Engineering Journal issn: 0125-8281

Article

Experimental Characterization of Maize Cob and Stalk Based Pellets for Energy Use

Musediq Adedoyin Sulaiman[1,a,*], Babatunde Olusola Adetifa[2,b], Sunday Oludaisi Adekomaya[1,c], Nurudeen Samuel Lawal[2,d], and Olukayode Olaleye Adama[2,e]

1 Department of Mechanical Engineering, Faculty of Engineering, College of Engineering and Environmental Studies, Olabisi Onabanjo University, 112104, Ibogun, Ogun State, Nigeria
2 Department of Agricultural Engineering, Faculty of Engineering, College of Engineering and Environmental Studies, Olabisi Onabanjo University, 112104, Ibogun, Ogun State, Nigeria
E-mail: [a]sulaimanadedoyin@oouagoiwoye.edu.ng (Corresponding author), [b]olusola.adetifa@oouagoiwoye.edu.ng, [c]adekomaya.oludaisi@oouagoiwoye.edu.ng, [d]nslawal@oouagoiwoye.edu.ng, [e]olukayode.adama@oouagoiwoye.edu.ng

Abstract. The quest for alternative energy sources is gradually shifting from natural fossil fuel to alternative bio-resources especially agricultural waste products due to their reduced pollution risk and sustainability. This study seeks to investigate the suitability of plant residue pellets to produce biomass. The plant residues investigated include; 100% granulated corn cob residues, 100% granulated corn stalks and a composite of 50:50 granulated corn cobs and stalk residues. The residues were compressed at 200 MPa and pelletized using cassava starch as a binder. The pellets were experimentally analyzed using emission, ultimate, proximate and calorimetry analyses. The result showed that the cob-stalk 50:50 combination had the most desirable properties. It has 0.64% nitrogen, 48.57% carbon, 0.38% Sulphur, 6.22% hydrogen, 55.81% oxygen, 3.25% moisture content, 2.20% ash content, 80.0% volatile matter, 17.80% fixed carbon percentage, HHV of 32.9 kJ/kg, an average CO_2 of 563±50 PPM, an average CO of 100±50 PPM, and an average value relative humidity of 69±4%. The study reiterates that corn residues are a good bio-fuel and should be encouraged to address the current energy shortfalls.

Keywords: Corn waste, pellet, ultimate analysis, proximate analysis, calorimetry.

ENGINEERING JOURNAL Volume 23 Issue 6
Received 14 June 2019
Accepted 30 September 2019
Published 30 November 2019
Online at http://www.engj.org/
DOI:10.4186/ej.2019.23.6.117

DOI:10.4186/ej.2019.23.6.117

1. Introduction

Maize is a major staple food in Nigeria, it can be cooked, roasted, ground, pounded or crushed directly or processed into other local secondary food products such as maize pap, *tuwo*, *gwate*, *donkunu* and host of others. It is the third most important cereal after rice and wheat, but in Nigeria, it is the most important cereal crop [1, 2]. Maize is a highly versatile crop with great socio-economic value, in that all the parts (the grain, leaves, stalk, tassel, and cob) can be processed to other food and non-food related products [3]. Nuhu [4] and Oyelade [5] found out that in Nigeria over 150 million people consume an average of 43 kilograms per year. The demand for maize as food for human and livestock as well as industrial purpose is evident in the demand and production increase.

Energy use is an important and pivotal factor needed in evaluating the status of an economy and in assessing whether the projected progression and transformation of a country is in line with its available resources. It is the bedrock of industrial revolution, propelling virtually all sectors of a country [6]. It reflects the level of industrial, agricultural, and transport activity, and, in fact, it is an indicator of gross domestic product (GDP). There is, undoubtedly, a two-way relationship between energy supply (exploration, generation and deployment) and consumption (use, transformation and storage). This implies that the economic transformation and technological advancement of a nation strongly depend on the energy use, and vice versa [7, 8]. This is evident in the high energy consumption of developed economies like the UK, China, America, and Europe when compared to developing countries in Africa with low energy consumption [9].

Presently, different factors are contributing to the increasing energy demand and energy crisis [9, 10]; consequently, this energy crisis has led to finding alternatives, which can substitute or make-up for the energy shortfall. This will reduce the world's dependence on non-renewable energy and its associated environmental impacts such as greenhouse gasses. Among the alternatives are renewable energy sources such as steam, solar, wind, and biomass. This study intends to focus on one of the alternative renewable energy biomass. Biomass is a renewable energy of biological origin and constituent. Biomass contains stored energy from the sun absorbed through a process called photosynthesis. It can be burned directly or converted to liquid biofuels or biogas that can be combusted as fuel [7, 11]. Examples of biomass include wood/wood processing waste, agricultural crops/waste materials, food waste, etc.

In Africa, the predominant source of energy in cooking and heating is majorly biomass (about 80%) which accounts for 14% of the global renewable energy supplied and 10% of the global energy consumption [12]. Generally, firewood and charcoal are the types of biomass used in most parts of Africa. This has led to increased indoor air pollution, thereby, constituting environmental and health risks [13]. This form of biomass is, therefore, not sustainable; hence there is an urgent need for new, improved, safe and yet cheap biomass capable of balancing the need for energy and environmental sustainability. The adoption of this sustainable biomass will dampen the effect of rising fossil fuel prices and other issues of environmental degradation connected to the use of fossil fuel products [6].

Numerous forms of biomass have been exploited as energy sources; some of which include; wood shavings/saw dust, agricultural wastes, forest product processing waste, etc. Presently the agricultural residues are receiving serious attention based on the current studies in this area [6, 10, 11-17]. In Nigeria, biomass is mostly obtained from agricultural crop residues and waste generated from the production and processing of corn, sugarcane, rice, forestry residues, cassava, palm kernel, coconut etc. [18]. Some of the forestry residues which have been used for biomass include; wood chips, bark, sawdust, timber slash, and mill scrap [19, 20]. In this study, the focus is on corn waste – one of the agricultural residues available in large quantity in Nigeria.

Globally, maize is the most produced cereal [1], in the year 2012 world production of maize was 875,226,630 tons [21]. According to FAO [21], Nigeria is the tenth highest producers of maize in the world with about 9.2 million MT/year as of 2011. With this high level of production, associated wastes in terms of residues will be high in the country. In fact, according to Ayamaga et al. [6], Black et al. [22] and Maithel [23] the maize residue to product ratio (RPR) value for maize stalks ranges between 1.2 - 1.7 while that of maize husk ranges between 0.23. This ratio implies that the maize residue is huge and tapping into this waste for the generation of energy will reduce emission associated with fossil fuel production and it will generate more revenue for farmers.

Grounded maize cobs with a moisture content of around 6.4% have a particle size, bulk density and porosity of 0.58 mm, 282.38 kg/m^3 and 67.93%, while for grounded maize stalk of the same moisture content, the respective values are 0.49 mm, 127.32 kg.m^3 and 58.51% [24]. Maize cobs have been reported to contain fixed carbon, volatile matter, high heating value of 5-21%, 65-80%, and 18-19 MJ/kg, respectively [25-28], depending on the moisture content and maize variety. Corn stalks have also been reported to be a good biomass energy source having a high heating value of 16-20 MJ/kg and an ash content of 5-21% depending on factors like moisture content, the period of harvest, variety, etc. [29-34]. The performance and properties of pellets are dependent on factors like compression methods [35-37], particle size [36, 38], pellet die diameter [39, 40], moisture content [36], chemical modification [41], mixture ratio [42], etc. This study intends to investigate and characterize maize residues (corn stalks, cob and a combination of the two) with an intention of suggesting the best for pellet biomass.

2. Materials and Methods

2.1. Preparation of Pellets

The maize residues (corn cobs and stalks) (Fig. 1(a)) used in this study were obtained from the Olabisi Onabanjo University CEES farm located at Ibogun in Ifo local government area of Ogun State, Nigeria. Figure 1 presents the production stages of the pellets. The maize residues were ground into fine particles (Fig. 1(b)) with the aid of a locally fabricated plate mill and three composite samples were produced; 100% granulated corn cob residues, 100% granulated stalks and a mixture of 50:50 granulated corn cobs and stalk residues. The 50:50 mixture of granulated corn cobs and stalk was selected because a composite mixture with 50% maize cob has been found to have high density, and good compressive strength, impact resistance index [43] and combustion rate [44].

Each of the granulated composite samples was thoroughly mixed with a locally produced cassava starch (the binder) using a kneading process. The binder made from starch obtained from cassava tuber was selected because it is relatively available and cheap in the study area. The mixed granulated residues were packed into a locally fabricated compression device and then compacted with the aid of a hydraulic press as shown in Fig. 1(c). This compaction closed up the spaces between the particles. The pellets were produced at a high compaction pressure around 200 MPa so as to increase the shear strength and the quality of the pellet [45]. The produced pellets (Fig. 1(d)) were thereafter sun-dried for seven hours per day for three days to reduce the moisture content and prepare the pellet samples for further analysis.

2.2. Analysis of Pellets

To determine the sample with the best combustion characteristics, emission test, proximate analysis, ultimate analysis, and calorimetry were performed on the three composite samples.

2.3. Emission Test

Emission test determines the level of pollutants emitted from a certain gas or compound. In this study, the emission test was carried out in a heat and mass laboratory with the aid of a stopwatch, a burner and CO and CO_2 meters. The meters were placed 4 meters away from the burner to allow for proper diffusion of the gas within the laboratory. Each of the pellet samples was allowed to combust for ten minutes in the burner and the CO and CO_2 readings were monitored and taken at various time intervals. The relative humidity of the laboratory was also measured during the testing period. This test was carried for five days.

2.4. Ultimate Analysis

A LECO CNS element analyzer was used in detecting the elements contained in the pellets. This approach has been used by several researchers [46]. Eq. (1) presents the model used in the analysis.

$$O = 100 - (\text{Carbon} + \text{Nitrogen} + \text{Hydrogen} + \text{Sulphur}) \quad (1)$$

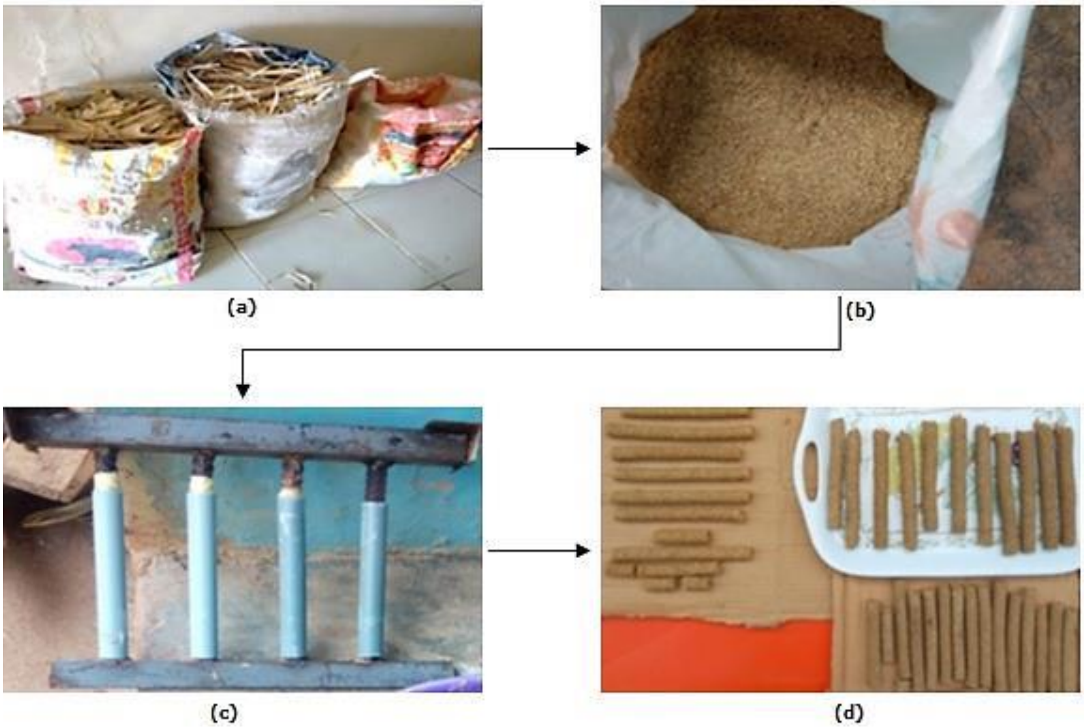

Fig. 1. Production stages in the preparation of pellets.

2.5. Proximate Analysis

Proximate analysis is a method widely used in characterizing biomass. It comprises four major parameters (i.e. moisture content, ash content, volatile matter, and fixed carbon percentages). The fixed carbon percentage was dependent on the results of the other three parameters investigated [16].

a. Moisture content (MC): The moisture was estimated using the Eq. (2), where; W_0 stands for the initial weight of the sample and crucible together, and W, is the resulting weight of the dry sample.

$$\text{Moisture content } \% = \frac{W_0 - W}{W_0} \quad (2)$$

b. Ash content: In all forms of solid fuel combustion, there are always residues left, these residues are inorganic and are called ashes [16]. The ash content was calculated using Eq. (3) where W_a is the ash weight of the sample.

$$\text{Ash content } \% = \frac{W_a}{W_0} \quad (3)$$

c. Volatile matter: Eq. (4) estimates the percentage of volatile matter as a function of the volatile mass after combustion; where W_v is the ash weight of the sample.

$$\text{VM } \% = \frac{W_v}{W_0} \quad (4)$$

d. Fixed carbon percentage: This parameter is obtained after the results of volatile matter and ash contents were obtained in the proximate analysis in line with Telmo et al. [47] using the model presented in Eq. (5) where FC is the percentage value of fixed carbon and VM is the volatile matter.

$$\text{FC } \% = 100 - (\% \text{ Ash} + \text{VM} + \text{MC}) \quad (5)$$

2.6. Calorimetry

This is an experimental approach was used to determine the higher heating value (HHV) of the biomass samples. However, owing to restricted access to equipment, empirical formulas (Eq. 6 and 7) were used to estimate the HHV and LHV as follows [48]:

$$\mathrm{HHV} = 2.326(147.6\mathrm{FC} + 144\mathrm{V}) \tag{6}$$

$$\mathrm{LHV} = \mathrm{HHV}(1 - \mathrm{MC}) - 2.447\mathrm{MC} \tag{7}$$

where FC = Fixed carbon percentage, V = volatile matter and MC = moisture content.

3. Results and Discussion

3.1. Ultimate Analysis

Results obtained from the ultimate analysis of the biomass samples are shown in Table 1 and while the effect of the different mix ratios is shown in Fig. 3. The presence of nitrogen, carbon, and oxygen serve as the major constituents of the solid fuels. As shown in Table 1, the nitrogen constituent in the pellets was 0.26%, 0.52% and 0.6% in corn cob, corn stalk, and cob-stalk respectively, with the corn cob having the lowest percentage. Figure 3 shows that the nitrogen constituent increased as the percentage of one of the mixture approached zero; the carbon constituent followed a similar trend. The carbon value in the pellets of corn cob was 44.61%, while that of corn stalk was 45.33%. The highest carbon value was observed in the cob-stalk mixture as 48.57%. The sulphur content of the biomass showed that corn-cob, corn-stalk, and cob-stalk (50:50) mixture values were 1.02, 0.98 and 0.38% respectively. The hydrogen value present for corn-cob, corn-stalk and cob-stalk (50:50) mixture were 6.23, 6.18 and 6.22% respectively, this value was observed to reduce with a decrease in the percentage of corn cob used (Fig. 3). In addition, the oxygen value of the cob-stalk (50:50) mixture had the lowest percentage compared to others; it reduced as the percentage of one of the mixture approaches zero. Generally, the three samples were within an expected range as reported by García et al. [16].

This small quantity of hydrogen compared with the carbon content indicates that hydrogen's contribution to the HHV of the biomass fuels is much lower than carbon's contribution. Sulphur content in biomass ranged from 0.3 to 1.0% in the three samples. By implication, the combustion reaction of sulphur will generate sulphates, which can liquefy in the walls of the heat exchanger and produce ashes. Thus, very low levels of sulphur in fuels are required [49].

Table 1. Ultimate analysis data for maize residue pellets.

Pellets Composition	Nitrogen (%)	Carbon (%)	Sulphur (%)	Hydrogen (%)	Oxygen (%)
Corn Cob	0.26	44.61	1.02	6.23	47.88
Corn Stalk	0.52	45.33	0.98	6.18	46.99
Corn Cob and Stalk (50:50)	0.64	48.57	0.38	6.22	44.19

Table 2 presents the ultimate analysis results of some selected biomass from García et al. [16], however, it should be noted that Carbon, Nitrogen, and Oxygen are the major components in biomass fuel. During combustion, these compounds will react exothermally, producing CO_2 and H_2O and these products play major roles in fuels HHV and LHV. As observed in Table 2, most of the biomass carbon values presented ranged between 46.35% and 49%, while the oxygen also ranges between 43% and 70%. This implies the result of the Ultimate analysis of the maize residue pellets investigated ranges within the expected limit. According to the report of Roussak and Gesser [50], bituminous coal has a very high carbon value above 85% and about 6.5% oxygen content which implies that high values of carbon and lower values of oxygen is very important in the quality of biomass.

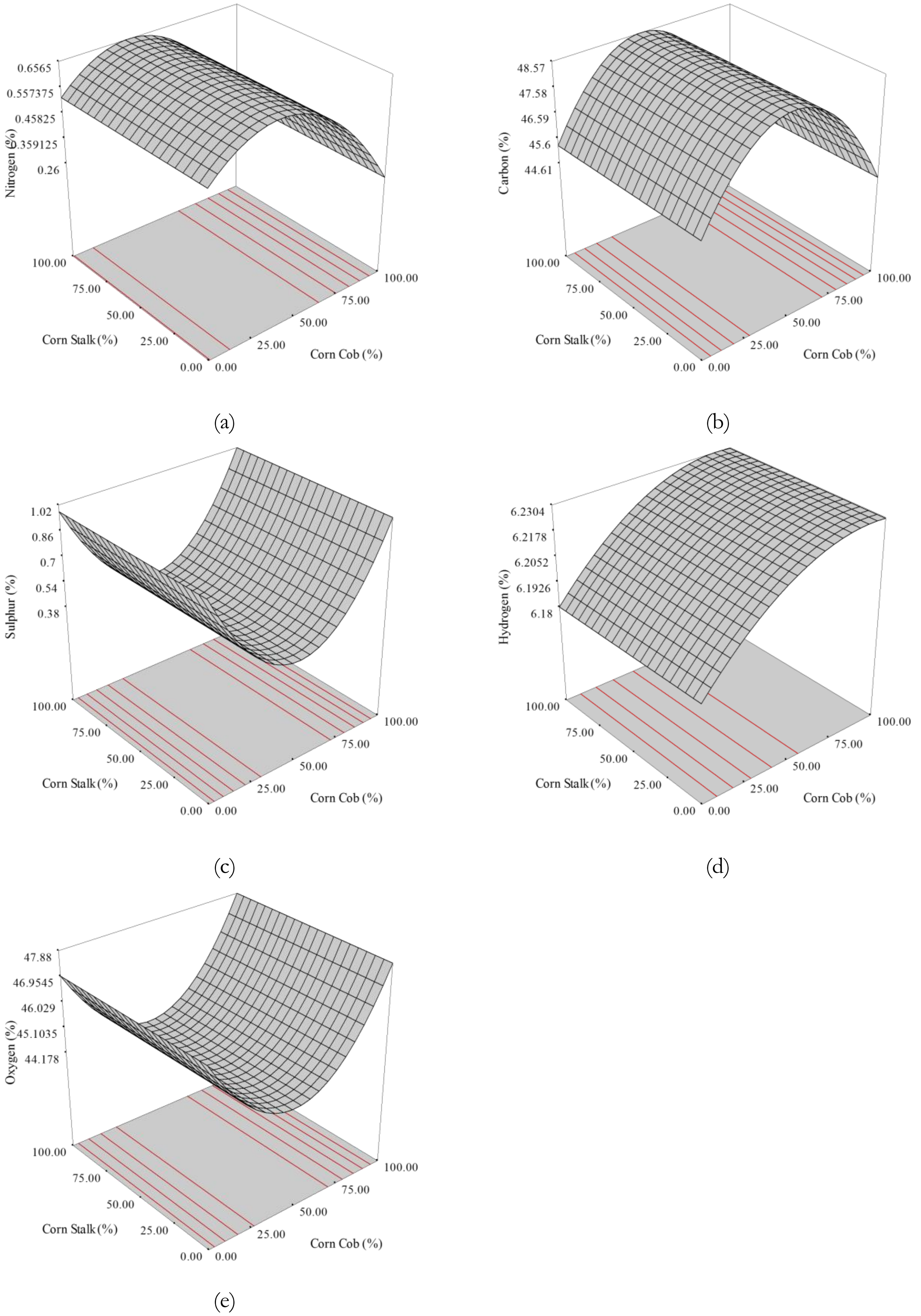

Fig. 3. Effect of cob and stalk ratio on the ultimate analysis data of maize residue pellets.

For a biomass to be adjudged good based on the result of the ultimate analysis, the carbon content should be around 47- 54%, hydrogen should range from 5.6-7%, oxygen content must be between 40- 44%, nitrogen can range from 0.1- 0.5% and sulphur should be around 0.1% [47, 51]. This, therefore, implies that the cob-stalk (50:50) mixture was the best pellet compared to the other two investigated.

Table 2. Ultimate analysis data for some biomass fuels [16].

Biomass fuel	Nitrogen (%)	Carbon (%)	Sulphur (%)	Hydrogen (%)	Oxygen (%)
Almond shell	0.3	46.35	0.22	5.67	47.20
Beetroot pellets	1.19	38.94	0.51	5.23	54.13
Rice Husk	0.21	26.69	0.17	2.88	70.05
Coffee husk	2.53	45.06	0.48	6.42	45.51
Corncob	0.22	44.78	0.21	6.02	48.77
Briquette	1.24	46.74	0.1	6.39	45.52
Pine kernel shell	0.31	47.91	0.6	4.9	46.28
Sawdust	0.53	45.34	1.07	6.02	47.05
Soya	1.16	44.42	0.24	6.33	47.86
Wheat	0.24	49.22	0.26	6.52	43.76
Sorghum	0.73	40.79	0.23	4.38	53.87

3.2. Proximate Analysis

Table 3 presents the result of the proximate analysis of the maize residues investigated. The moisture content of the corn cob, corn stalk and cob-stalk (50:50) mixture values are 3.05%, 3.75%, and 3.25% respectively, with corn cob having the lowest value and cob-stalk (50:50) mixture having the highest value. This low value can be attributed to the environmental condition during the time the pellets were sun dried for about three days with the temperature ranging between 0 and 33 ^{O}C. From Table 3, the Ash content ranged from 0.7 to 2.7%.

These values enable the biomass samples to be used for heat generation, the lowest among them being the corn stalk is the most suitable sample for thermal utilization, implying that it will generate less ash [52]. The result of volatile matter shows that all the volatile matter ranged between 55 to 80%. Also, the result showed that the fixed carbon in the corn cob, corn stalk, and cob-stalk (50:50) mixture values were 22.3%, 44.3%, and 17.8% respectively, with the cob-stalk (50:50) mixture having the lowest value. The result of higher heating values (HHV) are as follows for corn cob, corn stalk and cob-stalk (50:50) mixture values are 32.7, 33.6 and 32 kJ/kg, respectively.

Figure 4 shows the effect of corn cob and corn stalk on the proximate analysis data of the pellets. It was observed that an increase in the amount of corn stalk in the mixture increases the moisture content, fixed carbon, and HHV of the pellets. Congruently, an increase in the amount of corn cob in the pellets increased the ash content and the volatile matter of the pellets.

Table 3. Proximate analysis data for maize residue pellets.

Pellet components	Moisture Content (%)	Ash Content (%)	Volatile Matter (%)	Fixed Carbon (%)	HHV (KJ/kg)	LHV (KJ/kg)
Corn Cob	3.05	2.7	75	22.3	32.7	31.77
Corn Stalk	3.75	0.7	55	44.3	33.6	32.36
Cob Stalk 50:50%	3.25	2.2	80	17.8	32.9	31.83

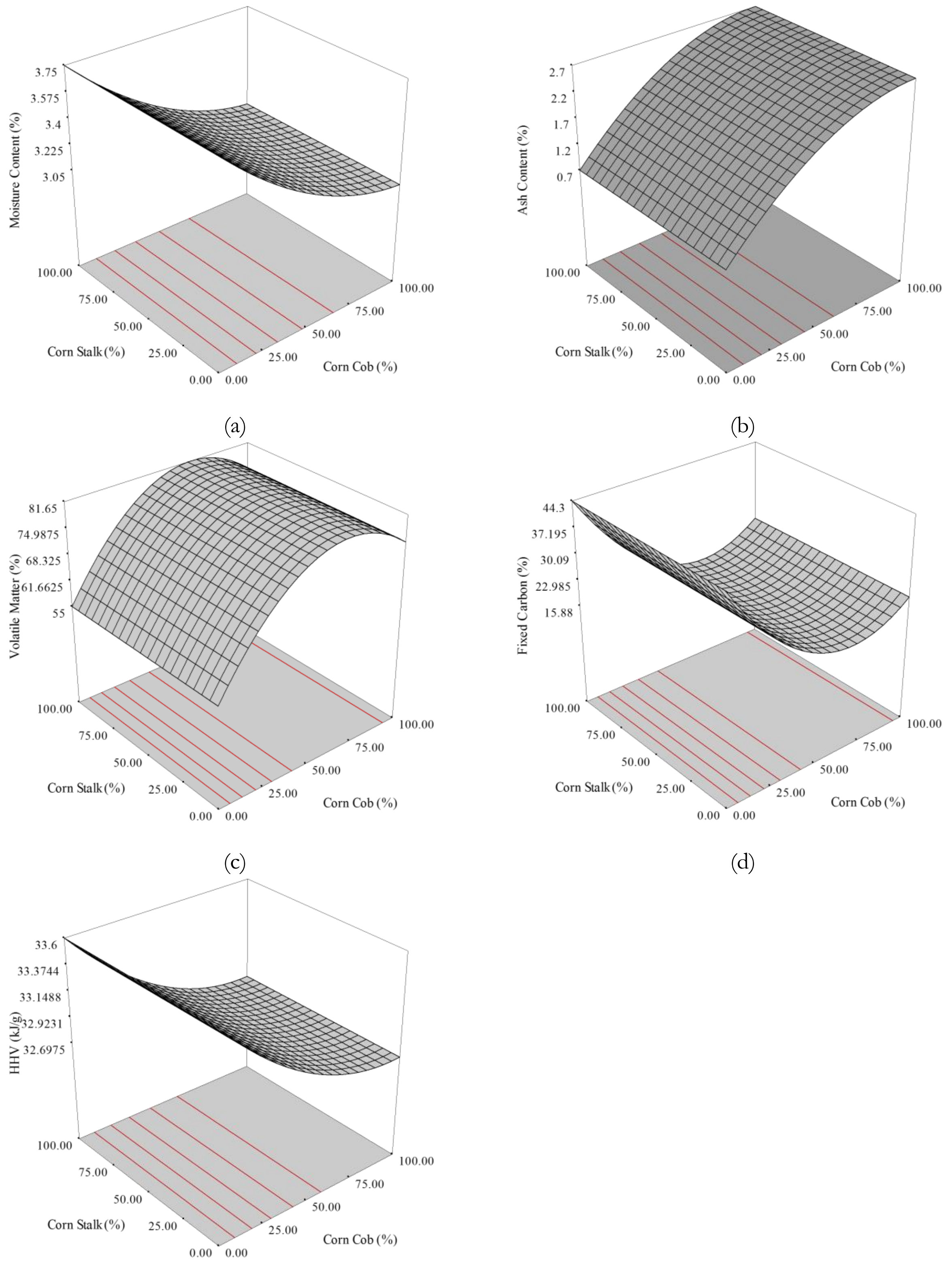

Fig. 4. Effect of cob and stalk ratio on the proximate analysis data of maize residue pellets.

Table 4 presents the results of previous works by other researchers on other agricultural residues. Also, the result of all the pellets corroborates previous works on corn cob. However, this research has been able to show that pellets investigated fall within the range of result earlier investigated.

The samples all have moisture levels under 5%, which implies they are good biomass and they are credible sources. Past researches on biofuels have shown that wood chips, orange rinds, and chestnut shells have a range of 25-30% moisture present in them and can sometimes go way up to 43%. This is evident in the corresponding HHV, which implies that the higher the HHV the high energy content of the investigated maize residues [16]. This further validates the application of these materials as fuel [53].

It is important to note that the results presented for the fixed carbon percentage are not experimental, but were estimated from an empirical formula. The ash content and volatile matter obtained from proximate analysis were used to obtain fixed carbon percentage [45]. The 50:50 sample having a value of 17.8% which is the lowest within the three samples and the cornstalk having the highest value of 44%.

Table 4. Agricultural wastes residues [16].

Agro-wastes	Moisture Content (%)	Ash Content (%)	Volatile Matter (%)	Fixed Carbon (%)	HHV (kJ/g)
Pineapple leaf	8.2 ± 0.1	3.2 ± 0.3	75 ± 1	21.8	18,147 ± 15
Straw pellets	7.3 ± 0.1	9.8 ± 0.2	79 ± 2	11.2	16,584 ± 6
Wood chips	25.6 ± 0.6	1.5 ± 0.7	68.6 ± 0.2	29.9	15,162 ± 81
Oats and vetch	7.8 ± 0.1	7.33 ± 0.08	72 ± 2	20.67	16,661 ± 22
Sainfoin	9.6 ± 0.2	9.2 ± 0.2	73± 2	17.8	16,412 ± 43
Corn cob	3.05	2.7	75	22.3	32,700
Corn Stalks	3.75	0.7	55	44.3	33,600
Corn & Stalk 50:50	3.25	2.2	80	17.8	32, 900
Barley	9.9 ± 0.2	3 ± 0.6	76.9 ± 0.6	20.1	16,519 ± 18
Oats bran	9.9 ± 0.3	4.15 ± 0.09	77 ± 1	18.85	18,058 ± 86
Rye	10.76 ± 0.06	1.8 ± 0.04	78.9 ± 0.5	19.3	16,141 ± 30
Pinecone leaf	9.3 ± 0.2	1.9 ± 0.2	75.9 ± 0.4	22.2	18,449 ± 9

3.3. Emission Analysis

Table 5 shows the result of the emission test carried out. It shows that corn cob pellets have higher CO emission while corn stalk pellets have higher CO_2 emission. The 50:50 mixture of the two materials reduced the CO_2 emission but increased the CO emission. The level of CO emission of pellets from corn cob and the mixture of cob and stalk is high according to the guideline of 100 mg/m^3 (87.29 ppm) over a 15 minute period [54]. This level of the CO emission is also higher than the value reported by Kažimírová and Opáth [55] and Zhang et al. [56]. This observed level of CO may be attributed to the quick burning of the pellets, resulting in incomplete combustion as a result of insufficient oxygen [56].

Table 5. Emission potential of pellets (time range: 12 minutes).

Pellets Composition	CO_2 (ppm)	CO (ppm)	R.H (%)
Corn Cob	825 ± 200	90 ± 30	45 ± 5
Corn Stalk	850 ± 300	60 ± 40	60 ± 10
Corn Cob and Stalk (50:50)	563 ± 50	100 ± 50	69 ± 4

4. Conclusion

This study examined three different maize residues (corn cob, corn stalk, and cob-stalk combination) for biomass production. An ultimate analysis of the pellets showed that, the corn cob has 0.26% nitrogen, 44.61% carbon, 1.02% sulphur, 6.23% hydrogen, 47.88% oxygen, the corn stalk has 0.52% nitrogen, 45.33% carbon, 0.98% sulphur, 6.18% hydrogen, 46.99% oxygen, and the cob-stalk combination has 0.64% nitrogen, 48.57% carbon, 0.38% sulphur, 6.22% hydrogen, 55.81% oxygen. For proximate analysis, the corn cob has 3.05% moisture content, 2.70% ash content, 75.0% volatile matter, 22.30% fixed carbon percentage, the corn stalk has 3.75% moisture content, 0.70% ash content, 55.0% volatile matter, 44.30% fixed carbon percentage and the cob-stalk combination has 3.25% moisture content, 2.20% ash content, 80.0% volatile matter and 17.80%. Thermodynamic analysis using calorimetry revealed that the corn cob has HHV of 32.7 kJ/kg, LHV of 31.77 kJ/kg. The corn stalk has HHV of 33.6 kJ/kg, LHV of 32.36 kJ/kg and the cob-stalk combination has HHV of 32.9 kJ/kg and LHV of 31.83 kJ/kg. The result of all the pellets investigated shows that the cob-stalk combination is relatively low in sulphur, CO_2 and CO gasses, with a negligible impact on the environment making it an environmentally friendly fuel. This study suggests the cob-stalk combination as best among the investigated residues and recommends further study to investigate the possibility of using the pellets from the corn cob and corn stalk composite as boiler fuel in power plants to address the usual high energy cost.

References

[1] A. B. Olaniyan, "Maize: Panacea for hunger in Nigeria," *African Journal of Plant Science,* vol. 9, pp. 155-174, 2015.

[2] Statkraft. (2012). *Annual Report 2012*. [Online]. Available: http://www.statkraft.no/globalassets/1-statkraft-public/05-investor-relations/4-reports-and-presentations/2004-2013-reports-and-presentations/2012/statkraft-annual-report-2012_tcm9-27539.pdf

[3] International Institute of Tropical Agriculture, *Annual Report.* Ibadan, Nigeria: IITA, 2001.

[4] N. Nuhu, "Economic analysis of maize production in soba local," Ahmadu Bello University Zaria, 2016

[5] O. A. Oyelade and A. N. Anwanane, "Maize and cowpea production in Nigeria," *Advances in Agriculture, Science and Engineering Research,* vol. 3, no 11, pp. 1343-1358, 2013.

[6] E. A. Ayamga., F. Kemausuor, and A. Addo, "Technical analysis of crop residue biomass energy in an agricultural region of Ghana," *Resources, Conservation and Recycling,* vol. 96, pp. 51-60, 2015.

[7] E. Kebede, J. Kagochi, and C. M. Jolly, "Energy consumption and economic development in Sub-Sahara Africa," *Energy Economics,* vol. 32, no. 3, pp. 532-537, 2010.

[8] E. Yildirim, Ş. Saraç, and A. Aslan, "Energy consumption and economic growth in the USA: Evidence from renewable energy," *Renewable and Sustainable Energy Reviews,* vol. 16, no. 9, pp. 6770-6774. 2012.

[9] B. A. Onakoya, J. S. Adejuwon, O. Jimi -Salami, and O. B. Omoniyi, "Energy consumption and Nigerian economic growth: An empirical analysis," *European Scientific Journal*, vol. 99, pp. 1857-7881, 2013.

[10] N. Abila, "Biofuels adoption in Nigeria: Attaining a balance in the food, fuel, feed and fibre objectives," *Renewable and Sustainable Energy Reviews,* vol. 35, pp. 347-355, 2014.

[11] J. Werther, M. Saenger, E. U. Hartge, T. Ogada, and Z. Siagi, "Combustion of agricultural residues," *Progress in Energy and Combustion Science,* vol. 26, no. 1, pp. 1-27. 2000.

[12] D. K. Okot, P. E. Bilsborrow, and A. N. Phan, "Biomass and bioenergy effects of operating parameters on maize COB briquette quality," *Biomass and Bioenergy,* vol. 112, pp. 61-72, 2018.

[13] F. Zuzarte, "Ethanol for cooking: Feasibility of small-scale ethanol supply and its demand as a cooking fuel: Tanzania case study," M.Sc. Thesis, KTH School of energy and Environment Technology Stockholm, Sweden, 2007.

[14] J. Ben-Iwo, V. Manovic, and P. Longhurst, "Biomass resources and biofuels potential for the production of transportation fuels in Nigeria," *Renewable and Sustainable Energy Reviews,* vol. 63, pp. 172-192, 2016.

[15] J. I. Eze, "Anaerobic production of biogas from maize wastes," *International Journal of the Physical Sciences* vol. 7, no. 6, pp. 982-987. 2012.

[16] R. García, C. Pizarro, A. G. Lavín, and J. L. Bueno, "Characterization of Spanish biomass wastes for energy use," *Bioresource Technology,* vol. 103, no. 1, pp. 249–258, 2012.

[17] K. J. Gondwe, S. S. Chiotha, T. Mkandawire, X. Zhu, J. Painuly, and L. J. Taulo, "Crop residues as a potential renewable energy source for Malawi's cement industry," *Journal of Energy in Southern Africa,* vol. 28, no. 4, pp. 19-31, 2017.

[18] G. W. Huber, S. Iborra, and A. Corma, "Synthesis of transportation fuels from biomass: Chemistry, catalysts, and engineering," *Chemical Reviews,* vol. 106, no. 9, pp. 4044-4098, 2006.

[19] L. M. Mohlala, M. O. Bodunrin, A. A. Awosusi, M. O. Daramola, N. P. Cele, and P. A. Olubambi, "Beneficiation of corncob and sugarcane bagasse for energy generation and materials development in Nigeria and South Africa: A short overview," *Alexandria Engineering Journal,* vol. 55, no. 3, pp. 3025-3036, 2016.

[20] J. S. Tumuluru, C. T. Wright, J. R. Hess, and K. L. Kenney, "A review of biomass densification systems to develop uniform feedstock commodities for bioenergy application," *Biofuels, Bioproducts, and Biorefining* vol. 5, no. 6, pp. 683-707, 2011.
[21] FAO, "Cereal supply and demand brief," World Food Situation, Food, and Agriculture Organization of the United Nations, 2018.
[22] R. E. Black, C. G. Victora, S. P. Walker, Z. A. Bhutta, P. Christian, M. De Onis, M. Ezzati, S. Grantham-McGregor, J. Katz, R. Martorell, and R. Uauy, "Maternal and child undernutrition and overweight in low-income and middle-income countries," *The Lancet*, vol. 382, pp. 427–451, 2013.
[23] S. Maithel, *Biomass Energy Resource Assessment Handbook*. UN Asian and Pacific Centre for Transfer of Technology, 2009.
[24] Y. Zhang, A. E. Ghaly, and B. Li, "Physical properties of corn residues," *American Journal of Biochemistry and Biotechnology*, vol. 8, no. 2, pp. 44-53, 2012. [Online]. Available: https://doi.org/10.3844/ajbb.2012.44.53
[25] S. Danje, "Fast pyrolysis of corn residues for energy production," doctoral dissertation, Stellenbosch University, 2011.
[26] M. Danish, M. Naqvi, U. Farooq, and S. Naqvi, "Characterization of South Asian agricultural residues for potential utilisation in future energy mix," *Energy Procedia*, vol. 75, pp. 2974–2980, 2015.
[27] J. Wannapeera, N. Worasuwannarak, and S. Pipatmanomoi, "Product yields and characteristics of rice husk, rice straw and corncob during fast pyrolysis in a drop-tube/fixed-bed reactor," *Songklanakarin Journal of Science and Technology*, vol. 30, no. 3, pp. 393–404, 2008.
[28] A. I. Anukam, B. P. Goso, O. O. Okoh, and S. N. Mamphweli, "Studies on characterization of corn cob for application in a gasification process for energy production," *Journal of Chemistry*, vol. 2017, Article ID 6478389, 2017. [Online]. Available: https://doi.org/10.1155/2017/6478389
[29] A. S. Bennett, C. J. Bern, T. L. Richard, and R. P. Anex, "Corn grain drying using corn stover combustion and CHP systems," *Trans. ASABE*, vol. 50, pp. 2161–2170, 2007.
[30] L. O. Pordesimo, B. R. Hames, S. Sokhansanj, and W. C. Edens, "Variation in corn stover composition and energy content with crop maturity," *Biomass Bioenergy*, vol. 28, pp. 366–374, 2005.
[31] R. Morissette, P. Savoie, and J. Villeneuve, "Combustion of corn stover bales in a small 146-kW boiler," *Energies*, vol. 4, pp. 1102–1111, 2011.
[32] A. Demirbas, "Combustion characteristics of different biomass fuels," *Prog. Energy Combust. Matter,* vol. 30, pp. 219–230, 2004.
[33] P. C. Hoffman. *Ash Content of Forages*. Marshfield, WI, USA, University of Wisconsin-Extension, 2005.
[34] P.-L. Lizotte, P. Savoie, and A. De Champlain, "Ash content and calorific energy of corn stover components in Eastern Canada," *Energies*, vol. 8, pp. 4827-4838, 2015. [Online]. Available: https://doi.org/10.3390/en8064827
[35] S. Poddar, M. Kamruzzaman, S. M. A. Sujan, M. Hossain, M. Jamal, M. Gafur, and M. Khanam, "Effect of compression pressure on lignocellulosic biomass pellet to improve fuel properties: Higher heating value," *Fuel*, vol. 131, pp. 43-48, 2014. [Online]. Available: https://doi.org/10.1016/j.fuel.2014.04.061
[36] S. Mani, L. Tabil, and S. Sokhansanj, "Effects of compressive force, particle size and moisture content on mechanical properties of biomass pellets from grasses," *Biomass and Bioenergy*, vol. 30, no. 7, pp. 648-654, 2006. [Online]. Available: https://doi.org/10.1016/j.biombioe.2005.01.004
[37] W. Uttamaprakrom and T. Vitidsant, "Production of smokeless briquette charcoals from wet cake waste of ethanol industry," *Engineering Journal*, vol. 16, no. 2, pp. 5-18, 2012.
[38] J. S. Tumuluru, "Effect of pellet die diameter on density and durability of pellets made from high moisture woody and herbaceous biomass," *Carbon Resources Conversion*, vol. 1, no. 1, pp. 44-54, 2018. [Online]. Available: https://doi.org/10.1016/j.crcon.2018.06.002, 2018.
[39] M. Križan, K. Krištof, M. Angelovič, J. Jobbágy, and O. Urbanovičová, "Energy potential of densified biomass from maize straw in form of pellets and briquettes," *Agronomy Research*, vol. 16, no. 2, pp. 474-482, 2018. [Online]. Available: http://dx.doi.org/10.15159/ar.18.074
[40] A. C. Adetogun, K. M. Ogunjobi, and D. B. Are, "Combustion properties of briquettes produced from maize cob of different particle sizes," *JFEWR*, vol. 6, no. 1, pp. 18-38, 2014.
[41] S. S. Mir, S. M. N. Hasan, M. J. Hossain, and M. Hasan, "Chemical modification effect on the mechanical properties of coir fiber," *Engineering Journal*, vol. 16, no. 2, pp. 73-84, 2012.
[42] S. Suvunnapob, B. I. N. Ayudhya, and B. Kusuktham, "A study of cotton dust mixed with wood dust for bio-briquette fuel," *Engineering Journal*, vol. 19, no. 4, pp. 57-70, 2015.

[43] S. J. Mitchual, K. Frimpong-Mensah, N. A. Darkwa, and J. O. Akowuah, "Briquettes from maize cobs and Ceiba pentandra at room temperature and low compacting pressure without a binder," *Int. J. Energy Environ. Eng.*, vol. 4, 2013. [Online]. Available: https://doi.org/10.1186/2251-6832-4-38
[44] O. A. Oyelaran and Y. Y. Tudunwada, "Determination of the bio-energy potential of melon shell and corn cob briquette," *Iranica Journal of Energy and Environment*, vol. 6, no. 3, pp. 167-172, 2015.
[45] N. Tippayawong, P. Piboon, and T. Wongsiriamnuay, "Parametric analysis of co-pelletization of corncobs and algae at moderate conditions," in *Proceedings of the World Congress on Engineering*, 2017, vol. 2, LDN, pp. 891-895.
[46] O. Ghetti, L. Ricca, and L. Angelini, "Thermal analysis of biomass and corresponding pyrolysis products," *Fuel,* vol. 75, no. 5, pp. 565-573, 1996.
[47] C. Telmo, J. Lousada, and N. Moreira, "Bioresource technology proximate analysis, backward stepwise regression between gross calorific value, ultimate and chemical analysis of wood," *Bioresource Technology,* vol. 101, no. 11, pp. 3808-3815, 2010.
[48] M. F. Marcos, "Caracterización energética de la biomasa de chopo (Populus euramericana I-214) en turnos muy cortos," *Revista Energética,* XXI. ed. Omnimedia, 2006.
[49] M. Mladenovic, D. Dakic, S. Nemoda, M. Paprika, M. S. Komatina, B. Repić, and A. Erić, "The combustion of biomass—The impact of its types and combustion technologies on the emission of nitrogen oxide," *Hemijska industrija*, vol. 70, no. 3, pp. 287-298, 2016. [Online]. Available: https://doi.org/10.2298/HEMIND150409033M
[50] O. V. Roussak and H. Gesser, "Solid fuels," *in Applied Chemistry: A Textbook for Engineers and Technologists*. New York: Springer Science Business Media, 2013. [Online]. Available: https://doi.org/10.1007/978-1-4614-4262-2
[51] A. A. Khan, W. Jong, P. J. De Jansens, and H. Spliethoff, "Biomass combustion in fluidized bed boilers: Potential problems and remedies," *Fuel Processing Technology,* vol. 90, no. 1, pp. 21-50, 2008.
[52] P. Pintana and N. Tippayawong, "Predicting ash deposit tendency in thermal utilization of biomass," *Engineering Journal*, vol. 20, no. 5, pp. 15-24, 2016.
[53] A. Asonja, E. Desnica, and L. Radovanovic, "Energy efficiency analysis of corn cob used as a fuel," *Energy Sources, Part B: Economics, Planning, and Policy*, vol. 12, no. 1, pp. 1-7, 2017. [Online]. Available: https://doi.org/10.1080/15567249.2014.881931
[54] World Health Organization, *WHO Guidelines for Indoor Air Quality: Selected Pollutants*. Copenhagen: WHO, 2010.
[55] V. Kažimírová and R. Opáth, "Biomass combustion emissions," *Res. Agric. Eng.,* vol. 62, pp. 61–65, 2016.
[56] Z. X. Zhang, Z. F. Sun, Y. H. Zhang, H. Y. Ding, Y. G. Zhou, Y. X. Zhang, A. Riaz, P.-P. Crispin, and R. Dong, "Effects of biomass pellet composition on the thermal and emissions performances of a TLUD cooking stove," *Int. J. Agric & Biol. Eng.*, vol. 10, no. 4, pp. 189–197, 2017.