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Research article

The evolution of compost stability and maturity during the full-scale treatment of the organic fraction of municipal solid waste

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ABSTRACT

Composting is the method most commonly applied worldwide for the recovery of the source sorted organic waste. The process aims at stabilizing the organic matter, so as to produce a material with soil improver properties, referred to as compost. The effective recovery of the organic waste fraction via composting implies compost safe use on soil. In this view, the assessment of compost characteristics, depending on both the quality of the input material and the process operation, is fundamental. At full scale, the process monitoring usually relies on parameters enabling the indirect control of its evolution, whereas the biological stability and maturity are usually evaluated on the final product. Aim of this work was in assessing both biological stability and maturity during the composting process of the organic fraction of municipal solid waste performed at industrial scale. Representative samples were collected over time in a composting facility operating in the South of Italy and analysed by the dynamic respirometric index, the content of humic substances as well as by their phytotoxicity. Results showed the key role of stability and maturity parameters in the monitoring of composting processes. Experimental outcomes further addressed wider considerations on the operational procedures for a sustainable compost production process.

1. Introduction

The organic fraction is the main portion of municipal solid waste (MSW), accounting for approximately 30–40% in Europe. Due to its high moisture content and biodegradability, it is usually source segregated and destined to valorization processes, aiming at material and/or energy recovery.

Composting is the method most commonly applied worldwide for the recovery of the source sorted organic waste, due to its easy implementation and operation (Jara-Samaniego et al., 2017; Meyer-Kohlstock et al., 2015). The process, relying on different practices applied in either developed or developing countries (Wei et al., 2017), provides the biological stabilization of the organic substrate under aerobic conditions and generates a sanitized product, with soil improver properties (Meena et al., 2016; Pérez et al., 2007), referred to as compost, which can be used in soil conditioning and nutrient supply (Alvarenga et al., 2007, 2015).

Several factors influence composting yields (Onwosi et al., 2017), but those directly related to the oxygen supply are fundamental to ensure the optimal microbial activity.

Laboratory scale tests showed that the respiration activity of bacteria is directly related to the airflow supply: above a threshold limit value, which depends on the kind of waste that is processed, any further increase affects the biological activity; below the same limit, the respiration activity slows down and it becomes directly dependent on the air flowrate (Mejias et al., 2017).

However, the influence of the air supply on the microbial activity is also indirect, as aeration affects the temperature as well as the moisture content of the mass under composting. An aeration rate lower than 0.2 L/min kg_{OM} was found to determine a low degradation rate, moisture and heat loss, reduction in ammonia (NH_3) generation and significant temperature decrease. As these conditions affected microbial diversity, aeration was identified as the main factor influencing compost stability (Guo et al., 2012). Conversely, when aeration ranged between 0.2 and 0.6 L/min kg_{OM}, relevant NH_3 improvements, C/N ratio reduction and compost maturity were reported (Cerda et al., 2018).

In full scale application the role of aeration turns to be fundamental, because it should ensure: i) the oxygen supply for the microbial activity; ii) the control of temperature as well as iii) the removal of the excess moisture. The airflow required for both temperature and moisture control is usually much higher than that needed for the biological

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oxidation of the organic substrate. The airflow rate is thus set to achieve either temperature control or excess moisture removal, depending on the characteristics of the organic substrate, and so as the aeration mode (Guo et al., 2012; Rasapoor et al., 2009; Shen et al., 2011).

The amount of oxygen supplied, the aeration system (Chowdhury et al., 2014; Rasapoor et al., 2016) and the mixture porosity (Iqbal et al., 2010) are among the main operating conditions influencing the proper evolution of composting as well as the quality of the final compost (Faverial et al., 2016).

In some European countries the regulatory framework for the production of waste-based compost requires the temperature profile to develop so as to prevent possible risks from both the presence of pathogens and the phytotoxicity, but the development of the stabilization process is not as strictly regulated as the quality of the final product (Cesaro et al., 2015a). Therefore, the process monitoring at full scale usually relies on parameters enabling the indirect control of its adequate evolution, whereas the biological stability and maturity are usually evaluated on the final product.

The biological stability accounts for the rate of the microbial activity in compost, which can be described by different parameters (Viaene et al., 2017). Conventional methods for the biological stability assessment have been recently classified in two categories, oriented either to the biotic response on the tested materials or to the physic-chemical characteristics of organic matter (Lü et al., 2018). The former have been extensively proven to be the most suitable to properly evaluate the biological stability of organic samples: respirometric techniques, in particular, are recognized to be highly effective (Barrena et al., 2009; Villaseñor et al., 2011) and suitable to reflect the process of organic matter biodegradation (Pognani et al., 2010, 2012; Ponsá et al., 2008).

The maturity identifies the extent of organic matter transformation during the composting process (Yuan et al., 2012) as well as the phytotoxicity of the final product. In order to assess the ecotoxicity of organic substrates for their land use, Huguier et al. (2015) recognized a direct approach, relying on solid-phase tests, and an indirect one, based on liquid-phase tests assessing the extracts of the samples. The former is more frequently used to describe the compost maturity and it is typically carried out via seed germination tests (Alvarenga et al., 2015; Saludes et al., 2008). Despite its effectiveness and economic competitiveness to evaluate the potential phytotoxicity of compost, the standardization of the test procedure and the modelization of the test seeds are still considered urgent needs to enhance the validity and reproducibility of the test results (Cesaro et al., 2015a; Luo et al., 2018; Villaseñor et al., 2011).

The evaluation of phytotoxicity is tightly related to that of biological stability, as the microbial activity of some unstable organic matter can produce phytotoxic compounds. Oviedo-Ocaña et al. (2015) assessed the stability and maturity of biowaste composts during the curing phase via both laboratory scale and on-site tests and found no statistically significant correlations among the adopted indices. This condition suggests that the simultaneous assessment of both stability and maturity during the aerobic biostabilization of organic waste would provide useful indication about the evolution of the biological degradation reaction, so as to promptly recognize possible qualitative problems and implement the necessary corrective actions to obtain a high quality compost. However, such approach can be effective if it relies on easy-to-implement as well as economical operating solutions.

Aim of this work was in evaluating the maturity evolution during the composting process of the organic fraction of municipal solid waste performed at industrial scale. To this end, representative samples were collected during the curing stage of composting and characterized by different parameters referred to both the agronomic value and the phytotoxicity potential. The biological stability was assessed as well, in order to define its relationship with the maturity parameter, addressing wider consideration on the monitoring strategies to be applied at full scale for the production of high quality compost.

2. Materials and methods

2.1. The composting plant: process lay out and operation

The samples used for the experimental activity were collected at a full-scale composting plant operating in the South of Italy, with a design treatment capacity of 20000 t/year.

The overall capacity is used to process 15000 t/year of source sorted organic fraction of municipal solid waste (OFMSW) and 5000 t/year of green waste, used as bulking agent within the aerobic process.

During the process operation, OFMSW is mixed with green waste and destined to composting. The active phase, lasting 14 days, is performed in biocells and then the material is sent to the curing step, further divided into two different ones: the organic matter is first processed using forced aerated windrows for 29 days (primary curing) and then directed to a static pile system for 47 days (secondary curing). The overall aerobic process cycle lasts 90 days, in accordance with the Italian legislation requirements.

The final product is sieved so as to obtain three material flows:

- the oversieve that mainly consists of impurities entering the process along with the source sorted OFMSW;
- a coarser undersieve fraction, composed of green waste not fully degraded during composting and thus available to be recirculated in a new process cycle;
- the finest fraction that is the compost, destined to characterization for its use on soil in accordance with the Italian legislation.

The flow scheme is outlined in Fig. 1, along with the mass balance.

2.2. Experimental set up

For the purposes of the experimental activity, approximately 50 tons of source sorted OFMSW, delivered at the plant to be treated, were mixed with green waste and the coarser undersieve fraction in a volumetric ratio of 1:2:1, which is the one adopted for the plant operation.

The OFMSW used to prepare the mixture originated from different municipalities. Before starting the composting process, its composition was characterized by manual sorting according to the procedures indicated by the Veneto Region Council Resolution 568/2005.

The mixture was then addressed to the biological process. To this end, a biocell was completely emptied to be destined to the

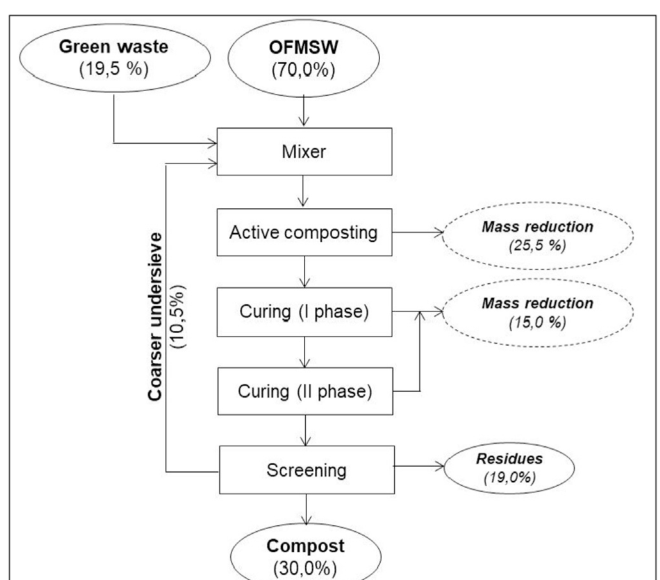

Fig. 1. Process layout and mass balance of the plant under investigation.

experimental activity and so as two areas of the plant, which were devoted to both the primary and secondary curing of the sole waste under investigation, in order to ensure the same origin for all the analysed samples. The composting process was then carried out according to the usual plant operation mode.

During the curing stage, representative samples were collected every 15 days, in accordance with the standard procedure UNI 10802:2013.

The quality of the final process product from the original mixture was further characterized in accordance with the Italian legislation for compost classification as fertilizer.

2.3. Analytical set up

2.3.1. Physic-chemical characterization

Total solid (TS), volatile solid (VS) and the Dynamic Respirometric Index (DRI) were estimated on the collected samples according to the standard procedures (UNI/TS 11184:2006). DRI was assessed after the adjustment of the water content to the value recommended in the reference protocol for the calculation of the potential respiration index.

For the evaluation of the C/N ratio, the content of both carbon and nitrogen were measured following the standard procedure UNI 10780:1998, which was also used to assess humic substances as well as the other parameters for the characterization of representative compost samples under the Italian Regulation.

The total humic carbon and the total organic carbon were used to determine the humification index as defined by Roletto et al. (1985).

All the analytical tests were performed in triplicate. The mean and standard deviation values are discussed. The data were analysed using the ANOVA method, at 5% significance level.

2.3.2. Phytotoxicity tests

Phytotoxicity tests employing seed germination and root elongation were used following a modified UNICHIM method (2003) to estimate compost maturity (Cesaro et al., 2015a; Said-Pullicino et al., 2007). To this end, water was mixed with compost samples to reach a moisture content equivalent to 85% (wet weight). After 2 h of contact time, the aqueous extracts were obtained by centrifugation at 6000 rpm for 15 min and filtration at 3.5 atm with membrane filter. The extracts were diluted to a 30%, 50% and 75% concentrations.

Lepidium sativum, Sorghum saccharatum and Cucumis sativus seeds were used to conduct germination and growth assays on compost aqueous solutions and placed in a Petri dishes (90 mm diameter) with one sheet of Whatman No. 1 filter paper as support, in three replicate experiments. After the addition of 10 seeds and 3 mL of test solutions, the Petri dishes were sealed with Parafilm to ensure closed-system models. The seeds were placed in a growth chamber at 25 °C. Bioassays took 72 h and after this period, the number of seeds germinated was counted and the radical length was measured. The Index of growth (IG) was calculated by multiplying the germinated seed number (G1) and length of roots (L1). The Germination Index results were used to calculate the effect, expressed as percentage (GI%) with respect to the control as follows:

$$GI\% = (IG_C - IG_S)/IG_C^{*}100$$

where IG_S and IG_C are the germination indices calculated for the samples and the control, respectively.

3. Results and discussion

The OFMSW destined to the aerobic stabilization process was found to be characterized by an average compostable material content of 93.8%, of whom approximately 92% consisted of organic waste, whereas the remaining portion was composed of paper tissues. The non-compostable fractions, namely plastic, metals and inerts, accounted for approximately 6% of the overall mass of the waste. These results were consistent with the expected composition of a source sorted OFMSW. The amount of impurities was found to be lower than the one reported for mechanically sorted organic waste (Cesaro et al., 2016), although still relevant. The plastic waste, which was the prevailing among non-compostable fractions, could be mainly attributed to the bags used to collect the waste as well as to the packaging containing spoiled food. This evidence indicates that the presence of non-compostable fractions could be lowered by either providing biodegradable bags for the collection of OFMSW or carrying out specific actions to promote the correct waste separation among the producers.

Table 1
Characterization of compost with reference to the Italian Regulation parameters.

Parameter	Value	Threshold limit value[a]
pH [-]	7.07 ± 0.74	6–8.5
Moisture [%]	18.8 ± 6.1	≤50
Organic Carbon [$\%_{DM}$]	24.5 ± 3.8	≥20
Humic and fulvic Carbon [$\%_{DM}$]	8.61 ± 1.71	≥7
C/N [-]	12.7 ± 2.2	≤25
Organic nitrogen [$\%_{DM}$]	88.0 ± 2.8	≥80 N tot
Cd [mg/kg_{DM}]	< 0.01	≤1.5
Hg [mg/kg_{DM}]	< 0.01	≤1.5
Ni [mg/kg_{DM}]	9.84 ± 0.93	≤100
Pb [mg/kg_{DM}]	34.9 ± 11.7	≤140
Cu [mg/kg_{DM}]	39.2 ± 26.8	≤230
Zn [mg/kg_{DM}]	114.7 ± 4.7	≤500
Cr(VI) [mg/kg_{DM}]	< 0.01	≤0.5
Tl [mg/kg_{DM}]	< 0.01	≤2
Plastic + glass + metals (≥2 mm)	0.48 ± 0.53	≤0.5
Inerts (≥5 mm)	1.3 ± 0.8	≤5
Salmonella in 25 g	Absent	Absent
E.Coli in 1 g [CFU/g]	< 1000	1000–5000
Germination Index (dil 30%)	75 ± 0.8	≥60

[a] Under the Italian Regulation for compost classification, Legislative Decree n. 75/2010.

This OFMSW was used as substrate for composting, after its mixing with bulky material. At the end of the process the compost quality fulfilled the requirements established by the Italian Regulation for all parameters (Table 1), although the plastic content was found to slightly exceed the limit value in one third of the analysed samples. Such outcome suggests that, when the quality of the input organic waste in terms of plastic content is low, the final sieving step is not sufficient in providing its adequate reduction. This condition, in turns, confirms the need to arrange up-stream strategies for the decrease of the plastic content in the separately collected organic waste. It is worth pointing out that the plastic content was not found to induce any phytotoxicity phenomena, as pointed out by the germination test results.

Similarly, the final C/N ratio of 12.7 seems to refer to a properly produced compost. This value is comparable with those reported in the study of Vázquez et al. (2015), investigating the quality of composts produced from small-scale composting programmes, which was found to be characterized by C/N values ranging between 10 and 15. Higher values, above 15 or 20, were recorded for compost samples collected during the initial stage of the process, indicating the instability of the substrate.

However, in the present study, the C/N ratio was observed to increase over time: the average value estimated after 15 days curing was indeed 4.4 and it slightly enhanced up to 12.4. Such increase was found to be in direct correlation (R^2 = 0.96) with the reduction in nitrogen content. After 15 days curing, the organic mixture was found to be characterized by an average nitrogen content of 8.2$\%_{DM}$ that dropped to an average value of 3.3$\%_{DM}$ at the end of the process (Table 2). Conversely, the carbon content slightly increased from an average value of 36.2$\%_{DM}$ to 42.0$\%_{DM}$ (Table 2), likely due to the concentration of total solid over time, that was already experienced in a previous study

Table 2
Carbon and nitrogen content evolution during the curing stage of composting.

Composting time [days]	C [$\%_{DM}$]	N [$\%_{DM}$]
30	36.2 ± 2.8	8.2 ± 1.8
45	42.6 ± 5.0	5.3 ± 0.8
60	41.9 ± 5.5	4.4 ± 0.6
75	41.3 ± 1.8	3.8 ± 0.2
90	42.0 ± 6.1	3.3 ± 0.7

(Cesaro et al., 2015b).

During composting the C/N ratio usually tends to decrease over time: this reduction is faster in the active phase, due to the carbon mineralization to CO_2 and slows down during the curing stage (Zhou et al., 2018). Following organic matter degradation, the organic nitrogen (N_{org}), which is the main nitrogen form, is mineralized to ammonia (NH_3) and forms NH_4^+ in the water phase, which increases the substrate pH. Ammonia can be stripped by aeration, oxidized to nitrate (NO_3^-) or immobilized in complex N-rich macromolecules. The NO_3^- could be further reduced to nitrogen gas (N_2) by the denitrifying microorganisms, acting in the anaerobic zones of the biomass under composting (Wang and Zeng, 2018). The identification of nitrogen transformation during aerobic biological processes is very complicated, being dependent on several factors including the substrate characteristics (Zhou et al., 2018) as well as operating conditions, like temperature and aeration rate (de Guardia et al., 2010).

The study of de Guardia et al. (2010), comparing the nitrogen dynamic during the aerobic biostabilization of five types of organic waste, pointed out that ammonification was higher than nitrogen immobilization for household waste. The authors also observed that the nitrogen removed from this kind of waste was mainly emitted as N_2. This mechanism could explain the reducing trend of nitrogen found in this study.

Despite the increasing trend of the C/N ratio, its values were always below the threshold limit usually attributed to a stable compost (Guo et al., 2012), suggesting that the active phase effectively provided the biological degradation of the organic waste. This evidence was further confirmed by the Dynamic Respirometric Index (DRI) that after 15 days of curing corresponded to 633.9 ± 42.2 mg_{O2}/kg_{VS} h. As shown in Fig. 2, DRI values were found to range between 500 and 1000 mg_{O2}/kg_{VS} h: according to the Technical Regulation UNI/TS 11184:2006, this interval indicates a moderately stable material. However, in the compost samples obtained at the end of the process, the DRI value reached 1168.3 ± 79.3 mg_{O2}/kg_{VS} h. Such condition can be partly attributed to the material sieving which allowed the removal of the bulky, green waste and the consequent concentration of the more putrescent fractions in the analysed samples, as pointed out in previous studies (Adani et al., 2004). The progressive reduction of the size of the material can be a further reason of the DRI increase. Although the curing phase relies on static systems, the material transfer among the different plant sections as well as the operations to load the final sieving device may have determined the size reduction and, in turn, the increase of the specific surface area. Nevertheless, the final DRI slightly exceeds the threshold limit value for biological stability, which is assumed at 1000 mg_{O2}/kg_{VS} h (Adani et al., 2004; Baffi et al., 2007). This evidence as well as the limited reduction of DRI values during the overall curing stage suggest that the composting product can be considered susceptible for further stabilization (Colón et al., 2017; Grilli et al., 2012).

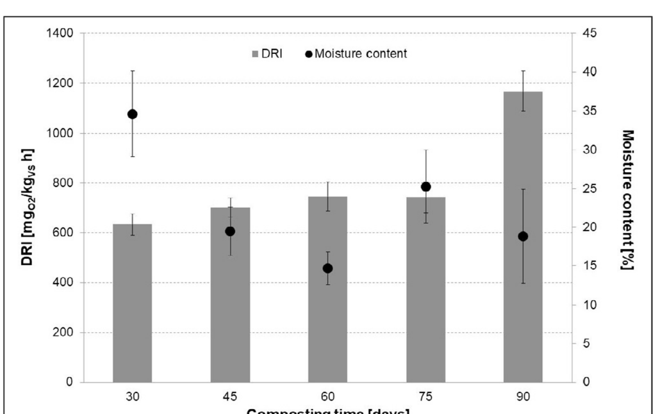

Fig. 2. DRI and moisture content evolution during the curing stage of composting.

It is worth pointing out that the analysed samples originated from the same initial mixture addressed to the composting process, which was carried out in accordance with the usual plant operating procedures. Nevertheless, minor inhomogeneity of the process conditions may have occurred within the piles under investigation and in this regard, another aspect of discussion can be recognized in the moisture content (Fig. 2). The reduction in the initial moisture content of the substrate under composting follows the temperature increase associated to the development of biological degradation reactions, which is more intense during the active phase and tends to slow down during the curing stage. However, it is also largely affected by both airflow rates and aeration mode (Mejias et al., 2017): excess of aeration can cause relevant water losses, hindering the biological process (Makan et al., 2013).

As the observed moisture values (Fig. 2) seem consistent with the occurrence of proper biological stabilization processes (Jain et al., 2018), the limited improvement in DRI values during the curing phase can be ascribed to an unsatisfactory aeration.

The curing phase is indeed carried out through a sequential system including forced aerated windrows and static pile. The effectiveness of these methods is tightly related to the bulking agent, which becomes fundamental to ensure the proper porosity and, in turn, the most effective aeration of the substrate. Iqbal et al. (2010) extensively studied the effects of different bulking agents in MSW composting and pointed out that free air space is influenced by both the particle size and the compression load and it decreases as the compression force increased. Static systems are more easily affected by compaction issues than those based on the pile turning (Ruggieri et al., 2008), so that the curing methods likely determined the compression of the bottom layers of the pile from the upper ones, determining the formation of anoxic zones (Mejias et al., 2017).

Low oxygen habitats can easily determine a strong coupling of aerobic and anaerobic metabolisms, which, in turn, promotes nitrification and denitrification processes (Chiumenti, 2015). Such condition could be responsible for the nitrogen reduction during the curing stage, observed in this study.

In this framework, the maturity evaluation of the product was fundamental to complete its characterization and to assess its possible adverse effects on soil. Results of the phytoxicity test on *L. sativum* are presented in Fig. 3. The trend in germination was in agreement with *C. sativus* and *S. saccharatum* results (data not shown) but *L. sativum* was found to be more sensitive.

According to Zucconi et al. (1985), germination index values lower than 60% indicate phytotoxic effects significantly different from the control. Experimental results showed that the *Lepidum sativum* germination index (GI) of the most diluted mixture (30%) after 15 days curing was 85.5 ± 0.8% and little differences were observed with higher concentrations, indicating the product maturity. However, this parameter showed a non-linear trend, with germination fluctuating over composting time.

As matter of fact, the germination index of extracts decreased after 45 days of composting, increased at 60 days and then decreased again, reaching at the end of the process a value of 61 ± 0.6%, 70.1 ± 0.2% and 75 ± 0.8% for 75%, 50% and 30% dilution, respectively.

Low germination indices are usually obtained at the beginning of a

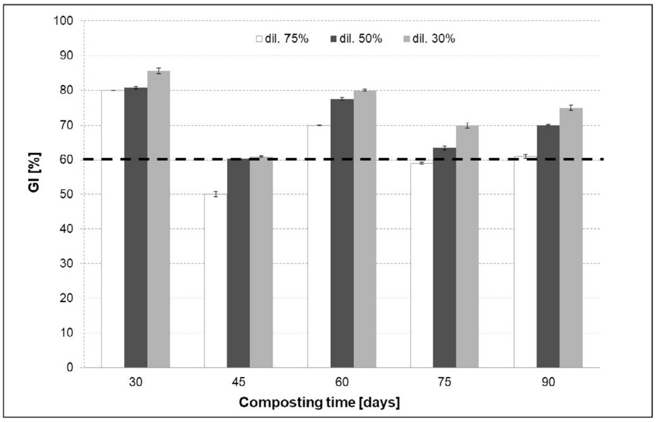

Fig. 3. Variation in germination index (GI), expressed as percentage of the control, during the curing stage of composting.

biostabilization process, as a result of the fast starting of biological activity and the formation of germination inhibiting compounds such as alcohols, phenolic compound and organic acids (Kazemi et al., 2016).

In the present study, the *Lepidum Sativum* GI values were found to be in the range 50–59% at 45 and 75 days composting, with samples prepared as a 75% dilution of the concentrated extract, which indicates that the tested materials can produce an inhibiting effect: such potential effect is increasing over the curing time, as a decreasing trend in GI was observed and it could be attributed to the biological degradation processes during the curing stage.

A residual amount of organic matter still susceptible to be degraded was thus expected to be present and this hypothesis was confirmed by the analysis of the humic substances. The humic acid-to-fulvic acid ratio (HA/FA) is indeed widely used to describe the relative speed of HA and FA transformation as well as the maturity of the final composts (Zhou et al., 2014): a HA/FA ratio ranging between 3.6 and 6.2 refers to a matured compost (Manu et al., 2017). In the present study, HA/FA ratio enhanced during the curing stage, reaching an average value of 2 at the end of process that indicates a maturity level of the final compost susceptible for further improvement. However, the humification index was always above the minimum value of 3.5% (Roletto et al., 1985), which was suggested as an indicator of the degree of compost maturity.

4. Technical considerations

The experimental outcomes confirmed that the dynamics of biological stabilization processes are definitely complex: in composting the perfect balance of the variables defining the treatment performances is fundamental to pursue the production of a stable, pathogen-free and non-phytotoxic material, that can be used as soil conditioner.

In this view, the importance of the process monitoring is largely recognized and full-scale facilities are usually equipped so as to control the main parameters that describe the evolution of the biological reactions. Such approach is easier if composting is carried out in closed systems, where these parameters can be automatically measured and recorded, whereas the monitoring of composting piles more commonly relies on manual methods.

In the plant considered for this study the active phase of composting is performed in biocells, equipped with probes to monitor temperature in the biomass as well as sensors to control the air rate flow, its oxygen content, relative moisture and pressure. The monitoring is continuous and handled via a remote control system: based on the analysis of temperature trend, the adjustment of the biomass moisture as well as the air flow regulation can be provided. However, the air distribution in the biomass as well as the nitrification/denitrification processes are not comprehensively evaluated with these systems, which do not allow the prompt identification of either the formation of anaerobic zones or the establishment of bio-drying conditions. The monitoring of methane and nitrogen compounds in the biocell could provide additional information on the evolution of the biological process, and so as the quantification of the leachate production.

Similar considerations raise for the curing phase. In this study, the analytical characterization of representative samples suggested that the biostabilization extent was not fully satisfactory, likely due to improper aeration during the curing stage. A reduction in nitrogen content was also observed and it was ascribed to the possible formation of anoxic zones. However, it was not possible to confirm this hypothesis, due to the difficulties in monitoring the nitrogen losses in the pile under curing.

The analysis of the DRI values over time highlighted the development of the biological stabilization process, confirming that the oxidative reactions did not occur properly. The use of respiration tests to monitor the biostabilization yields can thus be a useful tool for the plant operators to double check the process parameters.

It is worth pointing out indeed that the analysis of the sole DRI values can address different hypothesis about the cause of the unsatisfactory biostabilization level. Similarly, phytotoxicity tests cannot provide comprehensive information, given the tight link between stability and maturity. The identification of the reason beyond the respiration test results requires the assessment of the process parameters. In this study the aeration was recognized as potentially inadequate, because the observed DRI trend came along with the nitrogen content decrease, while moisture content reflected a proper biostabilization process. Conversely, any possible reduction in moisture content would have most likely indicated the occurrence of dehydration rather than biological stabilization reactions as the reason for the observed DRI values.

Coupling the monitoring of conventional process parameters with laboratory assessment of both the stability and maturity of the mass under curing has been already suggested (Oviedo-Ocaña et al., 2015), but such approach entails an economic efforts for sampling and analysis that plant operators often cannot face. In particular, for the stability assessment to be effective, biological tests have to be used and these are time-consuming as well as expensive if intended to be carried out during the overall composting process.

As the cost competitiveness of this integrated monitoring can be decreased by reducing the frequency of lab-scale analysis, the improvement of process monitoring system during the curing phase is necessary.

To this end, commercial systems providing the measurement of moisture and temperature could be applied to verify the process kinetics also during the maturation step. This systems could be then used to support a tier-based monitoring plan, setting alert levels in accordance with threshold limit values for the measured parameters, making the lab-scale characterization more efficient.

5. Conclusive remarks

Composting still represents the most applied technique for the biological stabilization of organic solid waste, as it is considered easier to operate than anaerobic processes. However, the proper evolution of degradation reactions must be carefully monitored as conventional parameters for compost quality characterization usually provide partial or incomplete information, which can prove to be not useful to improve process operation and performances.

The analysis of the OFMSW based compost sampled at an industrial Italian plant showed the fulfilment of the quality parameters established under the Italian legislation, with the occasional exception of the content of plastic that exceeded the threshold limit value. This condition is related to the quality of the incoming waste rather than the plant operation mode, so that it can be easily improved via up-stream strategies acting on the yields of organic waste separate collection methods.

Conversely, the overall analysis of the curing phase highlighted the key role that an integrated monitoring strategy can play to specifically address the process operation so as to positively influence the quality of the final product.

Although the process was indeed effective in producing a material that, in terms of stability and maturity, can be used as soil improver under the Italian legislation, the analysed properties indicated the need for advanced monitoring of the process parameters. The DRI trend as well as the analysis of the nitrogen content in the pile under curing suggested the need for more adequate aeration. This outcome can be considered not relevant as the overall biological stability level, although increasing over curing time, was still acceptable on the final product, indicating a moderately stable compost. However, it accounted for the scarce development of the compost agronomic properties, expressed as humic substances.

As the integration of in situ monitoring with lab-scale stability and maturity assessment results in additional operating costs, the proper monitoring of the conventional process parameters, at least temperature and moisture, should be implemented during the overall process and used to set up alert levels to address the periodic analysis of both stability and maturity more efficiently. This would enhance the confidence of stakeholders towards waste-based compost, thus improving the product competitiveness on the market of fertilizer.

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References

Adani, F., Tambone, F., Gotti, A., 2004. Biostabilization of municipal solid waste. Waste Manag. 24, 775–783. https://doi.org/10.1016/j.wasman.2004.03.007.

Alvarenga, P., Mourinha, C., Farto, M., Santos, T., Palma, P., Sengo, J., Morais, M.-C., Cunha-Queda, C., 2015. Sewage sludge, compost and other representative organic wastes as agricultural soil amendments: benefits versus limiting factors. Waste Manag. 40, 44–52. https://doi.org/10.1016/j.wasman.2015.01.027.

Alvarenga, P., Palma, P., Gonçalves, A.P., Fernandes, R.M., Cunha-Queda, A.C., Duarte, E., Vallini, G., 2007. Evaluation of chemical and ecotoxicological characteristics of biodegradable organic residues for application to agricultural land. Environ. Int. 33, 505–513. Environmental Contaminants and their Effects: Links Between Environmental Chemistry and Toxicologysixth Iberian and 3rd latinoamerican Congress on Contamination and Environmental Toxicology. https://doi.org/10.1016/j.envint.2006.11.006.

Baffi, C., Dell'Abate, M.T., Nassisi, A., Silva, S., Benedetti, A., Genevini, P.L., Adani, F., 2007. Determination of biological stability in compost: a comparison of methodologies. Soil Biol. Biochem. 39, 1284–1293. Organic Wastes in Soils Biochemical and Environmental Aspects. https://doi.org/10.1016/j.soilbio.2006.12.004.

Barrena, R., d'Imporzano, G., Ponsá, S., Gea, T., Artola, A., Vázquez, F., Sánchez, A., Adani, F., 2009. In search of a reliable technique for the determination of the biological stability of the organic matter in the mechanical–biological treated waste. J. Hazard. Mater. 162, 1065–1072.

Cerda, A., Artola, A., Font, X., Barrena, R., Gea, T., Sánchez, A., 2018. Composting of food wastes: status and challenges. Bioresour. Technol. 248, 57–67. Bioconversion of Food Wastes. https://doi.org/10.1016/j.biortech.2017.06.133.

Cesaro, A., Belgiorno, V., Guida, M., 2015a. Compost from organic solid waste: quality assessment and European regulations for its sustainable use. Resour. Conserv. Recycl. 94, 72–79. https://doi.org/10.1016/j.resconrec.2014.11.003.

Cesaro, A., Russo, L., Belgiorno, V., 2015b. Combined anaerobic/aerobic treatment of OFMSW: performance evaluation using mass balances. Chem. Eng. J. 267, 16–24. https://doi.org/10.1016/j.cej.2014.12.110.

Cesaro, A., Russo, L., Farina, A., Belgiorno, V., 2016. Organic fraction of municipal solid waste from mechanical selection: biological stabilization and recovery options. Environ. Sci. Pollut. Res. 23, 1565–1575. https://doi.org/10.1007/s11356-015-5345-2.

Chiumenti, A., 2015. Complete nitrification–denitrification of swine manure in a full-scale, non-conventional composting system. Waste Manag. 46, 577–587. https://doi.org/10.1016/j.wasman.2015.07.035.

Chowdhury, M.A., de Neergaard, A., Jensen, L.S., 2014. Potential of aeration flow rate and bio-char addition to reduce greenhouse gas and ammonia emissions during manure composting. Chemosphere 97, 16–25. https://doi.org/10.1016/j.chemosphere.2013.10.030.

Colón, J., Ponsá, S., Álvarez, C., Vinot, M., Lafuente, F.J., Gabriel, D., Sánchez, A., 2017. Analysis of MSW full-scale facilities based on anaerobic digestion and/or composting using respiration indices as performance indicators. Bioresour. Technol. 236, 87–96. https://doi.org/10.1016/j.biortech.2017.03.172.

de Guardia, A., Mallard, P., Teglia, C., Marin, A., Le Pape, C., Launay, M., Benoist, J.C., Petiot, C., 2010. Comparison of five organic wastes regarding their behaviour during composting: Part 2, nitrogen dynamic. Waste Manag. 30, 415–425. https://doi.org/10.1016/j.wasman.2009.10.018.

Faverial, J., Boval, M., Sierra, J., Sauvant, D., 2016. End-product quality of composts produced under tropical and temperate climates using different raw materials: a meta-analysis. J. Environ. Manag. 183, 909–916. https://doi.org/10.1016/j.jenvman.2016.09.057.

Grilli, S., Giordano, A., Spagni, A., 2012. Stabilisation of biodried municipal solid waste fine fraction in landfill bioreactor. Waste Manag. 32, 1678–1684. https://doi.org/10.1016/j.wasman.2012.04.022.

Guo, R., Li, G., Jiang, T., Schuchardt, F., Chen, T., Zhao, Y., Shen, Y., 2012. Effect of aeration rate, C/N ratio and moisture content on the stability and maturity of compost. Bioresour. Technol. 112, 171–178. https://doi.org/10.1016/j.biortech.2012.02.099.

Huguier, P., Manier, N., Chabot, L., Bauda, P., Pandard, P., 2015. Ecotoxicological assessment of organic wastes spread on land: towards a proposal of a suitable test battery. Ecotoxicol. Environ. Saf. 113, 103–111. https://doi.org/10.1016/j.ecoenv.2014.11.017.

Iqbal, M.K., Shafiq, T., Ahmed, K., 2010. Characterization of bulking agents and its effects on physical properties of compost. Bioresour. Technol. 101, 1913–1919. https://doi.org/10.1016/j.biortech.2009.10.030.

Jain, M.S., Daga, M., Kalamdhad, A.S., 2018. Composting physics: a degradation process-determining tool for industrial sludge. Ecol. Eng. 116, 14–20. https://doi.org/10.1016/j.ecoleng.2018.02.015.

Jara-Samaniego, J., Pérez-Murcia, M.D., Bustamante, M.A., Pérez-Espinosa, A., Paredes, C., López, M., López-Lluch, D.B., Gavilanes-Terán, I., Moral, R., 2017. Composting as sustainable strategy for municipal solid waste management in the Chimborazo Region, Ecuador: suitability of the obtained composts for seedling production. J. Clean. Prod. 141, 1349–1358. https://doi.org/10.1016/j.jclepro.2016.09.178.

Kazemi, K., Zhang, B., Lye, L.M., Cai, Q., Cao, T., 2016. Design of experiment (DOE) based screening of factors affecting municipal solid waste (MSW) composting. Waste Manag. 58, 107–117. https://doi.org/10.1016/j.wasman.2016.08.029.

Lü, F., Shao, L.-M., Zhang, H., Fu, W.-D., Feng, S.-J., Zhan, L.-T., Chen, Y.-M., He, P.-J., 2018. Application of advanced techniques for the assessment of bio-stability of biowaste-derived residues: a minireview. Bioresour. Technol. 248, 122–133. Bioconversion of Food Wastes. https://doi.org/10.1016/j.biortech.2017.06.045.

Luo, Y., Liang, J., Zeng, G., Chen, M., Mo, D., Li, G., Zhang, D., 2018. Seed germination test for toxicity evaluation of compost: its roles, problems and prospects. Waste Manag. 71, 109–114. https://doi.org/10.1016/j.wasman.2017.09.023.

Makan, A., Assobhei, O., Mountadar, M., 2013. Effect of initial moisture content on the in-vessel composting under air pressure of organic fraction of municipal solid waste in Morocco. Iran. J. Environ. Health Sci. Eng. 10, 3.

Manu, M.K., Kumar, R., Garg, A., 2017. Performance assessment of improved composting system for food waste with varying aeration and use of microbial inoculum. Bioresour. Technol. 234, 167–177. https://doi.org/10.1016/j.biortech.2017.03.023.

Meena, M.D., Joshi, P.K., Jat, H.S., Chinchmalatpure, A.R., Narjary, B., Sheoran, P., Sharma, D.K., 2016. Changes in biological and chemical properties of saline soil amended with municipal solid waste compost and chemical fertilizers in a mustard–pearl millet cropping system. Catena 140, 1–8. https://doi.org/10.1016/j.catena.2016.01.009.

Mejias, L., Komilis, D., Gea, T., Sánchez, A., 2017. The effect of airflow rates and aeration mode on the respiration activity of four organic wastes: implications on the composting process. Waste Manag. 65, 22–28. https://doi.org/10.1016/j.wasman.2017.04.008.

Meyer-Kohlstock, D., Schmitz, T., Kraft, E., 2015. organic waste for compost and biochar in the EU: mobilizing the potential. Resources 4, 457–475. https://doi.org/10.3390/resources4030457.

Onwosi, C.O., Igbokwe, V.C., Odimba, J.N., Eke, I.E., Nwankwoala, M.O., Iroh, I.N., Ezeogu, L.I., 2017. Composting technology in waste stabilization: on the methods, challenges and future prospects. J. Environ. Manag. 190, 140–157. https://doi.org/10.1016/j.jenvman.2016.12.051.

Oviedo-Ocaña, E.R., Torres-Lozada, P., Marmolejo-Rebellon, L.F., Hoyos, L.V., Gonzales, S., Barrena, R., Komilis, D., Sanchez, A., 2015. Stability and maturity of biowaste composts derived by small municipalities: correlation among physical, chemical and biological indices. Waste Manag. 44, 63–71. https://doi.org/10.1016/j.wasman.2015.07.034.

Pérez, D.V., Alcantara, S., Ribeiro, C.C., Pereira, R.E., Fontes, G.C., Wasserman, M.A., Venezuela, T.C., Meneguelli, N.A., de Macedo, J.R., Barradas, C.A.A., 2007. Composted municipal waste effects on chemical properties of a Brazilian soil. Bioresour. Technol. 98, 525–533. https://doi.org/10.1016/j.biortech.2006.02.025.

Pognani, M., Barrena, R., Font, X., Sánchez, A., 2012. A complete mass balance of a complex combined anaerobic/aerobic municipal source-separated waste treatment plant. Waste Manag. 32, 799–805. https://doi.org/10.1016/j.wasman.2011.12.018.

Pognani, M., Barrena, R., Font, X., Scaglia, B., Adani, F., Sánchez, A., 2010. Monitoring the organic matter properties in a combined anaerobic/aerobic full-scale municipal source-separated waste treatment plant. Bioresour. Technol. 101, 6873–6877. https://doi.org/10.1016/j.biortech.2010.03.110.

Ponsá, S., Gea, T., Alerm, L., Cerezo, J., Sánchez, A., 2008. Comparison of aerobic and anaerobic stability indices through a MSW biological treatment process. Waste Manag. 28, 2735–2742. https://doi.org/10.1016/j.wasman.2007.12.002.

Rasapoor, M., Adl, M., Pourazizi, B., 2016. Comparative evaluation of aeration methods for municipal solid waste composting from the perspective of resource management: a practical case study in Tehran, Iran. J. Environ. Manag. 184 (Part 3), 528–534. https://doi.org/10.1016/j.jenvman.2016.10.029.

Rasapoor, M., Nasrabadi, T., Kamali, M., Hoveidi, H., 2009. The effects of aeration rate on generated compost quality, using aerated static pile method. Waste Manag. 29,

570–573. https://doi.org/10.1016/j.wasman.2008.04.012.
Roletto, E., Barberis, R., Consiglio, M., Jodice, R., 1985. Chemical parameters for evaluating compost maturity. Biocycle 46–48 March.
Ruggieri, L., Gea, T., Mompeó, M., Sayara, T., Sánchez, A., 2008. Performance of different systems for the composting of the source-selected organic fraction of municipal solid waste. Biosyst. Eng. 101, 78–86. https://doi.org/10.1016/j.biosystemseng.2008.05.014.
Said-Pullicino, D., Erriquens, F.G., Gigliotti, G., 2007. Changes in the chemical characteristics of water-extractable organic matter during composting and their influence on compost stability and maturity. Bioresour. Technol. 98, 1822–1831. https://doi.org/10.1016/j.biortech.2006.06.018.
Saludes, R.B., Iwabuchi, K., Miyatake, F., Abe, Y., Honda, Y., 2008. Characterization of dairy cattle manure/wallboard paper compost mixture. Bioresour. Technol. 99, 7285–7290. https://doi.org/10.1016/j.biortech.2007.12.080.
Shen, Y., Ren, L., Li, G., Chen, T., Guo, R., 2011. Influence of aeration on CH4, N2O and NH3 emissions during aerobic composting of a chicken manure and high C/N waste mixture. Waste Manag. 31, 33–38. https://doi.org/10.1016/j.wasman.2010.08.019.
UNI 10802, 2013. Wastes - Manual Sampling and Preparation of Sample and Analysis of Eluates.
Vázquez, M.A., Sen, R., Soto, M., 2015. Physico-chemical and biological characteristics of compost from decentralised composting programmes. Bioresour. Technol. 198, 520–532. https://doi.org/10.1016/j.biortech.2015.09.034.
Viaene, J., Nelissen, V., Reubens, B., Willekens, K., Driehuis, F., De Neve, S., Vandecasteele, B., 2017. Improving the product stability and fertilizer value of cattle slurry solid fraction through co-composting or co-ensiling. Waste Manag. 61, 494–505. https://doi.org/10.1016/j.wasman.2016.12.037.
Villaseñor, J., Pérez, M.A., Fernández, F.J., Puchalski, C.M., 2011. Monitoring respiration and biological stability during sludge composting with a modified dynamic respirometer. Bioresour. Technol. 102, 6562–6568. https://doi.org/10.1016/j.biortech.2011.03.080.
Wang, S., Zeng, Y., 2018. Ammonia emission mitigation in food waste composting: a review. Bioresour. Technol. 248, 13–19. Bioconversion of Food Wastes. https://doi.org/10.1016/j.biortech.2017.07.050.
Wei, Y., Li, J., Shi, D., Liu, G., Zhao, Y., Shimaoka, T., 2017. Environmental challenges impeding the composting of biodegradable municipal solid waste: a critical review. Resour. Conserv. Recycl. 122, 51–65. https://doi.org/10.1016/j.resconrec.2017.01.024.
Yuan, Y., Tao, Y., Zhou, S., Yuan, T., Lu, Q., He, J., 2012. Electron transfer capacity as a rapid and simple maturity index for compost. Bioresour. Technol. 116, 428–434. https://doi.org/10.1016/j.biortech.2012.03.114.
Zhou, H., Zhao, Y., Yang, H., Zhu, L., Cai, B., Luo, S., Cao, J., Wei, Z., 2018. Transformation of organic nitrogen fractions with different molecular weights during different organic wastes composting. Bioresour. Technol. 262, 221–228. https://doi.org/10.1016/j.biortech.2018.04.088.
Zhou, Y., Selvam, A., Wong, J.W.C., 2014. Evaluation of humic substances during co-composting of food waste, sawdust and Chinese medicinal herbal residues. Bioresour. Technol. 168, 229–234. https://doi.org/10.1016/j.biortech.2014.05.070.
Zucconi, F., Monaco, A., Forte, M., De Bertoldi, M., 1985. Phytotoxins during the stabilization of organic matter. In: Gasser, J.K.R. (Ed.), Composting of Agricultural and Other Wastes. Elsevier Applied Science Publishers, London, pp. 73–86.