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Application of the X-ray densitometry in the evaluation of the quality and mechanical properties of biomass pellets

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ABSTRACT

The use of the X-ray technique and the X-ray densitometry to determine pellet particle distribution and to understand the biomass compaction and its effects in pellet properties has been limited. The present work evaluates the quality of pellets manufactured with several lignocellulosic materials by using X-ray photography for studying surface cracks and irregularities, and by using X-ray densitometry to evaluate density and its variation in longitudinal and transversal directions. Density values and their variation were correlated to the pellets' mechanical properties (mechanical durability and compression resistance). It was found that X-ray photography may be applied to evaluate the presence of cracks and irregularities in the pellets' surface; however, these are not indicators of pellet durability or compression resistance. Moreover, density evaluation by the X-ray densitometry technique allowed the determination of the pellets' mechanical resistance and durability. A negative correlation was observed between the force at break and the coefficient of variation of density. No correlation was found between the mechanical durability and the average density or its variation. According to the above results, X-ray technique can be utilized to study the pellet quality.

1. Introduction

Biomass is one of the most promising energy sources since it is an alternative to conventional energy sources such as petroleum and natural gas. One of its main advantages is that it's a clean and renewable product, which contributes to the reduction of greenhouse gas emission effects and of dependency on fossil fuels [1].

Today, wood residues are the main raw materials used in pellet production [2–4]. Nevertheless, agricultural residues, energetic crops and other waste products from the food industry are being used, such as: corn, oil palm residues, and some potato and tapioca varieties, among others [3–6].

Pellets present some weaknesses, among which are their mechanical resistance and compaction, which result in manipulation and durability problems [7]. Pellet quality shall depend, among other things, on the efficacy of particle bonds [8]. In consequence, many studies have been carried out to examine the effects of some variables on pellet resistance and durability [8–10].

Some techniques have been implemented to evaluate pellet quality – compaction and durability–, of which scanning electron microscopy (SEM) is one of the most widely used. For example, Kaliyan and Morey [10] used this technique to determine the particles' internal distribution for different materials within the pellet. Meanwhile, Stelte et al. [3] found when using SEM, that the defects in pellets decrease particle cohesion in beech wood pellets. Furthermore, Reza et al. [11] argue that some pellets show an apparent development of a solid bridge that maintains particles joined, which makes it impossible to observe cracks in the pellet's surfaces.

Although the SEM technique is adequate to evaluate pellet quality, it has the disadvantage that it cannot be easily applied in a process. However, other techniques such as the X-ray and X-ray microCT, allow the evaluation of the material during the process instantly [12]. The X-ray technique is broadly used in diverse applications and material types. Several X-ray application methods are used for agriculture [12]. One of them is the X-ray photography, which is widely used as a tool to determine the spatial distribution of different solid phases or structures, for deformations, fatigues and fractures that result from the processing, as well as corrosion and environmental interactions [13,14].

This technique has been implemented for many years in solid wood and composite materials [15]. In solid wood for example, it is applied to determine the variability in density and ring growth [16]. In composite materials, including wooden ones such as fiberboards or particleboards, it is applied to estimate its performance [17]. It is also applied in other materials similar to wood. For example, Zhaohui et al. [18] use this same technique to determine the radial density variation profile of

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bamboo; while Belini et al. [19] use densitometry to evaluate the quality of medium density fiberboards (MDF).

However, implementing X-ray photography or X-ray densitometry to determine the distribution of pellet particles, or else to understand biomass compaction and its effects on pellet properties or briquettes, has been limited. One of the few studies was led by Ferreira et al. [20], who studied X-ray densitometry in briquettes made from wooden residues to determine whether their internal density had a homogeneous distribution, which would have an effect in briquette quality.

As a result, the present work evaluates pellet quality through visualizing the presence of surface cracks and surface pellet uniformity, and by using X-ray densitometry to determine density in twelve forestry and agricultural crops (*Cupressus lusitanica*, *Tectona grandis*, *Ananas comosus*, *Elaeis guineensis*, *Arundo donax*, *Gynerium sagittatum*, *Pennisetum purpureum*, *Sorghum bicolor*, *Phyllostachys aurea*, *Coffea arabica* and *Saccharum officinarum*) from Costa Rica. Likewise, density and its variability are correlated to pellet mechanical properties (durability and compression resistance) of the above-mentioned crops. These forestry and agricultural crops were chosen because they have gained popularity and technological adaptations to the pellet production process.

2. Materials and methods

2.1. Materials and source

Twelve crops growing in Costa Rica were selected to manufacture the pellets: 2 forest species and 10 agricultural crops. Table 1 presents the information for the twelve crops used. The raw materials were collected from representative area of crop plantation. A detailed description can be consulted in Aragón et al. [21] and Tenorio et al. [22].

2.2. Pellet manufacturing process

The pellet production process was conducted in PELLETICS S.A., in San Carlos, Alajuela province (Costa Rica). Fig. 1 presents the production process from the point where crops enter the processing plant and throughout the pellet production process. For the manufacture of pellets, the equipment and procedures already described by PELLETICS were used: the material was chipped in a JENZ chipper, model AZ 50, and later the milling was done using a fixed ring matrix with holes of 15 mm in diameter, KAHL brand. Afterwards, the granulate material was dried to reach 8 to 14% moisture content, using a rotary drum (12 m long × 3 m) and air-heated to 400 °C. Finally, the pelletizing process was performed in a KAHL machine, model 35780, consisting of a fixed ring matrix of 780 mm in diameter, with 6 mm diameter and 30 mm long holes, with three rotating rollers, which can reach a temperature of 120 °C during the process. The particle was from 2 to 4.5 mm. A detailed description of the process may be consulted in Aragón et al. [21].

2.3. Pellet preparation for densitometry measurements

The X-ray densitometry density measurement was performed in longitudinal and transversal directions (Fig. 2) on 10 randomly selected pellets for each crop. These pellets were adjusted to 12% moisture content (temperature at 22 °C and 66% relative humidity). Afterwards, weight, diameter and length of pellets were determined to calculate their actual density. For the densitometry measurement in longitudinal direction, pellet preparation was not necessary since these were placed directly in the X-ray equipment's bracket (Fig. 2a). In order to determine density in transversal direction, the 10 pellets were placed longitudinally on a base with two wooden supports (Fig. 2b), and then carefully cut into transversal sections of approximately 1.8 mm thick (Fig. 2c).

2.4. Densitometrical measurements

For the longitudinal direction measurement, 10 randomly selected pellets for each crop were placed horizontally on the bracket included with the X-ray equipment, where the X-ray source runs longitudinally through the sample. Thus, the X-ray photograph is obtained and the density profile determined. For densitometry in transversal direction, the pellet samples 1.8 mm thick were once again placed on the equipment's bracket to obtain the images and density readings. The exposure of the samples in longitudinal and transversal directions was performed using an X-ray scanner, from Quintek Measurement Systems Inc., QTRS-01X model. The exposure conditions were performed at 7 kV tension in the tube, and the density readings were carried out for 1 s every 40 μm.

2.5. Density variation and calculation by X-ray densitometry

Firstly, the pellet's actual average density was previously determined by measuring its weight, length and diameter (Eq. (1)) on 10 randomly selected pellets for each crop. Later, X-ray densitometry was used to determine the average pellet density (Eq. (2)). The density values calculated with the X-ray equipment were corrected with the correction factor (Eq. (3)), which is calculated by the difference between the average density of all measurements obtained by densitometry (Eq. (2)) and the actual average density of the pellet.

$$\text{Actual density} = \frac{\text{Pellet weight(kg)}}{\text{Pellet radius}\ (\text{m}^2) * \text{Pellet length}\ (\text{m}) * \pi} \tag{1}$$

$$\text{Average density by densitometry} = \frac{\sum_{i=1}^{n} x_i}{n} \tag{2}$$

$$\text{Correction factor} = \text{Average density by densitometry} - \text{Actual density} \tag{3}$$

where: x: density value for each measure, n: number of densitometrical pellet measurements and i represents the ith measurements. Correction factor was determined for each pellet sampled in all crops.

Table 1
Description and source of twelve crops used to manufacture pellets.

Crops	Scientific name	Precedence	Abbreviation
Sawlog residuals of *C. lusitanica*	*Cupressus lusitanica*	Agua Caliente, Cartago	CL
Sawlog residuals of *T. grandis*	*Tectona grandis*	Abangares, Guanacaste	TG
Pineapple leaves from the plant	*Ananas comosus*	Buenos Aires, Puntarenas	PLP
Empty fruit bunch of the oil palm	*Elaeis guineensis*	Parrita, Puntarenas	EFB
Oil palm mesocarp fiber of the fruit	*Elaeis guineensis*	Parrita, Puntarenas	OPMF
Giant cane	*Arundo donax*	Filadelfia, Guanacaste	AD
Wild cane	*Gynerium sagittatum*	Río Frío, Limón	GS
King grass	*Pennisetum purpureum*	Paraíso, Cartago	PP
Sorghum	*Sorghum bicolor*	Upala, Alajuela	SB
Golden bamboo	*Phyllostachys aurea*	Cartago, Cartago	PA
Coffee pulp	*Coffea arabica*	Tarrazú, San José	CA
Sugarcane	*Saccharum officinarum*	San Carlos, Alajuela	SO