Pellets of *Hordeum vulgare*, *Pisum sativum* and *Vicia faba* agricultural biomass residues for bioenergy production

Kelly Caballero Melgarejo, Br.; Sheyli Lara Lumba, Br.; Danny Lizarzaburu Aguinaga, Dr.; Carlos Castañeda Olivera, Dr.; Eusterio Acosta Suasnabar, Dr.; Elmer Benites-Alfaro, Dr.
[1]Universidad César Vallejo, Lima: kellycaballeromelgarejo@gmail.com, sill.7261@gmail.com, dlizarzaburu@ucv.edu.pe, ccastanedaucv.edu.pe, eacostas@ucv.edu.pe, ebenitesa@ucv.edu.pe

Abstract*– Some agricultural activities generate a large amount of residues that are discarded during harvesting. In recent times, these vegetable biomass residues have been used as raw material in the production of bioenergy, with important environmental advantages. The objective of the research was the manufacture of pellets using as raw material residual biomass from the harvesting activity of the cereal Hordeum vulgare and the grain legumes Pisum sativum and Vicia faba. Manihot esculenta starch and stony endocarp of Carya illinoinensis were used as binders in the preparation of the pellets. Subsequently, the energy power and combustion capacity of the pellets and other characteristics were evaluated by analytical methods. It was found that Vicia faba pellets with Manihot esculenta (coded as HA+AY) had the highest calorific value of 11,534,720 kcal/kg; Hordeum vulgare pellets with Manihot esculenta (coded as CE+AY) presen ted better physicochemical character istics with 85. 086% volatile matter, 1.163% ash, 13.751% fixed carbon, 1.299 g/cm3 density and with 11,337.866 kcal/kg calorific value. The pellets with the best mechanical characteristics were those coded as HA+AY, which presented 0.17 kg/cm2 of compressive strength; likewise, for this same type of pellets it was found that in the combustion of the pellets for the boiling of half a liter of water, it was done in the shortest time (6 min). Therefore, it is feasible the use of this type of agricultural waste in the production of bioenergy within the efforts of environmental sustainability and circular economy, which reaches especially rural populations and low economic capacity.

***Keywords*— Pellets, Biomass, bioenergy, Hordeum vulgare, Pisum sativum and Vicia faba.**

I. INTRODUCTION

Given the current energy demand for fossil fuels, the use of agricultural waste pellets is an alternative, with advantages of easy processing, good mechanical strength and high calorific value, in addition to producing a change in the energy matrix, giving added value to the waste generated in the agro-industrial and food industries [1] as well as reducing the negative impact resulting from the indiscriminate use of natural resources in the form of firewood for cooking and heating [2], which with incomplete combustion cause damage to health [3]. A study indicates that the cost of this energy is economic [4], which is why clean energy projects are being promoted in developed countries using residual biomass from agriculture [5]. Pelletization allows conditioning the biomass as a pre-treatment for direct use in thermal processes due to the high humidity with low calorif ic value and low oxygen content [6], there are standardization and quality certif ication norms such as DIN 51731 and DIN plus [7].

In rural populations in Peru, such as the Huánuco region, agricultural activity produces residues during the harvesting of cereals and legumes such as barley (*Hordeum vulgare*), vetch (*Pisum sativum*) and beans (*Vicia faba*), residues that are generally used as animal feed, fertilizer or badly discarded. Cereals produced in Peru in 2018 were 5,644,208 tons [8], in 2019 280,000 t of legumes were produced [9] and therefore in parallel results in the generation of a large amount of waste.

In this context, the research aimed to elaborate pellets from residual biomass of *Hordeum vulgare, Pisum sativum and Vicia faba* using also in this process the natural binders starch of Manihot esculenta and stony endocarp of *Carya Illinoinensis*; also, the physicochemical properties and resistance to mechanical compression of the pellets were determined to identify the most optimal dosage of biomass components and binders

II. METHODOLOGY

In the preparation of the pellets, 15 kg of harvest residues (threshing) of *Hordeum vulgare, Pisum sativum and Vicia faba* residues were used. The process followed in the elaboration is shown in Fig. 1.

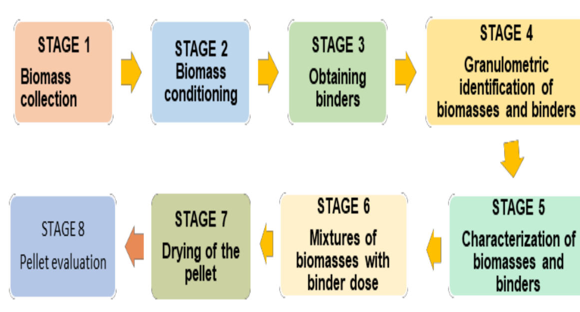

Fig. 1 Stages of the pellet production process

Stage 1: Harvest residues were obtained from crop fields in the town of Dos de Mayo - Huánuco.

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a b c

Fig.2 Biomass of: a) *Hordeum vulgare*, b) *Pisum sativum* y c) *Vicia faba*.

Stage 2: The cereal and grain legume biomasses were conditioned by drying at room temperature, chopping and grinding.

Stage 3: Natural binders were extracted from Manihot esculenta and stony endocarp of *Carya illinoinensis*. See Fig. 3 and 4.

Fig. 3 Manihot esculenta starch

Fig. 4 Stony endocarp of Carya illinoinensis

Stage 4: Granulometric preparation of cereal and legume residues, using 45 (0.355 mm), 20 (0.850 mm), 10 (2.00 mm) and 5 (4.00 mm) meshes (ASTM-422 method). For the natural binder of Carya illinoinensis stone endocarp, a 100 mesh (0.150 mm) was used and 60% was obtained and 40% was retained, using the passant.

Stage 5: Natural binders were characterized (physicochemical properties in laboratory, using potentiometric method (temperature, pH, electrical conductivity, redox potential), beveled cylinder method (density), ASTM D-2216(2010) /ISO 1170 method (for moisture), ASTM D-3175/2015 method (volatile matter), ASTM D-512/ 2015 (ash) and ASTM D3172-2015 (fixed carbon).

Stage 6: Mixtures of cerea l biomasses, legumes and binders were tested with water in a time determined a ccording to Table I. A mold was built to make pellets with dimensions 7.5 mm in diameter and 50 mm in length. An equipment with 2,000 kg of pressure was used for the compaction process, the pellets were obtained according to Fig. 5.

Fig. 5 *Vicia faba* biomass pellet

TABLE I
MIXTURE OF BIOMASS WITH DOSE OF BINDERS

Biomass	Biomass ratio (g)	binder ratio (g)		H_2O volume (ml)	Homogenization time (min)
		Manihot esculenta	*Carya illinoinensis*		
Hordeum vulgare	500	350	-	150	20
	500	-	350	150	20
Pisum sativum	500	350	-	150	20
	500	-	350	150	20
Vicia faba	500	350	-	150	20
	500	-	350	150	20

Stage 7: The granules were dried at room temperature for 15 days to release volatile material(water), see Fig.6.

Fig. 6 Dray pellets

Stage 8: The pellets were characterized, determining the resistance to mechanical compression, density and time of use for the boiling of wate (water boiling test).

III. RESULTS AND DISCUSSION

3.1 Biomass granulometric analysis

With the ground biomasses of *Hordeum vulgare*, *Pisum sativum* and *Vicia faba*, it was sieved with meshes 40, 30, 20, 10 and 5 (ASTM 422). With each biomass and using the different granulometries, pellets were manufactured, the same ones whose quality was evaluated, observing that the pellets manufactured with biomass at a 30 mesh granulometry were the most optimal for the three types of biomasses, for this reason the biomass was chosen in this mesh to manufacture pellets which were subjected to the corresponding characterization and tests. Table II shows the result of this 30 mesh granulometric separation of the biomasses. The scientific theory indicates that the grain size of the biomass is important to take into account for the production of pellets, so this process is very necessary in the conditioning of the biomass, in such a way that it allows its pelletization to be carried out. in the best way [6].

TABLE II
GRANULOMETRIC ANALYSIS OF BIOMASS AT OPTIMAL MESH

Type of biomass	Mesh	Opening (mm)	Retained Weight (g)	Retained (%)	Accumulated (%)	
					+ Retained	- past
Hordeum vulgare	N° 30	0.600	6.118	14.34	79.18	20.81
Pisum sativum	N° 30	0.600	5.633	13.43	68.35	31.64
Vicia faba	N° 30	0.600	6.635	11.80	80.49	19.50

3.2 Physicochemical characteristics of biomass and binders

Solutions of 50 g of biomass in 200 ml of water were prepared, and the physicochemical properties indicated in Table III were then determined. It is appreciated that they have a pH close to neutral, electrical conductivity and redox potentialthat varies accordingto the biomass or binder.

Likewise, the biomasses presented relatively low humidity, high percentage of volatile material, *Pisum sativum* and *Vicia faba* low percentage of ashes. These values were referential to predict the properties of the mixtures of biomass and binders in the elaboration of the pellets.

TABLE III
PHYSICOCHEMICALPARAMETERS OF BIOMASS AND BINDERS

Biomass and Code	Hydrogen potential (at 20.7 °C)	Electrical conductivity at 20.7 °C	Redox potential at 20.7 °C (m)	Density (g/cm^3)	Humidity (%)	Volatile Matter (%)	Ashes (%)	Fixed carbon (%)
Pisum sativum (AR)	5.71	3,004	110	0.157	11.65	83.61	4.11	12.28
Hordeum vulgare (CE)	5.77	1,540	80	0.126	9.87	89.38	10.61	0.01
Vicia faba (HA)	5.49	3,980	115	0.222	14.89	76.55	4.25	19.2
Manihot esculenta (AY)	6.46	645	61	-	40.87	9.74	0.04	90.22
Carya illinoinensis (CP)	5.46	1260	68	-	47.11	47.83	3.70	48.47

Likewise, the calorific power of the biomasses and binders used in the elaboration of the pellets, which is presented in Table IV, was determined. The calculation was made through Eq (1) using the data of ASTM factors, fixed carbon and volatile matter calculated in Table III.

$$\text{Calorific power} = (82 \times \%\ CF) + (120 \times \%\ MV)\ \text{Kcal/Kg} \quad (1)$$

It was determined that the biomass of *Pisum sativum* presented a higher calorific value, that is, it represents a greater increase in heat exchange towards another body. [10].

Fixed carbon is also an important indicator because it is an indicator that favours calorific value as opposed to the percentage of ash, which is unfavourable. [11].

TABLE IV
CALORIFYING CAPACITYOF BIOMASSES AND BINDERS

Type of biomass and binder	ASTM Factors	Volatile matter (%)	Fixed carbon (%)	Calorific power (kcal/kg)
Pisum sativum (AR)	82 %CF – 120 %MV	83.61	12.28	11,040.16
Hordeum vulgare (CE)	82 %CF – 120 %MV	89.38	0.01	10,726.54
Vicia faba (HA)	82 %CF – 120 %MV	76.55	19.2	10,760.40
Manihot esculenta (AY)	82 %CF – 120 %MV	9.74	90.22	8,566.64
Carya illinoinensis (CP)	82 %CF – 120 %MV	47.83	48.47	9,790.94

3.3 Physicochemical parameters of the mixture of biomass with natural binders for the production of pellets

The elaboration of the pellets followed the proportions indicated in Table I, making different combinations of biomass with binders at the same time. The physicochemical properties shown in Table V were determined for these mixtures, where it was found that for the binder starch of *Manihot esculenta* presented higher values of pH, electrical conductivity and redox potential than when stone endocarp of *Carya illinoinensis* was used. This pH in most of the pellet's mixtures was around 7 (neutral).

The moisture in the mixture favours pelleting, thus the highest value was obtained for the AR+AY mixture (*Pisum sativum* with *Manihot esculenta* starch) and for CE + CPE (*Hordeum vulgare* with *Carya illinoinensis* stone endocarp), which improves the cohesion of the material. The HA+AY mixture presented the highest percentage of volatile material (92,997) and the CE+AY mixture the lowest percentage (85,086), similar to wood pellets that have a range of 72 to 85% [12], facilitating rapid ignition to give move on to energy release.

The DIN 51731 pellet standard indicates for ashes in the range of 1.5%, the mixtures of biomass and binders in the research carried out gave the majority outside this range, this is justified by the high humidity of the biomass. Regarding the % of fixed carbon, the CE+AY mixture presented the highest value (13.751%) and HA+CPE the lowest (1.242%), this indicator is important because the higher the percentage, the higher the calorific value [12].

TABLE V
PHYSICOCHEMICALPARAMETERS OF THEMIXTURE OF BIOMASS AND BINDERS

Composition of the mixture of biomasses and binders	Hydrogen potential (1-14)	Electrical conductivity (µS/cm)	Redox potential (mV)	Humidity (%)	Volatile Matter (%)	Ashes (%)	Carbono fijo (%)
HA + AY	8.00 (a 20 °C)	3,650 (a 20 °C)	130 (a 20 °C)	69.23	90.589	1.313	8.098
AR + AY	7.68 (a 20 °C)	2,750 (a 20 °C	112 (a 20 °C	72.89	88.685	3.115	8.120
CE + AY	7.98 (a 20 °C)	2,200 (a 20 °C	118 (a 20 °C	71.52	*85.086*	*1.163*	13.751
HA + CPE	5.92 (a 20.8 °C)	1,613 (a 20.8 °C)	25 (a 20.8 °C)	56.59	92.997	5.761	1.242
AR + CPE	6.93 (a 20.8 °C	1,578 (a 20.8 °C)	55 (a 20.8 °C)	59.73	90.062	4.912	5.027
CE + CPE	7.21(a 20.8 °C	12,35 (a 20.8 °C)	102 (a 20.8 °C)	65.69	87.168	6.977	5.855

Where:
HA + AY: Biomass of *Vicia faba* + *Manihot esculenta*
AR + AY: Biomass of *Pisum sativum* + *Manihot esculenta*
CE + AY: Biomass of *Hordeum vulgare* + *Manihot esculenta*
HA + CPE: Biomass of *Vicia faba* + *Carya illinoinensis*
AR + CPE: Biomass of *Pisum sativum* + *Carya illinoinensis*
CE + CPE: Biomass of *Hordeum vulgare* + *Carya illinoinensis*

3.4 Calorific Power of Pellets

Determining the calorific value of the pellets, taking into account the biomass and binder mixtures, it was found that the pellet of the H A+AY mixture (biomass of *Vicia faba* and *Manihot esculenta*) presented the highest value (see Table VI); however, all the other pellets presented values higher than 4,302.1 kcal/kg (18 MJ/kg), as stipulated by the German DIN Plus Standard for pellets, which indicates that the calorific value cannot be lower than this value. A factor that has a negative effect on the calorific value is moisture, which should not be less than 10% [12], so moisture and calorific value are inversely proportional [13].

TABLE VI
CALORIFIC VALUE OF PELLETS FROM BIOMASS ANDBINDER MIXTURES

Pellet type: mixture of biomass with binders	ASTM Factors	Volatile matter (%)	Fixed carbon (%)	Calorific power (kcal/kg)
HA + AY	82 %CF – 120 %MV	90.5889	8.0982	11,534.7204
AR + AY	82 %CF – 120 %MV	88.6852	8.1996	11,314.5912
CE + AY	82 %CF – 120 %MV	85.0857	13.7510	11,337.866
HA + CPE	82 %CF – 120 %MV	92.9971	1.2416	11,261.4632
AR + CPE	82 %CF – 120 %MV	90.0621	5.0272	11,219.6824
CE + CPE	82 %CF – 120 %MV	87.1680	5.8553	10,940.2946

3.5 Characterization of pellets

The pellets as a final finished product presented the characteristics indicated in Table VII, for the six types of pellets, taking into account the composition (mixture of biomasses and binders). After 15 days of drying, 4 types of pellets already had moisture within the DIN 51731 Standard, which indicates that pellets should have moisture content lower than 12%, being the HA+ AY type the one that presented the lowest moisture content (9.4%). The density of the pellets complies with the DIM 51731 Standard (1 to 1.4 kg/cm3) [14], except for the HA+AY type pellets, which presented the lowest value; on the contrary, the best value corresponded to the CE+AY composition (*Hordeum vulgare + Manihot esculenta*). Density is an indicator that favours transport and storage.

It was found that the pellets type AR+CPE (*Pisum sativum + Carya illinoinensis*) had the highest value of compressive strength with 0.17 kg/cm2, probably due to good wetting, this characteristic known as hardness determined by a durometer indicates the limit force that the pellet resists before breaking, facilitating its transport [15].

TABLE VII
PHYSICOCHEMICAL CHARACTERISTICS OF PELLETS FROM THE MIXTURE OF BIOMASS AND BINDERS

Pellet type: mixture of biomass with binders	Pellets moisture after 15 days of drying (%)	Pellet density (g/cm3)	Compressive strength
HA + AY	9.4	0.810	0.028
AR + AY	11.3	1.009	0.062
CE + AY	15.4	1.299	0.091
HA + CPE	11.8	1.108	0.12
AR + CPE	12.5	1.168	0.17
CE + CPE	15.4	1.127	0.14

3.6 Boiling time of water with biomass pellets and natural binders

Table VIII shows the time used for boiling water (500 ml) using the six types of pellets dried at 15 days (water boiling test). It was determined that HA + AY (*Vicia faba + Manihot esculenta*) pellets boiled the water in less time (6 min), due to its high calorific value and lower humidity that favoured combustion (thermalefficiency)

TABLE VIII
WATER BOILING TIME BY COMBUSTION ACCORDING TO PELLET TYPE

Pellets type	Time (min)	Water temperature (°C)	Biomass temperature (°C)
HA + AY	6	100	402.5
AR + AY	8	100	308
CE + AY	10	100	274
HA + CPE	7	100	434
AR + CPE	9	100	285
CE + CPE	11	100	332

IV. CONCLUSIONS

It was determined that it is feasible to make biomass pellets from Hordeum vulgare, *Pisum sativum* and *Vicia faba* mixed with natural binders (Manihot esculenta starch and *Carya illinoinensis* stone endocarp), to aid in their compaction.

The pellets with the highest caloric power were those made from Vicia faba and *Manihot esculenta* starch binder (HA+AY), which reached 11,534.720 kcal/kg, meeting the standards of the German DIN 15731 norm for pellets; also, this type obtained the highest combustion and thermal efficiency by reaching the shortest t ime for the water boiling test with the time of 6 minutes.

In terms of mechanical compression characteristics, the pellets with the highest compressive strength were those made with *Pisum sativum* biomass with *Carya illinoinensis* stone endocarp binder (AR+CPE) with 0.17 kg/cm2. Therefore, the use of biomass is an alternative to change the energy matrix to a renewable and sustainable energy, while the use of this type of biomass residues from agricultural activity generates economic and environmentaladvantages.

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