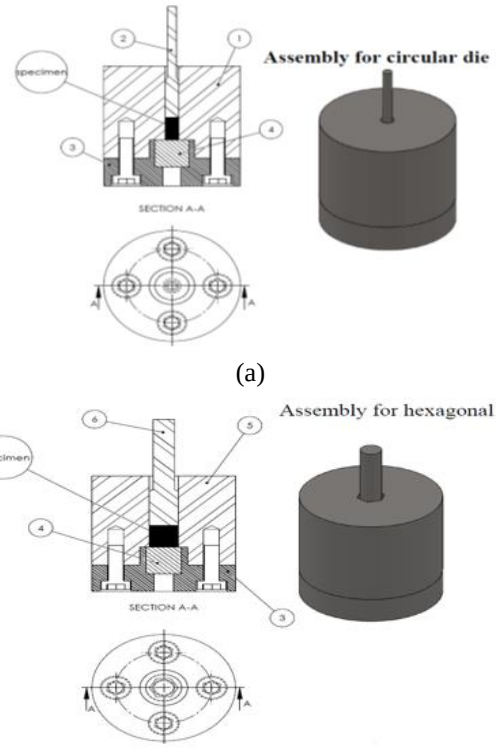


Figure 4. (a) Assembly for circular die, (b) Assembly for a hexagonal die

Size and density of biomass pellets

After ejection the pellets from the die, the mass of the pellet was measured using a digital scale (1kg ±0.01g) and the diameter and length of pellet were determined

using a caliper (±1mm) to calculate the volume. The single pellet density was determined according to UNE-EN 15150 [43] by weighing the individual pellet, calculating its volume based on the length and diameter previously determined. To determine the bulk density, the volume and the weight of the pellet samples were measured according to UNE-EN 15103 [44], using a laboratory balance and graduated cylinder.

Mechanical testing

Crushing resistance (hardness) is the maximum load a pellet can withstand before cracking or breaking. The crushing resistance test provides a quick measure of the quality of pellets as soon as the pellets are producedand aids in adjusting the pelleting process to improve the pellet quality [45, 46]. Crushing resistance of the densified products is determined by diametrical compression test. To determine the relationship between the pressing force and deformation, the compressive device [Avery – dennison - England with capacity 1000kN, 1hp, 440V, 3 phase, AC supply, manual control and maximum speed 20mm/min] as shown in **Fig. 5** was used. The samples were compressed radially between two parallel horizontal plates which moved together and have facial areas greater than the projected area of the pellet. At a fixed rate, the load applied is being increased till the test specimen fails either by cracking or breaking. The experiment was repeated three times for each pellet at different pressures and at different shapes and take the mean value in each case to determine the maximum compressive force and the maximum deformation at maximum load then, calculate maximum compressive stress and maximum strain. The compression strength was defined as the ratio between the maximum force during deformation and the test specimen surface area.

Figure 5. Compression testing machine

Impact (drop) resistance test is applied to simulate the forces encountered during evacuation of densified products from trucks uponthe ground, or from chutes into bins. Different researchers have used the term "durability" to determine the impact resistance [23]. Drop tests can be used to define the secure height of pellets production [47]. The ASTM method D440-86 of drop shatter tests developed for coal is used [47] to estimate the impact resistance of biomass logs. The biomass logs were dropped twice from 1.83 m upon a concrete ground. The weight retained as the percentage of the initial weight was taken as the pellet/briquette durability. Each drop test was replicated ten times.

Water gain represents short-term exposure to rain or high humidity conditions during transportation and storage could adversely affect the quality of the densified products. It is a measure of percentage water absorbed by a pellet when immersed in water. Each pellet was immersed in 150 mm of water column at 27°C for 30 s. The percent water gain was calculated and recorded by using following relation [48].

$$\text{Water gain by pellets}\% = \frac{(W_2 - W_1)}{W_1} \times 100 \quad (1)$$

Where, W_1= Initial weight of the pellet, g, W_2= Weight of wet the pellet, g

All property analyses were run in triplicate, taking the average values. Results were compared with the standard values establishedfor straw pellets indicated in the non-woody pellet norm [49] to determine any possible restrictions on the use of the corn cob and wheat dust pellets. Table 1 summarizes the parameters and guidelines established in thenormal.

TABLE 1: Parameters and guidelines published in UNE-EN IS0 17225–6 [50], including specifications for non-woody pellets

Parameter	Guidline
Diametere (mm)	Die diameter$\pm$1.00
Length (mm)	3.15$\leq$ $lenght$ $\leq$ 45.00
Moisture content%	$\leq$ 10.00
Durability (%)	$\geq$ 97.50
Bulk density (kg/m^3)	$\geq$ 6000
Additive (%)	Declare type and quantity
Heating value (kg/gm)	17.5-19.5

Statistical analysis

In order to evaluate the test results, the effect of different compacting pressures and die sizes on the bulk density, compressive force and displacement of biomass pellets was determined using the analysis of variance (ANOVA) and significant differences of means were comparedduring the Duncan's multiple range test at 5% significance level with the SPSS software 20.0 (IBM Corp., Armonk, New York, NY). For quality assurance of measurement results, evaluation of measurement performance is especially important, because the measurement results depend on the measurement method. There is an international standard, ISO 5725-2, basic method for determination of repeatability,which leads to an estimate of the minimum value of precision, reproducibility which leads to an estimate of the maximum value of precision, reliability,which leads to an estimate the proportion of variability ascribed to random error and the total measurement system variation of a standard measurement method.

Scanning electron microscopy

SEM observations of the surface were carried out on samples and pellets. Using SEM Model Quanta 250 FEG (Field Emission Gun) attached with EDX Unit (Energy Dispersive X-ray Analyses), with accelerating voltage 30 K.V., magnification14x up to 1000000 and resolutions for Gun.1n). FEI Company, Netherlands.

RESULTS AND DISCUSSION

Particle size distribution

It's been noticed that the particle size of biomass feedstock has significant influence on the stability of the final pellet produced. The geometric mean particle diameter and geometric standard deviation of particle diameter for corn cob are 0.577 and 0.335mm, respectively, 0.467 and 0.277mm for wheat dust. The perfect particle size range between 0.5 to 0.7 mm is suggested as stated in literature [47]**,** the particle sizes of greater than 1mm will act as predetermined breaking points in the pellet and this matched with our results. With regard to pelletizing, it is usually assumed that small particles which have a large surface area raise density and lead to tougher pellets. On the other hand, larger particles tend to be fissure points which lead to cracks and also fracture in pellets and reduce the pellet durability. Histograms of the corn cob and wheat dustare constructed as shown in Figs. 6a and 6b. The columns of the histogram have a width proportional to the size range of grains for each test sample. The column height will be proportional to the percent retained on the respective screen and the tallest column indicates the mode of the grain size distribution. Fig. 6 shows that the cumulative retained oversize curve is concave and the cumulative retained undersize is convex because the mass retained over the intermediate (i.e. sieves 0.8, 0.6 mm) are nearly low that makes the cumulative retained over size low in this range of sizes, and the cumulative retained undersize high. Furthermore, Fig. 6 shows that the slope of the cumulative retained oversize curve increase starting from the 0.8mm sieve until the pan because the mass retained within this range is high as compared to that retained on the 1.8 to 0.8mm sieves. For the same hammer mill screen size, the geometric mean particle diameter of the corn cob sample was slightly higher than that of wheat dust samples. This might be due to the variation in moisture content, difference in mechanical, chemical properties of biomass samples and type of particles as it was observed that the wheat particles were longer than the corn cob particles. The corn cob particles were almost spherical, while the wheat dust particles were like needles or flakes [4]. A particle size distribution was followed in order to fulfill strength and durability standards for high quality pellet manufacturing [27].

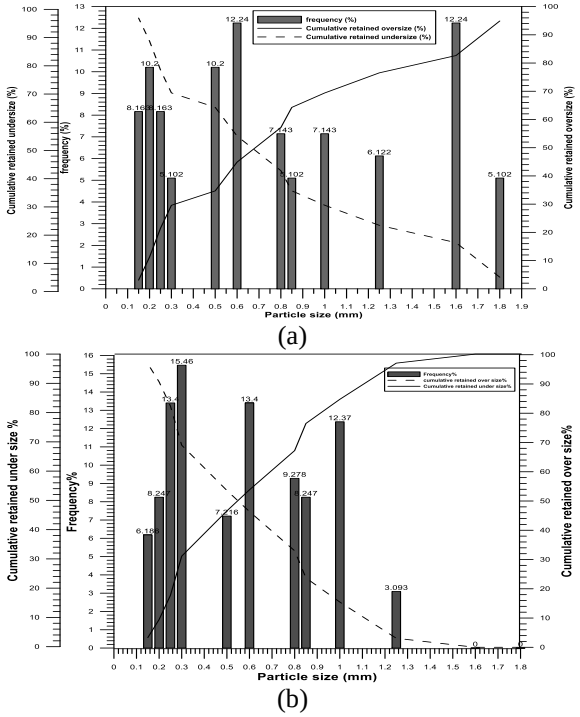


Figure 6. (a) Histogram, % cumulative retained oversize, under size and frequency versus grain size of the corn cob, (b) Histogram, % cumulative retained oversize, under size and frequency versus grain size of wheat dust powder

Proximate and ultimate properties

The proximate and ultimate analyses of corn cob, wheat dust and its corresponding pellets are presented in Table 2. These analyses assist firstly, to evaluate the fuel characteristics of raw materials. Moreover, due to pelletization the fuel quality was more enhanced than raw biomass because of reduced moisture content, elevated fixed carbon content, decreased ash content and increased HHV. As shown in Table 2 the raw biomass aswell as its pellets and binder contain high amount of volatile matter, which has a positive effect on the sustainability of combustion. This shows that the residues are easier to ignite and burn, although the combustion is expected to be rapid and difficult to control. The results show that the volatile matter of corn cob increased from 66% for raw material to 67% for pellet due to pelletization process only,and the amount of volatile matter in Epoxy 1092 that reached to 87.612 % has no effect. However, the volatile matter of wheat dust increased from 69.2% of raw material to 76.2% for pellet due to pelletization and addition of binder. These results were similar to those obtained in other studies [50, 51]. The fixed carbon content is the portion of carbon available for the char combustion after all the volatile matter has been expelled. Fixed carbon acts as the main energy generator during combustion [52]. For an example, it was found that the fixed carbon ratio in raw materials for corn cob and wheat dust were 18 and 8.3%,

respectively, which were increased to 29% for corn cob and 15.8% for wheat dust after pelleting due to densification process only because epoxy 1092 contains a low amount of fixed carbon that reached to 8.3%. As a result of the increased fixed carbon ratios, the HHVs also increased from 16.6 (kJ/g) for crushed corn cob to 24.92 (kJ/g) for corn cob pellet and from 14.61(kJ/g) for wheat dust to 25.35 (kJ/g) for wheat dust pellet, this due to the densification method and addingcombustible binder that have HHV reach to 34 (kJ/g). Moisture affects inversely on the heating value, where high moisture content lowers the heat liberated during combustion [53]. It has been demonstrated that over certain moisture content it's not possible to create a coherent pellet due to the high relaxation of the material on elimination from the die [54]. In addition, a notable decrease of the ash content was also observed by pelletization, which is possibly associated with the increased combustion temperature of the pellets compared to that of powder fuel [55, 56]For example, the ash content decreased from 21.1% for crushed corn cob to 3.1% for corn cob pellet and from 14.7 for wheat dust to 4.1% for wheat dust pellet as the low amount of ash for the binder that reach to 4.28%.

The decreased ash contents and decreased moisture contents implied that higher thermal efficiency could be achieved during the combustion of the biomass pellets [57, 58]. The ultimate analysis shows the elemental chemical constituents of biomass such as carbon, hydrogen, oxygen, nitrogen and sulfur. This evaluation assists to determine the quantity of air necessary for full combustion, the volume and composition of combustion gases and heat of combustion of biomass which is dependent mainly on its carbon and hydrogen content. Carbon, hydrogen and oxygen are the majorelements in biomass. Through the analysis of biomass carbon increased from 44.43 and 39.21% for crushed corn cob and wheat dust respectively to 71.67 and 65.5%, this mainly because of adding combustible binder that has carbon ratio 70.56% and due to densification process and oxygen emits during the thermal decomposition and covers a part of overall oxygen required for the reaction to take place as oxygen decrease for crushed corn cob and wheat dust powder from 47.67 and 52.83 to 24.95 and 27.1%, respectively by pelletization [57, 58]. Nitrogen and sulfur mainly contribute to the formation of harmful emissions. During combustion nitrogen is almost entirely converted to gaseous N_2 and oxides of nitrogen (NOx). Through the analysis of biomass nitrogen increased from 0.51 and 1.11% for crushed corn cob and wheat dust respectively to 0.7 and 1.77% by pelletization**.** [56] Give a value of 0.6% N above which emission related problems could occur. Through the analysis of biomass sulfur increased from 0.15 and 0.41% for crushed corn cob and wheat dust respectively to 0.41 and 0.59% by pelletization**.** The remaining S is emitted in gaseous form as SO_2. A value of 0.2% by weight was stated in literature [61] above which sulfur can have a very damaging effect.

Characterization of the pellets

Unit and bulk density are an essential parameters as a result of being associated with the space essential forsafekeeping and transport in addition to the derived cost of transport. EN 14961 -2 [22] established a minimum for nonindustrial pellets of 600 kg/m^3. Evidently, the mass density was even more increased significantly for both raw biomass and by pelletization (8 to 10 times for all the pellets);an identical observation was described in literature [58]. Table 3 shows that the most dense pellet, was prepared from the D2of the corn cob at pressure 15 bar whereas the pellet was prepared from the D3 of wheat dust at pressure 10 bar was the most loose products. As the pressure increased from 10 bar to 15 bar, the density of D2 corn cob pellet increased from 2372.49 to 3001.048 kg/m^3. This might be explained that corn cob at D2 required lower compression energy to fill the inter-particle spaces during the compression process. In addition, the increase of pellet density will increase the bulk density and the volumetric energy density, which make easier handling, transportation and storage.The maximum bulk density occurs at [D3 - pressure 15 bars] for corn cob and wheat dust pellets.As the density of the pellets which constructed from all samples significantly elevated with a rise in the applied pressure at any kind of die size due to thedecrease of the number of empty spaces between particles.

TABLE 2. The Proximate and ultimate analysis of corn cob and wheat dust before and after pelleting

Characteristics of energy crops (% wet basis)	Binder [epoxy 1092]	Corn cob before pelleting	Corncob after pelleting	Wheat dust before pelleting	Wheat dust after pelleting
Proximate analysis[TGA analysis]					
Moisture	0.0	3.9	2.9	7.8	3.9
Ash	4.274	12.1	3.1	14.7	4.1
Volatile matter	87.612	66	67	69.2	76.2
Fixed carbon	4.284	18	29	8.3	15.8
Ultimate analysis					
carbonHydrogen	70.56	44.43	71.67	39.21	65.5
Oxygen	7.8	7.24	2.42	6.44	5.04
Nitrogen	17.178	47.67	24.95	52.83	27.1
Sulfur	4.18	0.51	0.7	1.11	1.77
Heating value(kJ/gm)	34	16.6023	24.9177	14.61035	0.59

Figs. 7a-7f demonstrate the curves of compressive force against the compressive distance of raw biomass pellets. The maximum compressive forces, compressive strengths and the stain at maximum load for all the pellets are presented in Table 4. It is found that, the compression

force increases gradually until the rupture point was identified, then the pressing was stopped and the first rupture peak is taken as a breaking load. As shown in the Table 4, the maximum force occurs at [D1- pressure 15 bars] (13.382kN) for corn cob and (9.5kN) for wheat dust. Weak mechanical hardness of pellets will lead to high breakage levels during handling, transportation, and storage. It would also reduce the efficiency of a pellet stove or burner, to some extent. The improved mechanical strength and reduced compression energy use of the corn cob pellets is attractive for the end-users. The maximum displacement for deformation occurs at

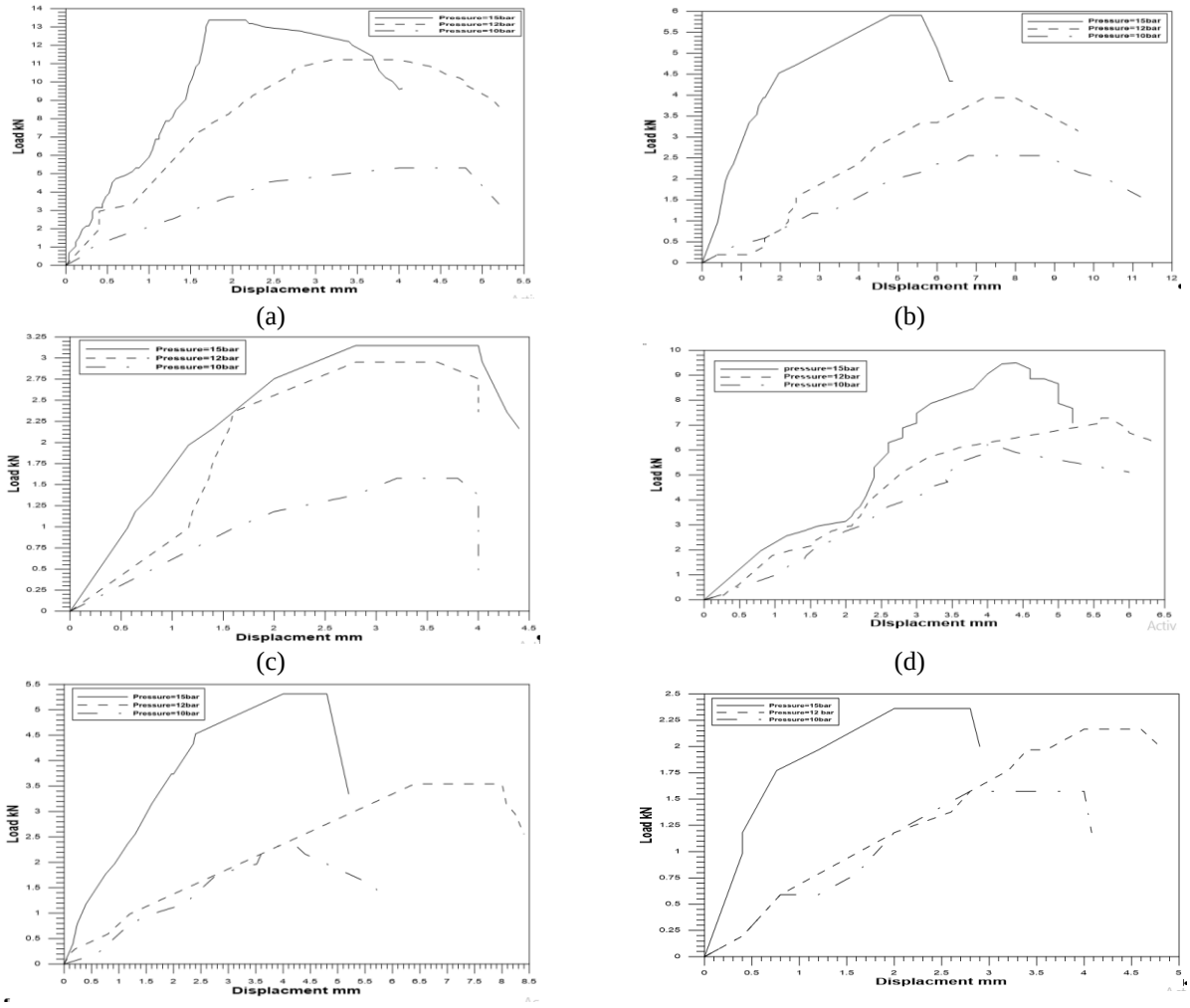


Figure 7. (a) Load – displacement for corn cob D1, (b) Load – displacement for corn cob D2, (c) Load – displacement for corn cob D3, (d) Load – displacement for wheat dust D1, (e) Load – displacement for wheat dust D2, (f) Load – displacement for wheat dust D3

pressure 10 bars for D2 (8.8 mm) for corn cob and at pressure 12 bar for D2 (8.04 mm) for wheat dust. The minimum displacement occurs at pressure 15 bars for D3 (2.12mm) for corn cob and occurs at pressure10bars for D1, D3 and at pressure 15 bars for D3 (4mm) for wheat dust. Water impermeability is a value of showing the capability of solid pellets to absorb the moisture or water penetration during handling, transportation or storage. Pellets with satisfied quality should have low water impermeability in order to be stored for a long period without water absorption.

The level of compaction pressure has effected on water impermeability of biomass pellets as seen in **Table 4**. With increasing the pressure level from 12 to 15 MPa, water impermeability of pellet decreased to the minimum value and then slightly increased at the higher pressure. Wheat dust pellet has a larger value of water impermeability than corn cob when the pressure level is all the same. This might be caused by the strongest water absorbing power of wheat dust. The lowest water permeability of 2.2134% was found in D3 corn cob pellet prepared 15bars.

From **Table 5** the ANOVA results show that the compacting pressures (P), die sizes (D) and the interaction of the two factors (P×D)significantly affects the bulk density of corn cob and wheat dust.According to the statistical results the compacting pressure was found to affect the bulk density of corn cob and wheat dust the most (F-value =206.373, 299.77 respectively, while the F-value of die size =91.146, 191.898 of the bulk density of corn cob and wheat dust respectively). At high pressure, elastic and plastic deformations occur which lead to the particles in order to flow into void spaces and increase the contact area between particles. At low pressure, the particles rearrange and maintain their original physical properties. Raising the compressive force leads to a plastic deformation of ground materials and consequently creates pellets with higher densities.

TABLE 3. The unit density and bulk density of corn cop and wheat dust pellets

Biomass pellets	Mass (gm)	Unit density (kg/m^3)	Bulk density (kg/m^3)
Corn cop pressure=10bar			
Cylindrical pellet (D=18mm)	13.8260	1293.636	856.54
Cylindrical pellet (D=10mm)	7.8261	2372.49	834.56
Hexagonal pellet(s=6mm)	3.9703	1010.69	995.36
Corn cop pressure =12 bar			
Cylindrical pellet (D=18mm)	14.2032	1328.93	1020.37
Cylindrical pellet (D=10mm)	8.6217	2613.68	956.25
Hexagonal pellet (s=6mm)	4.9139	1250.9	1059.38
Corn cop pressure =15 bar			
Cylindrical pellet (D=18mm)	16.0855	1505.049	1125.25
Cylindrical pellet (D=10mm)	9.8995	3001.048	1052.59
Hexagonal pellet (s=6mm)	5.7989	1476.189	1263.21
Wheat dust pressure=10bar			
Cylindrical pellet (D=18mm)	13.0342	1219.55	855.63
Cylindrical pellet (D=10mm)	7.6385	2315.623	790.93
Hexagonal pellet(s=6mm)	3.9700	1010.61	989.37
Wheat dust pressure =12 bar			
Cylindrical pellet (D=18mm)	13.865	1297.28	935.38
Cylindrical pellet (D=10mm)	8.563	2595.886	890.43
Hexagonal pellet (s=6mm)	4.9093	1249.7	1013.97
Wheat dust pressure =15 bar			
Cylindrical pellet (D=18mm)	15.886	1486.38	1110.63
Cylindrical pellet (D=10mm)	9.4533	2865.78	980.30
Hexagonal pellet (s=6mm)	5.6383	1435.304	1180.36

TABLE 4. Mechanical properties of corn cob and wheat dust pellets

Properties	Pressure=10bar			Pressure=12bar			Pressure=15bar		
	D1	D2	D3	D1	D2	D3	D1	D2	D3
Corn cob									
Max. Force (kN)	5.3136	2.5584	1.574	11.2176	3.936	2.952	13.382	5.904	3.1488
Displacement at max. Force(mm)	4.8	8.8	3.8	4.0	8.0	3.6	2.12	5.6	4.0
Compressive stress (MPa)	20.881	32.574	16.828	44.0823	50.115	31.562	52.589	75.1718	33.666
Strain at max. Force %	11.428	20.95	4.9182	9.52	19.047	8.5714	5.074	13.33	9.5238
Water gain%	2.6010	5.0	7.597	2.4135	3.938	4.01	2.2134	3.625	3.895
Impact Resistance %	98.89	98.80	97.45	99.12	99.05	98.56	99.21	99.34	99.02
Wheat dust									
Max. Force (kN)	6.2976	2.3616	1.5741	7.26	3.5424	2.1648	9,5	5.3136	1.5741
Displacement at max. Force(mm)	4.0	4.2	4.0	5.6	8.0	4.6	4.6	4.8	4
Compressive stress (MPa)	24.755	30.063	25.247	28.5377	45.103	23.143	37.34	67.65	16.83
Strain at max. Force %	9.524	10	6.67	13.333	19.143	10.952	10.714	11.4285	9.524
Water gain%	3.0823	6.8806	9.435	2.8354	6.0183	7.984	2.436	4.358	4.325
Impact Resistance%	98.77	98.535	97.033	99.412	99.033	98.184	99.01	98.903	95.56

Table 5 shows also that the compacting pressures (P), die sizes (D) and the interaction of the two factors (P×D)significantly affect the maximum force of corn cob and wheat dust. According to the statistical results the die size was found to affect the maximum force of corn cob and wheat dust the most (F-value =210.096, 418.869 respectively, while the F-value of compacting pressure=68.902, 103.243 of the maximum force of corn cob and wheat dust respectively). From T**able 5** the ANOVA results show that the compacting pressures (P), die sizes (D) and the interaction of the two factors (P×D) significantly affect the maximum displacement at maximum force of corn cob and wheat dust except the interaction of the two factors (P×D) did not significantly affect the maximum displacement at maximum force of wheat dust. According to the statistical results the die size was found to affect the maximum displacement of the maximum force of corn cob the most (F-value =133.862, while the F-value of compacting pressure=33.427) but the compacting pressure was found to affect the maximum displacement at the maximum force of wheat dust the most (F-value 14.728 while the F-value of die size = 7.2472). It is really found in all samples, as the compaction pressure increases the maximum force that the samples can with stand increases and the displacement at the maximum force decreases. Mainly because as the compaction pressure increases void spaces between particles decreases. These spaces can reduce the pellet resistance to the deformation and promote the relative movement of the particles inside the pellet matrix, ultimately causing weak mechanical durability. Table 6 shows the repeatability, the reproducibility, the reliability and the total measurement system variation of a standard measurement method for the bulk density and the maximum force of wheat dust is lower than the bulk density and the maximum force of the corn cob.

Scanning electron microscopy (SEM)

In the present study SEM illustrated the layout structure of corn cob and wheat dust particles before pelleting and after pelleting. Images were taken at the same magnification of the corn cob and wheat dust as shown in Figs. 8 and 9. From the scanned images shown in Fig. 8**,** the corn cob exhibit as almost spherical shape, but wheat

TABLE 5. ANOVA results: Dependent variables bulk density kg/m3, Max. Force (kN) and displacement at max. Force (mm) for the corn cob and wheat dust pellets

Dependent variable	Source of variation	Sum of squares	Degree of freedom	Mean square	F_static	P value
a) The bulk density of corn cob	Pressure (P)	275679.9	2	137839.95	206.373	0.00
	Diesize (D)	121755.9	2	60877.95	91.146	0.00
	P×D	14285.96	4	3571.49	5.3472	0.0051428
	Error	12022.49	18	667.916		
	Total	423744.3	26	16297.819		
b) The bulk density of wheat dust	Pressure (P)	210472.2	2	105236.1	299.77	0.00
	Diesize (D)	136552.6	2	68276.3	191.8989	0.00
	P×D	10224.082	4	2556.0205	7.1840	0.001218
	Error	6404.276	18	355.793		
	Total	363653.2	26	13986.6615		
c)the max. force of corn cob	Pressure(P)		2	43.739	68.902 210.096	0.00
	Diesize (D)	87.47 270.52	2	135.26		0.00
	P×D	41.2 11.58926	4	10.30675	64.103	0.00
	Error	410.85726	18	0.6438		
	Total		26			
d)the max. force of wheat dust	Pressure(P)	73.7628	2	36.8814	103.243	0.00
	Diesize (D)	299.2644	2	149.6322	418.869	0.00
	P×D	27.49356	4	6.87339	6.87339	0.0015301
	Error	6.430123	18	0.357229		
	Total	406.9504	26			
e) Maximum displacement at maximum force for corn cob	Pressure (P)		2	8.42635	33.427	0.00
	Diesize (D)	16.8527 67.488	2	33.74	133.8622	0.00
	P×D	28.2368 4.5376	4	7.0592	28.0038	1.63742E-07
	Error	117.1147	18	0.25208		
	Total		26			
f) Maximum displacement at maximum force for wheat dust	Pressure (P)	20.16	2	10.08	14.728	0.000162492
	Diesize (D)	9.92	2	4.96	7.2472	0.004911067
	P×D	9.52	4	2.38	3.47749	0.09011865
	Error	12.32	18	0.6844		
	Total	51.92	26			

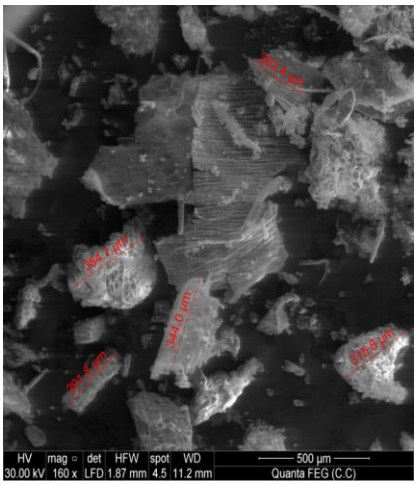
TABLE 6. The repeatability, reproducibility, reliability and the total measurement system variation results: the dependent variables as; bulk density kg/m3, Max. Force (kN) and displacement at max. Force (mm) for the corn cob and wheat dust pellets

Dependent variables	Repeatability	Reproducibility	Reliability	The total measurement system variation
a) The bulk density of corn cob	133.097	629.0322	0.0447	779.707
b) The bulk density of wheat dust	97.1417	550.084	0.03118	724.6755
c) Maximum force of corn cob	4.1322	9.9258	0.173313	23.84
d) Maximum force of wheat dust	3.07808	9.4	0.107226	8.0322
e) Maximum displacement at maximum force for corn cob	2.585	2	1.670556	12.22
f) Maximum displacement at maximum force for wheat dust	4.2605	5.041	0.714311	7.49422

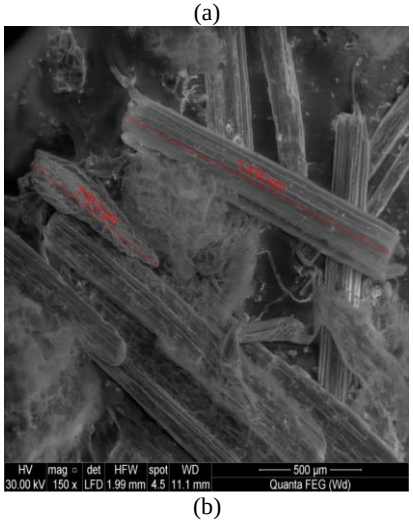
dust particles exhibit as elongated shape due to the natural construction of corn cob and wheat with length around 0.325 mm for corn cob and 1.066 mm for wheat dust. The length of the particles differs from the geometric mean diameter value calculated from sieving because the scanned images which scanned a microscope using a very small sample that cannot really represent the whole sample. From the scanned images Fig. 8, it's noticed that there is a mixture of different particle size, which give the optimum durability of pellet as they have a better inter-particle bonding with less interspaces. Since microscopy is only capable of capturing small portions of the distribution of particles and bonds between particles, additional figures chosen to represent the range of observed shape and surface characteristics of corn cob and wheat dust pellets. The formation of solid bridge, attraction forces between solid particles and mechanical interlocking bonds are important binding mechanisms in biomass densification [7, 49] as shown in Fig. 9. The larger number of solid bridges between corn cob and wheat dust particles created may have improved the binding of particles, and thus, the higher compressive strength. Due to the applied pressure, solid bridges may be progrssing by molecules diffusion from one particle to another at the contact points. Further, during the compression process flat-shaped particles and particles of binder may interlock each other, resulting in interlocking bonds that can be observed in Fig. 9. SEM was used to understand the state of lignin in the biomass pellets. Lignin in its natural form appears as droplets or agglomerated small spheres on the surface shown in Figs. 9[29, 30]. In addition, more bonds between corn cob and wheat dust particles are formed with increasing in lignin content, resulting in the production of more durable pellets. Generally, the more irregular in shape and more angular a particle, the greater the mechanical interlocking effect.

Combustion characteristics

TG/DTG profiles describe the combustion process of binder material and biomass materials before and after pelleting were presented in Figs. 10a to 10c. Four stages can be distinguished, as shown in Fig. 10: (I) A drying stage under 200ºC, where moisture evaporated from the fuel samples in most thermogravimetric analyses, the authors often neglect this stage because of the very low moisture content of the samples and this stage will not therefore be discussed here. (II) Devolatization stage, where volatiles were released, the thermal decompositions of cellulose and hemicelluloses occurred and the rate of devolatilization reached its peak. (III) Combustion stage, where loss of heavier hydrocarbons and lignin occurred and the rate of reaction decreased with increasing temperature where there is combustion of volatiles in the gas phase during



(a)

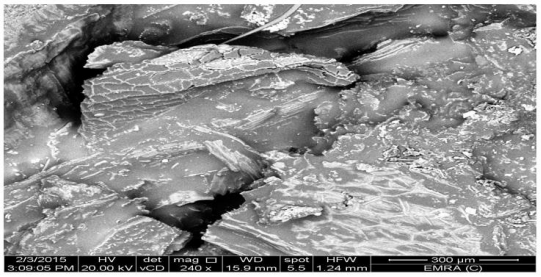


(b)

Figure 8. Scanned image of crushed corn cob, (b) Scanned image of wheat dust

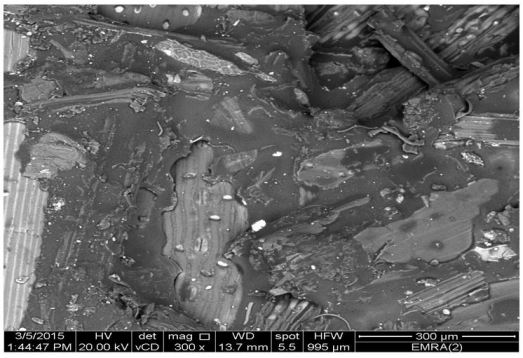
this stage. Due to the exothermic quality of this process, the additional heat permits the emission of remaining.

(IV) Residual combustion stage, where the combustion process is nearly ended. These four stages were identified in several previous studies for other materials [59-61].



(a)

(b)



(c)

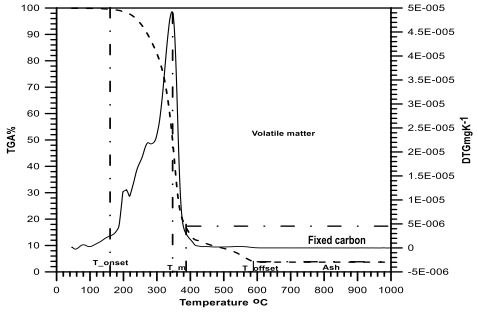
(d)

Figure 9. Scanning electron microscopic image of the outer surface of corn cob pellets, (b) Micrograph image of the outer surface of corn cob pellets, (c) Scanning electron image of the outer surface of wheat dust pellets, (d) Micrograph image of the outer surface of wheat dust pellets

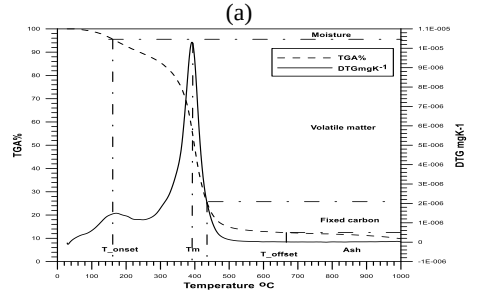
The most important combustion characteristic parameters as (T_ onset), peak(T_m) and (T_offset) are given in Table 7. Onset temperature show how easily a special fuel ignited and it is defined as the temperature at which a sudden decrease in weight loss on the DTG curves is occurred. Table 7 shows that (T_ onset) before pelleting is higher than (T_ onset) after pelleting and (T_ onset) for corn cob after pelleting is lower than the (T_ onset) for wheat dust after pelleting. Peak temperature is the temperature that corresponds to the maximum rate of weight loss $(dm/dt)_{max}$ due to volatilization accompanied by the formation of carbonaceous residue. Table 7 shows that the peak(T_m) before pelleting is higher than peak(T_m) after pelleting and peak(T_m) for corn cob after pelleting is lower than the peak(T_m) for wheat dust after pelleting. Peak temperature and its corresponding rate are a measure of combustibility and reactivity respectively as low peak temperature that means the fuel is easier to ignite. Offset temperature was defined as the temperature at which the weight of the sample remains unchanged. It can beobserved in Table 7 that (T_offset) before pelleting is lower than (T_offset) after pelleting and (T_offset) for corn cob after pelleting is lower than (T_offset) for wheat dust after pelleting. From TG curves, it was clearly seen that corn cob and wheat dust pellets had decreased residues after combustion than corresponding raw biomass pellets. The combustion of corn cob and wheat dust pellets shifted to higher temperature ranges and the final combustion temperatures sharply increased compared to their corresponding raw biomass. The increased final temperatures and the decreased maximum weight loss rates indicate that the biomass pellets combusted in a more moderate way than raw biomass. The continuous and elevated combustion temperature ranges coupled with significantly increased final temperatures proposed that the thermal efficiency can be higher for biomass pellets combustion [6]. Also, lower combustion temperatures of biomass materials are associated with high pollutant emissions. Therefore, with the high combustion temperature ranges, reduced pollutant emissions are also expected by using biomass pellets.

Fouling and slagging inclinations of fuel pellets

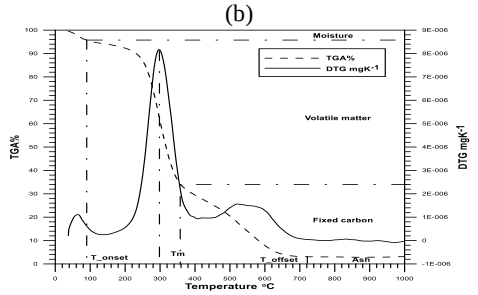
Scanning electron micrographs of residual ash from single pellet combustion of corn cob and wheat dust atfurnace temperature400 °C and air velocity 0.21 m/s have been done. Biomass feedstocks generally consist of high contentsof alkali and alkaline earth metals (AAEMs), which cannot beremoved by pelletization. Consequently, ash-related complications including slagging and fouling, which are often happen on during combustion of powdered biomass, are still present during



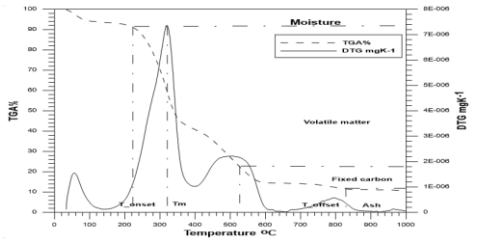
(a)



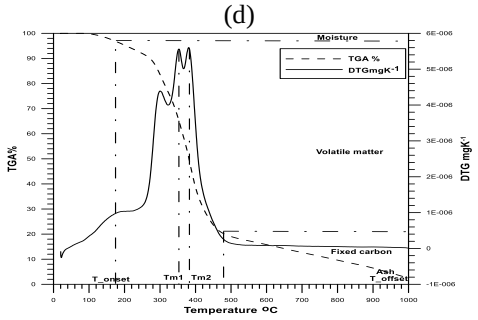
(b)



(c)



(d)



(e)

Figure 10. (a) TGA% and DTG mg K-1 for epoxy 1092 at 30K/min, (b) TGA% and DTG mg K-1 for crushed corn cob before pelleting at 30K/min, (c) TGA% and DTG mg K-1 for , crushed corn cob and after pelleting at 30K/min, (d) TGA% and DTG mgK-1 for wheat dust before pelleting at 30 K/min, (e) TGA% and DTG mgK-1 for wheat dust after pelleting at 30 K/min

TABLE 7. Combustion characteristics of the corn cob and wheat dust before pelleting and after pelleting

Parameter	Binder [epoxy 1092]	Corn cob before pelleting	Corn cob after pelleting	Wheat dust before pelleting	Wheat dust after pelleting
T_onset°C	160	160	80	220	180
T_peak°C	340	398	300	320	380
T_offset °C	580	660	720	820	1000

biomass pellets combustion because they represent simple physical mixtures of biomass [62, 63]. Some alkali metal aerosols condense on the surface of the fly ash and either form a sticky layer or form low-melting substances by reaction with SiO_2 and Fe_2O_3 contained in the fly ash. In this study, the fouling and slagging tendency of corn cob and wheat dust pellets were investigated using the modified method suggested by Pronobis [64]. The corresponding indices were calculated using the following equations:

$$\text{Fouling index (FI)} = (B/A) \times (Na_2O+K_2O) \quad (2)$$

$$\text{Slagging index (SI)} = (B/A) \times S\% \quad (3)$$

where $B/A = (Fe_2O_3 + CaO + MgO + Na_2O + K_2O) / (SiO_2 + Al_2O_3 + TiO_2)$; S is the percent of the sulfur in the dry fuel sample.

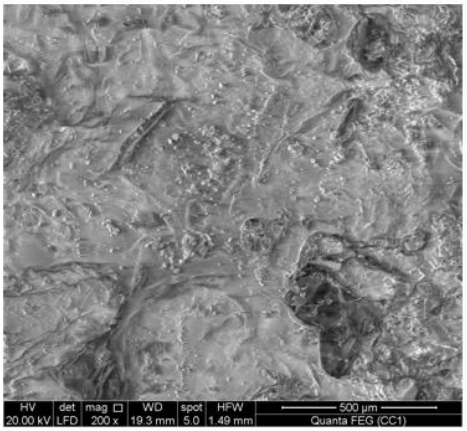
As shown in Table 8, the SI value for wheat dust pellets (0.72) indicates that this material has a medium slagging tendency andthe SI values of the corn cob pellets (0.28) are well below the sill of 0.60 for low slagging. From Table 8, it can be seen that very little difference in chemical composition is observed between the ash from corn cob pellets and wheat dust pellets. Therefore, the significant decrease in SI values of biomass pellets is mainly ascribed to the lower sulfur content in corn cob

TABLE 8. Chemical composition of ash from corn cob and wheat dust pellets

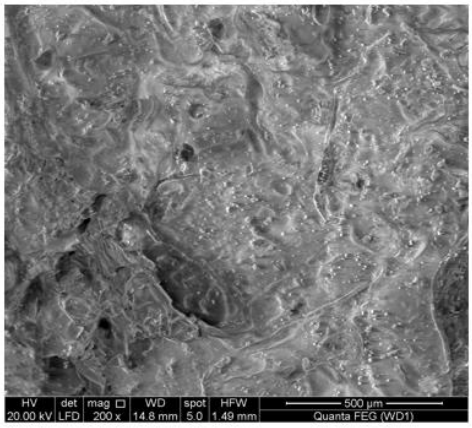
Biomass species	Corn cob	Wheat dust
Na_2O	0.17	0.75
MgO	10.21	10.37
Al_2O_3	11.2	11.48
SiO_2	8.49	10.08
SO_3	1.9	1.65
Cl_2O	0.13	0.29
K_2O	0.79	1.39
CaO	10.74	11.13
TiO_2	0.14	1.18
Fe_2O_3	1.16	2.26
Zno	0	0.86
SI	0.28	0.72
FI	1.72	1.88
BAI	1.208	1.056

compared to that of wheat dust. For the fouling tendency FI, corn cob and wheat dust have a relatively high fouling tendency level. Several other

agglomeration indexes exist; for example, BAI that is equal to the ratio of Fe_2O_3 to (K_2O + Na_2O). Bed agglomeration occurs when the BAI value is lower than 0.15 [65]. Though, the solution to agglomeration requires further study, especially to investigate the most effective combinations of fuel and bed material as well as practical and available agglomeration indicators. The ash residues were analyzed for morphology by scanning electron microscopy as shown in Figs. 11a and 11b.



(a)



(b)

Figure 11. Scanning electron micrographs of residual ash from single pellet combustion of corn cob and wheat dust respectively

CONCLUSION

This study focuses on pelletization of crushed corn cob and wheat dust with 40% Epoxy binder and the following conclusions are derived as follows:

- The most dense pellet was prepared from the D2 of the corn cob at pressure 15 bars whereas pellets prepared from the D3 of wheat dust at pressure 10 bars was the most loose products.
- It was found that at pressure 15 bars, hexagonal pellet produced highest bulk density and the ANOVA results show that the compacting pressures (P), die sizes (D) and the interaction of the two factors (P×D)significantly affect the bulk density of corn cob and wheat dust.
- More importantly, by pelletization the fuel quality was further enhanced for raw biomass as: decreased moisture content, increased fixed carbon content, reduced ash content and elevated HHV. It was found that the fixed carbon ratio in raw material for corn cob and wheat dust is 18 and 8.3%, respectively, which were increased to 29 and 15.8% for pellet and so the HHV also increased from 16.6 (MJ/kg) to 24.92 (MJ/kg) for corn cob and from 14.61 (MJ/kg) to 25.35 (MJ/kg) for wheat dust. In terms of chemical composition, it was found that carbon increased and oxygen decrease due to pelletilization.
- The increased mechanical durability and significantly improved combustion characteristics suggested that corn cob and wheat dust pellets are more suitable as solid fuels in comparison with raw biomass. Therefore, the pelletization process provides an alternative way for biofuel production from biomass feedstocks in the form of easily friable pellets, especially for abundant agricultural residues.
- The compressive resistance, water resistance and the impact resistance of the pellets were, in general, higher for pellets produced at higher pressure.
- The corn cob and wheat dust pellets had improved combustion characteristics compared with raw biomass pellets as: elevated combustion temperature ranges [T_onset for pelleting is lower than raw material and T_offset for pelleting is higher than raw material], decreased maximum weight loss rates and reduced residues, therefore high combustion efficiency and low pollutant emissions are expected for wheat straw pellets.
- (T_ onset) for corn cob after pelleting is lower than (T_ onset) of wheat dust after pelleting, (T_ offset) for corn cob after pelleting is lower than (T_ offset) of wheat dust after pelleting and peak(T_m) for corn cob after pelleting is lower than the peak(T_m) of wheat dust after pelleting .

The SI and FI for wheat dust pellets are higher than corn cob pellets.

REFERENCES

1. Mamma, D., E. Kourtoglou and P. Christakopoulos, 2008. Fungal multienzyme production on industrial by-products of the citrus-processing industry. Bioresource technology, 99(7): 2373-2383.
2. Golbitz, P., 1995. Traditional soyfoods: processing and products. The Journal of nutrition, 125(3): 570S.
3. Said, N., S. El-Shatoury, L. Díaz and M. Zamorano, 2013. Quantitative appraisal of biomass resources and their energy

potential in Egypt. Renewable and Sustainable Energy Reviews, 24: 84-91.
4. Werther, J., M. Saenger, E.-U. Hartge, T. Ogada and Z. Siagi, 2000. Combustion of agricultural residues. Progress in energy and combustion science, 26(1): 1-27.
5. El-Sayed, S.A. and M. Khairy, 2015. Effect of heating rate on the chemical kinetics of different biomass pyrolysis materials. Biofuels, 6(3-4): 157-170.
6. Obernberger, I. and G. Thek, 2004. Physical characterisation and chemical composition of densified biomass fuels with regard to their combustion behaviour. Biomass and bioenergy, 27(6): 653-669.
7. Rumpf, H., 2013. The strength of granules and agglomerate.
8. Lewandowski, I. and A. Kicherer, 1997. Combustion quality of biomass: practical relevance and experiments to modify the biomass quality of Miscanthus x giganteus. European Journal of Agronomy, 6(3): 163-177.
9. Fagan, C.C., C.D. Everard and K. McDonnell, 2011. Prediction of moisture, calorific value, ash and carbon content of two dedicated bioenergy crops using near-infrared spectroscopy. Bioresource technology, 102(8): 5200-5206.
10. Everard, C., C. Fagan and K. McDonnell, 2012. Visiblenear infrared spectral sensing coupled with chemometric analysis as a method for on-line prediction of milled biomass composition pre-pelletising. Journal of Near Infrared Spectroscopy, 20(3): 361.
11. Adapa, P., L. Tabil, G. Schoenau, B. Crerar and S. Sokjansanj, 2002. Pelletization of Alfalfa Grinds-Compression Characteristics of Fractionated Alfalfa Grinds. Powder Handling and Processing, 14(4): 252-259.
12. Adapa, P., G. Schoenau, L. Tabil, E. Arinze, A. Singh and A. Dalai, 2007. Customized and value-added high quality Alfalfa products: A new concept.
13. Kaliyan, N. and R.V. Morey. *Densification of corn stover*. in *2005 ASAE Annual Meeting*. 2005. American Society of Agricultural and Biological Engineers.
14. Stevens, C.A., Starch gelatinization and the influence of particle size, steam pressure and die speed on the pelleting process1987.
15. Kaliyan, N. and R.V. Morey. *Roll press briquetting of corn stover and switchgrass: A pilot scale continuous briquetting study*. in *2007 ASAE Annual Meeting*. 2007. American Society of Agricultural and Biological Engineers.
16. Shaw, M.D. and L.G. Tabil. *Compression and Relaxation Characteristics of Selected BiomassGrinds*. in *2007 ASAE Annual Meeting*. 2007. American Society of Agricultural and Biological Engineers.
17. Colley, Z., O. Fasina, D. Bransby and Y. Lee, 2006. Moisture effect on the physical characteristics of switchgrass pellets. Transactions of the ASABE, 49(6): 1845-1851.
18. Lam, P., S. Sokhansanj, X. Bi, C. Lim, L. Naimi, M. Hoque, S. Mani, A. Womac, S. Narayan and X. Ye, 2008. Bulk density of wet and dry wheat straw and switchgrass particles. Applied Engineering in Agriculture, 24(3): 351-358.
19. Sun, Y. and J. Cheng, 2002. Hydrolysis of lignocellulosic materials for ethanol production: a review. Bioresource technology, 83(1): 1-11.
20. Larsson, S.H., M. Thyrel, P. Geladi and T.A. Lestander, 2008. High quality biofuel pellet production from pre-compacted low density raw materials. Bioresource technology, 99(15): 7176-7182.
21. Mani, S., L. Tabil and S. Sokhansanj, 2003. Compaction of biomass grinds-an overview of compaction of biomass grinds. Powder Handling and Processing, 15(3): 160-168.
22. Mani, S., S. Sokhansanj, X. Bi and A. Turhollow, 2006. Economics of producing fuel pellets from biomass. Applied Engineering in Agriculture, 22(3): 421.
23. Zhou, B., K.E. Ileleji and G. Ejeta, 2008. Physical property relationships of bulk corn stover particles. Trans. ASABE, 51(2): 581-590.
24. Kaliyan, N. and R.V. Morey, 2009. Densification characteristics of corn stover and switchgrass. Transactions of the ASABE, 52(3): 907-920.
25. Erol, M., H. Haykiri-Acma and S. Küçükbayrak, 2010. Calorific value estimation of biomass from their proximate analyses data. Renewable energy, 35(1): 170-173.
26. Kaliyan, N. and R.V. Morey, 2009. Factors affecting strength and durability of densified biomass products. Biomass and bioenergy, 33(3): 337-359.
27. Thek, G. and I. Obernberger, The pellet handbook: the production and thermal utilization of biomass pellets2012: Routledge.
28. Sokhansanj, S., S. Mani, X. Bi, P. Zaini and L. Tabil. *Binderless pelletization of biomass*. in *2005 ASAE Annual Meeting*. 2005. American Society of Agricultural and Biological Engineers.
29. Tumuluru, J.S., C.T. Wright, J.R. Hess and K.L. Kenney, 2011. A review of biomass densification systems to develop uniform feedstock commodities for bioenergy application. Biofuels, Bioproducts and Biorefining, 5(6): 683-707.
30. Bryers, R.W., 1996. Fireside slagging, fouling, and high-temperature corrosion of heat-transfer surface due to impurities in steam-raising fuels. Progress in energy and combustion science, 22(1): 29-120.
31. Várhegyi, G., H. Chen and S. Godoy, 2009. Thermal decomposition of wheat, oat, barley, and Brassica carinata straws. A kinetic study. Energy & Fuels, 23(2): 646-652.
32. Cai, J. and L. Bi, 2009. Kinetic analysis of wheat straw pyrolysis using isoconversional methods. Journal of Thermal Analysis and Calorimetry, 98(1): 325.
33. Yin, C., L.A. Rosendahl and S.K. Kær, 2008. Grate-firing of biomass for heat and power production. Progress in Energy and Combustion Science, 34(6): 725-754.
34. Bashir, M.S., P.A. Jensen, F. Frandsen, S. Wedel, K. Dam-Johansen, J. Wadenbäck and S.T. Pedersen, 2012. Ash transformation and deposit build-up during biomass suspension and grate firing: Full-scale experimental studies. Fuel Processing Technology, 97: 93-106.
35. Näzelius, I.-L., J. Fagerström, C. Boman, D. Boström and M. Öhman, 2015. Slagging in Fixed-Bed Combustion of Phosphorus-Poor Biomass: Critical Ash-Forming Processes and Compositions. Energy & Fuels, 29(2): 894-908.
36. Fagerström, J., I.-L. Näzelius, C. Gilbe, D. Boström, M. Öhman and C. Boman, 2014. Influence of peat ash composition on particle emissions and slag formation in biomass grate co-combustion. Energy & Fuels, 28(5): 3403-3411.
37. Khashaba, U., 2016. Nanoparticle type effects on flexural, interfacial and vibration properties of GFRE composites. Chinese Journal of Aeronautics, 29(2): 520-533.
38. International, A., Standard test methods for direct moisture content measurement of wood and wood-base materials. ASTM D4442-07, 2007, ASTM International West Conshohocken, Pennsylvania.
39. McCabe, D.E., J.G. Merkle and K. Wallin, An introduction to the development and use of the master curve method2005: ASTM International.
40. Chin, O.C. and K.M. Siddiqui, 2000. Characteristics of some biomass briquettes prepared under modest die pressures. Biomass and Bioenergy, 18(3): 223-228.
41. Mani, S., L.G. Tabil and S. Sokhansanj, 2006. Effects of compressive force, particle size and moisture content on mechanical properties of biomass pellets from grasses. Biomass and Bioenergy, 30(7): 648-654.
42. Behnke, K.C. *Factors affecting pellet quality*. 1994. Maryland Nutrition Conference. Dept of Poultry Science and animal Science, collage of Agricultural, University of Maryland, collage Park.
43. Franke, M. and A. Rey, 2006. Pelleting quality. World Grain, 24(5): 78-79.
44. Pietsch, W.B., Agglomeration processes: phenomena, technologies, equipment2008: John Wiley & Sons.

45. ASTM, D., 440-86. Standard test method of drop shatter test for coal. Annual book of ASTM Standards, 5: 188-91.
46. Tayade, S., 2009. Evaluation of differentb briquette making for gasifier. Unpublished M. Tech. Thesis, PGI, Dr. PDKV, Akola.
47. ISO, E., 2014. Solid biofuels–fuel specifications and classes–Part 1: general requirements.
48. Kaliyan, N., Densification of biomass2008: ProQuest.
49. Vassilev, S.V., D. Baxter, L.K. Andersen and C.G. Vassileva, 2010. An overview of the chemical composition of biomass. Fuel, 89(5): 913-933.
50. Akowuah, J.O., F. Kemausuor and S.J. Mitchual, 2012. Physico-chemical characteristics and market potential of sawdust charcoal briquette. International Journal of Energy and Environmental Engineering, 3(1): 20.
51. Gravalos, I., D. Kateris, P. Xyradakis, T. Gialamas, S. Loutridis, A. Augousti, A. Georgiades and Z. Tsiropoulos. *A study on calorific energy values of biomass residue pellets for heating purposes*. in *Proceedings on Forest Engineering: Meeting the Needs of the Society and the Environment, Padova, Italy*. 2010.
52. O'dogherty, M. and J. Wheeler, 1984. Compression of straw to high densities in closed cylindrical dies. Journal of Agricultural Engineering Research, 29(1): 61-72.
53. Keown, D.M., G. Favas, J.-i. Hayashi and C.-Z. Li, 2005. Volatilisation of alkali and alkaline earth metallic species during the pyrolysis of biomass: differences between sugar cane bagasse and cane trash. Bioresource technology, 96(14): 1570-1577.
54. Pedersen, A.J., S.C. Van Lith, F.J. Frandsen, S.D. Steinsen and L.B. Holgersen, 2010. Release to the gas phase of metals, S and Cl during combustion of dedicated waste fractions. Fuel Processing Technology, 91(9): 1062-1072.
55. Niedziółka, I., M. Szpryngiel, M. Kachel-Jakubowska, A. Kraszkiewicz, K. Zawiślak, P. Sobczak and R. Nadulski, 2015. Assessment of the energetic and mechanical properties of pellets produced from agricultural biomass. Renewable Energy, 76: 312-317.
56. Carroll, J.P. and J. Finnan, 2012. Physical and chemical properties of pellets from energy crops and cereal straws. Biosystems Engineering, 112(2): 151-159.
57. Obernberger, I., T. Brunner and G. Bärnthaler, 2006. Chemical properties of solid biofuels—significance and impact. Biomass and Bioenergy, 30(11): 973-982.
58. Masnadi, M.S., R. Habibi, J. Kopyscinski, J.M. Hill, X. Bi, C.J. Lim, N. Ellis and J.R. Grace, 2014. Fuel characterization and co-pyrolysis kinetics of biomass and fossil fuels. Fuel, 117: 1204-1214.
59. Ghaly, A. and A. Ergudenler, 1991. Thermal degradation of cereal straws in air and nitrogen. Applied biochemistry and biotechnology, 28(1): 111-126.
60. Jeguirim, M., S. Dorge and G. Trouvé, 2010. Thermogravimetric analysis and emission characteristics of two energy crops in air atmosphere: Arundo donax and Miscanthus giganthus. Bioresource technology, 101(2): 788-793.
61. Biagini, E. and L. Tognotti, 2006. Comparison of devolatilization/char oxidation and direct oxidation of solid fuels at low heating rate. Energy & fuels, 20(3): 986-992.
62. Jensen, P.A., F.J. Frandsen, J. Hansen, K. Dam-Johansen, N. Henriksen and S. Hörlyck, 2004. SEM investigation of superheater deposits from biomass-fired boilers. Energy & Fuels, 18(2): 378-384.
63. Khan, A., W. De Jong, P. Jansens and H. Spliethoff, 2009. Biomass combustion in fluidized bed boilers: potential problems and remedies. Fuel processing technology, 90(1): 21-50.
64. Pronobis, M., 2005. Evaluation of the influence of biomass co-combustion on boiler furnace slagging by means of fusibility correlations. Biomass and Bioenergy, 28(4): 375-383.
65. Bapat, D., S. Kulkarni and V. Bhandarkar, Design and operating experience on fluidized bed boiler burning biomass fuels with high alkali ash, 1997, American Society of Mechanical Engineers, New York, NY (United States)..

Persian Abstract

DOI: 10.5829/idosi.ijee.2017.08.01.13

چکیده

م