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Pressure and specific energy requirements for densification of compost derived from swine solid fraction

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Abstract

Compost derived from swine solid fraction is a low density material (bulk density less than 500 kg m^{-3}). This makes it costly to transport from production sites to areas where it could be effectively utilized for value-added applications such as in soil fertilization. Densification is one possible way to enhance the storage and transportation of the compost. This study therefore investigates the effect of pressure (20-110 MPa) and pressure application time (5-120 s) on the compaction characteristics of compost derived from swine solid fraction. Two different types of material have been used: composted swine solid fraction derived from mechanical separation and compost obtained by mixing the first material with wood chips. Results obtained showed that both the pressure applied and the pressure application time significantly affect the density of the compacted samples; while the specific compression energy is significantly affected only by the pressure. Best predictor equations were developed to predict compact density and the specific compression energy required by the densification process. The specific compression energy values based on the results from this study (6-32 kJ kg^{-1}) were significantly lower than the specific energy required to manufacture pellets from biomass feedstock (typically 19-90 kJ kg^{-1}).

Additional key words: hydraulic press; density; swine manure; composting.

Introduction

In Italy pig farms produce approximately 17 million tons per year of slurry (Dinuccio *et al*., 2012). At the same time, specialization of livestock production has led to a concentration of animal production on large farms in restricted areas, a pattern found throughout Europe (Møller *et al*., 2000). In Italy 70% of the national livestock asset is concentrated in 5 regions in the north part of the country. In these areas slurry storage and land application is the predominant manure management practice (Pampuro *et al*., 2010) due to its simplicity, low cost and the possible reduction in crop production costs through the replacement of chemical fertilizers by manure nutrients (Kunz *et al*., 2009). This practice leads to water pollution through run-off, often culminating in fish kills, eutrophication, phosphate leaching and high ammonia losses to the atmosphere accompanied by serious odor problems causing a public nuisance (Rao *et al*., 2007).

In order to avoid environmental pollution several technologies have been recently developed. Among these techniques, solid-liquid separation of slurry is a common practice in Italy. It leads to a solid fraction rich in phosphorous and organic matter, and to a liquid fraction which is rich in soluble nitrogen (Fangueiro *et al*., 2012). The liquid fraction can be used in land application or reused on the farm as flushing water (García *et al*., 2009) and the solid fraction can be composted directly and/or co-composted with vegetable residues.

Composting is an aerobic process which involves the decomposition of organic matter under controlled temperature, moisture, oxygen and nutrient conditions (Nolan *et al*., 2011). Composting also implies organic matter deodorization and sanitization regarding weeds and pathogens. Indeed, composting is considered an environmentally acceptable method of waste treatment (Imbeach, 1998). Compost is a valuable product that can be distributed on land and used as a source of organic matter in agricultural soil (Ko *et al*., 2008). This practice improves the quality of the crops and preserves the environment (Benítez *et al*., 1998).

Compost derived from swine solid fraction is a low density material (bulk density less than 500 kg m^{-3} – Pampuro *et al*., 2012). This makes it costly to transport

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composted swine solid fraction from production sites to areas where it could be effectively utilized for value-added applications such as in soil fertilization.

One possible solution to these problems is densification of compost derived from swine solid fraction. Densification has been shown to increase the biomass bulk density from an initial bulk density of 40-200 kg m^{-3} to a final one more than 800 kg m^{-3} (Mani *et al*., 2003; Obernberger & Thek, 2004; McMullen *et al*., 2005). Thus, densification of biomass materials could reduce the costs of transportation, handling and storage (Kaliyan & Vance Morey, 2009; Miao *et al*., 2013). Generally, two techniques have been used for densification: tumble agglomeration and pressure agglomeration (Kaliyan & Vance Morey, 2009). In tumble agglomeration, agglomerates are formed during suitable movement of the particulate materials containing binder in equipment such as balling discs, balling cones and balling drums. In pressure agglomeration, high forces are applied to a mass of particulate materials within a confined volume to increase the density (Kaliyan & Vance Morey, 2009).

Traditionally, agricultural materials are densified into pellets, cubes and bales. Pellets are the densest of these agglomerates. Therefore, they require the highest amount of input energy (19-90 kJ kg^{-1}) during manufacturing (Tabil & Sokhansanj, 1996). This high energy input makes it uneconomical and impractical for pig farmers to purchase and operate a pellet mill. The manufacture of cubes uses lower pressure than pelletizing. Production of cubes is largely limited to forage crops such as alfalfa (Bernhart *et al*., 2010). Cubes are usually in the form of a square cross section (Sokhansanj & Wood, 1991), manufactured from chopped biomass and typically vary from 12.7 to 38.1 mm dimensionally (Sokhansanj & Turhollow, 2004). Baling is a process that combines compression and packing operations. It is typically used for grassy or fibrous-like materials that are stringy in nature (Bernhart *et al*., 2010). Compost derived from swine solid fraction is not stringy and therefore not suitable for baling.

Some previous work had been reported by Bernhart *et al*. (2010) and by Bernhart & Fasina (2009) on compaction of poultry litter. However, the authors were unable to find any literature on densification of compost derived from swine solid fraction. Therefore, the overall goal of this study was to investigate the densification process of compost derived from swine solid fraction for efficient transportation and off-site utilization. The specific objectives of this research were to study: (i) density-pressure relationship in densification of compost derived from swine solid fraction; (ii) specific energy required to compact compost derived from swine solid fraction at different pressure and at different pressure application time; and (iii) equations able to predict compact density and the specific compaction energy required to manufacture compacts from two composts derived from swine solid fraction.

Material and methods

Composting trial

The tests were carried out using two different types of compost: swine solid fraction compost (SSFC) and wood chips compost (WCC). The SSFC pile was obtained from composting 6,000 kg of swine solid fraction, while the WCC windrow resulted by mixing 8,000 kg of swine solid fraction with 2,400 kg of wood chips obtained processing residues from park maintenance. In both cases swine solid fraction was obtained from a screw press separator. For SSFC, C/N ratio was equal to 28 and therefore suitable to be composted. For WCC, materials were mixed in order to obtain a theoretical C/N ratio equal to 30 and to optimize the composting process development (Bernal *et al*., 2009). Composting of the two materials was carried out for 150 days. In order to prevent the dispersion of leachate generated during the composting trials, the piles were placed on a concrete floor covered by a coverture.

Temperature inside the heaps at 0.4 m, 0.8 m and 1.2 m high above the floor and of the surrounding air were continuously recorded. The decision to turn the composting piles was based on the temperature of the decomposing material. When the temperature of two of the three probes in the decomposing material was over 60°C, the pile was turned, as per Cáceres *et al*. (2006).

Sample preparation

The initial moisture content of SSFC and WCC were 51.1 and 49.6% (wb), respectively. The moisture content of the samples (mass of 10 kg for each compost type) was reduced to 10% by drying in an oven set to 50°C (Bernhart & Fasina, 2009). The samples were subsequently stored in plastic bags and kept in a cold room at 4°C for a minimum of 72 h (Adapa *et al*., 2009). The moisture content was determined using American

Society of Agricultural and Biological Engineers (ASABE) Standard S358.2 (ASABE, 2006), where oven drying of the samples was carried out at 103°C for 24 h. Only one moisture level of 10% (wb) was used and this was based upon literature review that at this moisture level, high density and quality pellets/briquettes were produced from various straw and biomass (Li & Liu, 2000; Obernberger & Thek, 2004; Mani *et al*., 2006; Adapa *et al*., 2009).

Bulk density

The initial bulk density of SSFC and WCC were 240 and 480 kg m^{-3}, respectively. The bulk density was determined using ASABE Standard S269.4 (ASABE, 2007). This method involves pouring the bulk solid into a cylindrical container with a diameter of 380 mm and an height of 495 mm (volume of 0.05615 m^3). The material was leveled across the top of the surface of the container and weighed. Mass per unit volume gave the bulk density of the biomass in kg m^{-3}. Bulk density measurements were repeated three times and the average value was reported.

Compression equipment

The press used to obtain the compressed material has two opposite hydraulic cylinders. The unit, fitted with an oil-hydraulic unit, can deliver up to 297 kN in a time variable from 0 to 210 seconds. The press can be equipped with different compressing chambers as needed. In order to obtain the test samples, a chamber with a diameter of 45 mm and a volume of 440 cm^3 was used.

Upper and lower cylinders are fitted with load cells (model TMT-HY-C/PS, max rated load 200 kN) that give signals proportional to the compressing force. The top of the plunger is connected with a potentiometric displacement sensor (model Gefran LT-M-0500-S 500 mm full stroke) giving the exact position and volume of the compressing chamber. The oil feed line has a pressure transducer (Gems sensor 3100 series, 0-250 bar). These signals are processed by a pc-based acquisition system (DS-NET with BR8 module) capable of acquiring up to 10 ks s^{-1}. For this application the sampling rate was fixed to 1 ks s^{-1}. All the collected data were recorded with properly configured software (Dewesoft 7.0) for post-processing operations.

Figure 1. Samples obtained applying 50 MPa for 40 s (SSFC on the left and WCC on the right).

Compression tests and energy calculations

The mass of samples used for making compacts was 55.00 g. Four preset pressures of 20, 50, 80 and 110 MPa corresponding to loads of 31.5, 62.3, 126.1 and 173.4 kN, were used to compress samples in the chamber. Five applications times (5, 10, 40, 90 and 120 s) for each pressure level were applied during densification process. For each material every combination of pressure and time was carried out with five replications (Fig. 1).

After compression, the base plate was removed and the compact was ejected out of the chamber by using the plunger. A digital caliper was used to measure the length and the diameter, while a digital balance accurate to 0.01 g was used to measure the mass of densified material. The densities of the samples were calculated from the ratio of mass to volume (obtained from length and diameter measurements).

During the compression of individual compacts, force-displacement data were recorded. Specific compression energy (SCE) was calculated following the methodology of Adapa *et al*. (2006) and Mani *et al*. (2006). The area under the force-displacement curve was integrated using the trapezoid rule (Santamarta *et al*., 2012); when combined with the briquette mass, it yielded the specific energy values in kJ kg^{-1}.

Data analysis

Regression analysis was performed using the proc reg function in SPSS statistical software package (Version 17.0) and plotted with the experimental data using Microsoft Excel (Microsoft Office 2007). Significance testing was carried out using one way analysis of variance (ANOVA) in the SPSS statistical package.

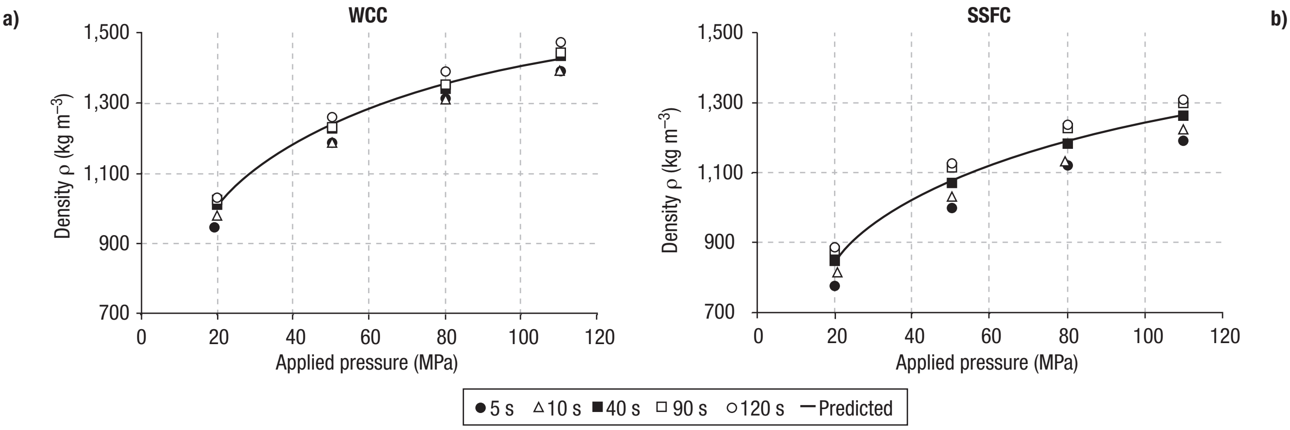

Figure 2. Effect of pressure and pressure application time on the density of WCC (a) and SSFC (b).

Results

Compact density

The pressure application time in the compression process has a highly significant effect on the density as well as the maximum applied pressure ($p < 0.05$). The interaction between the two parameters is not significant ($p > 0.05$).

For WCC the increase in density was significant ($p < 0.05$) for an increase of pressure application time from 10 to 40 s and from 90 to 120 s. For SSFC the increase in density was significant ($p < 0.05$) for an increase of pressure application time from 5 to 10 s, 10 to 40 s and from 40 to 90 s.

Results from the experiments showed that average density values ranged from 1,001 to 1,435 kg m^{-3} and from 843 to 1,259 kg m^{-3} for WCC and the SSFC respectively, upon application of pressure in the range of 20-120 MPa (Fig. 2).

For each pressure level applied, WCC showed density values significantly ($p < 0.05$) higher than SSFC (Fig. 3).

This could be due to the presence of a bulking material (wood chips) that has initial density values greater than the swine solid fraction as it is.

Eqs. [1] and [2] were fitted to the experimental density values as a function of pressure application time (t) and pressure (p) for WCC and SSFC, respectively.

$$\rho_{compact} = 179 + 0.5 * t + 260.1 * \ln(p) \quad R^2 = 0.996 \qquad [1]$$
$$5\ s \le t \le 120\ s;\ 20\ MPa \le p \le 120\ MPa$$

$$\rho_{compact} = 52 + 0.93 * t + 247 * \ln(p) \quad R^2 = 0.995 \qquad [2]$$
$$5\ s \le t \le 120\ s;\ 20\ MPa \le p \le 120\ MPa$$

Specific compression energy requirement

The ANOVA showed no significant ($p > 0.05$) effect of pressure application time on specific compression energy consumption.

Fig. 4 shows the relationship between the applied pressure and the specific compression energy to form the WCC and SSFC briquettes.

For applied pressures of 20, 50, 80 and 110 MPa the average specific compression energy required to form the briquettes was equal to 5.6, 12.7, 19.2 and 24.9 kJ kg^{-1} for WCC and 9.0, 17.9, 25.4 and 32.2 kJ kg^{-1} for SSFC.

For each pressure level applied, WCC showed specific compression energy values significantly ($p < 0.05$) lower than SSFC (Fig. 5). This could be due to the effect of the composting process that leads to a weakening of the wood fires, compared to the swine manure, causing different energy adsorption (Fig. 6).

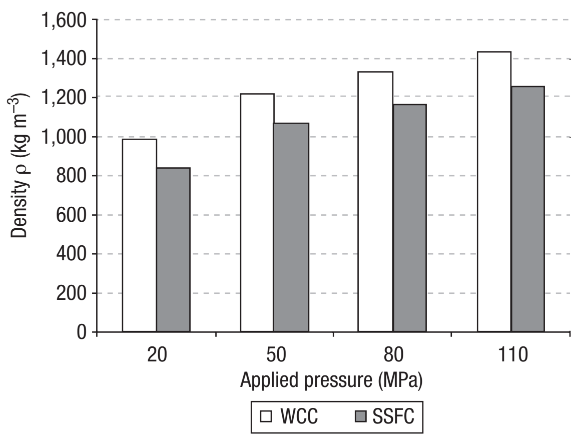

Figure 3. Average density values (kg m^{-3}) of WCC and SSFC obtained using different pressure levels (20, 50, 80 and 110 MPa).

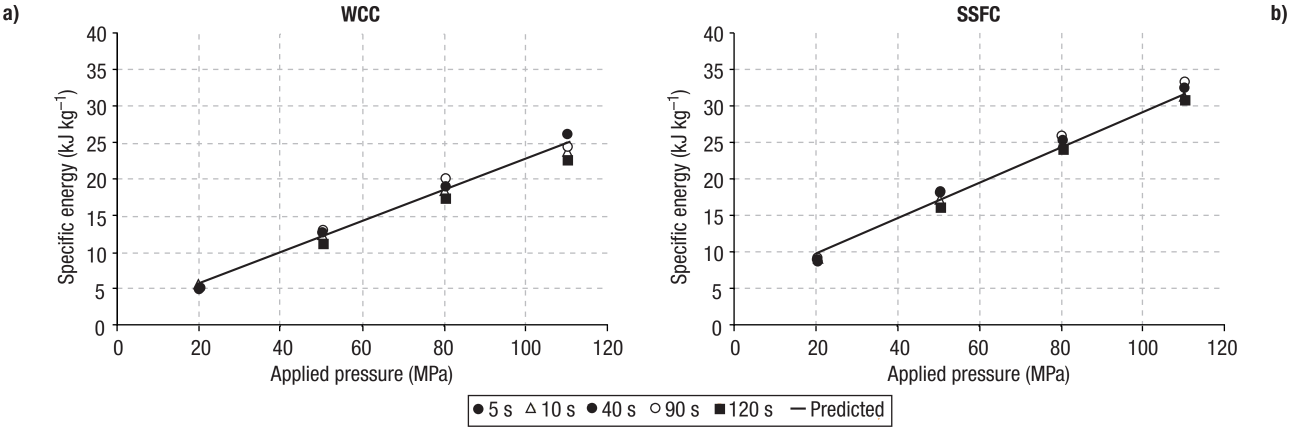

Figure 4. Relationship between applied pressure and specific compression energy to form the WCC (a) and SSFC (b) briquettes (pressure range 20-110 MPa).

For both materials there is a linear relationship between pressure and specific compression energy (SCE) following the Eqs. [3] (WCC) and [4] (SSFC).

$$SCE_{WCC} = 0.2124 * p + 1.666 \quad R^2 = 0.980 \quad 20 \text{ MPa} \leq p \leq 120 \text{ MPa} \quad [3]$$

$$SCE_{SSFC} = 0.254 * p + 4.694 \quad R^2 = 0.962 \quad 20 \text{ MPa} \leq p \leq 120 \text{ MPa} \quad [4]$$

Fig. 7 shows the relationship between specific compression energy and density of the densified samples. For each density value obtained, SSFC showed specific compression energy values significantly ($p < 0.05$) higher than WCC (Fig. 7).

For WCC and SSFC there is a non linear relationship between $\rho_{compact}$ and SCE that can be explained with a exponential equation reported as follows:

$$SCE_{WCC} = 0.186\ e^{0.0034 \cdot \rho_{compact}} \quad R^2 = 0.987 \quad 950 \text{ kg m}^{-3} \leq \rho_{compact} \leq 1{,}450 \text{ kg m}^{-3} \quad [5]$$

$$SCE_{SSFC} = 0.735\ e^{0.0030 \cdot \rho_{compact}} \quad R^2 = 0.956 \quad 800 \text{ kg m}^{-3} \leq \rho_{compact} \leq 1{,}300 \text{ kg m}^{-3} \quad [6]$$

Discussion

Previous studies conducted by Demirbas (1999) have shown a logarithmic relationship between applied pressure and resulting density of briquettes manufactured from waste paper and wheat straw mixtures and applied pressure. Even though considerably higher pressures were used in that study (300-800 MPa), the briquette densities obtained (50-850 kg m^{-3}) were lower than the densities obtained in this study. We sus-

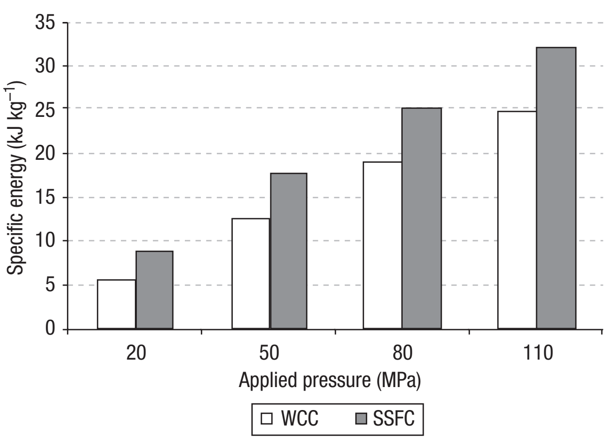

Figure 5. Average specific compression energy values (kJ kg^{-1}) required for densification of WCC and SSFC obtained using different pressure levels (20, 50, 80 and 110 MPa).

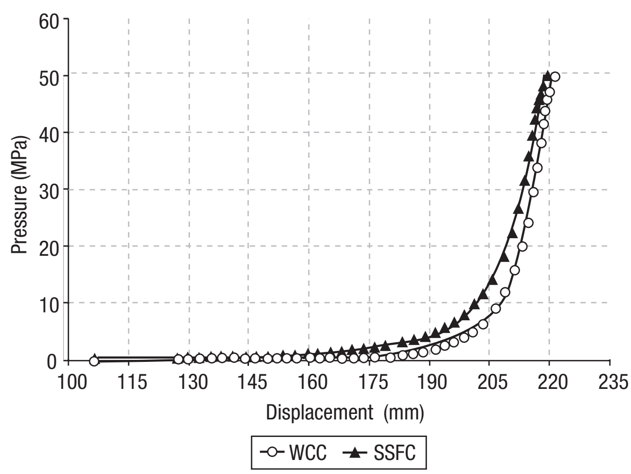

Figure 6. Force-displacement plot comparison between SSFC and WCC obtained applying 50 MPa for 40 s.

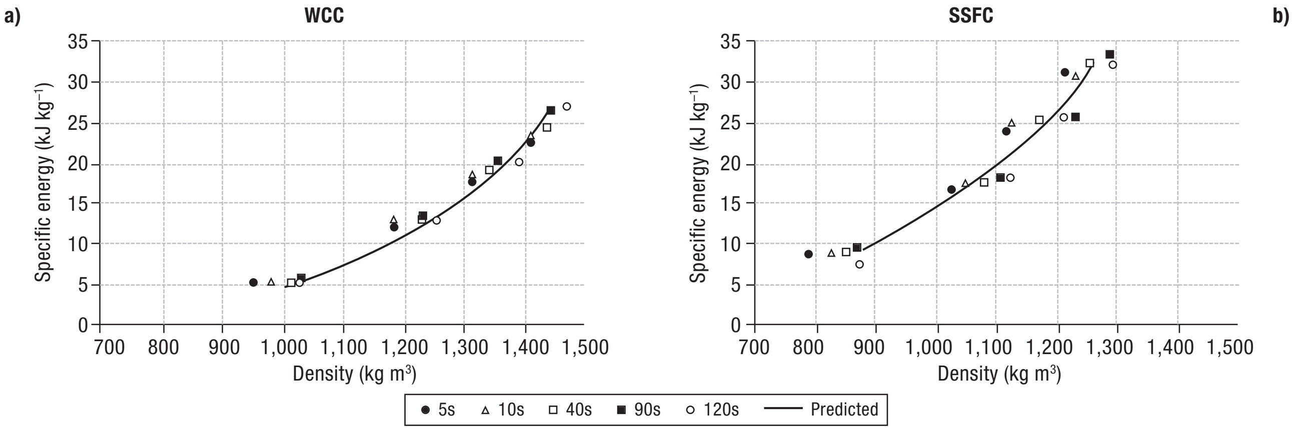

Figure 7. Relationship between specific compression energy and density to form the WCC (a) and SSFC (b) briquettes.

pect this is due to the different properties of the materials under test.

Adapa *et al.* (2009) during pellettization of different types of straw, found a polynomial relationship between applied pressure and resulting density. The mean densities of barley, canola, oat and wheat straw compacts increased from 907 to 988 kg m^{-3}, 823 to 1,003 kg m^{-3}, 849 to 1,011 kg m^{-3} and 813 to 924 kg m^{-3}, respectively, upon application of pressure in the range of 31.6-138.9 MPa. Although the moisture level of 10% (wb) used by Adapa *et al.* (2009) was equal to the moisture content used in this study, we have obtained higher density values applying pressure levels of 20-110 MPa. This could be due to the different characteristics of the densification process investigated.

The specific compaction energy values found in this study were considerably higher than those found by Bernhart *et al*. (2010) during the compaction tests of poultry litter. The two main reasons for this difference were that the densities reached by Bernhart *et al*. (2010) were much lower than the densities found for this work and the moisture content of poultry litter was substantially higher.

The specific compression energies calculated for the densification of compost derived from swine solid fraction were lower than the values found by Santamarta *et al*. (2012). Using a moisture content of 10.76% and an applied pressure of 47.7 MPa, the specific energy required to form the oilseed rape (OSR) straw briquettes was 24.95 kJ kg^{-1}, compared to 12.7 and 17.9 kJ kg^{-1} used to produce WCC and SSFC briquettes, respectively, when the applied pressure was 50.0 MPa and the moisture content was 10%.

Moreover the average specific compression energy values found with this trial were lower than the specific energy required to manufacture pellets from biomass feedstock (typically 19-90 kJ kg^{-1}; Colley *et al*., 2006).

As stated by Mani *et al*. (2004), the energy requirements depend mainly upon the applied pressure and moisture content, but also on the physical properties of the material and the method of compaction.

It can be concluded that the pressure agglomeration process is more efficient than the pelletization process – the specific energy values obtained were significantly lower and the final density values were higher when applying the same compaction pressure level. The results from this study could be used in the design of economical and simple on-farm pressure agglomeration equipment.

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