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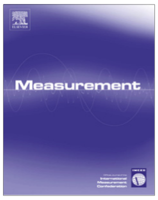

Mapping oxygen-induced temperature patterns of round bale silage based on 3D stepwise-profiling measurement

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ABSTRACT

Abnormal rise of temperature in silage is regarded as a signal of aerobic deterioration caused by the permeation of atmospheric oxygen into the silage, which indicates the growth of lactate-assimilating yeasts and energy release. Although baled silage has distinct advantages over other forms of silage, the high surface-area to volume ratio of the bale leads to a high risk of aerobic deterioration due to plastic cover damage. With an objective to spatially assess any aerobic deterioration within round-bales silage, we modified a bale-penetrometer that is capable of profiling temperature distribution. For each tested bale having a cylindrical volume of 2.154 m^3, 72 path profiles including 504 stepwise measurements were made. Furthermore, two paths were re-profiled to check if the proposed invasive method has a significantly contaminative effect on the internal temperature field. The resulting $R^2 = 0.9978$ between the profiling data and the re-profiling data verified that the contamination due to the invasion of ambient air following the temperature probe penetration could be negligible. We presented two mapping methods, one for two-dimensional (2D) cross-sections and one for three-dimensional (3D) volumes. To demonstrate the applicability of the proposed method, six representative samples of round bales with varied damage to plastic covers were tested. All temperature patterns, generated in both 2D- and 3D-space, were informative and clearly interpretable. Therefore, we conclude that the tested measurement method can benefit advance of bale silage research and production.

1. Introduction

Silage is a high quality feed-supplement for ruminants in developed countries [1,2]. Bale silage production increases the efficiency of storage capacity by reducing the unit cost of storage [3], provides farmers more long-term flexibility in feeding [1] and can significantly reduce the harvest and post-harvest losses of biomass [4]. Due to these advantages, nowadays bale silage has become increasingly attractive in China. However, two adverse factors make bales vulnerable to aerobic deterioration. One is the high surface-area to volume ratio of the bale, thereby increasing the risk of damage to the plastic film [4–6]. The other factor is longer chop-length, which can result in a relatively low packing density [4,7,8].

Aerobic deterioration in silage is primarily initiated by either acetic acid bacteria or yeast, or by both acting

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together [9]. The degree of deterioration can be diagnosed through biochemical or microbiological or physical indices, such as concentration of oxygen (O_2) against that of carbon dioxide (CO_2) [10,11], growths of microorganisms [12] and abnormal rises of internal temperature [1,11] and pH [13,14]. Generally, the abnormal variations of these parameters may be an alarm that O_2 may have penetrated the ensiled silage, leading to aerobic decomposition and energy release.

Of sensing aerobic deterioration, even though diverse O_2 sensors and CO_2 sensors have been commercially available, very limited applications have been found in monitoring silage production [15]. Several reasons have to be considered including the fact that silage belongs to a type of porous biomaterials so that either composition or concentration of gas varies with the porosity/density of the silage [4]. Second, the acidic liquids within silage may cause corrosion and damage to the sensors [1]. Additionally, the high costs of these sensors, including pH sensors, restrict practical applications. In contrast, temperature sensors have high accuracy and reliability with considerably low cost. Therefore, silage temperature has become a common index for monitoring silage safety. However, the O_2-induced rise of temperature inside silage is highly variable over time and also spatially dependent [13]. Previous studies have only provided time-courses of silage temperature based on single-point measurement or the mean value of multiple points [1,11,13,16]. The map-based characterization of temperature distribution inside silage remains scarcity due to the technical bottle-neck for non-disturbed measurements in two- dimensional (2D) or three-dimensional (3D) space. Certainly, the available combined results of temporal and spatial variations of temperature will provide a comprehensive and precise estimation of the rate and severity of aerobic deterioration occurring in silage. The major objectives of this study include: (i) to present a stepwise-profiling sensing apparatus modified from a bale-penetrometer for spatially measuring the silage temperature field within round bales, and (ii) to visualize the O_2-induced temperature field redistributions in 2D or 3D space by the silage temperature data sets from a group of round bales with various types of damage to the plastic films housing the bales.

2. Materials and methods

2.1. Sampling network and temperature measurement method

For 3D-based temperature measurements within the bale silage, a sampling network was constructed, as shown in Fig. 1, where each node corresponds with an orientated point of temperature measurement within a cylindrical volume. Consequently, an array of data set in 3D space was achieved after each bale was measured. According to Fig. 1, the temperature probe should be able to reach any point inside the round bale. More importantly, the temperature measurement should prevent the bale from any ambient air when the probe enters the bale; otherwise the temperature field is disturbed. To avoid this contamination, a tiny thermocouple sensor (T-type, −200 to 350 °C, copper vs. copper–nickel, resolution: ±0.1 °C) was integrated into a cone (Fig. 2) of a bale penetrometer (Fig. 3), which was previously designed for measuring bale compaction [17]. As the probe goes stepwise into the bale, the packed grass deformed inward around the shaft and rubbed against probe because of the strongly elastic property of the grass packed in the bale [8,18]. Immediately after the probe was withdrawn out of the bale, each hole was sealed with adhesive tape to insure the bale remained air-tight. In addition, when whole profiling measurements were completed for each bale, two of all paths were re-profiled (denoted with pink arrows in the left column of Fig. 5) to assess the contaminative effect on the measurements. The data of the first stepwise profiling measurements and the re-profiled ones were compared statistically using regression analysis. If there is a high correlation between them, it confirms that the elasticity of the grass bale (which mainly depends on the packed density and the particle size of grass) can substantially reduce the air gaps created by the penetration shaft, preventing the measured bale from the ambient air invasion during the temperature profiling process, and therefore the achieved data sets are credible for digital mapping.

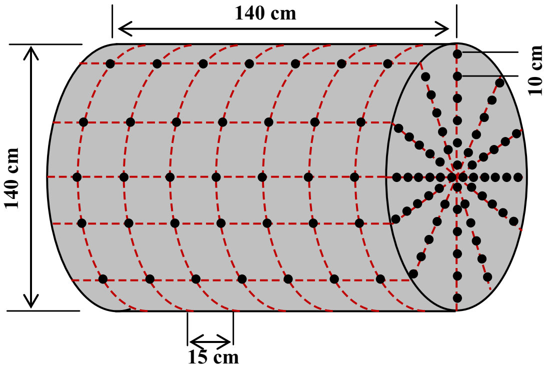

Fig. 1. Schematic diagram of the sampling network within a measured round bale. The maximum penetration of the probe is approximately 70 cm.

2.2. Experimental bench for round bale

As shown in Fig. 3, a bale rests on the platform of the penetrometer test bench, which has six driven rollers (diameter: 100 mm) with a corrugated surface. By the aid of a guiding roller (diameter: 100 mm, freewheeling) across the side-frame, these driven rollers are able to rotate the bale with sufficient friction force against slipping and meanwhile avoid damage to the plastic film wrapping the bale because of no sharp-edged contact between them. The power for the driven rollers is generated from an AC-motor via a chain-sprocket mechanism. An optical encoder (RE-38, ANGTRON, China, operating supply: 5 V) that generates 2048 pulses per revolution is used to track the rotational angle of the bale. By counting/controlling the numbers of pulse, desired rotational angles are available. Fig. 3b and c demonstrated the penetrating