Journal of Environmental Management 222 (2018) 207–215

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Adding worms during composting of organic waste with red mud and fly ash reduces CO_2 emissions and increases plant available nutrient contents

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A R T I C L E I N F O

Keywords:
Composting
Vermicomposting
Red mud
Fly ash
Carbon

A B S T R A C T

Alkaline industrial wastes such as red mud and fly ash are produced in large quantities. They may be recycled as bulking agent during composting and vermicomposting, converting organic waste into soil amendments or plant growth media. The aim of this study was to assess the microbial parameters, greenhouse gas emissions and nutrient availability during composting and vermicomposting of household waste with red mud and fly ash 15% (dry weight). CO_2, CH_4 and N_2O emissions were monitored during 6 months in controlled laboratory conditions and microbial biomass and phospholipid acids, N and P availability were analysed in the end-products.

Higher CO_2 emissions were observed during vermicomposting compared to composting. These emissions were decreased by red mud addition, while fly ash had no effect. Nitrate (NO_3-N) content of the end-products were more affected by worms than by alkaline materials, while higher ammonium (NH_4-N) contents were recorded for composts than vermicomposts. Red mud vermicompost showed higher soluble P proportion than red mud compost, suggesting that worm presence can counterbalance P adsorption to the inorganic matrix. Final composts produced with red mud showed no harmful heavy metal concentrations. Adding worms during composting thus improved the product nutrient availability and did not increase metal toxicity. From a practical point of view, this study suggests that for carbon stabilisation and end-product quality, the addition of red mud during composting should be accompanied by worm addition to counterbalance negative effects on nutrient availability.

1. Introduction

Composting and vermicomposting are used worldwide to reduce the degradability of waste organic matter (OM) and generate organic soil amendments (Tejada et al., 2010; Ngo et al., 2012). The end-products, rich in nutrients and stabilized OM, can also be used as plant growth media (Hashemimajd et al., 2004; Lim et al., 2015). However, both transformation processes emit greenhouse gases (GHG) such as carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) (He et al., 2000; Velasco-Velasco et al., 2011), depending on the aeration of the composting pile (Hobson et al., 2005; Hao et al., 2001), the presence of worms (*i.e.* vermicomposting) (Chan et al., 2011) and bulking agents (Bustamante et al., 2013; Martínez-Blanco et al., 2010; Nolan et al., 2011; Santos et al., 2016), and the size of the composter (Dias et al., 2010).

In the IPCC (2014) carbon budget, CO_2 emissions originating from mineralization during composting are not considered as contributing to global GHG emissions due to their biogenic origin. However, they have similar impacts on the environment and on climate change as non-biogenic emissions and are quantitatively important (Lim et al., 2016). Around half of the composted biomass is generally lost in the form of CO_2, depending on the composting process (Lim et al., 2016). Reducing CO_2 emissions during composting may be a strategy to increase C sequestration and therefore contribute to climate change mitigation.

In recent years, new composting processes were developed, using bulking agents such as biochar (Chowdhury et al., 2014) or minerals (Awasthi et al., 2016; Barthod et al., 2016) in order to enhance carbon stabilisation and compost quality (Barthod et al., 2018). The presence of minerals such as goethite or allophane during composting of poultry manure increases carbon stabilisation (Bolan et al., 2012). Other

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https://doi.org/10.1016/j.jenvman.2018.05.079
Received 16 March 2018; Received in revised form 22 May 2018; Accepted 24 May 2018

Abbreviations

$C_{control}$	compost without worms and without additives
CFA	compost with 15% (w/w) fly ash
CH_4	Methane
CO_2	Carbon dioxide
CRM	compost with 15% (w/w) red mud
DOC	dissolved organic carbon
EC	electrical conductivity
GC-FID	gas chromatograph coupled to a flame ionization detector
GHG	greenhouse gases
ICP-AES	inductively coupled plasma-atomic emission spectroscopy
IPCC	Intergovernmental Panel on Climate Change
MB	extracted organic carbon
MBC	microbial biomass carbon
N	nitrogen
N_2O	Nitrous oxide
NH_4^+	Ammonium
NO_3^-	Nitrate
OC	Organic carbon
OM	organic matter
P	phosphorus
PLFA	Phospholipid fatty acids
Po	organic P
TOC	Total organic carbon
$V_{control}$	vermicompost without additives
VFA	vermicompost with 15% (w/w) fly ash
VRM	vermicompost with 15% (w/w) red mud
Pi	inorganic P
Pt	total P
Pi H_2O	water-soluble P

authors used alkaline minerals from industries such as coal fly ash, generated by the coal combustion for electricity production (Fang et al., 1999; Wong et al., 2009; Chowdhury et al., 2015) or red mud, a product obtained during the process of alumina extraction from bauxite (Chowdhury et al., 2015; Wang et al., 2016; Zhou et al., 2017). These alkaline materials have large stabilisation capacity for C and heavy metals (Wong and Selvam, 2009; Nadaroglu and Kalkan, 2012; Si et al., 2013) and their high pH leads to pathogen decrease (Wong and Selvam, 2009). Moreover, industrial waste products are easily available (Gomes et al., 2016) at low cost. Red mud and fly ash are thus valuable additives to improve composting processes as they can decrease mineralised carbon and dissolved organic carbon (DOC) content of the end-product (Chowdhury et al., 2015).

One of the issues to address when using these bulking agents is their potential effect on OM decomposition and thus compost stabilisation, that may affect the bio-availability of nutrients such as nitrogen (N) or phosphorus (P). The presence of red mud during composting immobilizes phosphates and thus limits the plant available P (Belyaeva and Haynes, 2012).

In the context of ecological engineering, composting with worms may be used to enhance OM decomposition (Lazcano et al., 2008; Paradelo et al., 2009, 2010) and increase the contents of the end-products in plant available nutrients, in particularly P (Ghosh et al., 1999; Garg et al., 2006). In general, worm presence during composting leads to larger CO_2 release than regular composting (Lim et al., 2016). But, in the presence of mineral bulking agents, worms enhanced carbon stability due to the simultaneous ingestion of OM and minerals (Barthod et al., 2016). Thus, during co-composting with alkaline materials, the addition of worms may limit the adsorption of nutrients on the additives and increase the carbon stability.

Many studies were published in the last years on composting with alkaline minerals from industries, while only few studies combined mineral additives and worms, and none alkaline substrates and worms. The objective of this study was to test the benefits of adding industrial waste materials (red mud and fly ash) during co-composting without or with worms (*Eisenia andrei* and *foetida*) to produce high quality soil amendments and/or plant growth substrates. For this aim, this study presents the effects of alkaline additives and worms on (1) GHG emissions during co-composting; (2) microbial and physico-chemical characteristics and (3) heavy metal toxicity of the end-products. The originality of this approach is to combine recycled additives to worms in order to propose innovative composting processes. Furthermore, most of the studies on alkaline material substrates in composting focused on the C present in the final product or remaining in soil after amendment (Bolan et al., 2012; Chowdhury et al., 2015), while improving knowledge on C stabilization mechanisms occurring during composting and vermicomposting necessitates measuring gas emissions and biomass parameters during composting, as designed in the present study.

2. Materials and methods

2.1. Organic materials, bulking agents and worms

Raw organic materials used for the incubation experiments were lettuces, apple flesh, residual maize leaves, ground spent coffee and pieces of cardboard (2 × 3cm). Lettuces and apples, products of organic agriculture, were obtained from a general store, spent coffee ground from a public cafeteria, and the maize from a field in Grignon (France). Organic mixtures were prepared by mixing these materials in controlled proportions: 1.2% (in dry weigh) lettuce, 19.6% apples, 39.1% spent coffee ground, 10.1% maize and 27.9% cardboard. These proportions resulted in an initial C:N ratio of 40 for the organic mixture. The main characteristics of these materials are listed in Table 1.

The organic materials were co-composted with fly ash and red mud, alkaline by-products respectively of a coal fired power station (Alinta Energy, South Australia) and a bauxite mining site (Colmaco Alumina refinery, Queensland Australia). Red mud and fly ash have a pH of 10.4 and 10.6 and a specific surface area of 23 and 1 $m^2 g^{-1}$, respectively. Composition in major elements of these materials was described by Chowdhury et al. (2014).

Eisenia andrei and *Eisenia foetida* worms were initially purchased from La Ferme du Moutta, a worm farm in France and reproduced in the

Table 1
Main characteristics of the initial materials used for composting.

Material	Water content (%)	C (mg g^{-1})	N (mg g^{-1})	C:N ratio
Apple	86.4 ± 0.43	443.37 ± 27.5	2.86 ± 0.2	155.2 ± 1.2
Cardboard	< 1%	387.92 ± 1.36	2.31 ± 0.01	167.7 ± 0.49
Lettuce	96.98 ± 0.24	375.92 ± 0.29	43.79 ± 0.11	8.6 ± 0.03
Residual maize	64.61 ± 0.66	393.54 ± 2.52	4.9 ± 0.04	80.3 ± 0.26
Spent coffee ground	71.97 ± 2.1	529.80 ± 2.03	21.36 ± 0.12	24.8 ± 0.16

Data are presented as means and standard error (n = 4).