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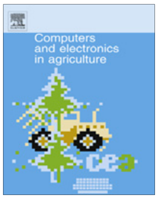

Image-based comparison between a γ-ray scanner and a dual-sensor penetrometer technique for visual assessment of bale density distribution

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ABSTRACT

There is an increasing desire to have an insight into the density distribution of silage bales because a low initial air content can significantly reduce the risk of temperature rise and the loss of sugar content. In addition, biomass moisture also plays a determinant role in the risk of temperature rise of bale and biomass degradation. For the visual assessment of the bale density, γ-ray scanner is regarded as an accurate and reliable technique but has potential risk of exposure to radiation. This study proposed a practical technique using a dual-sensor penetrometer for the simultaneous measurements of penetration resistance (PR) and moisture content (MC) in conjunction with image-based analysis. Four round bales made by two types of balers were prepared for the test. During a measurement process, both MC and PR data were collected following the signal of a penetrating depth transducer in-phase. Each bale included 72 penetration measurements that were transformed into an image referring to either PR or MC, respectively. With the reference to the two-dimensional (2D) results obtained from a γ-ray scanner, the dual-sensor images revealed the similar discrepancies of the baled density. Moreover, the proposed dual-sensor penetrometer method could discover the density discrepancies from the different sections of the measured bale so that the visualizations in three-dimensional (3D) space were also feasible. In contrast, the MC sensor seemed more reliable since the PR measurements were relatively susceptible to the interference from the penetrating friction between the shaft wall and material.

1. Introduction

There are a number of silage production processes such as round/square bales, tower and bunkers used for the preservation of forage. Of these, the bale silage is an optimal choice for reducing harvest and post-harvest losses of biomass materials, controlling fermentation quality of ensiling and remaining safety storage of forage.

To investigate the ensiling quality, previous studies focused on variety of factors concerning chop length, packed density, the moisture content (MC) of biomass, layer thickness and harvesting time (Messer and Hawkins, 1977a,b; Pitt and Gebremedhin, 1989; Coblentz et al., 2000; Han et al., 2004). Among these factors, the packed density is particularly important because a lower density means a higher porosity (Bernier-Roy et al., 2001; Toruk et al., 2009), which could result in a longer aerobic phase and induce spontaneous heating within the bale. Besides, the biomass MC is also a complicated factor affecting the silage quality. For example, if the biomass MC is high, antioxidant bacteria may be more active in a high-density bale than a regular one to rise temperature and degrade biomass. However, temperature may not be increased significantly, when biomass is very dry, even for a high- density bale. In general, for a ensilage process that both factors were not in optimal, dry matter (DM) and sugar content of the silage could be reduced (Muck and Holmes, 2000; Roy et al., 2001). Indeed, Ruppel et al. (1995) found that over a storage period of six-month the DM loss for the chopped corn increased from 10% to 20% as the packed density reduced from 320 to 160 kg m^{-3}.

Theoretically, an ideal bale should be uniformly packed with a high density (Ross et al., 2008). However, until now none of ideal methods has been found to satisfactorily assess the packed bale density. For example, gross density (GD, kg m^{-3}) was calculated from the packed mass and the volume of bale but unable to show density discrepancies within the bale. The recent studies verified the γ-ray scanner to be an effective tool for the visual assessment of packing quality in 2D space (Fuerll et al., 2008; Mumme and Katzameryer, 2008). This instrument initially was equipped with a Cesium-137 spot scanner (258 MBq activity), and subsequently replaced a similar model but with a total activity of 5550 MBq, thereby significantly improved the measurement accuracy (error < ±1%) for characterizing bales compaction with rather

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higher wet densities (>700 kg m^{-3}). However, according to the knowledge of nuclear physics, Cesium-137 beta decays into Barium-137 emitting gamma ray, and then becomes stable. That is, what makes Cesium-137 a dangerous isotope is the gamma ray from its product, Barium-137. Just as the authors pointed out, the half-life-period of the nuclide in this situation had to be taken into account due to so high gamma activity (Mumme and Katzameryer, 2008). Since the potential risk of exposure to radiation restricted its wide application, Sun et al. (2010) proposed a new method using a conventional penetrometer technique to create a digitalized image. In their preliminary study PR data and the penetrating depths were transformed into a density discrepancy image, but no comparative study was undertaken with a reference method to verify their proposed method, and the measurement for the biomass MC was just ignored.

It is known that all plant-based materials are hygroscopic and MC within bale exists in different phases. At low levels of relative humidity (RH) of air in local space, water vapor molecules inside bale 'cling' to the pore walls, in a phase called molecular adsorption. As the air RH increases the water molecules will 'clump' together and begin to fill the pores and form layers on the capillaries, starting the phase called capillary condensation (Carfrae et al., 2011). Because exceed MC on these packed materials (hay, straw and cotton) can resulting in the decay of bales, diverse sensor techniques have been explored for the MC measurement (Byler et al., 2003; Goodhew et al., 2004; Carfrae et al. 2011). These techniques are grouped as resistance-, voltage- and capacitance-based methods (Nady and Saïd, 2007). Rather than directly determining the MC of plant-based materials, some studies focused on the relationship between the MC of these materials and the RH of air inside bales so that the different models were also established (Hedlin, 1967; Lawrence et al., 2009).

For the requirement of field survey, a novel measurement technique, called dual-sensor penetrometer, was devised and then successfully used to simultaneously determine soil MC and PR profiles (Sun et al., 2004). Whether this novel technique can be similarly applied to determine the packed density of bale silage, it is worthy testing. Thus, followed our preliminary study (Sun et al., 2010), both the developed dual-sensor penetrometer and the γ-ray methods were used in this study. The former yields image-based results relating to the biomass MC and the PR distributions inside bale, and the latter acted as an accurate reference to assess the dual-sensor penetrometer method. To provide different testing samples for the results analysis, four bales were packed by two types of balers.

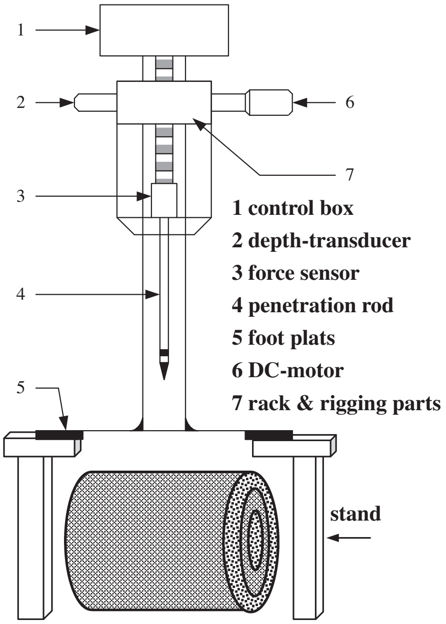

Fig. 1. Schematic diagram of bale density measurement using dual-sensor penetrometer.

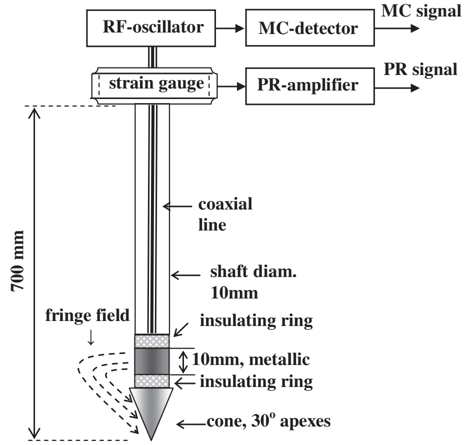

Fig. 2. Configuration of dual-sensor cone.

2. Materials and methods

2.1. Dual-sensor penetrometer

The proposed bale density measurement using the penetrometer technique is shown in a schematic diagram (Fig. 1). This penetrometer had a MC sensing cone that could simultaneously determine MC and PR during a penetration process (Sun et al., 2004). The measurement principal of the MC sensor is based on the fact that the relative dielectric permittivity of free water ($\varepsilon_{water}/\varepsilon_0 \approx 81$) is greater than that of dried biomass materials ($\varepsilon_{wood}/\varepsilon_0 \approx 3$) and that of air ($\varepsilon_{air}/\varepsilon_0 = 1$). Therefore MC could be indirectly estimated by determining the dielectric property of biomass materials after harvested. Fig. 2 shows that two electrodes (a cone with 30° apexes and a metallic ring) in conjunction with a pair of insulating rings were embedded into the penetration cone. Considering the penetration friction between the shaft and the measured soils, the maximum diameter of the cone (12.83 mm) was slightly larger than that (9.53 mm) of shaft (ASABE Standards, 2009). In addition, a segment of coaxial line cable through the center of penetration shaft connected both electrodes to an RF-oscillator (100 MHz). The output signal referred to a differential voltage between a pair of wave-detectors. For the measurement principle of the MC sensor, it depended on the fringe-effect field across the two electrodes and the relative dielectric permittivity of the biomass material, which varied due to the ratio of water to the volume of dry matter. That is, the reading of the MC sensor was in terms of the volumetric MC (θ_v, cm^3 cm^{-3}) surrounding the measured material, which is defined as

$$\theta_v = \rho\theta_g \qquad (1)$$

where ρ is the packed density (g cm^{-3} or kg m^{-3}) and θ_g (g g^{-1}), the gravimetric MC of the measured material, is determined by

$$\theta_g = \frac{M_w - M_d}{M_d} \qquad (2)$$

where M_w (g) and M_d (g) are the mass of wet and dried materials, respectively. Eq. (1) implies that either ρ or θ_g can alter the reading of the MC sensor, such that