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Prediction of free air space in initial composting mixtures by a statistical design approach

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ABSTRACT

Free air space (FAS) is a physical parameter that can play an important role in composting processes to maintain favourable aerobic conditions. Aiming to predict the FAS of initial composting mixtures, specific materials proportions ranged from 0 to 1 were tested for a case study comprising industrial potato peel, which is characterized by low air void volume, thus requiring additional components for its composting.

The characterization and prediction of FAS for initial mixtures involving potato peel, grass clippings and rice husks (set A) or sawdust (set B) was accomplished by means of an augmented simplex-centroid mixture design approach. The experimental data were fitted to second order Scheffé polynomials. Synergistic or antagonistic effects of mixture proportions in the FAS response were identified from the surface and response trace plots in the FAS response. Moreover, a good agreement was achieved between the model predictions and supplementary experimental data. Moreover, theoretical and empirical approaches for estimating FAS available in literature were compared with the predictions generated by the mixture design approach.

This study demonstrated that the mixture design methodology can be a valuable tool to predict the initial FAS of composting mixtures, specifically in making adjustments to improve composting processes containing primarily potato peel.

1. Introduction

Potato peel (PP) waste is a by-product from the processed potato products industries such as French fries, chips and puree. Although PP is a zero value waste for those plants, disposal, sanitation, and environmental problems must be overcome (Arapoglou et al., 2010). During the processing of potatoes at industrial level, depending on the technology used (steam, abrasion or lye peeling) losses caused by potato peeling can reach 15–40% of the total raw materials (Schieber et al., 2001).

Though the food industry manages PP waste as a non-valuable by-product, its composition may be suitable for several applications such as dietary fibre for baking products and animal feeding (Djomo et al., 2008), biohydrogen and ethanol production (Arapoglou et al., 2010; Djomo et al., 2008; Mars et al., 2010), source of natural antioxidants (Al-Weshahy et al., 2013; Schieber et al., 2001; Wijngaard et al., 2012) and bio-methane production (Parawira et al., 2004; Kaparaju and Rintala, 2005; Kryvoruchko et al., 2009). Our study addressed the PP valorisation through composting. This process may be defined as the biological decomposition and stabilization of organic subtracts, under aerobic conditions that allow development of thermophilic temperatures, as result of biologically generated heat, to obtain a final product that is stable, free of pathogens and plant seeds, that can be beneficially applied to land (Haug, 1993). It should be noted that PP valorisation by composting can be quite interesting for the food industry, given that a volume reduction of by-products up to 40% can be achieved (Schaub and Leonard, 1996). Nevertheless, to the best of our knowledge, PP composting has been scarcely addressed in literature. PP waste is usually characterized by high interparticle water content which might hinder composting evolution, due to higher oxygen diffusion resistance in pores between particles. Therefore, its valorization may require previous mixture with other materials, aiming to reach an adequate formulation for composting.

Mixture formulations for composting are often based on physical and chemical properties of the wastes (Barrena et al., 2011) in

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order to adjust moisture content and C:N ratio to optimal values that favor growth and activity of microbial populations. Indeed, it is well known that one of the most important factors for thermophilic composting is the carbon to nitrogen ratio (C/N) with optimum values around 25–30:1 (Abdullah and Chin, 2010; Hamoda et al., 1998; Huang et al., 2006) and moisture content in the range of 50–65% (Abdullah and Chin, 2010; Liang et al., 2003).

However, more recently the free air space (FAS) of a mixture has also been indicated as a physical property that may play an important role during composting (Agnew et al., 2003; Barrena et al., 2011; Eftoda and McCartney, 2004; Richard et al., 2004; Ruggieri et al., 2009). This parameter is defined as the ratio of gas filled pore volume to total compost mixture volume and it determines the air quantity and movement inside the mixture, as well as the intrinsic air content, carbon dioxide, moisture and heat removal from the system (Richard et al., 2004; Ruggieri et al., 2009). FAS depends on the structural characteristics of the materials used such as bulk density, particle density and water content. A minimum value of 30% is usually required to ensure aerobic condition in the composting mixture (Haug, 1993), and optimum values for FAS may be in the range of 60%. In literature there are references to FAS as high as 85–90% without significant negative impact (Ahn et al., 2008; Ruggieri et al., 2009). To quantify FAS for a given composting mixture, some theoretical empirical correlations have been developed (Agnew et al., 2003; Haug, 1993, Oppenheimer et al., 1997; Richard et al., 2004). Moreover, experimental procedures by using air pycnometry have been studied and compared (Ruggieri et al., 2009). But so far, the study of an approach able to predict FAS for a given mixture based on its individual components proportions has been seldom addressed (Soares et al., 2012).

Mixture design is a statistical technique associated to the concept of planning and execution of informative experiments concerning a mixture of different components, and it has been widely used to establish formulations in chemical, pharmaceutical and food industries (Eriksson, 1998). The method consists in varying the proportions of two or more ingredients of the mixture and studying the influence of the independent variables (proportions of different components) into the measured response, which is dependent on the ingredient composition (Akalin et al., 2010).

In this scope, our work aims to use the mixture design approach to understand and predict the influence of each component, on the FAS of an initial mixture containing primarily potato peel waste (PP) for further composting. Rice husk (RH) or sawdust (SD) were selected as bulking agents, and grass clippings (GC) as nitrogen source.

2. Materials and methods

2.1. Composting materials

The materials used were collected from different sources: potato peel (PP) is from a national industry of potato chips, rice husk (RH) was provided by a rice husking factory, sawdust (SD) is from a local pine sawmill, and grass clippings (GC) were obtained from a national football stadium. Grass clippings were sieved through a 5 cm mesh to obtain a homogeneous material in size and shape. The other materials did not require any specific treatment. The characterization of the each material was carried out using a composite sample of 25 L obtained from five individual samples of 5 L taken from the initial laboratory samples of about 120 L. Then, each composite sample of 25 L was homogenized and divided into four parts, with one being eliminated. This procedure was repeated until samples of about 1–2 L were obtained for further analysis.

2.2. Mixture design establishment and validation

The mixtures tested in this study were grouped in two sets (Set A and Set B) according to the type of bulking agent used. Each set comprised three mixture factors or ingredients (set A: PP + GC + RH); (set B: PP + GC + SD) and their mixing proportions were individually allowed to range from 0 to 1.

Therefore, a regular and triangular experimental design region is expected for each set, with the constraint that the sum of all feedstock's proportions must be 1. Vertices of the design region correspond to the formulations that are pure blends.

The main objective of this design was to predict the free air space (desired response) for any mixture tested by modelling the mixing surface with mathematical equations. It was assumed that the measured response was only dependent on the relative proportions of the ingredients (considered as independent variables) but not on the amount of the mixture.

The models considered in this study were Scheffé canonical polynomials (Smith, 2005):

Linear:

$$E(Y) = \sum_{i=1}^{q} \beta_i X_i \tag{1}$$

Quadratic:

$$E(Y) = \sum_{i=1}^{q} \beta_i X_i + \sum_{i=1}^{q-1} \sum_{j=i+1}^{q} \beta_{ij} X_i X_j \tag{2}$$

Special cubic:

$$E(Y) = \sum_{i=1}^{q} \beta_i X_i + \sum_{i=1}^{q-1} \sum_{j=i+1}^{q} \beta_{ij} X_i X_j + \sum_{i=1}^{q-2} \sum_{j=i+1}^{q-1} \sum_{k=j+1}^{q} \beta_{ijk} X_i X_j X_k \tag{3}$$

Full cubic:

$$E(Y) = \sum_{i=1}^{q} \beta_i X_i + \sum_{i=1}^{q-1} \sum_{j=i+1}^{q} \beta_{ij} X_i X_j + \sum_{i=1}^{q-1} \sum_{j=i+1}^{q} \gamma_{ij} X_i X_j (X_i - X_j) + \sum_{i=1}^{q-2} \sum_{j=i+1}^{q-1} \sum_{k=j+1}^{q} \beta_{ijk} X_i X_j X_k \tag{4}$$

Special Quartic:

$$E(Y) = \sum_{i=1}^{q} \beta_i X_i + \sum_{i=1}^{q-1} \sum_{j=i+1}^{q} \beta_{ij} X_i X_j + \sum_{i=1}^{q-1} \sum_{j=i+1}^{q} \gamma_{ij} X_i X_j (X_i - X_j) + \sum_{i=1}^{q-2} \sum_{j=i+1}^{q-1} \sum_{k=j+1}^{q} \beta_{ijk} X_i^2 X_j X_k + \sum_{i=1}^{q-2} \sum_{j=i+1}^{q-1} \sum_{k=j+1}^{q} \beta_{ijk} X_i X_j^2 X_k + \sum_{i=1}^{q-2} \sum_{j=i+1}^{q-1} \sum_{k=j+1}^{q} \beta_{ijk} X_i X_j X_k^2 \tag{5}$$

where *E(Y)* is the expected value of the output variable *Y*, *X* are the independent variables, β and γ correspond to the polynomial coefficients, q is the number of components (in this case $q = 3$).

Since the experimental mixture region is regular and constitutes a simplex shaped region, an augmented simplex-centroid mixture design approach was used to define the number of mixtures necessary to attain the desired response (FAS value). This