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Review

Air filled porosity measurements by air pycnometry in the composting process: A review and a correlation analysis

Luz Ruggieri, Teresa Gea, Adriana Artola, Antoni Sánchez *

Composting Research Group, Department of Chemical Engineering, Escola Tècnica Superior d'Enginyeria, Universitat Autònoma de Barcelona, Campus Bellaterra, Cerdanyola, 08193 Barcelona, Spain

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ABSTRACT

Air filled porosity (AFP) appears as the best measure to determine the available porosity in a composting material or, in general, in an organic matrix. Several methodologies, including theoretical and empirical approaches have been developed to estimate AFP. Among them, air pycnometry has been considered the most suitable and accurate technique to obtain reliable measures of AFP. In this review, the published methodologies to determine AFP by air pycnometry are explained in detail, and the main advantages and disadvantages of such methodologies are discussed. Also, a massive sampling of several organic wastes and mixtures intended for composting has been characterized by air pycnometry, and the theoretical and empirical correlations proposed in literature are compared in terms of accuracy in AFP measurement. Results obtained show that some theoretical correlations are suitable for estimating AFP in the majority of organic wastes studied. However, some waste samples need an experimental determination to obtain a realistic value of AFP.

1. Introduction

Composting is an aerobic biotechnological process by which different microbial communities initially degrade organic matter in solid substrates into simpler nutrients, carbon dioxide and water. In a second stage known as maturation, complex organic macromolecules such as humic acids are formed, producing an organic fertilizer named compost (Hsu and Lo, 1999). The process begins with the selection of the materials to be composted and several factors must be taken into account regarding the nature of these materials in order to obtain good quality compost. These factors are referred mostly to the physical properties that play an important role in every stage of compost production as well as in the handling and the utilization of the end product (Agnew and Leonard, 2003). The most studied physical properties of the composting materials are water content, water holding capacity, bulk density (BD), porosity (ε) and air filled porosity (AFP, also known as free air space, FAS). These parameters depend on each other since the beginning of the process, and a deep knowledge of them is needed for a correct performance of the process. Water and oxygen content of a composting matrix are determining factors for the biological activity of the microorganisms involved and their availability is intrinsically related to the total and the AFP (Haug, 1993). The air content and air movement through the composting material is important to maintain an optimum oxygen concentration, to remove carbon dioxide and excess moisture, and to limit excessive heat accumulation (Haug, 1993). Maintaining adequate AFP levels satisfies the air content and pore continuity levels required to achieve desired composting conditions (Agnew et al., 2003).

As cited by Oppenheimer et al. (1997), there exist different methods for measuring solid matrix AFP like the specific gravity bottle, water retention apparatus, paraffin wax method and particle density method. All these methods are tedious and time consuming. Due to the fact that these methods were originally designed for soil characterization, they are non-appropriate for solid wastes and compost AFP determination because they use few quantities of material, which usually does not provide a representative value for a heterogeneous composting matrix.

Other methods in use in the composting field are water pycnometry (Annan and White, 1998), and water saturation and draining procedures (US Department of Agriculture and US Compost Council, 1997); which were found to be more accurate than the methods mentioned above (Oppenheimer et al., 1997). Some negative implications of these methods have been described such as air entrapment (Annan and White, 1998), the fact that some substances can react or interact with water (Tamari, 2004) and the destruction of the sample during the analysis. On the contrary, the kerosene particle density methodology was developed for organic soils and avoids the swelling and the volume increase of organic particles that occurs in contact with water (Barrington et al., 2002). This method is precise although it presents some drawbacks such as the destruction of the sample, the manipulation of a harmful flammable substance and the generation of a hazardous waste.

* Corresponding author. Tel.: +34 935811019; fax: +34 935812013.
E-mail address: antoni.sanchez@uab.cat (A. Sánchez).

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Air pycnometry is considered, by a wide number of researchers, to be the most adequate methology for AFP determination in composting materials (Agnew and Leonard, 2003; Annan and White, 1998; Eftoda and McCartney, 2002; Oppenheimer et al., 1997; Su et al., 2006). Roughly, air pycnometry consists of applying Ideal Gas's law to indirectly measure the volume of the air voids within a solid matrix using air at a known pressure in a known-volume sealed system.

The above mentioned limitations do not exist in air pycnometry. It has been demonstrated that the air pycnometry procedure does alter neither the physical properties nor the biological activity of the organic matrix (Berthe et al., 2007). Obviously, to obtain an accurate AFP measurement it is necessary to undertake a careful sampling and handling of the material and to proceed systematically according to am adequate protocol (Ruggieri, 2008).

The main goal of this work is to review the utilization of air pycnometry in the measurement of air filled porosity in the composting field. This is (i) to summarize the main issues related to air pycnometry methodology, (ii) to review the comparisons undertaken with other AFP measurements, (iii) to report theoretical and empirical relationships among AFP and other parameters and (iv) to review main cases and findings of AFP application in the experimental work on the composting field.

Moreover, a battery of experiments were run in order to corroborate all the reviewed information, and all obtained data was analysed with three purposes: (i) to compare AFP values empirically obtained by air pycnometry with AFP values obtained by theoretical approaches proposed by other authors, (ii) to compare AFP values empirically obtained by air pycnometry with values obtained by empirical approaches determined by other authors and (iii) to study the relationship between AFP obtained by air pycnometry and other physical parameters also experimentally determined.

2. Air pycnometry

2.1. Involved concepts: Porosity and air filled porosity

The concept of void volume, and related ideas such as porosity, void ratio and degree of saturation; have their origin in the science of soil mechanics. Both, concepts and nomenclatures, have been borrowed and applied to composting systems. Volume ratios commonly used in composting are the porosity and air filled porosity (AFP), also known as free air space (FAS). Porosity (ε) of a composting mass is defined as the ratio of void volume of the sample (V_v) to total volume of the sample (V_s), including air and water filled voids as shown in Eq. (1).

$$\varepsilon = \frac{V_v}{V_s} \tag{1}$$

On the other hand, AFP is defined as the ratio of air volume (V_g) to total volume of the sample (V_s) (Haug, 1993) as presented in Eq. (2).

$$\mathrm{AFP} = \frac{V_g}{V_s} \tag{2}$$

Eftoda and McCartney (2002) proposed that the total volume of air in a composting matrix can be further divided into inter-particle and intra-particle air voids based on whether it is contained in interstitial voids between particles or in pore spaces within particles, respectively. They distinguished the first one as the readily available air for aerobic microorganisms and named it free air space (FAS), on the other hand the intra-particle voids represent what they called unavailable air space (UAS) as it is not accessible to microorganisms.

According to these authors, the sum of both concepts FAS and UAS results in the total air space (TAS). The discussion on how to discriminate FAS and UAS from TAS has been discussed in previous studies (Agnew and Leonard, 2003; Eftoda and McCartney, 2002; Su et al., 2006) and it is explained below.

2.2. Air pycnometer principle

Air pycnometers provide indirect air space measurements by relating the system's pressures and volumes using the ideal gas law (Eq. (3)).

$$PV = nRT \tag{3}$$

where P, pressure (kPa); V, volume (L); n, moles of gas (mol); R, ideal gas constant (8.2 kPa L mol^{-1} K^{-1}); T, temperature (K).

The air pycnometer consists of a gas reservoir chamber (V_{gc}) containing air at a known pressure (P_1) and a sample chamber (V_{sc}) filled with a known volume of material (V_s), yet initially opens to atmospheric pressure, and both connected by an air valve. After sealing the system, compressed air from the reservoir chamber is released to the sample chamber by opening the connecting valve and the pressure is allowed to equilibrate. A pressure gauge at the reservoir chamber registers the pressure before and after the connecting valve is opened. It is assumed that in a closed system with moderate pressures, as in the pycnometer, the temperature remains constant so the term nRT of the ideal gas law remains constant (Agnew and Leonard, 2002). Boyle's law can be used to derive the general equation for the pressure–volume relationships under these two pressure regimes, by assuming that relative pressure in the reservoir chamber is initially zero. The resulting equation is presented below (Eq. (4)).

$$P_1 V_{gc} = P_2 V_t \tag{4}$$

where P_1, initial pressure in compressed air vessel; P_2, final pressure of equilibrated system; V_{gc}, volume of the compressed gas chamber; V_t, volume of overall system (compressed air chamber, air volume in sample chamber, pipes and fittings).

Eq. (4) can be rearranged (by ignoring the air volume of fittings and pipes) producing the resulting Eq. (5) for V_g.

$$V_g = \frac{(P_1 - P_2)V_{gc}}{P_2} \tag{5}$$

where V_g, volume of gas air voids in the sample; V_{gc}, volume of the gas chamber; P_1, initial pressure in the reservoir chamber and P_2, the equilibrium pressure in the entire system.

As mentioned before, AFP is expressed as the ratio of gas filled pore volume of the sample (V_g) to total sample volume (V_s). For AFP determination using an air pycnometer a theoretical relationship between AFP of the sample and the equilibrium pressure in the entire system (P_2) can be obtained by combining Eqs. (3)–(5) and assuming that the exact volume of the air pycnometer is known, as shown in Eq. (6).

$$\mathrm{AFP} = \frac{V_g}{V_s} = \frac{(P_1 - P_2)V_{gc}}{P_2 V_s} \tag{6}$$

On the other hand an empirical relationship of AFP with P_2 can be obtained and used for the calibration of the system. A calibration curve can be generated by plotting the different P_2 readings obtained for the different V_s with a known AFP (as can be the resultant of adding successive water volumes to the sample chamber). The experimental data obtained will follow the expression in Eq. (7) as well as the theoretical application of Eq. (6).

$$\mathrm{AFP} = a + \frac{b}{P_2} \tag{7}$$